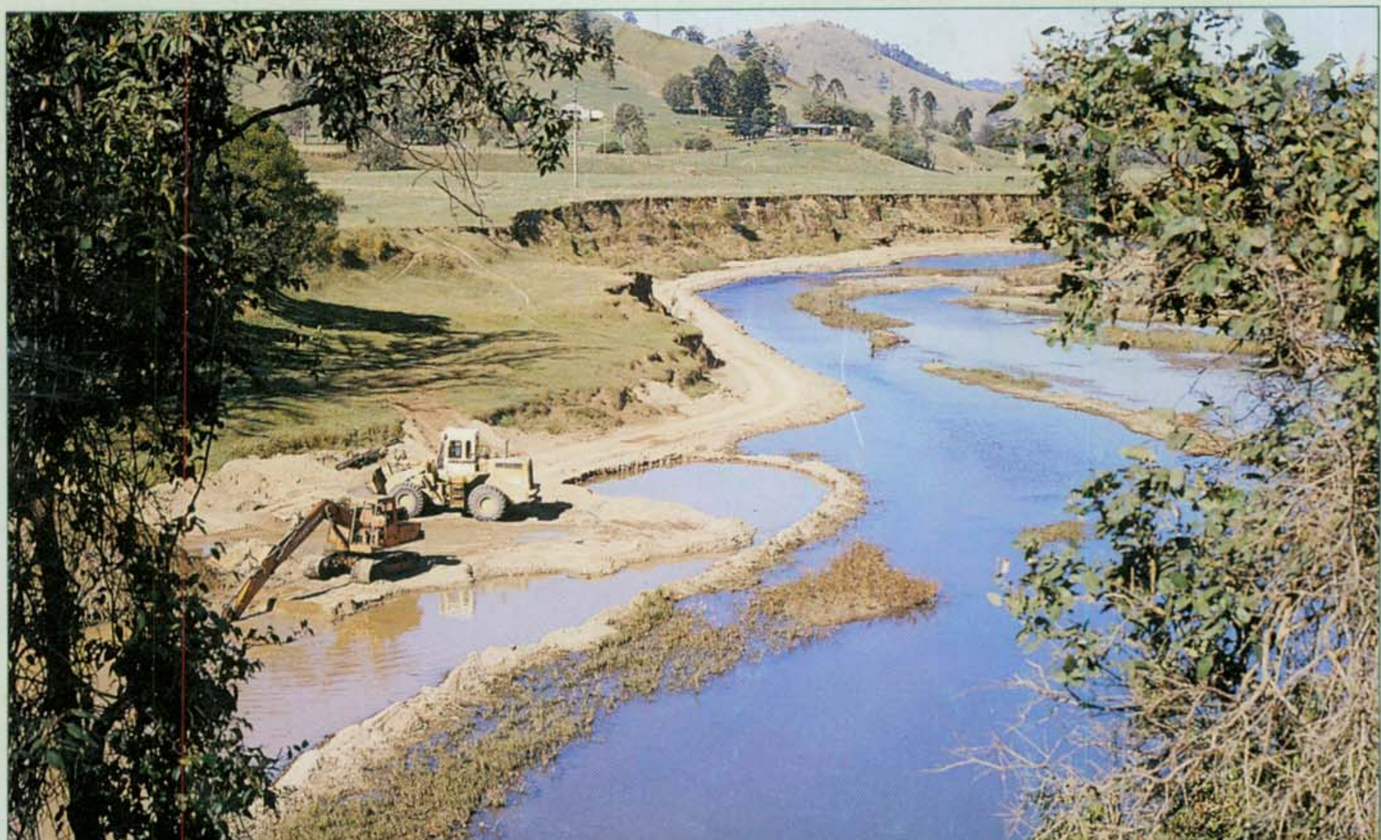
Proceedings of
FIRST NATIONAL CONFERENCE ON STREAM MANAGEMENT IN AUSTRALIA

STREAM MANAGEMENT '96



MERRIJIG

19 - 23 FEBRUARY 1996

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19-23 February 1996

Presented by

COOPERATIVE RESEARCH CENTRE FOR

CATCHMENT HYDROLOGY

Sponsored by

RIVER BASIN MANAGEMENT SOCIETY (Inc)

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Edited by
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Mark Walker

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Front Cover: Upper Mary River, Queensland (flow from right to left). The Mary River flows north from near Brisbane to Maryborough. About 100,000 m^3 of sand is extracted from the Mary River above Moy Pocket each year, which compares with the preliminary estimate of the average and maximum annual bedload transport rates or 6,000 m^3 and 27,000 m^3 respectively (Waye (1995) sand and gravel resources of the Mary River, QDPI, Water Resources Tech. info. Paper, Brisbane). There are anecdotal reports that rates of bank erosion have increased with the increase in sand extraction in the Mary River.
(Photograph: Ian Rutherfurd).

(**Please note:** captions for the photographs on the back cover are provided on the facing page on the inside of the back cover).

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PREFACE

River management is the art of human interference in streams systems to achieve some end. That end may be reduced flood frequency, improved habitat, improved fishing, reduced instability, or any number of other goals. The theme of this inaugural stream management conference is the management of change in stream morphology. Although this is only one element in river and catchment management, it is a good place to start what we hope will be a regular conference series.

In the past, in Australia, stream management has been very much a State responsibility, with little interaction between the States. This isolation is declining. There are papers in this volume dealing with stream management in every State and Territory, and this conference marks what is hoped will be increasing national cooperation in stream and catchment management. Furthermore, all of the authors in this volume would agree that these are exciting times for river managers in Australia. They are exciting because we have the convergence of four trends: first the waning of many forms of human impact on stream systems; second, an increasing understanding of stream processes; third, the rise of an holistic view of catchment management; and fourth, the decline of public involvement in the water industry, coupled with a rise in local control of management priorities.

The 52 papers collected in these proceedings are loosely grouped into five themes that reflect these trends in stream management.

1. Our understanding of stream erosion and sedimentation is improving. This is reflected in better understanding of the sources of sediment in a catchment, and the movement of sediment through various stores. Conceptual and numerical models are increasingly able to predict changes in these sources and sinks given a change of inputs (eg. a dam, gravel extraction, greenhouse effect, etc.).

2. We have a growing appreciation of the relative role of human impact (eg. clearing vegetation and channelisation) against the natural variation in the rates of erosion and sedimentation (eg. catastrophic floods).

3. Revegetation, particularly riparian vegetation, is becoming the primary tool in stream management, and research in this area is growing.

4. Restructuring of the water industry in Australia, and a redirection of public resources, has seen an increasing role for catchment-based community groups in stream management, and new roles for State government authorities.

5. Catchment-based management has also led to broader definitions of stream management. We have several papers that discuss the resolution of conflicts around the use of land in catchments, and the allocation of water in regulated systems.

It is also important to consider the themes in stream management that are not well represented in this suite of conference papers. Of course, these absences may reflect the people attracted to the conference, but they are worth noting. First, there is only one paper that considers the design of engineering structures for stream management. We suspect that if we had had this conference twenty years ago, it would have been dominated by such papers. Second, apart from vegetation issues, there are few papers that consider the links between stream management and stream ecology. Again, we predict that if we had this conference in ten years time, such papers would be common, as stream 'restoration' becomes our management goal.

We would like to thank Michael O'Brien and Maureen Kemp of the Office of Continuing Education at Monash University who have tirelessly managed much of the conference administration, and assisted in the printing of these proceedings.

Ian Rutherfurd
Mark Walker

Cooperative Research Centre for Catchment Hydrology
Monash University

AUTHOR INDEX

The contribution of channel banks and gully walls to total phosphorus loads in the Murrumbidgee River

P.J. Wallbrink*, J.M. Olley*, A.S. Murray* and L.J. Olive**

ABSTRACT: *It is important that land managers have a quantitative understanding of the relative contributions to the suspended sediment and nutrient loads in our inland waterways of topsoil and subsoil. This is especially so in view of the increased frequency of algal blooms and the fact that P has been identified as a key nutrient for algal growth. This paper argues that the sediment load in the lower Murrumbidgee River is dominated (90%) by subsoil material from channel banks and gully walls primarily from tributary catchments between Burrinjuck Dam and Wagga Wagga. Particulate phosphorus concentrations measured in Murrumbidgee channel and tributary sediments, are consistent with those observed in the fine fractions of catchment soils, suggesting that the source of P is predominantly natural. This is supported by the uniform concentration of P along the length of the Murrumbidgee channel, which show no evidence of significant point source impact. In combination the data suggest that the concentrations of P in the Murrumbidgee suspended sediments are derived from subsoil sources within the tributary catchments between Burrinjuck Dam and Wagga Wagga.*

1. INTRODUCTION

1.1 The Murrumbidgee catchment

The Murrumbidgee River is one of Australia's largest inland rivers and drains approximately 84,000 km^2 of the Murray Darling Basin (see Figure 1). The river rises in the Snowy Mountains and flows through undulating terrain to Wagga Wagga. Between Gundagai and Wagga Wagga the river has formed a well defined floodplain approximately 1 to 2 km wide (Page, 1994). Downstream of Wagga Wagga the gradient decreases and the floodplain width increases to between 5 and 20 km. At Narrandera the Murrumbidgee enters the Riverine Plain and from there follows a highly sinuous course to its junction with the Murray River below Balranald. The area studied extends from Burrinjuck and Blowering Dams downstream to the Murray junction. In this reach most of the major tributaries join the river between the storages and Wagga Wagga. Downstream of Wagga Wagga there are a number of distributaries.

Grazing is the main land use in the upper basin. The more undulating area around Wagga Wagga is a major grain producing area. There is extensive grazing in the Riverine and Hay plains, with intensive cropping in the irrigation areas. A strong rainfall gradient exists across the basin and most of the downstream flow is derived from the storage reservoirs (Burrinjuck and Blowering) and the tributaries upstream of Wagga Wagga. Maximum discharge is at Wagga Wagga; downstream the river enters a semi-arid area and there is a progressive decrease in flow with distance.

The river is a major supplier of irrigation water and flow is heavily regulated, both by the two major dams and a series of weirs below Wagga Wagga. The flow regime before regulation was highly variable with a winter maximum. However the combination of regulation and extraction for irrigation has resulted in a major change with flow now being spring and summer dominated when water demand by irrigators is highest.

1.2 The Problem

In recent years there has been wide-spread community concern about turbidity and the occurrence of algal blooms in the lower Murrumbidgee River. It is widely believed that the recent blooms in rivers such as the Murrumbidgee are due to elevated nutrient levels. Diffuse anthropogenic sources (eg. agricultural fertiliser) and point sources (sewage treatment plants, feedlots etc.) are often considered the most likely cause of this enhancement (Bek and Robinson, 1991).

In the generally turbid waters of rivers such as the Murrumbidgee, phosphorus is predominantly bound to particles (Oliver, 1993). Therefore if P levels in the Murrumbidgee have increased as a result of human activity, it would be expected that P concentrations on the suspended sediments would be higher than those present on unfertilised catchment

*CSIRO, Division of Water Resources, PO Box, 1666, ACT, 2601, Australia
Tel (06) 246 5823 Fax (06) 246 5800 Email wallbrin@cbr.dwr.csiro.au
** Australian Defence Force Academy, (ADFA), Northcott Drv. Campbell, 2600, ACT, Australia

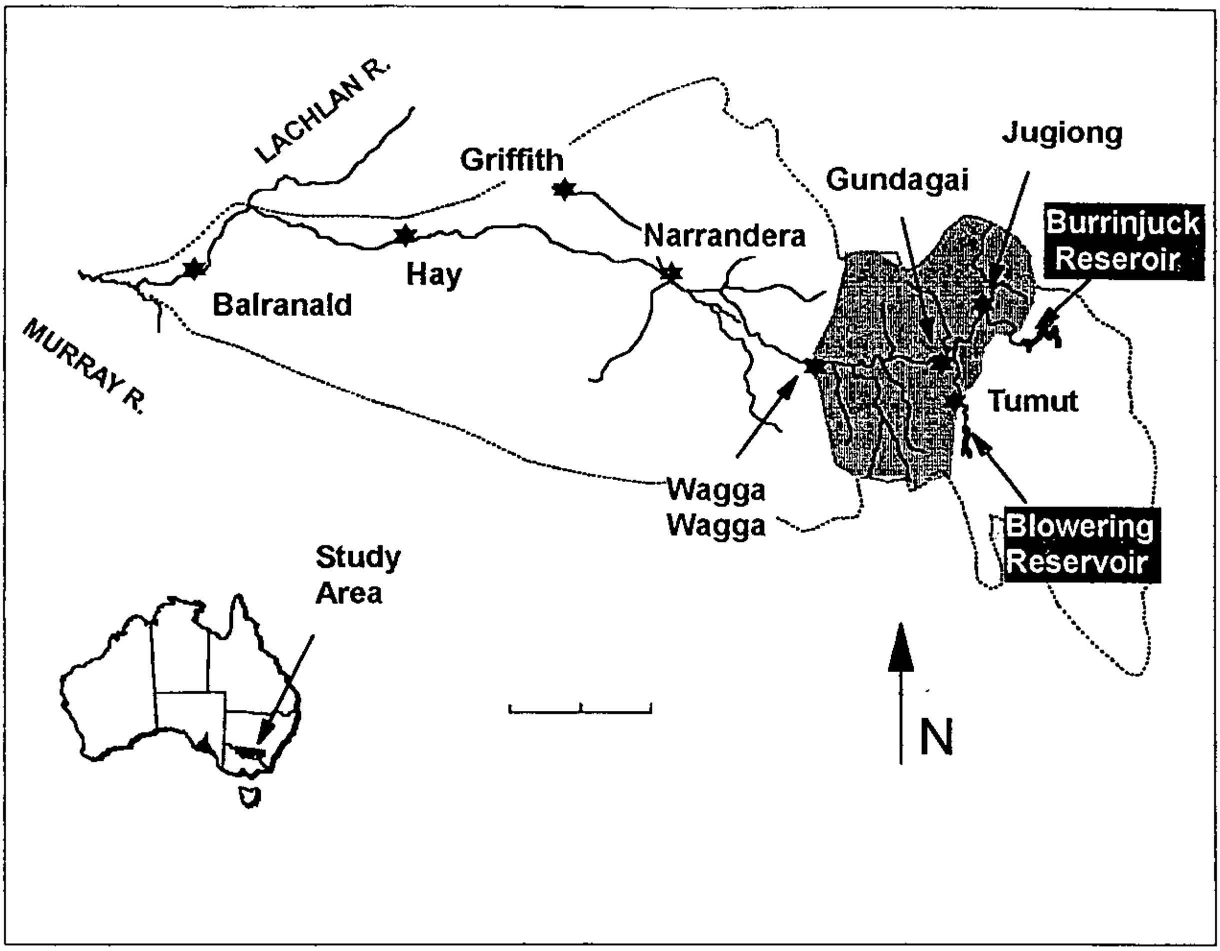

Figure 1: Location diagram of Murrumbidgee catchment, NSW, Australia.

soils. More importantly, if the phosphorus is being derived from fertilised farmland then a significant topsoil component in the suspended sediments of the Murrumbidgee River would be expected. Consequently in order to investigate the source of P to the Murrumbidgee river we have i) determined the relative contribution of topsoil to the suspended sediment load using fallout ^{137}Cs and ii) compared P concentrations on suspended sediments with those in unfertilised catchment soils.

2. MATERIALS AND METHODS

2.1 Catchment sampling strategy

Measurements of ^{137}Cs and P have been undertaken on soils and suspended sediments. The soils in the catchment were sampled both by depth and lithology (two types of granite and an Ordovician metasediment) and taken from locations at which it was believed that no addition of phosphorus had occurred. About 25 % of the samples were from the soil surface and 75 % were from subsoils, to about two metres soil depth.

The suspended sediment samples were obtained by a CFC (continuous flow centrifuge, Alfa Laval model M102b) which can accumulate masses up to 300 grams. Suspended sediment samples were taken from the larger tributaries; Adelong, Jugiong, Tarcutta, Billabung, Kyeamba, Tumut and the Lachlan River, just upstream of their junction with the main Murrumbidgee channel. They were also taken from thirteen sites along the main channel between the towns of Jugiong and Balranald (approx. 1,000 km dist.). Sampling was undertaken over a period of four years in a range of conditions from baseflow to a one in 12 year flood event.

2.2 ^{137}Cs radioactivity

The anthropogenic radionuclide ^{137}Cs has been used extensively in erosion studies to distinguish surface soil from subsoil (eg Ritchie et al., 1974; Burch et al., 1988; Walling and Woodward 1992; Wallbrink and Murray, 1993). Fallout of this nuclide was derived from atmospheric testing of atomic weapons during and after the 1950's. While deposition of ^{137}Cs in Australia began in 1954 it did not reach levels detectable today until about 1958 (Olley et al., 1991). Fallout essentially ceased in the mid 1970's. In south-east Australia detectable ^{137}Cs tends to occur in only the top 100 to 200 mm of soil profiles (Wallbrink and Murray, 1993). Therefore, it is an ideal tracer to examine the relative contributions of surface to subsoils in suspended sediments. ^{137}Cs concentrations were determined by high resolution gamma spectrometry, as described by Murray et al. (1987).

2.3 Phosphorus

The concentrations of total phosphorus in soils and sediments were measured using standard X-ray fluorescence (XRF) and are given as weight percent P. Concentrations were determined using a Phillips PW1404 spectrometer; samples were prepared according to the method described by Norrish and Chappel (1977).

3. RESULTS

3.1 ^{137}Cs Concentrations in suspended sediments

The ^{137}Cs concentrations in suspended sediment samples from the Murrumbidgee and its tributaries are all generally low, less than 3 Bq/kg (see Table 1). The average value of all the samples collected along the main channel is 2.38 $\pm$ 0.13 (n=164) and from the tributaries, 2.29 $\pm$ 0.19 (n=49) (see Table 1). These are statistically indistinguishable and support the hypothesis of Olive et al; (1994a) that most of the suspended sediment in the main channel is derived from the tributaries which enter the river below Burrinjuck Dam and above Wagga Wagga. This zone has been defined by the hatched area given in Figure 1.

Location	^{137}Cs (Bq/kg)	se	(n)
Main Channel	2.38	0.13	164
Tributaries	2.29	0.19	49
Topsoil sediment	26.4	4.9	190

Table 1: ^{137}Cs concentrations in suspended sediment from the Murrumbidgee catchment.

The average ^{137}Cs concentration of the surface derived fine particles is about 26 $\pm$ 5 Bq/kg (n=190), see Table 1. The considerable difference between this value and those observed on the suspended sediments can be explained in terms of dilution by subsoil material, which is not labelled by ^{137}Cs. About 90 % of non-labelled subsoil is required to dilute these surface concentrations to those observed in the Murrumbidgee river.

The ^{137}Cs concentration values from the tributaries, channel and topsoils can also be used to estimate the proportion of fines derived from surface versus gully erosion processes. Unlabelled subsoils are usually derived from channel or gully wall collapse. When this collapse occurs a topsoil contribution is also added to the volume of sediment entering the drainage line. The fine grained fraction of topsoil will be labelled by ^{137}Cs (at approximately 26 $\pm$ 5 Bq/kg), however it will be diluted to approximately 0.7 $\pm$ 0.2 Bq/kg if the channel walls are about 4 m in height (a reasonable estimate of bank height within the Murrumbidgee channel below Wagga Wagga). The collapse of a 2 m section of wall (such as typically found within the tributary catchments) would produce fine grained sediments with an average net ^{137}Cs signature of approximately 1.3 $\pm$ 0.3 Bq/kg.

These data can be used to calculate an upper limit to the relative contribution to total sediment load in the Murrumbidgee by sediment derived from surface erosion processes alone. If the tributary ^{137}Cs concentration is C_T, the predicted concentration from channel/gully erosion is C_G, and the concentration from sheet/rill erosion is C_S, then the fractional contribution F_S of sheet/rill erosion in the sediment derived from the tributaries is:

$$F_S = \left(\frac{C_T - C_G}{C_S - C_G}\right) \times 100$$

Substituting the values given in Table 1 gives a limit to the sheet/rill contribution of < 4 %.

3.2 Phosphorous in soils

Estimates of the natural concentrations of P in Murrumbidgee soils were first obtained by Colwell (1977), who reported concentrations on 41 Murrumbidgee catchment soils. In this study an additional 48 samples were collected from the locations described in section 2.1. In combination these 89 soils are considered to be typical of the region and P concentrations are in the range 0.009 to 0.062 wt% P, mean 0.030 $\pm$ 0.001 (see Table 2).

3.3 Effects of fluvial sorting

It is known that fine soil particles contain the highest concentrations of P. In non-aggregated soils, such as those in the Murrumbidgee catchment,

Location	Phosphorus (wt %) measured range	Phosphorus (wt %) mean	Number of samples (n)
Soils			
Soils (bulk)	0.009 - 0.061	0.03 ± 0.001	89
Soils (<2 μm)	0.025 - 0.157	0.07 + 0.01	12
Sediments			
Tributaries (susp. sed.)	0.026 - 0.137	0.065 ± 0.004	87
Main Channel (susp. sed.)	0.060 - 0.210	0.096 ± 0.004	134

Table 2: Summary of Phosphorus concentrations of sediments and soils within the Murrimbidgee

the fine soil fraction (<2 μm) can be enriched in P over the bulk soil by up to 10 times (Sharpley and Menzel, 1987). Krumbein and Sloss (1963) also suggest that fluvial transport will result in a gradual decrease in average particle size by selective transportation. This effect has been examined in 12 Murrumbidgee catchment soils in wet sieving and particle size settling experiments. The concentration of P on the < 2 μm fraction ranged from 0.025 to 0.157 wt% (Table 2); a maximum concentration factor of about 6 was observed compared to initial bulk concentrations. It should also be noted that the soils chosen for particle size analysis did not contain the highest phosphorus concentrations and it is possible that clay fractions from other soils within the catchment may have higher phosphorus concentrations than those reported here.

3.4 **Phosphorous in tributary sediments**

The P concentration of suspended sediments from the tributaries were analysed from samples collected using the CFC and rising stage samplers, (installed by N.S.W. Department Water Resources). A summary of these data are presented in Table 2 and all tributary values fall below the maximum concentration observed in the <2 μm fraction from the catchment soils.

3.5 **Phosphorus in channel sediments**

P concentrations were also analysed on 134 separate suspended sediment samples taken from the main Murrumbidgee channel between Burrinjuck Dam and Balranald (see Table 2). More than 94 % of these data had values lower than the maximum observed from the sieved soil. These data, as well as those from the tributaries, have been plotted against

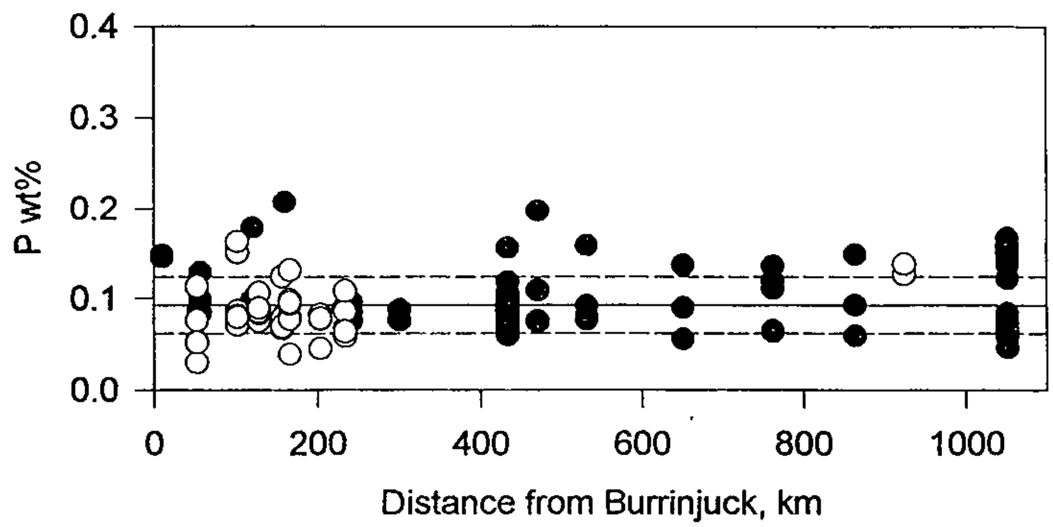

Figure 2: Phosphorus concentrations in suspended sediments from the main Murrumbidgee channel (closed circles) and its tributaries (open circles) plotted against sampling distance from Burrinjuck Dam.

river length to determine the possible influence from point sources (Figure 2). There is no systematic variation in the phosphorus concentrations with distance. In particular there is no increase in P concentration on these particles downstream of the Wagga Wagga sewage works, which used to enter the river at about 230 km on the scale in Figure 2. This lack of significant variation in concentration with river length indicates that inputs from point sources are not important compared to diffuse loads of P (eg. Olive et al., 1994b).

4. DISCUSSION

Concentrations of ^{137}Cs on suspended sediments derived from topsoil erosion processes alone are high. In contrast the concentrations observed on similar sized particles in the Murrumbidgee River and its tributaries are very low. The difference between the two is most probably due to dilution by a substantial amount of unlabelled subsoils derived from gully wall and channel bank erosion. The amount of contribution from surface soil (ie 0-10 cm depth) to total suspended sediment load is calculated to be less than ten percent. The ^{137}Cs concentrations measured in the channel are consistent with those from the tributaries between the dams and Wagga Wagga. This supports the evidence from flow and turbidity data which indicates that these tributaries are the main source of suspended sediment to downstream channel flow, (Olive et al., 1994b). The low ^{137}Cs concentrations at the tributary outlets also suggest that most of the subsoil contribution has occurred within these upland catchments prior to entering the Murrumbidgee River itself.

The concentrations of P measured in suspended sediments throughout the main channel and its tributaries are consistent with those from the fine fractions of a representative selection of catchment soils. Indeed, the mean phosphorus concentrations observed within the tributary and channel sediments are only factors of 2 and 3 respectively, above the mean bulk soil P concentration. Within our own limited number of fine samples extracted from bulk soils we have observed concentration factors up to 6 times. Others, (Sharpley and Menzel, 1987) report factors of up to 10. It must be concluded that the argument for a significant addition of particulate P by importation (eg fertilisers) to the catchment is weak. Further evidence for this is given by the uniform concentration of P observed along the length of the main river channel.

5. CONCLUSIONS

The data presented here strongly infer that the major source of particulate P to the Murrumbidgee channel is natural. The ^{137}Cs data also suggest that P is predominantly provided by erosion of subsoil material from channel banks and gully walls of the tributary catchments upstream of Wagga Wagga and below Burrinjuck Dam.

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WATER TURBIDITY AND CATCHMENT MANAGEMENT WITHIN THE MURRAY RIVER SYSTEM

John O'Donnell[1], Laurie Olive[2], David Lamb[3]

ABSTRACT

Turbidity can reach high levels in the Murray River catchment, particularly during flood events. The Murray Sediment Working Group was established in November 1994 and is comprised of agencies in Victoria and NSW. One of the major tasks of this group was to collect daily water turbidity data from Water Treatment Plants along the Murray and tributary rivers. A computer-based data set has now been assembled using data from ten plants. A number of other projects have also been completed including a comparison of water turbidity data with daily flow levels and an airborne video exercise to evaluate the potential of remotely estimating water quality from the air. These activities will all be discussed.

1. INTRODUCTION

Turbidity represents the light scattering properties of water and is commonly reported in Nephelometric Turbidity Units (NTU). Turbidity in water is caused by suspended matter such as clay, silt, finely divided organic and inorganic material and soluble coloured organic compounds (Olive and Fredericks, 1995). The Murray River is used for a wide variety of purposes, many of which are not compatible with high turbidity levels. Highly turbid water can affect irrigation and industrial water users and recreational users. It can also interfere with the growth of aquatic plants and fish (Murray et al, 1993).

The paper is broken up into four major parts, and includes information on the Murray Sediment Working Group; an assessment of daily water turbidity data at seven Water Treatment Plants (WTPs); an airborne video water quality assessment project along the Murray River and consideration of future actions of the Murray Sediment Working Group and researchers.

2. MURRAY SEDIMENT WORKING GROUP

During November, 1994 a meeting was convened by the NSW Environmental Protection Authority (EPA) to discuss turbidity issues, problems and use of Water Treatment Plant datasets in the Murray River Catchment above the Murrumbidgee River Junction. Representatives from both NSW and Victoria attended this meeting as did experts in the turbidity/sediment field from CSIRO Division of Water Resources and Australian Defence Force Academy (ADFA) in Canberra. One of the outcomes of this meeting was the establishment of the Murray Sediment Working Group. This working group includes representatives from the NSW EPA, NSW Murray Catchment Management Committee, NSW Department of Land and Water Conservation (2 representatives), Victorian Department of Conservation and Natural Resources, Goulburn-Murray Water and the Victorian EPA. The working group is chaired by the NSW EPA. Meetings were conducted in November 1994, January 1995 and May 1995. To date, a major focus of the working group has been the collection and input of the raw WTP turbidity data into the computer package Excel. WTP data is valuable since it is measured using Hach turbidity meters and is normally collected on a daily basis. The best similar data in the catchment is collected weekly on behalf of the Murray-Darling Basin Commission. Other data, including raw water colour and pH was also collected and entered into the computer. In many cases the data has been collected for long periods, for example Mulwala since 1944 and Echuca since 1971. Given that flood events are often of short (2-3 days) duration (Olive and Fredericks, 1995) and may not be sampled by weekly monitoring, daily data sets more accurately

[1] NSW Environment Protection Authority, P.O. Box 544 Albury, Telephone: (060) 414963, Fax: (060) 414973
[2] Australian Defence Force Academy, Canberra
[3] Charles Sturt University, Wagga Wagga

reflect the increases in turbidity associated with flood peaks much better than weekly data. The data sets collected include Albury, Mulwala, Yarrawonga, Cobram, Echuca, Swan Hill, Wangaratta, Shepparton, Deniliquin and Jerilderie (Figure 1). This data was entered into the Excel by two systems. One involved the input of data as part of a consultancy for the NSW EPA by the Australian Defence Force Academy (ADFA) and the other was through a Skillshare project.

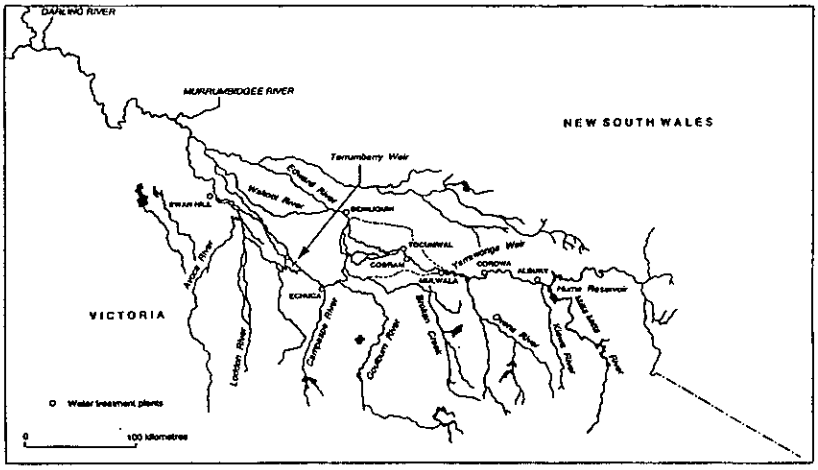


Figure 1. River Murray

3. DAILY WATER QUALITY PROJECT FOR SEVEN WATER TREATMENT PLANTS ALONG THE MURRAY RIVER SYSTEM

This project was undertaken by ADFA as a consultancy for the NSW EPA, with CSIRO Division of Water Resources being the project manager. The project involved the input of daily raw water WTP data into Excel (turbidity, colour, pH), analysis of this data against Murray River and tributary flow levels and where possible determination of the main sources of turbidity. This was completed for seven sites including Albury, Mulwala, Tocumwal, Cobram, Echuca, Swan Hill and Deniliquin. Six reports have been prepared by Olive and Fredericks (1995) for these WTPs with one report being produced for Tocumwal and Cobram due to the proximity of the two sites. It must be emphasised that the data in these reports is raw with minimal checks on the accuracy of observations and no cross calibration between locations. However turbidity is determined with HACH turbidity meters at all locations with regular internal calibration checks and the data does reflect the pattern of responses.

3.1 Albury

The turbidity response of the Murray River at Albury (Albury WTP) during flood events is relatively small (Olive and Fredericks, 1995). This was based on WTP data between May 1992 and December 1994. This response pattern is likely to be related to the location at Albury; immediately downstream of the Hume Weir on the Murray and Dartmouth Dam on the Mitta Mitta. Both of these structures act as sediment traps which result in a reduction of turbidity in discharged waters (Thoms and Walker, 1991).

3.2 Tocumwal/Cobram

WTP records of turbidity span the period of June 1986 to April 1995 for Cobram and January 1991 to December 1993 for Tocumwal. The report of Olive and Fredericks(1995) concluded;

* highest turbidity levels are associated with floods;
* duration of very highly turbid flows is generally only 1-3 days;
* daily flow data cannot be used to infer turbidity fluctuations because of the variation in flood sources;

* high turbidities are generally associated with floods from, or which include a large proportion of flow from the tributaries downstream of Albury rather than from the catchment upstream of Hume Weir. This is emphasised in Figure 2.

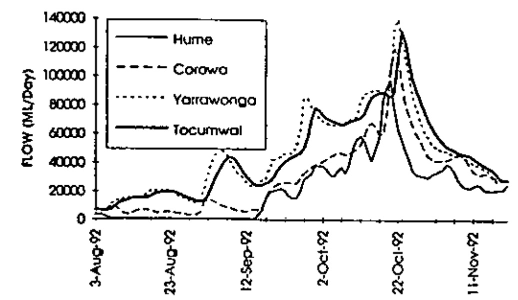
* there is a large difference in observed turbidities at Tocumwal and Cobram. However, the trends in turbidity are very similar at the two locations (refer to figure 2). More recent data indicates that it is possible that the Tocumwal WTP may be overestimating turbidity.

* high turbidities are associated with floods with the highest turbidities levels associated with the large floods of 1973 and 1974. The turbidity in one flood event in 1974 reached 450 NTU;

* the turbidity showed a peak response pattern during floods despite the subdued flood hydrographs;

* there are marked turbidity rises associated with the early winter relatively small river rises and then a decrease in the magnitude of subsequent responses (Figure 3);

* many turbidity peaks are associated with flood events in the Goulburn River, while others are associated with flow events in tributaries further upstream with the peak transmitted downstream though the system.



Murray River flood hydrographs 1992.

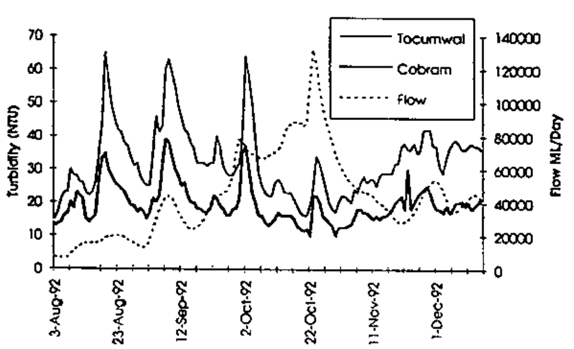


Figure 2. Murray River at Cobram/Tocumwal, flow and turbidity 1992

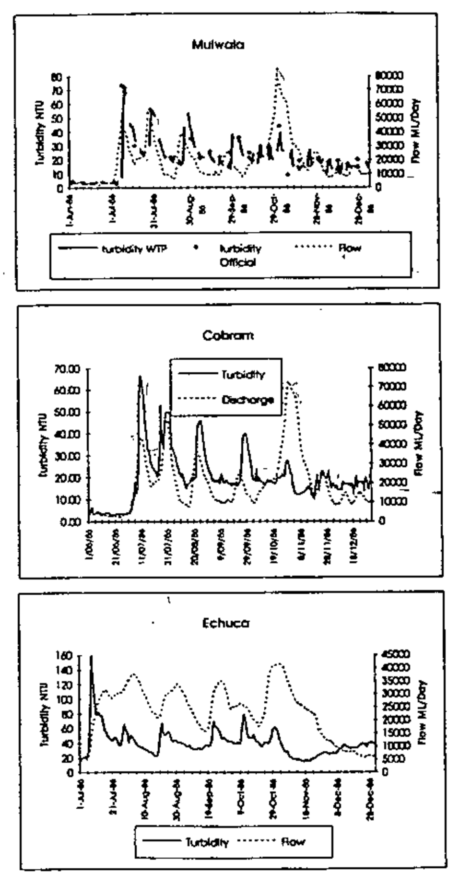


Figure 3. Flood hydrographs and turbidity at Mulwala, Cobram and Echuca during the 1986 flood

3.3 Echuca

Echuca WTP records of turbidity span January 1971 to March 1995. The Echuca report concluded;

Further detailed information on each of these sites can be obtained from the six individual reports.

4. MURRAY AIRBORNE VIDEO PROJECT

In February, 1995 an exercise was carried out along the Murray River to evaluate the potential of an airborne video system (ABVS) to measure a number of selected water quality parameters from the air including turbidity, total suspended solids and apparent colour. The ability to remotely assess water quality parameters from the air provides the user with the potential to save the many person-hours consumed with routinely obtaining and analysing water samples in the field, an ability to extend assessment over a much larger area, an unlimited increase in density of effective sampling points and allows access into regions often unavailable for ground-based sampling. Advantages associated with airborne video over other aerial imaging techniques include high-medium ground resolution (0.7-3.0 m), high revisit capability and provision of multi-spectral digital images. The ABVS comprises 4 downward-looking high resolution video cameras, along with camera controlling and image acquisition hardware, carried in a Cessna 210 aircraft. Each camera acquires information in a preset spectral band determined by an interchangeable filter. General purpose imaging filters of blue (450 nm), green (550 nm), red (650 nm)and near infrared (770 nm) were used. Composite multi spectral images are acquired and recorded using a frame grabber and a 486 computer (Louis et al, 1995). A global positioning system (GPS) is incorporated into the system to automatically provide location coordinates for each image. Images were obtained at 26 specific locations in a region stretching from Khancoban to the junction of the Murray and the Murrumbidgee Rivers, where water samples were acquired for laboratory/field testing of parameters including turbidity, suspended solids and apparent colour (Clesceri et al, 1989). The raw digital information provided by ABVS imagery was used to assess the correlation with one or more of the measured water quality parameters from the sample sites. Images were obtained at other non-sample sites for estimation of the water parameters based on the calibration provided by the sample sites. Reasonable levels of rainfall were recorded over the catchment in the weeks immediately preceding the flight, resulting in rain rejection flows in the Murray River, downstream from Lake Mulwala, at the time of the flight. The locations of sampling sites were determined by the Environmental Protection Authority prior to the flight. Extracting the digital information from each image was performed on a SUN workstation using a conventional image processing software package. Linear multiple regression analyses, based on least squares, were performed to link the digital information from images of the sample sites to measured values of turbidity, total suspended solids and apparent colour. The resulting equations are listed in Table 1. The R^2 values of each regression equation suggests a significant correlation exists between the combined waveband data and each water quality parameter.

Water quality parameter	Intercept	Infrared coefficient	Red coefficient	Green coefficient	Blue coefficient	R^2	No. sample sites used
Combined Turbidity	-1.80051	0.524678	0.541532	1.182209	-1.48641	0.844	21
Horiba Turbidity	-35.9102	3.975116	-1.63118	2.915288	-2.577	0.968	8
Total Suspended Solids	-52.5023	3.621483	-0.91218	-1.97971	1.600126	0.994	9
Apparent colour (EPA lab)	224.238	-2.056	8.485	1.736	-8.745	0.971	10

Table 1. Regression coefficients for fitted data.

Note: The value of each water quality parameter = Intercept + (a x IR) + (b x R) + (c x G) + (d x B), where a, b ,c and d are the infrared, red, green and blue regression coefficients respectively.

Figure 4, for example, compares values of turbidity calculated from the regression equation with those measurements obtained from the sample sites. If the regression equation was 100% accurate then data would lie on a 45^{o} line (indicated by a solid line).

The established regression equations were then used to estimate values of turbidity, suspended solids and colour for the other non-sampled sites, resulting in a synoptic profile along the extent of the Murray River covered in the mission.

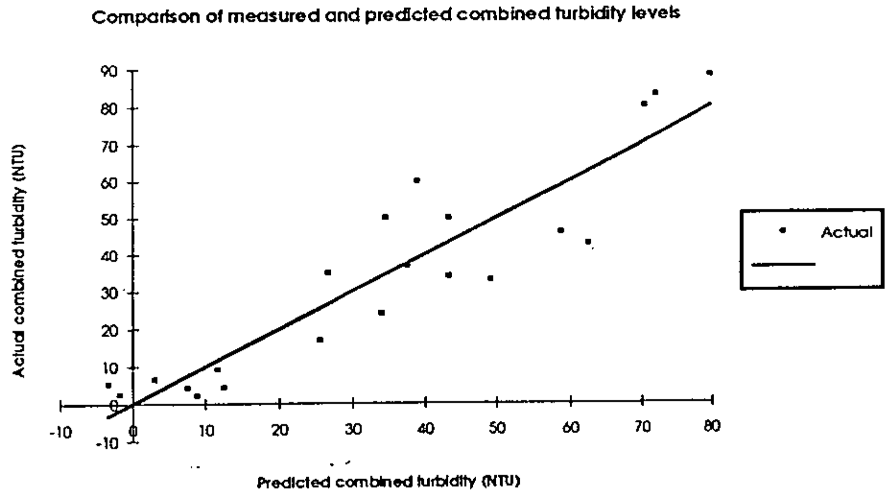


Figure 4. Comparison of predicted turbidity (NTU) from regression equation and measured value.

The results of this preliminary work has clearly demonstrated the potential of an airborne video system for estimating selected water quality parameters from the air. Although in this mission strong correlations were identified between each measured water quality parameter and raw information provided by the ABVS, further work is required to reduce the standard error associated with the estimation of parameters at image-only sites (for example approximately 10 NTU for turbidity). This will include developing the ABVS to provide target reflectance data rather than raw data, a detailed characterisation of water quality parameters and their effect on detected radiance, use of river-only calibration sites and careful selection of appropriate water quality filters.

5. FUTURE ACTIONS OF THE MURRAY SEDIMENT WORKING GROUP AND RESEARCHERS.

The Murray catchment now has many valuable new datasets for use in understanding turbidity and sediment sources. Such information allows for an improved assessment of loads of sediments, and potentially nutrients, and for the ranking of projects by catchment committees. The Murray Sediment Working Group, and researchers including Mr L Olive, Mr D Post and Dr D Lamb, is now in an excellent position to further develop this work. Options currently under consideration include;

i. calibration of daily turbidity and suspended solid data at all WTPs and use of this data in sediment load estimation.

ii. assessment of attributes of all catchments and effect of attributes on water quality;

iii. attaining a better understanding of the high initial turbidity levels resulting from early winter flooding events, and consequent sediment exhaustion with later events;

iv. assessment of the influence of rainfall intensity on turbidity levels;

v. consideration of radionuclide studies to assess topsoil and subsoil influence on turbidity.

vi. further refinement of the air video technique to further improve estimates of water turbidity and suspended solids.

6. CONCLUSIONS

The main findings and conclusions of this paper are highlighted below:

*The Murray Sediment Working Group has obtained ten daily turbidity datasets for the Murray River catchment. These datasets more accurately reflect fluctuations in turbidity associated with flood peaks than weekly data since flood events most often occur over a duration of a few days.

*Highest turbidity levels are associated with floods

*At Tocumwal and Cobram WTPs, high turbidities are generally associated with floods from, or which include a large proportion of, flow from the tributaries downstream of Albury.

*At Echuca WTP, many turbidity peaks are associated with flood events in the Goulburn River, while others are associated with flow in tributaries further upstream.

*An airborne video system has clearly demonstrated its potential for assessing water quality from the air. Strong correlations were identified between measured water quality parameters and raw digital number information provided by the ABVS, allowing an estimation of the same parameters from images taken at selected locations along a major inland river. Further work is required to improve the accuracy of estimation of water quality parameters.

*The Murray Sediment Working Group, and associated researchers, is currently considering six options to progress understanding of turbidity and suspended solids in the Murray River.

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The Sources Of Sediment In The Darling-Barwon Rivers: Some Preliminary Results

G. Caitcheon, J. Olley, and A. Murray *

ABSTRACT: *Major element chemistry and naturally present magnetic minerals are used to trace the source of sediment in the Darling-Barwon Rivers. Specifically, we show that basalt derived sediment is likely to be a major source, and by inference a significant source of particulate bound phosphorus. Data from the Barwon-Namoi confluence show that the contemporary sediment and phosphorus contribution by the Namoi River may be as much as 30-40%. Data from undated core sediment indicate that a long term average of <10% is likely.*

1. INTRODUCTION

The massive algal bloom that occurred along the Darling River in late 1991 resulted in a considerable increase in research to determine the causes of such blooms. One of these studies is a collaborative effort between the Water Studies Centre at Monash University, the Murray-Darling Freshwater Research Centre at Albury, and the CSIRO, Division of Water Resources, Canberra. The study is partially funded by the Murray-Darling Basin Commission as part of the Natural Resources Management Strategy, and aims to understand the sources and cycling of nutrients, as well as the conditions that promote algal growth in the Darling-Barwon Rivers.

One of the objectives of the CSIRO part of the study is to identify the sources of phosphorus reaching the river. We have concentrated on tracing phosphorus associated with fine suspended sediment that makes up about 95% of the rivers' sediment load (Woodyer, 1978).

Our approach to spatial sediment tracing is to measure the properties of sediment from major tributaries, and the main channel, to determine whether or not sediment characteristics can be distinguished by major element chemistry and magnetic mineral properties. If the tributaries can be distinguished from the main channel, then it is usually possible to quantify relative tributary sediment contributions.

Recent New South Wales Department of Land and Water Conservation reports have indicated that the Namoi River is a major source of particulate associated phosphorous reaching the Barwon River (Houldsworth, 1995; Daly, 1994). In this paper we present quantitative estimates of the proportion of sediment, and associated phosphorus delivered to the Barwon-Namoi confluence from each tributary. A prior study undertaken by the authors (Caitcheon *et al.*, 1995) has shown that phosphorus-rich basalt soils in the headwaters of the Namoi River are the major source of sediment associated phosphorus. We attempt to estimate the contribution of basalt derived soils to sediment in the Darling-Barwon Rivers.

2. SAMPLING AND MEASUREMENTS

Two suspended sediment sampling runs from Wilcannia to Mungindi were undertaken at the beginning of the study, but since then this has not been an option due to very low, or nonexistent flow. Bed and bank sediment samples were collected from major tributaries, and along the Darling-Barwon upstream and downstream of the tributaries in late 1994 when there had been no flow in the river system for several months. Fine sediment was collected from what appeared to be recently deposited mud on sloping banks. Core samples were taken from an upstream flood terrace, and a downstream infilled channel on the Barwon River at the Namoi confluence, as well as from a low bench beside the channel of the Namoi River. All of the core sites are below the bank full level, so they would be inundated during less than bank full floods, although sediment deposition rates are probably low. We are presently attempting to date the fine sand in the mainly clay cores using optically stimulated luminescence.

All samples were sonified, and underwent settling in a water column to recover the <10 μm fraction (clay and very fine silt). This is the fraction that will contain most of the particle associated phosphorus.

Major and minor elements were measured by X-ray fluorescence analyses using standard methods (e.g. Norrish, 1968).

Magnetic measurements included susceptibility and isothermal remanence. Low frequency (0.45 kHz) specific susceptibility (χ) was measured with a Bartington meter and MS2B sensor. Specific magnetic susceptibility is approximately proportional to the concentration of all magnetic minerals in a sample. Isothermal remanent magnetisations (IRM) were imparted at 850 milli Tesla with a Molspin pulse magnetiser, and the resulting magnetisation

* CSIRO, Division of Water Resources, GPO Box 1666, Canberra.

measured with a Molspin fluxgate magnetometer. IRM measurements are sensitive to magnetic minerals that remain magnetised after being subjected to artificial magnetic fields. These parameters are generally representative of magnetic mineral assemblages (Caitcheon, 1993; Oldfield, 1991).

3. SEDIMENT TRACING RESULTS

3.1 Mineralogy

The mineralogy of the <10μm fraction of sediments from the Darling-Barwon Rivers is dominated by clays and quartz, with minor amounts of residual feldspar (Woodyer 1978; Douglas 1993; Donnelly *et al.*, in prep.). The clays consist predominantly of a mix of kaolinite, smectite and illite. Smectite is produced by the weathering of basic rocks (Deer et al., 1980), and its presence in Darling-Barwon sediments is indicative of a basaltic soil source (Woodyer, 1978). Kaolinite and illite are typically produced by the weathering of feldspars and micas. As these minerals are present in a variety of rock types, their presence in the Darling-Barwon sediments is not indicative of any particular rock source.

3.2 Quantifying The Basalt Contribution To Barwon River Sediments

Phosphorus-rich Tertiary basalt soils were found to be the dominant source of particulate-bound P in Chaffey Catchment in the headwaters of the Namoi River. Tertiary basalts are present in the headwaters of most of the tributaries of the Darling-Barwon, including the Namoi, Gwydir, MacIntyre and Culgoa Rivers. In this section we attempt to quantify the contribution of basalt derived sediment reaching the Darling-Barwon Rivers.

Concentrations of Al_2O_3 and SiO_2 in the <10μm fraction of sediments collected from along the main channel of the Darling-Barwon Rivers are shown in Figure 1. Average Al_2O_3 and SiO_2 contents of the major clay minerals present in Darling-Barwon sediments (kaolinite, illite, smectite) are also shown in this figure, calculated from data in Norrish and Pickering (1983). There is a good correlation (r^2=0.96) between Al_2O_3 and SiO_2 in the sediment data indicating a consistent mix of minerals. The regression line tends towards 100% SiO_2 (quartz) in one direction, and intercepts a line joining smectite+illite to kaolinite in the other. The intercept between the regression line and that joining the clay components can be used to estimate the mean kaolinite content of the sediment. The data presented in Figure 1 are consistent with kaolinite being on average about 50% of the clays (if we ignore the

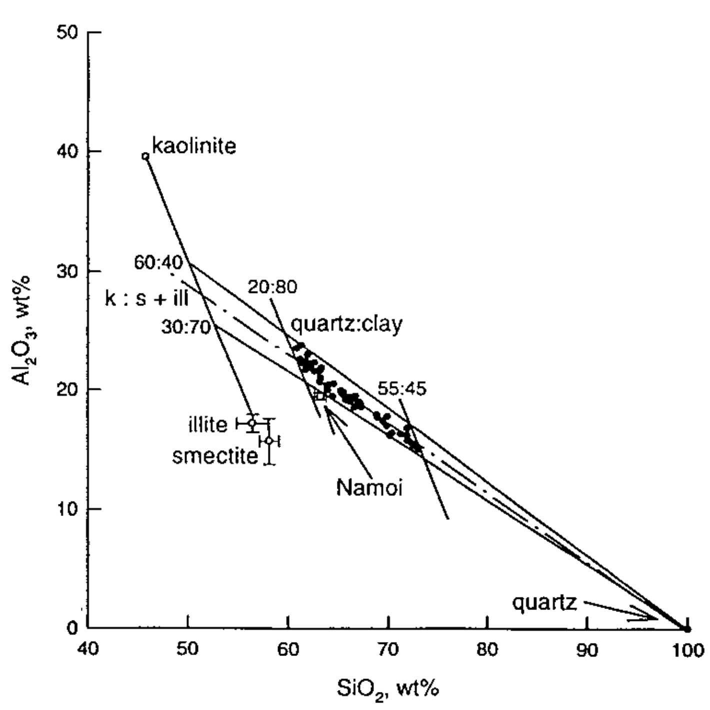

Figure 1. Concentrations of Al_2O_3 and SiO_2 in the <10μm fraction of sediments collected from along the main channel of the Darling-Barwon Rivers.

effects of a minor amounts of residual feldspars). The scatter in the data about the regression line indicates that the kaolinite content varies from about 30-60% of the clays. The spread in the data along the regression line is a result of variations in the ratio of quartz to clay in the sediments, and indicates that this ratio varies from 20:80 to 55:45. As quartz is not produced by the weathering of basalts, this provides an upper limit of about 80% for the contribution from basalt soils to the Darling-Barwon sediment.

The clay chemistry of the sediments can be examined further by plotting the Al_2O_3, Na_2O + CaO, and K_2O data as molar proportions in a ternary diagram (Figure 2). The average clay mineral compositions are also shown in this figure, along with the chemical index of alteration (CIA). This index can be used to indicate the degree of weathering of the alumino-silicate minerals (McLennan, 1993). Unweathered alumino-silicate minerals have CIA values of about 50, whereas clay minerals typically have values of between 75-100. All of the <10μm fraction of the sediment samples from the Darling-Barwon Rivers have CIA values of >75, indicating that they contain little or no residual alumino-silicate minerals. The sediment data lies on a line pointing at kaolinite, and passing between the average smectite and illite compositions. The left-right position of the bottom end of the line is controlled by the relative proportions of smectite and illite, and the vertical spread shows the relative proportions of kaolinite and smectite plus illite. These data indicate that the clays in the Darling-Barwon channel consist of a relatively uniform 60:40 mix of smectite:illite, with kaolinite contents (as a proportion of the clays) ranging from 30 to 60%.

Smectite is primarily produced from the weathering of basaltic rocks, and so we can use the smectite content of the Darling-Barwon sediments to estimate a lower limit for the contribution of basaltic soils from the uplands. A minimum of 45% of the <10μm sediment sample is clay minerals. Kaolinite is a maximum of 60% of the clay minerals. Of this remaining 40% smectite contributes a minimum of 22%. Therefore, the minimum amount of smectite is 10%. We conclude from this, and the data presented above, that basalt derived sediment contributes 10-80% of the <10μm sediment in the Darling-Barwon Rivers.

The geochemical data show that basalt derived sediment is present in the river system. However, the range is large, so it would be useful to better define the extent of the contribution. In Table 1 are magnetic mineral data from the Barwon River, and catchments that (i) only contain basalt rocks, (ii) the Bogan River catchment, and (iii) soils developed on sedimentary rocks in the Chaffey Reservoir catchment (Namoi basin). The basalt derived sediment data are from the Mooki River in the Namoi Basin, and Rocky Creek on the Darling Downs near Toowoomba. The Bogan River catchment has a range of rock types including, granite, volcanics, metamorphic and sedimentary rocks, but no basalt.

It is evident from the regression coefficients in Table 1 that the sediments from the Barwon River and the basalt are very similar. From this we conclude that basalt derived sediment is making a major contribution to the Barwon River sediments. However, it should be noted that while we believe that these results are representative, we do not have data from all of the potential rock types in the basin. Therefore our conclusion should be regarded as indicative until more data are available.

Table 1. IRM_{850} vs. χ regression coefficients.

	Regression Coefficient	r^2
Barwon River	13.8±0.6	0.91
basalt derived sediments	12.9±2.3	0.73
Bogan River	8.2±0.3	0.96
sedimentary rock soils	5.3±1.7	0.97

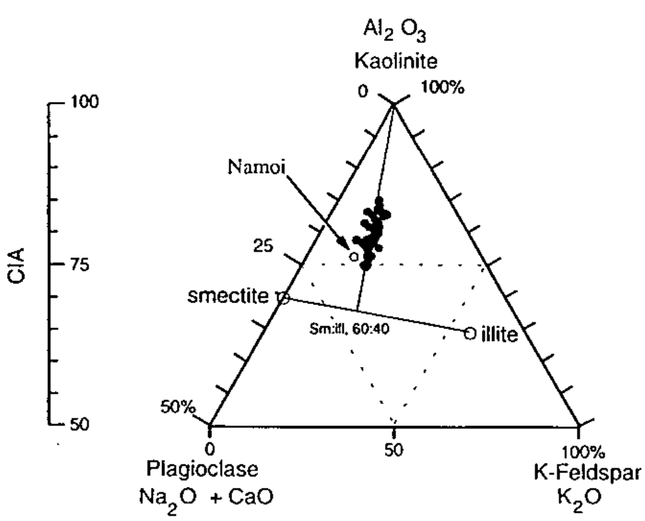

Figure 2. Al_2O_3, Na_2O + CaO, and K_2O in the Darling-Barwon Rivers sediment. The filled circles are from the main channel.

3.3 Quantifying Relative Sediment And P Contributions From The Namoi River

Major element data from 16 <10μm sediment samples collected from the Namoi River have been averaged and are presented in Figures 1 and 2. These data indicate that the Namoi sediments tend to be more smectite rich than the main channel sediments. In general smectite contains more Mg than the other clay minerals present. Consequently, we have used the MgO/Al_2O_3 ratio to determine the relative sediment contribution of the Namoi to the Barwon River (see Figure 3). The mean MgO/Al_2O_3 ratio for sediments collected upstream of the Namoi is 0.072±0.002 (n=12), and downstream this ratio is 0.091±0.004 (n=11). The mean MgO/Al_2O_3 ratio in Namoi sediments is 0.116±0.003, so the relative sediment contribution from the Namoi to the Barwon is 43±10 %.

Table 2. Mean magnetic parameter values from the core data shown in Figure 4.

	χ	IRM_{850}
Barwon River	0.174±0.007	1.06±0.14
Barwon upstream	0.175±0.003	0.96±0.05
Namoi	0.338±0.016	2.84±0.17

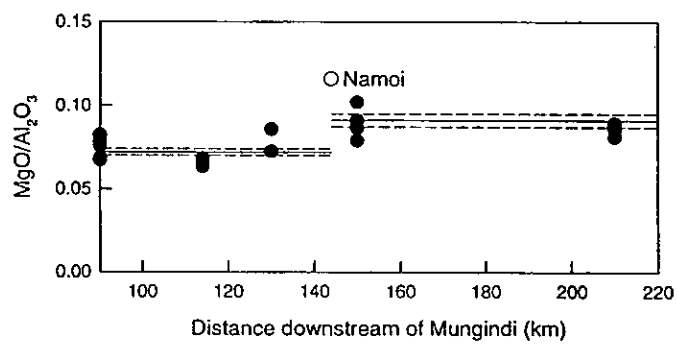

Figure 3. MgO/Al_2O_3 ratios from the Barwon and Namoi Rivers. The solid and dashed lines are the mean and standard errors respectively.

Magnetic measurements made on the core samples from the Barwon-Namoi confluence are shown in Figure 4. Relative average sediment contributions are estimated from the mean values of each parameter, given in Table 2. The relative sediment contributions based on the χ and IRM_{850} mean values are 0±5% and 5±8% respectively. Both of these values are consistent given the standard errors. However, the Namoi contribution determined from the magnetic data is substantially less than that calculated from the element chemistry. At this stage all that we can conclude is that the contemporary sediment contribution from the Namoi River may be as high as 40%, but the core data indicate that the long term average may be somewhat less than this. It is worth noting that the total proportionate water contribution from the Namoi to the Barwon is 29%, calculated from 1968-1994 flow data.

Sediment associated phosphorus concentrations (wt% P) in the main channel are generally low, ranging from 0.04% to 0.11%, with a mean of 0.068±0.002% (n=74). Concentrations in the Namoi are higher, ranging from 0.07% to 0.23%, with a mean of 0.122±0.001% (n=16). Average concentrations in the Barwon above and below the Namoi junction are 0.053±0.001%, and 0.076±0.004% respectively. These data indicate a 33±6% contribution of particle bound P from the Namoi to the Barwon, and are consistent with the 43±10% sediment input calculated above. This result shows that at the Barwon-Namoi confluence, the Namoi probably

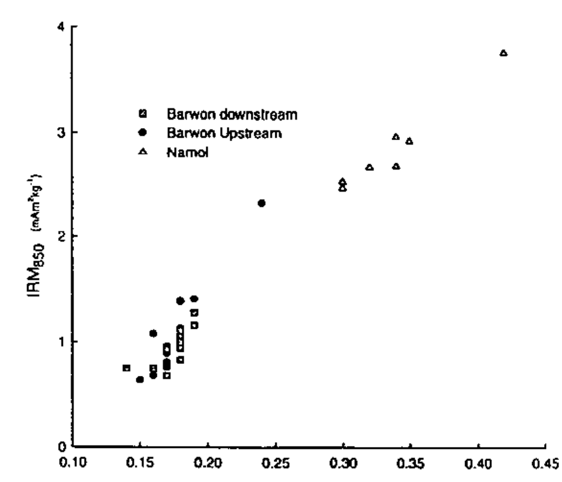

Figure 4. Core data from the Barwon-Namoi confluence.

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makes a significant contribution of sediment associated phosphorus, but it is not the dominant source.

4. CONCLUSION

Based on the element chemistry, the contemporary sediment, and associated phosphorus contributions from the Namoi River to the Barwon are about 30-40%. The magnetic data from the cores indicate a Namoi contribution of <10%. It may be possible to reconcile these two different estimates after geochemical measurements, and further sampling of the cores is completed. Dating of the core sediments will provide temporal limits for our estimate of the long-term average contribution.

The geochemical and magnetic data indicate that basalt derived sediment is probably a major source of sediment in the Darling-Barwon river system, and by inference, a significant source of particulate bound phosphorus. This conclusion will be tested further as more data become available. However, the implications for river and catchment management are far reaching if it can be conclusively demonstrated that sediment associated phosphorus substantially originates from natural sources.

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Sediment Transport In The Fitzroy River During Flood Events.

JN Kelly and WT Wong***

ABSTRACT: *The Fitzroy River is part of a Queensland wide coordinated Sediment Sampling Program. The Fitzroy River at Rockhampton has a catchment area of 139 000km² with a mean annual runoff of 5.7 million megalitres. The major catchment activities include agriculture, grazing and coal mining.*

Total discharge for the sampled event in March 1994 was 2.5 million megalitres, with a peak instantaneous flow of 2700 cubic metres per second.

Up to 2.3 tonnes of suspended sediment per megalitre of water was measured. This amounted to 3.4 million tonnes of soil for a relatively small event.

1. INTRODUCTION

Sediments are an important part of a river system and can have an impact on biological habitat, flooding, pollution and our drinking water. They are a vital natural resource in some places but present a problem in others. Within the stream itself active fluvial processes take place which involve the deposition and erosion of sediments on the bed and banks. Most if not all of the sediments are transported and deposited during flood events and hence measurements must be carried out during the flood itself.

This paper examines sediment transport in the Fitzroy River at Laurel Bank near Rockhampton during a minor flood event which occurred in March 1994. Bed load, suspended sediment load, major ions and nutrients were measured. Further measurements during higher flood events are planned.

The Fitzroy River is part of a new statewide and coordinated Sediment Sampling Program established by the Queensland Department of Primary Industries (QDPI) in 1993.

Sediment monitoring is currently planned for ten key rivers in Queensland and the aims of the program are to:

- Quantify the sediment transport rate by establishment of a sediment rating curve.
- Provide reliable data for siltation studies by using improved measurement techniques.
- Determine a sustainable rate of sand and gravel extraction.
- Improve the understanding of fluvial processes.
- Quantify the amount of sediment export or erosion from a catchment.
- Provide water quality data including nutrients during flood events.

This program provides a package for sediment sampling taking into account many factors involved in the whole spectrum of data collection. QDPI has developed and implemented several improved and efficient sampling techniques in this field. These improvements include a weighing system for field determination of dry weight of bedload and modification of stream gauging equipment to allow sediment sampling to take place in conjunction with current meter measurements.

2. FLOOD EVENT MEASURED

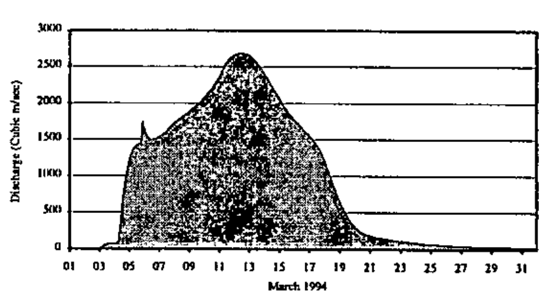

Figure 1. Discharge Hydrograph Fitzroy River At Laurel Bank

The Fitzroy River at Rockhampton has a catchment area of 139 000km² with a mean annual runoff of 5.7 million megalitres. Its catchment consists of five major sub-basins, the Mackenzie, Nogoa, Dawson, Isaac, and Comet Rivers. The major catchment activities include agriculture, grazing and coal mining.

In this paper we report the sediment load of the Fitzroy River during a small flood event in March 1994. Total discharge for the sampled event was 2.5 million megalitres, with a peak instantaneous flow of 2700 cubic metres per second. This represents an annual return interval of 1 in 2 years in the Fitzroy River. The majority of runoff originated in the Dawson, Mackenzie and Nogoa River sub basins, following an extended dry period of 3 years.

*Department of Primary Industries, PO Box 736, Rockhampton Qld 4700.
Telephone: (079) 319600 Fax: (079) 273079
**Department of Primary Industries, GPO Box 2454, Brisbane Qld 4000.
Telephone: (07) 2247253 Fax: (07) 2247219

Multipoint samples were taken at six verticals across the stream using a boat mounted USGS P61 point suspended sediment sampler. Bedload samples were also taken at the same six locations using a Helley Smith bed load sampler. Samples were analysed by Queensland Health, Scientific Services and QDPI's Rocklea Soils Laboratory.

During the flood event measured at Laurel Bank, about 3.4 million tonnes of sediment was exported.

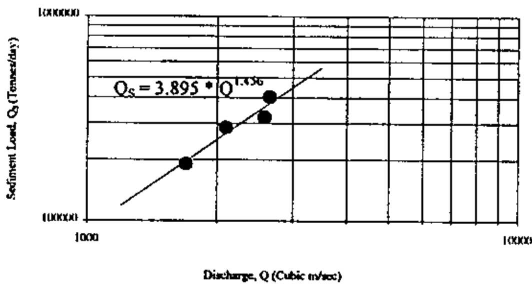

Figure 2. Sediment Rating Curve
Fitzroy River at Laurel Bank

Sediment rating curve, relating streamflow (Q, cubic m/sec) to the Sediment Discharge (Q_S, Tonnes/day) is defined by:

$Q_S = 3.895\ Q^{1.456}$

Coefficient of determination:
$R^2 = 0.92$ which is a good correlation for sediment transport.

3. SPATIAL VARIATION OF SEDIMENT CONCENTRATION

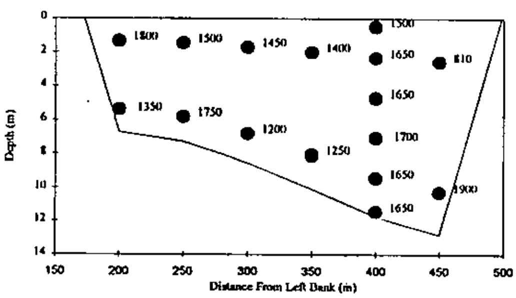

Figure 3. Distribution of Sediment Concentration
Suspended Solids in mg/litre
Fitzroy River at Laurel Bank
Date of Sampling: 12/03/1994

The measurement program allows for detection of spatial variation in sediment concentration within a cross-section. The ratio between the maximum and minimum suspended sediment concentration is about 2 within a cross section.

4. DISTRIBUTION OF SEDIMENT SIZES

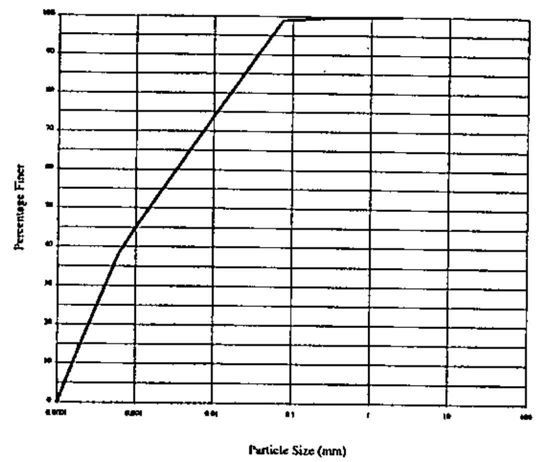

Figure 4. Particle Size Analysis
Fitzroy River at Laurel Bank
Date of sampling: 12/03/1994

- At stream discharges below 2700 cubic metres/sec, practically all sediment was transported as suspended load.
- Particle size of suspended sediment load generally becomes finer towards the surface.
- Suspended sediment samples are made up of:
    - 3% sand
    - 44% silt
    - 53% clay

5. SEDIMENT LOAD 1965 - 1994

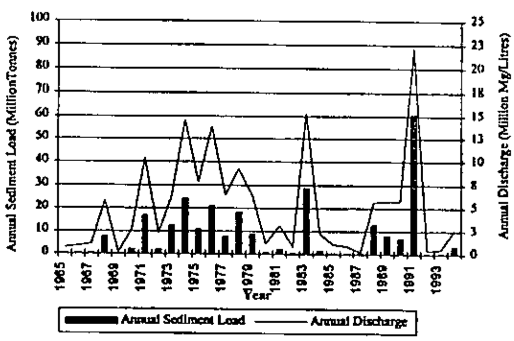

Figure 5. Annual Sediment Load And Discharge

The sediment rating curve, was applied to instantaneous streamflow information for the Fitzroy River .
Based on the sediment rating curve:

- About 264 million tons of sediment load was exported from the Fitzroy River basin over the last 30 years (1965-1994), or 8.8 million tons per year.
- An average of 0.65 tonnes/hectare per year or 64.6 tonnes/sq km per year.

7. CONCLUSIONS

- Total sediment exported from the Fitzroy River during the March 1994 flood event was 3.4 million tonnes.

- Sediment rating curve for the Fitzroy River at Laurel Bank is defined by $Q_S = 3.895\ Q^{1.456}$

- About 264 million tonnes of sediment has been exported from the Fitzroy River catchment over the last 30 years (1965-1994).

- Average sediment yield of the Fitzroy River catchment is 8.8 million tonnes per year or 64.6 tonnes per square km per year.

- Bedload results showed that sand and gravel of larger than 1.2mm diameter was not mobile at this site during this event. This is of significance to local extractive industry which relies on regular replenshiment of sand and gravel to maintain industry sustainability at this site.

- Sediment concentration varies considerably within the cross section at this site. The ratio between the maximum and minimum suspended concentration is about 2. Lower concentrations generally occur close to the stream banks. Higher concentrations generally occur in the the stream centre.

- A sediment measurement program must be carefully designed to ensure reliable results. It should also consider the spatial variation in sediment concentration within the cross section.

- A single point measurement of sediment concentration or tubidity reading which is commonly used may lead to incorrect total sediment load being computed and hence incorrect conclusions. Multipoint samples taken throughout the stream cross section will give more accurate results.

- Further sediment measurements during higher flood events in the Fitzroy River are planned to validate the sediment rating curve. Linkages to land use and catchment condition at the time of sampling will also be explored.

7. ACKNOWLEDGMENTS

The contribution of hydrographic staff in Rockhampton in carrying out the field work is acknowledged.
This program is partially funded by the National Landcare Program.

Using Major Element Chemistry to Determine Sediment Source in the Tarago Catchment: Preliminary Findings

Fiona Dyer Jon Olley, and Andrew Murray***

ABSTRACT

Clay mineralogy and major element chemistry show promise as indicators of sediment source in Melbourne Water's Tarago Reservoir. The catchment supplying the reservoir, which is subject to multiple land use, has two distinct lithologies. Soils sampled from two small sections of differing lithology can be distinguished by their clay mineralogy and the relationships between Al_2O_3 and SiO_2, and Fe_2O_3 and Al_2O_3. Initial indications are that near the inlet of the Tarago River into the reservoir, sediment is an even mixture of material derived from the two lithologies, but further down the reservoir the sediment appears to be derived predominantly from the basalt. These findings are preliminary but do suggest that the soils formed on basalt (and used for a variety of agricultural practices) are the predominant source of sediment to the reservoir.

1. INTRODUCTION

The Tarago catchment, located 85 km east of Melbourne (Figure 1) is one of Melbourne Water's supply catchments. The quality of water in Tarago reservoir is significantly lower than from Melbourne Water's other catchments (Jayasuriya et al., 1994) and does not always meet National Health and Medical Research Council (NHMRC) guidelines for drinking water (J. Riddiford, personal communication 1995). Use of the water from the reservoir is currently limited due to it's poor quality. However, Melbourne Water's predictions indicate that it will be required as part of Melbourne's supply system in the near future (Jayasuriya et al., 1994).

Twenty five percent of the 11,400 ha catchment supplying the reservoir is used for agricultural purposes, with forestry and recreational activities occurring on the remainder (Jayasuriya et al., 1994). The major agricultural activities are dairying and grazing, with some potato cropping and hobby farming. Forestry activities are controlled by the Department of Conservation and Natural Resources (DCNR) and the 1987 "Code of Forest Practices for Timber Production" is enforced.

The major source of water to the Tarago Reservoir is the Tarago River which flows through the Tarago -

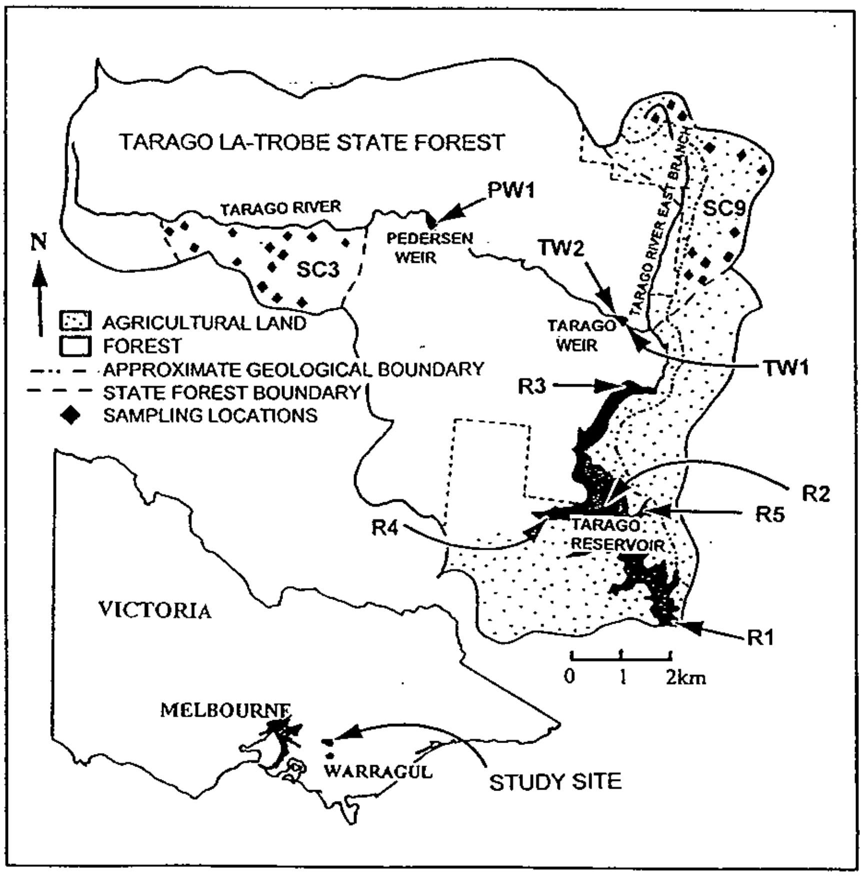

Figure 1. Map showing the location of the Tarago Catchment

* CRC for Catchment Hydrology, CSIRO Division of Water Resources, GPO Box 1666, Canberra ACT 2601
Telephone: 06 246 5754 Fax: 06 246 5800 Email: fiona@cbr.dwr.csiro.au

** CSIRO Division of Water Resources

La Trobe State Forest into the northern end of the reservoir. It is joined about 1.5 km upstream of the reservoir by the Tarago River East Branch which flows along the boundary of the State Forest and the agricultural land (Figure 1).

In 1991 there was a minor blue-green algal bloom in the reservoir which increased Melbourne Waters concerns over the supply of nutrients to the reservoir. Phosphate is regarded as the limiting nutrient for algal growth in inland waters (Hecky and Kilham, 1988). It has a strong affinity for soil and organic particles and significant proportion of the phosphate transported in Australian waterways is attached to particles (Oliver, 1993; Cullen, 1995) This particulate phosphorus may subsequently become available for algal growth. This paper reports the preliminary findings of a study which aims to identify the major sources of sediment and associated phosphorus in the Tarago Reservoir.

2. METHODOLOGY

2.1 Potential Sources

Land use, lithology and location have been used to identify three main potential source areas. These are:

(i) the Tarago La-Trobe State Forest which is largely drained by the Tarago River (Figure 1). The area is covered by wet sclerophyll forest and is subject to logging operations. It is underlain by granite (VandenBerg, 1977) which occasionally outcrops throughout the area;

(ii) the agricultural land along the north east side of the catchment. This area drains into the Tarago River East Branch and is underlain mainly by basalt (VandenBerg, 1977) although some granite occurs along the edge of the Tarago River East Branch (Figure 1); and

(iii) the steep hills surrounding the reservoir which drain directly into the reservoir and are underlain by granite on the western side of the reservoir and mainly by basalt on the east.

2.2 Sampling

Sediment mineralogy and major element chemistry have previously been used to distinguish sediments derived from soils formed on different lithologies (see for examples: Klages and Hsieh, 1975; Wall and Wilding, 1976; and Argast and Donnelly, 1987). The initial sampling carried out for this study aimed to determine whether mineralogy and major element chemistry could be used in the Tarago catchment to distinguish sediments derived from soils formed on the granite from those formed on the basalt.

Surface soil samples to a maximum depth of 5 cm were taken from two subcatchments (denoted SC3 and SC9) at the extremities of the catchment. Approximate sampling locations are given in Figure 1. The underlying geology of SC3 is granite and the area is forested. A small section of this subcatchment has been subject to recent logging operations. The majority of SC9 is used for agriculture and the underlying geology is basalt. Samples were collected using a trowel and are presumed to be representative of the surface soil at each site.

An Eckmann grab sampler was used to take samples from the two weirs on the main Tarago River (TW1, TW2 and PW1) and from five different positions in the Reservoir (R1-R5).

2.3 Analytical Methods

Major element concentrations of individual samples were determined by X-ray fluorescence (XRF) spectrometry using a Phillips PW1404 spectrometer according to the procedure outlined in Norrish and Hutton (1969). Finely ground samples were dissolved in molten lithium borate and cast to form a disc. The analysis was carried out on the borate glass disc.

Equal weights of individual samples from within each subcatchment were combined and these bulked soil samples, as well as sample R3 from the reservoir and sample TW1 from Tarago Weir were particle size separated by sieving (using 2 mm, 1.4 mm, 500 μm, 250 μm, 125 μm, 63 μm, 38 μm, 20 μm and 10 μm sieves) and settling (to less than 2 μm).

Clay mineralogy of the <2 μm fractions from the two bulked soils, sample TW1 and sample R3 was determined by X-ray diffraction (XRD) using a Phillips PW-1729 X-ray diffractometer equipped with a Cu-K_α x-ray source. Phillips APD search and match software was used to analyse and interpret diffraction patterns.

3. RESULTS

3.1 Clay mineralogy

Differences were found in the clay mineral composition of the soils from SC3 and SC9. Kaolinite, gibbsite and illite were the major clay minerals identified in the soils of SC3. The major clay minerals found in SC9 soils were kaolinite and vermiculite. The clay fraction of Tarago weir sediment contained kaolinite and illite. This is expected as the sediments from Tarago weir are derived from similar granitic soils to those of SC3.

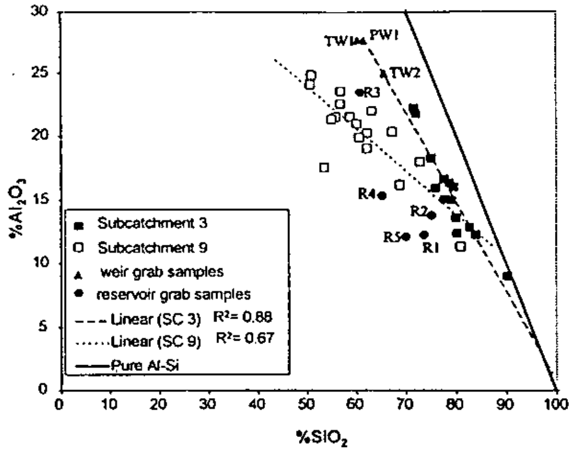

Figure 2. Relationship between Al_2O_3 and SiO_2 concentrations for soils and sediment of the Tarago catchment

The major clay minerals identified in the reservoir sediment (R3) were kaolinite and illite, suggesting a granitic origin.

3.2 Major Element Chemistry

3.2.1 Soils:

In combination, SiO_2, Al_2O_3 and Fe_2O_3 make up more than 92% of the major element composition of the soils analysed.

<u>SiO_2 and Al_2O_3:</u>

Concentrations of SiO_2 and Al_2O_3 in the soil samples from sites SC3 and SC9 are plotted in Figure 2. There is a well defined correlation between these elements in the samples from SC3 ($r^2 = 0.88$). This is consistent with the soils being made up of a mainly two component mix:

1. an SiO_2 rich component (quartz), and
2. an Al_2O_3 rich component (clay and/or feldspar).

The spread in the data along the line is the result of differences in the relative contribution of these fractions with the finer clay rich fractions having higher Al_2O_3 contents. Concentrations of SiO_2 and Al_2O_3 are not as well correlated in the samples collected from site SC9 ($r^2 = 0.67$), which indicates that these soils are not a simple two component mix. However the data sets from the two sites are clearly separated, suggesting that it may be possible to distinguish sediment derived from each site using these parameters.

<u>Al_2O_3, CaO^* + Na_2O, K_2O:</u>

The K_2O, CaO^*[1] + Na_2O and Al_2O_3 data as molar proportions are presented in a ternary diagram in Figure 3. The Chemical Index of Alteration (CIA) (McLennan, 1993) is shown on the left hand side of this figure. This index indicates the degree of weathering of the alumino-silicate minerals in soils. CIA values of 45-55 indicate almost no weathering; a value of 100 indicates extreme weathering with complete removal of Na_2O, K_2O and CaO^*. The soil samples from both sites have high CIA values, most samples being above 80. This indicates that the main alumino-silicate minerals in the soils are clays and little residual feldspar is present. Unfortunately, the two data sets plot very closely together in this diagram, despite the fact that they contain different suites of clay minerals (see XRD data). This means that distinguishing sediment derived from the different sites using the Al_2O_3, CaO^* + Na_2O and K_2O data is not possible.

<u>Fe_2O_3 and Al_2O_3:</u>

The relationships between Fe_2O_3 and Al_2O_3 concentrations in the soils from both sites are shown in Figure 4.

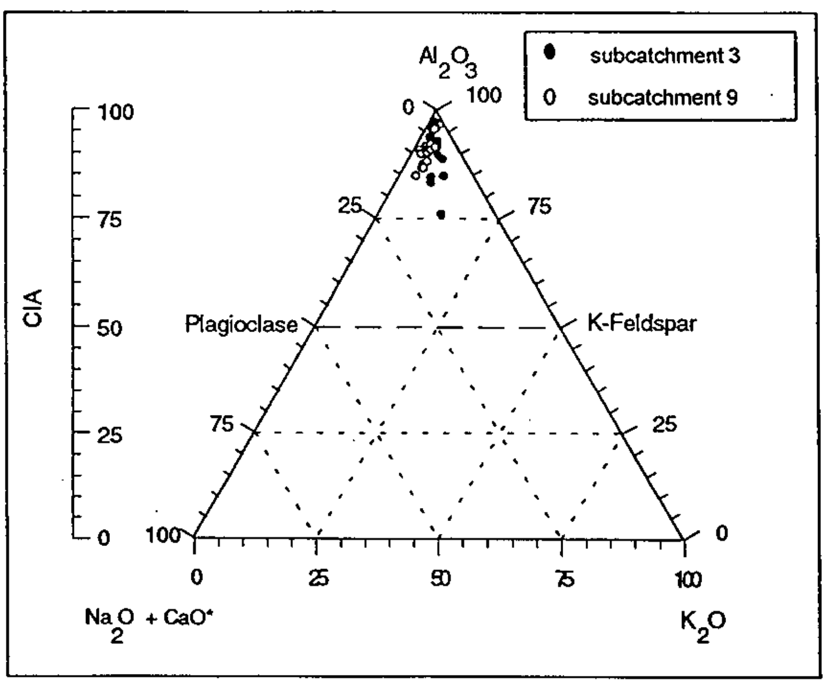

Figure 3. Ternary diagram showing the molar proportions of Al_2O_3, Na_2O+CaO* and K_2O in the soils of SC3 and SC9

[1] calcium associated with minerals other than apatite or carbonate

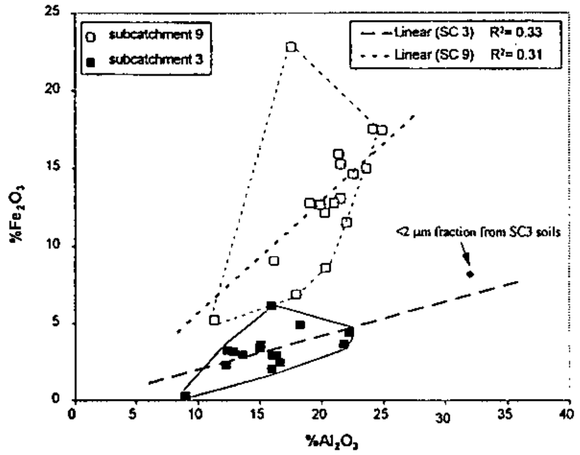

Figure 4. Relationship between Fe_2O_3 and Al_2O_3 concentrations for the soils of SC3 and SC9

The concentration of Fe_2O_3 does not correlate well with the concentration of Al_2O_3 for the soils of either SC3 or SC9 (r^2 = 0.33 and 0.31 respectively). However the soils from each subcatchment form two distinct fields suggesting that these parameters may provide a signal by which we can distinguish sediment derived from the two areas. Al_2O_3 and Fe_2O_3 are well correlated ($r^2 = 0.98$) in the particle size fractions from the bulk SC3 soil (Figure 5). Similar correlated increases in Al_2O_3 and Fe_2O_3 concentrations have been observed in other non-aggregated soils (Olley and Murray, unpublished data). These data suggest that mixing and particle size separation of the SC3 soils by fluvial transport will produce sediment in which Al_2O_3 and Fe_2O_3 are correlated. As would be expected this regression passes through the field defined by the bulk soils data (Figure 6). Al_2O_3 and Fe_2O_3 are less well correlated in the particle size fractions derived from the SC9 bulked soils ($r^2 = 0.70$), however the regression also passes through the field defined by the bulk soils and is distinct to that for the SC3 soils (Figure 6). This suggests that we should be able to use the combination of the fields defined by the bulk soils and the correlations between these parameters in the different particle size fractions to distinguish sediments derived from the two soils.

3.2.2 Sediments:

SiO_2 and Al_2O_3:

The SiO_2 and Al_2O_3 data from the sediment collected from the weirs on the Tarago River (which drain granite) are also plotted in Figure 2. They are consistent with the regression fitted through the soils data collected from the granite site indicating that they contain the same mineral suite as the soils formed on the granite. Data from the reservoir samples are also shown in Figure 2. Sample R3 plots between the two regression lines fitted through the soils data from SC3 and SC9 suggesting that if these two subcatchments were the only two sources it would consist of a mix (approximately 50:50) of sediment derived from the two lithologies. The four remaining reservoir sediment samples plot below the trend line defined by the SC9 soils and thus outside the fields of the two subcatchments. This suggests different sources for sediment near the inlet of the Tarago River and sediment further down the reservoir.

Given that the two subcatchments sampled are at the extremities of the catchment and make up only a small percentage of the whole catchment, other more direct sources must be considered. Characterisation of clay mineralogy and major element composition of these closer subcatchments may result in a more accurate identification of source. Nevertheless, it is concluded that with the exception of sample R3, the reservoir sediments are most like the basaltic soils derived from SC9.

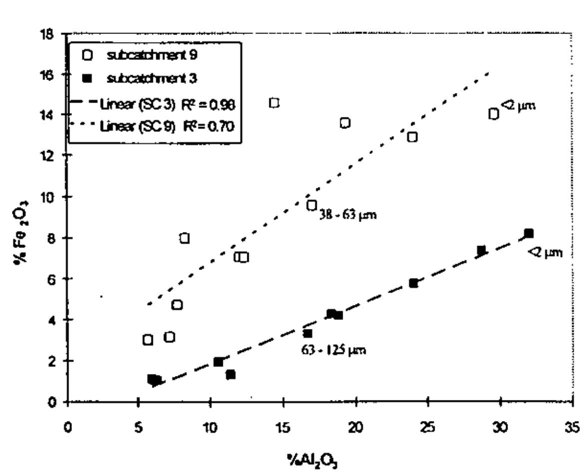

Figure 5. Relationship between Fe_2O_3 and Al_2O_3 for particle size data for the soils of SC3 and SC9

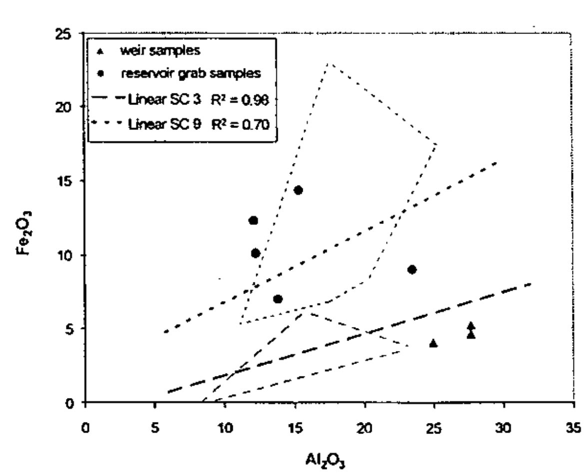

Figure 6. Relationship between Fe_2O_3 and Al_2O_3 for soils and sediment of the Tarago catchment

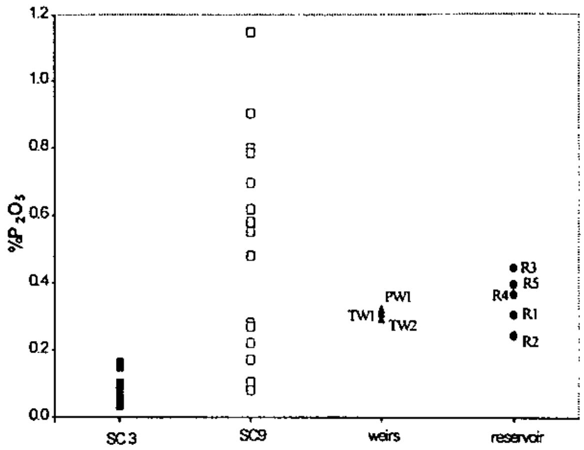

Figure 7. Concentration of P_2O_5 for soils and sediment of the Tarago catchment

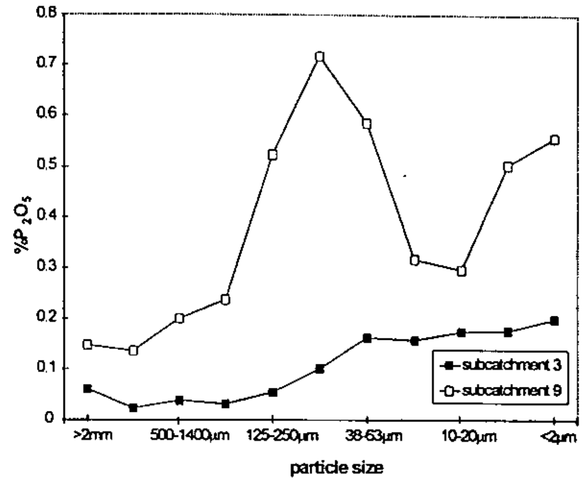

Figure 8. Concentration of P_2O_5 against particle size for the soils of SC3 and SC9.

<u>Fe_2O_3 and Al_2O_3:</u>

The Fe_2O_3 and Al_2O_3 data from the weir and reservoir sediment are plotted in Figure 6. The data from the sediment collected from the weirs plots along the regression line defined by the particle size data from the soils of SC3. The concentrations are between those of the soils (which contain the full particle size distribution) and the <2 µm clay fraction. This is not surprising; particle size selection during fluvial transport has produced sediment in the weirs with a maximum particle size of 125 µm.

If the granitic soils were a major contributor to the reservoir sediment it is expected that their Fe_2O_3 and Al_2O_3 concentrations would plot close to the regression line defined by the particle size data from SC3 soils. However, the reservoir sediments have Fe_2O_3 and Al_2O_3 contents that are more closely aligned with those of SC9 soils. As before the reservoir sample from near the inlet of the Tarago River (R3) appears to be the only reservoir sample that is a mix of the two sediment sources. This supports the information provided by the Al_2O_3 - SiO_2 data. Although the majority of the reservoir samples (R1, R2, R4 and R5) are more closely aligned with the soils of SC9 it is important to note that not all possible sources have been characterised.

<u>Phosphorus:</u>

One of the objectives of this study is to identify the source of phosphorus (P) in the reservoir. The concentrations of P_2O_5 in the soils and sediments of the Tarago catchment are plotted in Figure 7.

The granitic soils of SC3 have a narrow distribution of P_2O_5 concentrations whereas that of the basaltic soils of SC9 is much broader. The concentrations in the SC3 soils are also considerably lower than those of the SC9 soils.

Sediment from the weirs (TW1, TW2 and PW1) and reservoir (R1-R5) have similar P_2O_5 concentrations. The reservoir sediment samples have P_2O_5 concentrations that fall within the range of concentrations found in the soils of SC9. This is consistent with the Al_2O_3 - SiO_2 and Fe_2O_3 - Al_2O_3 data, which suggested that the reservoir sediment is derived from basaltic soils such as those found in SC9.

Sediment from the weirs is derived from granitic soils similar to those found in SC3 and yet the P_2O_5 concentration is three times higher in the weir sediment than in the soils. Sediment samples from the weirs have a maximum particle size of 125 µm and the soils of SC3 show an almost monotonic increase in P_2O_5 content with decreasing particle size (Figure 8). At least in part, the higher concentration in the weir sediments could arise from particle size sorting during fluvial transport.

4. CONCLUSIONS

The major element signature of the two subcatchments based on different lithologies have been shown to be distinct. The signature of the sediment from the two weirs in the granite side of the catchment is consistent with that of the soils in the granite subcatchment. The sediments from the body of the reservoir have concentrations more similar to those in the basalt soils although the sample from the upper end of the impoundment appears to be made up of both granitic and basaltic sediment. The clay mineralogy and the phosphorus concentrations are consistent with these observations.

It is concluded that it is practical to use major element geochemistry to distinguish the sources of sediment and particulate phosphorus in the Tarago Reservoir. The next phase of this study will concentrate on a more complete description of the soils based on the two lithologies.

5. ACKNOWLEDGMENTS:

G. Moore, S. Gras and B. Dyer helped with sample collection, Melbourne Water staff provided access to some areas of the catchment and assistance in sampling the reservoir. F. Dyer is supported by a Melbourne University Postgraduate scholarship and CRC for Catchment Hydrology studentship.

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Sand-slugs in South East Australian streams: origins, distribution and management

Ian Rutherfurd *

ABSTRACT: Since European settlement, mining, stream incision (gullying), and catastrophic widening of streams, have released waves of sand that have choked stream channels in SE Australia. These sand-slugs are among the most obvious of human impacts on stream channels. Sand-choked channels are particularly common in streams that drain granite catchments. Sediment yields from mining and gullying are generally declining across SE Australia, reducing sediment supply to the upstream end of the slugs. The focus of management must now shift to the fate of sediment in storage in the stream system. Sand-slugs usually pass through stream channels as discrete, moving waves, with well defined 'snouts'. The rate of migration of the sand typically declines as it moves downstream, with rates declining from kilometres per year to tens of metres.

The return of stream-beds to their former elevations will probably be followed by a new phase of channel erosion. This is because, in some cases, the sand has protected the channel from higher flood peaks from cleared catchments and gully networks; and because the erosion that was halted with the arrival of the slug will resume when the slug is gone. Removing the sand-slug manually is a very real management option that will not cause erosion of the original channel, but it will remove the protection that the sand afforded the channel, so that erosion can recommence.

1. INTRODUCTION

There is no doubt that the rate and magnitude of sediment movement in the Australian landscape was increased by European settlement. Mining, gully erosion, and less commonly, sheet erosion, have increased sediment yields by several orders of magnitude (Neil & Fogarty, 1991) . Much of the finer fraction of the sediment eroded over the last 150 years (eg. the fine sand, silt, and clay) has either passed through the stream system, or is stored on floodplains (Peterson, 1995; Rutherfurd & Smith, 1992). It is the sand fraction of the sediment that we are interested in here, and this is often stored in the stream channel. This sand tends to move through stream systems in discrete slugs.

In the past, most research has focussed on the sources of sediment. However, there is a growing consensus that the rate of anthropogenic sediment yield to streams is declining across much of SE Australia. This means that the focus of research and management should now be turning to the fate of the sediment that is in storage in various parts of stream systems. The purpose of this paper is to briefly review the sources of sand in sand-slugs in S.E. Australia; the distribution of slugs in the region; how the sand moves through stream networks, and how the sand can be managed. I emphasise that large volumes of sediment have been stored on floodplains and other storage sites in catchments, but this paper concentrates on the movement of sand through stream channels.

2. SAND-SLUGS: DISTRIBUTION AND SOURCES OF SAND

Sand enters channels from point or diffuse sources. There are three major sources of sand to streams in SE Australia: mining, gully erosion, and catastrophic widening of streams. Figure 1 shows the distribution of some sand-slugs in S.E. Australian streams for which there are published descriptions.

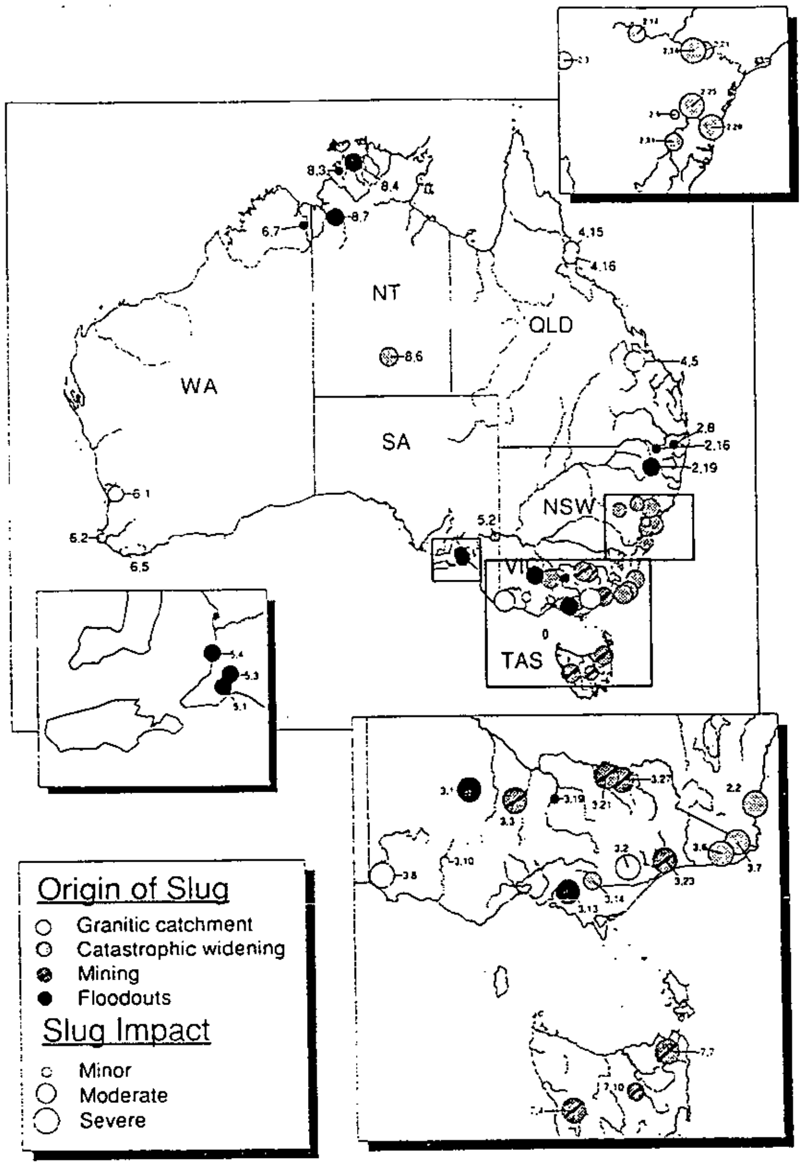
2.1 Mining

A classic example of a point source of sediment is the Mt Lyle Copper mine in Tasmania (see Locher, this volume). This mine has released nearly 100 million tonnes of sediment directly into the Queen River (probably the largest single artificial source of sediment to an Australian stream). Mining can also produce 'multiple point sources' of sand where there are many mines. This was the case in the Ringarooma River in NE Tasmania where numerous mines introduced a total of 40 million m^3 of sediment into various tributaries, particularly in the period 1900-20 (Knighton, 1987). Numerous streams throughout Victoria were also inundated with sediment from gold mining between the 1850s and 1920s (Peterson, 1995; Sherrard, 1990).

2.2 Gullying

Rapid stream deepening, and drainage network extension, was a ubiquitous response to European settlement of Australia (Woods, 1983). Gullies developed rapidly, but most had reached a stable length by the 1950s (Abernethy & Prosser, this volume; Herron, 1993) Most of the sand released from gullies is stored in 'floodouts' high in the channel network and does not reach the trunk stream (Melville & Erskine, 1986; Rutherfurd & Smith, 1992) (Figure 1). An important exception, where sand from gullying has moved through the entire stream network, is in granite catchments. Granite catchments are dominated by sand-sized sediment, and clay and gravel are usually less abundant. Possibly because a higher proportion of the load is transported as bedload in these catchments, there are many granite catchments around Australia (Figure 1) where sand from channel network extension has reached even the largest streams within decades. Examples include the upper Lachlan and Murrumbidgee Rivers in NSW, and the Glenelg River in Western Victoria.

* Cooperative Research Centre for Catchment Hydrology, Dept. of Civil Engineering, Monash University, Clayton, 3168. Ph. (03) 9905 2940 Fx (03) 9905 5033 Email: Rutherfurd@eng.monash.edu.au



State	No.*	River/Creek	State	No.*	River/Creek
2	2	Bega	3	20	Pykes Creek
2	3	Bell	3	21	Sandy Creek
2	8	Clarence	3	22	Snowy
2	9	Colo	3	23	Tambo
2	16	Dumaresq	3	25	Thomson
2	18	Goulburn	3	27	Yackandandah Creek
2	19	Gwydir	4	5	Don
2	20	Hawkesbury	4	15	South Johnstone
2	21	Hunter	4	16	Tully
2	25	Macdonald	5	1	Hindmarsh
2	31	Nepean	5	2	Murray
2	38	Wollombi Brook	5	3	Nangkita Creek
3	1	Avoca	5	4	Onkaparinga
3	2	Avon	6	1	Avon
3	3	Bendigo Creek	6	2	Blackwood
3	6	Cann	6	5	Frankland
3	7	Genoa	6	7	Ord
3	8	Glenelg	7	4	King
3	13	Lang Lang	7	7	Ringarooma
3	14	Latrobe	8	3	Finniss
3	19	Pranjip Creek	8	4	Mary
			8	7	Victoria

Figure 1: Distribution of some published records of sand-slugs in Australia (incomplete) (Note: this map shows only streams for which there is a published account of sand-slugs. The published reference for each example can be found in Rutherfurd et al. (1995) by cross-referencing the code number for each stream) ("Slug impact" is a qualitative measure of the volume of sand involved in each slug or flood-out)

2.3 Catastrophic widening

Dramatic widening of streams during major floods provides a pulse of sand into streams. This can occur in the absence of human disturbance, but the magnitude of widening may be increased by removal of riparian vegetation. Several examples of such widening have been reported in Eastern Victoria and in the NSW coastal streams (Figure 1). The most prominent example of such widening was in the Hunter River in NSW. A series of floods in the 1940s and 50s, particularly the flood of 1955, transformed reaches of the Hunter River from a sinuous, single-thread channel, to a braided river (Reddoch, 1957). The sand released by this widening is still moving through the Hunter in discrete slugs (C. Thomas, pers. comm., 1995). In the same way, in-channel benches on the Goulburn River in NSW are periodically eroded by large floods. The liberated sand moves down the stream system as a slug, but is gradually redeposited as channel benches (Erskine, 1994). Floods from cyclones cause similar episodic widening of streams in coastal Queensland.

There are other sources of sand to stream channels, but mining, gullying in granite catchments, and catastrophic widening are the major sources. The length of time that the sand is being introduced into the stream varies from over a century in the case of some mines, to days or hours in the case of catastrophic channel widening. Most individual mining and gullying inputs last less than one to two decades. Once the supply of sand into the stream has declined, the most important management question is how does the pulse of sand move through the stream system?

3. FORM AND MOVEMENT OF SAND-SLUGS

G.K. Gilbert in his classic paper on hydraulic mining debris in California, suggested that sediment that is episodically introduced into a channel ..."is analogous to a flood of water in its mode of progression through a river channel. It travels in a wave"... (1917 p.31) . Thus the bed of the river will rise and then fall as the wave passes. Gilbert observed that both the amplitude of sediment waves, and their velocity, decline as the wave moves downstream. This model of sediment movement has been observed in many streams (Madej & Ozaki, in press; Pickup,Higgins, & Grant, 1983). For a single slug of given size, the rate of sediment transport declines downstream because the rate of bedload transport declines with small decreases in slope. The amplitude (depth) of the slug also decreases downstream because the sediment is 'sorted' as it migrates, with finer sediment moving further. This dispersion is described by Pickup (1983). I will describe some Australian examples that show the rate at which sand-slugs can move, and that illustrate that the simple 'wave' model can become more complex in reality.

3.1 Sand-slugs Formed by Catastrophic Widening

Sand-slugs generated by flood-erosion in the Goulburn River (NSW) move through the stream system within 3-4 decades (Erskine, 1994). This is shown by the rise and fall of the channel bed at gauging stations (Figure 2). The rapid rise and fall of the bed in the Goulburn, and in many similar streams, occurs partly because this river has a high bedload transport capacity, but also because not all of the sand slug is removed. That is, the sand fills the stream channel, but it is then incised by a narrow channel, leaving most of the sand as in-channel benches that will be re-eroded in the next major flood.

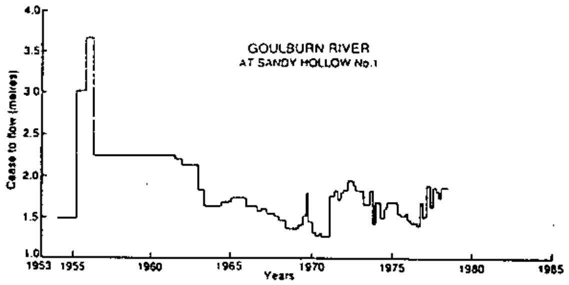


Figure 2: Bed level changes at Sandy Hollow Gauge No. 1, Goulburn River, NSW (from Erskine, 1995, p.147).

3.1 Sand-slugs Derived from Mining

Where sand enters a stream network from the catchment, rather than from erosion of the lower reaches (as in the Goulburn example) the transit time of the sand will be longer, and the interaction of the tributaries will make the process much more complicated. Knighton (1987; 1989; 1991) has described the complex movement of sand through the Ringarooma River stream network following over a century of inputs from some 20 tin mines. A model of bedload transport in the stream shows that the complex changes in bed-level in the upper reaches become progressively more regular with distance downstream. Close to the main source of sediment the bed had returned to its original level within 35 years of the cessation of mining, but the model predicts that it will be at least 50 more years before the sand-wave has moved through the lower reaches.

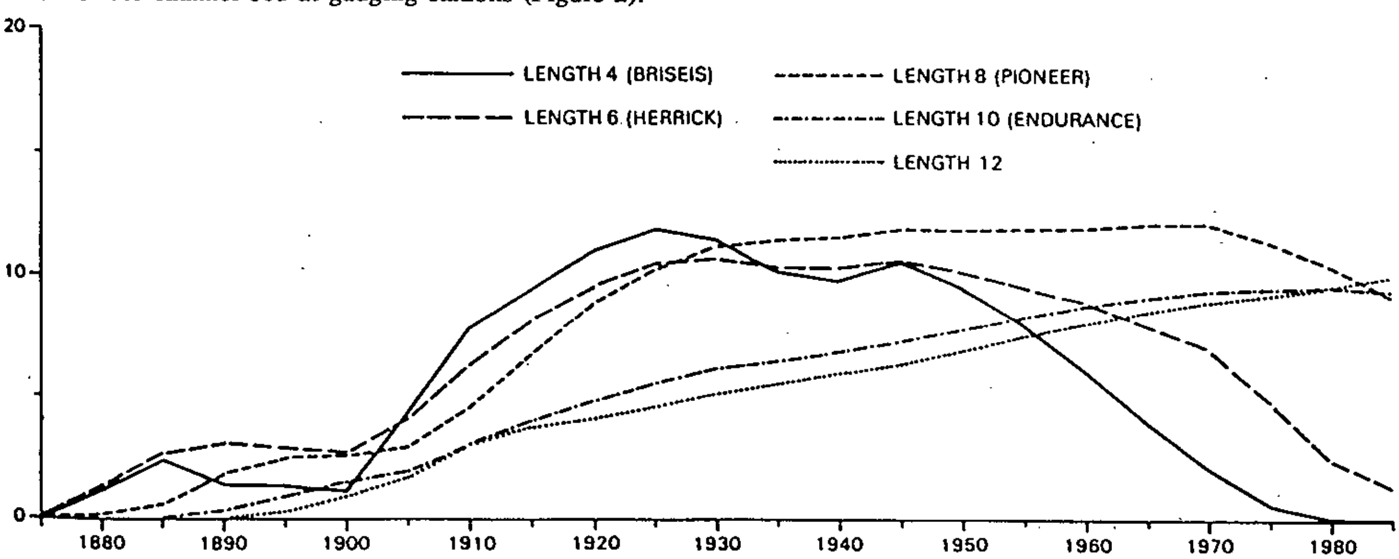


Figure 3: Predicted changes in the relative depth of deposition along the Ringarooma River (from modelling) (from Knighton, 1989). N.B. the reaches are numbered downstream. Thus one can see that the sand-slug has moved through the upstream reach 4, but the slug is still to peak in the downstream reach 12.

The Ringarooma also shows a complex interaction between tributaries and the trunk stream. Where sediment from tributaries reached the Ringarooma before the main wave of sediment, they deposited a delta into the channel. In other cases, aggradation of the Ringarooma dammed the tributaries. The result is a classic 'complex response' situation (Schumm, 1973). That is, the wave of sediment in the Ringarooma will move downstream, but the tributaries will incise as their base-level falls, producing a continuous source of sediment to the system for many decades.

Another example of a sand slug is provided by the Tambo River in Gippsland (Erskine,Rutherfurd, & Tilleard, 1990). Gold mining in the late 1880s produced a slug of sand that moved through the 50 km long Tambo gorge. Remarkably, the bed-level at the Bruthen gauge (at the downstream end of the gorge) had already begun to rise by 1890, and had aggraded by 4 m within 10 years. Bed-level at Bruthen only began to fall in the 1960s. The front of the sand-slug is now marked by a 4m avalanche-face of sand in the channel. Even in large floods this avalanche face now moves less than 20m per year, in comparison with the 1000s of metres per year at which the slug migrated through the Tambo gorge.

3.3. Sand-slugs from Gully Erosion

The Glenelg River (and its tributary the Wannon) in Western Victoria provides another example of a complex response to sand input. Since the 1850s, gully erosion and, to a lesser extent, sheet erosion of the granite portions of the Dundas Tablelands have produced a reasonably uniform injection of sand into many tributaries of the catchment. The rate of sediment contribution is now declining (Erskine, 1994). There is between 4 and 11 million m^3 of sand stored in the Glenelg catchment, however, the interaction between the tributaries and the trunk stream means that the sand is spread discontinuously through the network (Rutherfurd & Budahazy, 1995). On the Ringarooma River, the tributaries were dammed by the slug in the trunk stream. In the Glenelg catchment, large sand loads from tributaries have fromed dams at the confluence with the trunks streams. As a result, sand movement through the Glenelg system is disjointed because it must first pass through the backwaters produced by these 'tributary junction plugs' (TJPs). Unlike the Ringarooma then, transmission of sand down the trunk streams depends on the decline of sediment yield from the tributaries, rather than on migration of the sand-slug through the trunk stream. This will lead to the removal of the TJPs and a new wave of sand down the trunk streams.

It is also interesting to note that the present distribution of sand in the Glenelg was in place by the 1940s, and has changed little since that time. Between the TJPs, sand is stored in discrete waves 200-1000m in length, but these do not change their position over time. Instead sand moves from wave to wave at a slow rate. It will certainly be centuries before the anthropogenic sand in the Glenelg River system will have moved through the stream network.

3.4 Summary of Case Studies

Some points from these cases studies can be summarized in the following points.

- On both the Tambo and Ringarooma, despite numerous point sources of sediment, the sand-slugs tend to coallesce into a single slug as they move downstream.
- Rates of migration decline exponentially downstream, reducing from 1000s of metres per year to 10s of metres. Sand typically evacuates the upper tributaries within a few decades, but it takes over a century to leave the lower reaches of streams.
- The bed-level will return to its original level more quickly when a large proportion of the sand is stored in lateral deposits such as benches.
- Damming of both the tributaries and the trunk stream can make the movement of sand through a stream network very complex.

4. MANAGEMENT IMPLICATIONS OF SAND-SLUGS

4.1 Impacts as the sand-wave peaks

There are several management implications of a sand-slug passing through a stream system. Sand-slugs influence flooding, erosion rates, stream ecology, and recreation. The primary effect of a sand-slug is to reduce channel depth. On the Glenelg River, sand occupies up to 75% of the cross-section. This reduces the frequency of low flows in the channel because water flows within the sand body. The reduced channel capacity also produces an increased frequency of minor flooding, although it probably has little impact on major floods.

Hydraulic geometry relations and other models of channel response predict that an increase in bedload should lead to an increase in channel width. There is no doubt that the width-depth ratio increases as depth decreases, but the absolute width of the channel does not increase unless the channel is completely filled with sand. I have not seen examples of streams in which a sand-slug has led to bank erosion. This is probably explained by the cohesive character of the banks in many of the lower reaches of streams affected by sand-slugs. A more common geomorphic effect of sand-slugs is channel avulsions because of the increased frequency and depth of flooding over the floodplain. A good example is the avulsion on the Tambo River where the combination of a sand-slug with willow infestation reduced channel capacity and triggered a full channel avulsion for a distance of 7.4 km.

Converting a narrow and deep channel, with regular pools, into a featureless sheet of sand, has disastrous ecological consequences (Alexander & Hanson, 1986). On the Pranjip-Creighton Creek system in Victoria the migration of a slug of sand through the creek has not only destroyed habitat, but it has also led to a change in seasonal diversity (O'Connor & Lake, 1994). Because the sandy substrate is more mobile than the original bed, it is scoured every winter. This produces large declines in macroinvertebrate species richness and poulations. In addition, the water temperature increases in the shallower water over sand-slugs.

4.2 Impacts as the sand-wave passes

As the sand-slug passes, and the channel deepens again, there are a new suite of management issues. When sand-slugs have moved through catchments, the channel is likely to begin a new phase of erosion. This will occur for two reasons, first, because erosion and channel adjustment that was interrupted by the sand-slug will continue; and second because the channel will be subjected to the new anthropogenic flow regime. For example, the channel may have been in a phase of erosion that was interrupted by the arrival of the sand-slug. This was the case in Bryan Creek, a tributary of the Wannon River in Victoria. Bryan Creek was originally a chain-of-ponds that was drained. This triggered a phase of erosion last century that was interrupted when the sand-slug arrived. The extraction of 415,000 m^3 of sand from the creek from the 1950s removed the bulk of the sand-slug. This was followed by up to 2 metres of incision upstream of the extraction. This incision has been explained by the reduction of sediment yield from the catchment (Erskine, 1994), but it could equally be explained by a simple continuation of the erosion that was already occurring in Bryan Creek before the sand-slug arrived.

Similarly, sand-slugs have also protected channels from erosion caused by a changed flow regime. Since sand-slugs can take several decades to move through a reach, conditions in the catchment may change in the intervening years. When humans transformed catchments from forest to pasture they increased flood peaks and volumes (Burch,Bath,Moore, et al., 1987). In addition, the development of a gully network alone can increase flood peaks by up to 20% (Rutherfurd,Hoang,Prosser, et al., In press).

5. MANAGEMENT OPTIONS FOR SAND-SLUGS

The first task when managing sand-slugs is to estimate the volume of sediment in storage, and the second is to estimate the rate at which the slug is moving. The former is best estimated by probing combined with repeat cross-sections. The latter can be estimated by the migration rate of the front of the sand wave, and sediment transport modelling (Knighton, 1989; Pickup, et al., 1983). Knowing the volume of sand and the rate of migration, there are several management options for sand-slugs. One is to do nothing, and wait until the slug passes. In some cases this option is not viable. The slug could be moving rapidly toward some asset. For example, the Tambo slug is moving into the portion of the river that is one of the prime Bass breeding sections of the Gippsland Lakes. Similarly, the slugs in the Glenelg are moving into the Nelson National Park - a Heritage River under Victorian legislation. However, in both the Tambo and Glenelg, the present rates of migration suggest that it will take several decades for the sand to reach the sensitive reaches. Another example would be where a slug is moving into an urban area where it will increase flooding. If the 'do-nothing' option cannot be tolerated, the sand must be manually removed. Stream sand is often prized by the aggregate industry, and extraction of the sand can be used to raise revenue that can be used to improve the management of the stream (eg. revegetation, or buying environmental flow allocations).

A sand-slug represents a temporary storage of sand in a reach. It is important to appreciate that this sand can be artificially extracted without triggering the type of up and downstream erosion described by Galay (1983). Extraction will certainly lead to erosion of the sand slug, but not of the original channel into which the sand-slug has migrated. However, it is important to appreciate that, as discussed above, once the sand is removed, the stream may well begin to deepen because the stream is no longer protected by the sand. In addition, the increased depth of the channel could lead to increased bank erosion simply because the banks will be relatively higher.

6. CONCLUSIONS

Mining, stream incision (gullying), and catastrophic widening of streams since European settlement, , have released waves of sand that have choked stream channels in SE Australia. These sand-slugs are among the most obvious of human impacts on stream channels. Sand-choked channels are particularly common in streams that drain granite catchments. Sediment yields from mining and gullying are generally declining across SE Australia, reducing sediment supply to the upstream end of the slugs. As a result a major management issue is the dynamics of these sand-slugs.

A single injection of sand into a stream will pass through the stream channel as a discrete wave or slug, often with a well defined 'snout'. In many streams, however, the movement of sand is more complicated. Where the injection of sand to the stream network occurs from many points, over a long period, more complex sediment transport occurs - particularly because of interactions between sand moving down the tributaries and the trunk.

The rate of migration, and the amplitude, of the sand wave in Australian streams typically declines as it move downstream. A typical slug would move at 1000s of metres per year in the headwaters, declining to 10s of metres per year in the lower reaches. Depending on the size of the stream (Lewin & Macklin, 1987), it will typical takes more than a century for bed-levels to return to their former levels throughout the stream system. Large volumes of sand will remain in storage in floodplains and benches for longer periods.

The progressive waning of sand-slugs over coming decades (particularly in headwater streams) will probably be followed by a new phase of channel erosion. This is because, in some cases, the sand has protected the channel from higher flood peaks from cleared catchments and gully networks; and because the erosion that was halted with the arrival of the slug will resume when the slug is gone. Removing the sand-slug manually is a very real management option. Because the sand-slug represents a store of sand in the channel, its artificial removal will not lead to up or downstream erosion of the original cross-section, however, removing the sand will remove the protection that the sand provides, thus bringing forward the expected erosion in the channel.

The significance of sand-slugs must be seen in terms of time scales (Meade, 1988). Over the time scale of decades, sand-slugs can be seen as devastating changes in stream morphology, with many secondary effects. However, over longer time-scales of centuries, sand-slugs are transitory features that will pass through stream systems.

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Sedimentation in the Lower Hunter River Estuary: Some Insights from ^{137}Cs Distribution

*Gavin Doyle**

ABSTRACT: *The applicability of using ^{137}Cs as a tool for investigating the recent sedimentary history of Australian estuaries has been tested in the lower Hunter River estuary. Mean annual sedimentation rates determined from the ^{137}Cs sediment profiles closely correspond to a previously empirically measured rate. A strong consistency exists between the cores from similar sedimentary environments. The ^{137}Cs profile mean activity was used to suggest that there is a greater topsoil contribution to the suspended sediment load during high flow conditions than during normal flow.*

1. INTRODUCTION

Erosion and deposition are processes inherent in the natural geological cycle of the earth. Problems have arisen as a result of human interference in this cycle that has seen accelerated erosion and deposition as a result of poor land management practices.

The Hunter River catchment lies approximately 180 km north of Sydney on the east coast of NSW. The total catchment area comprises over 21000 km^2. The catchment has been considerably altered since European settlement to the point where it was considered, in the 1950s, as the most degraded coastal catchment in NSW. Since this time many millions of dollars has been spent on the control of soil and stream bank erosion across the catchment and on the removal of sediment from Newcastle Harbour to maintain navigable shipping channels.

The aim of this paper is to show the applicability of using ^{137}Cs in Australian estuarine environments. While it has been used extensively for soil erosion studies (e.g. Ritchie & McHenry, 1990; Loughran *et.al.*, 1992) and lacustrine sedimentation studies (e.g. Campbell, 1983; Walling & He, 1992), little work has focussed on its applicability to the study of estuarine sediments in Australia.

^{137}Cs is present within the environment solely as the result of atmospheric testing of nuclear weapons since the 1950's (Ritchie & McHenry, 1990). Large tests resulted in ^{137}Cs being distributed world-wide via stratospheric circulation from which the fallout has been measurable in soils since 1954 (Longmore, 1982).

This paper is part of a much broader study that is attempting to determine whether, or not, the sources and amount of sediment being deposited in the Lower Hunter River estuary has changed as a result of catchment stabilising efforts.

2. THE USE OF ^{137}Cs IN ESTUARINE ENVIRONMENTS

There have been questions raised about the applicability of using ^{137}Cs as a tool for examining the recent sedimentary history of an estuarine, or other similarly saline environments (Riel, 1970; Santschi *et.al.*, 1983; Zucker *et.al.*, 1984; Longmore *et.al.*, 1986). To date, the uncertainty has focussed on the possible desorption of ^{137}Cs from sediments under saline conditions, however, there are several other factors that must be considered when using ^{137}Cs in estuarine environments.

The strength of ^{137}Cs adsorption to sediment will ultimately be controlled by the clay mineralogy of that sediment. Certain clay minerals adsorb ^{137}Cs more strongly than others. The ^{137}Cs adsorption ability of specific clay minerals is directly related to the number, and type, of adsorption sites available within the crystal lattice structure of the mineral (Evans *et.al.*, 1983).

Interlayer sites (those sites in-between the separate layers of the repeated clay mineral crystal lattice) are the most permanent of ^{137}Cs adsorption sites. Coman & Hockley (1982) suggest that ^{137}Cs migrates relatively slowly along the crystal lattice towards the interlayer sites from where it is difficult to remove under normal environmental conditions.

The interlayer sites will eventually fill if there is sufficient ^{137}Cs available. Once the interlayer sites are saturated, excess ^{137}Cs will bind to less specific, and less permanent, adsorption sites on the clay mineral surface (Sawhney, 1970). This is most likely to occur under relatively high ^{137}Cs concentrations, such as those found in the effluent of nuclear processing plants.

The majority of ^{137}Cs desorption studies have been conducted on sediments contaminated with high concentrations of ^{137}Cs. Under these conditions the ^{137}Cs concentrations can be several orders of

*The University of Newcastle, Department of Geography, Callaghan, NSW, 2308
Telephone: (049) 215 080 Fax: (049) 215 877 Email: GGGBD@cc.newcastle.edu.au

magnitude greater than those found within sediments of the lower Hunter estuary e.g. 6.2 Bq g^{-1} (Stanners & Aston, 1981) compared to 0.0045 Bq g^{-1} (highest value found during this study).

Singh & Gilkes (1990) found that ^{137}Cs retention is stronger for lower ^{137}Cs concentrations adsorbed by the sediment, irrespective of its clay mineralogy. This was due to excess ^{137}Cs binding to non-specific sites from which it was more easily removed.

Stanners & Aston (1981) reported a 30% desorption of ^{137}Cs from nuclear waste contaminated estuarine sediment. If only 30% of ^{137}Cs was readily exchangeable from sediment with a ^{137}Cs concentration more than 1000 times that found in this study then there is little evidence to suggest that ^{137}Cs specific adsorption sites of sediments will be saturated by the very low ^{137}Cs concentrations found in atmospheric deposition.

One must conclude that ^{137}Cs adsorbed onto sediments entering the estuary from higher in the catchment will remain strongly adsorbed to the sediment and will not be available for transport other than attached to the sediment.

Unlike a lacustrine system, an estuary is a freely open system. Sediment retention within lakes and reservoirs are generally very high, as opposed to estuarine systems, where a significant portion of the inflowing suspended sediment moves through the estuary and out to sea. There are no data available on the sediment trapping efficiency of the Lower Hunter estuary. The loss of this sediment limits the quantitative use of ^{137}Cs within the estuarine environment.

There is uncertainty about the degree to which direct atmospheric fallout of ^{137}Cs onto the estuarine water surface was incorporated into the estuarine sediments. The uptake of ^{137}Cs from water by suspended sediment is a rapid process (Aston & Duursma, 1971). The limiting factor for directly deposited ^{137}Cs being incorporated into the estuarine sediments is the sediment settling velocity. The sediment that has adsorbed the ^{137}Cs can move up or down stream, depending on the tide. This will strongly influence if, or where, the labelled sediment will be deposited. An unknown percentage of direct fallout will have been incorporated into the estuarine sediments which makes it very difficult to determine how much of the ^{137}Cs in the profile has been contributed by catchment soils.

Bioturbation can be a significant problem when attempting to date core profiles. Benthic fauna, if present and active, can cause mixing of the sediment profile (Sharma *et.al.*, 1987). Bioturbation tends to extend the 'tail' of the ^{137}Cs profile downward as the organisms mix the labelled sediment with the un-labelled sediment below. There is little evidence, direct or otherwise, to suggest that bioturbation in the Lower Hunter Estuary has resulted in significant changes to the core ^{137}Cs profiles.

2. METHODS

Nine sediment cores were taken from locations, known not to have been dredged, within the Lower Hunter Estuary between April and May, 1993. Some of the cores were taken in pairs to provide some degree of replicability to the results. Each core pair, and some individual cores, were taken from what were thought to be separate depositionary environments. The location of core sample sites are shown on Figure 1.

Cores were collected by driving a PVC drainage pipe (100 mmØ) into the sediment with a slide hammer until consolidated sediments were reached. The pipe was then capped, extracted and returned to the lab where it was sectioned at 50 mm intervals. The upper sediments were very soft and there was no evidence of core compaction resulting from the sampling technique (e.g. dragged laminae). The samples were dried (45°C) and crushed to pass through a 2 mm sieve.

The ^{137}Cs content was determined using a G & E Ortec hi-purity germanium detector attached to a multi-channel spectrum analyser. Results were expressed on an areal activity basis (Loughran *et.al.*, 1988).

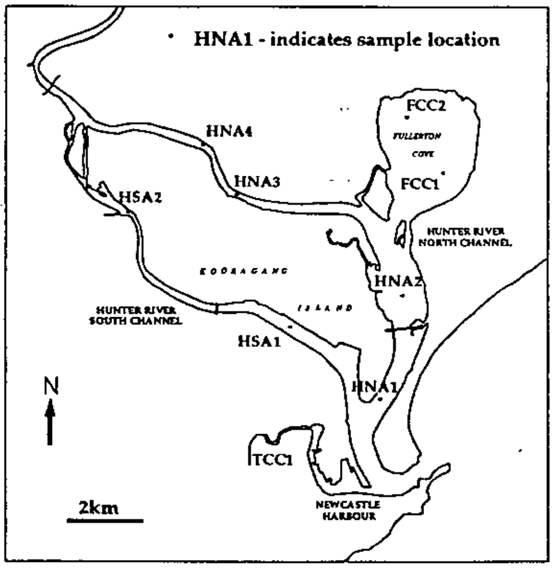

FIGURE 1 Map showing the location of the sediment cores in relation to the Lower Hunter River Estuarine morphology.

3. RESULTS

The most useful application of ^{137}Cs to estuarine sedimentation studies is that it enables a date to be ascribed to the first appearance of ^{137}Cs in the profile. While atmospheric ^{137}Cs fallout has been measurable in soils since 1954 (Longmore, 1982) the effect of radioactive decay and low initial concentrations would suggest that the presently measurable extent of ^{137}Cs should be ascribed a date several years later than 1954. The first minor peak in atmospheric ^{137}Cs fallout occurred in 1958 (Longmore, 1982) and it is this date that will be ascribed to the first presence of ^{137}Cs in the estuarine sediment profiles in this paper.

The depth to which ^{137}Cs was measured within the profile, the mean annual sedimentation rate, total core areal activity and mean core areal activity for all cores are shown in Table 1. Examples of the ^{137}Cs core profiles are shown as Figures 2a-d.

Cores that were taken from similar sedimentary environments (FCC1&2, HNA1&2, HNA3&4) showed a strong degree of within pair consistency. This would indicate that there is homogeneity within sedimentary environments suggesting that single cores (HSA1, HSA2, TCC1) would provide a reasonably adequate sample size.

Mean annual sedimentation rates calculated from the ^{137}Cs profiles show that considerable differences occur across the estuary. There has been between 0.3 and >1.5 m of depostion in the estuary since 1958. This represents deposition rates of between 8 and >42 mm yr^{-1}. The lowest sedimentation rates occur within Fullerton Cove, while the highest occur further up the estuary on the North Channel.

Fullerton Cove is a large (7 km^2) shallow (~2 m at high tide) basin off the Hunter River North Channel. This site is the only site within the study area where there exists sedimentation rate data from previous studies. The NSW Department of Public Works (1969) estimated, from physical model studies, that the sedimentation rate within Fullerton Cove was approximately 8 mm yr^{-1}. This is in strong agreement with the data from this study (8 and 10 mm yr^{-1}) and provides confidence in the use of ^{137}Cs as a dating tool in this estuarine environment.

Sedimentation rates close to Newcastle Harbour (HNA1, HNA2, HSA1) are all fairly consistent and close to 30 mm yr^{-1}. The greatest sedimentation rates occur at cores HNA3 and HNA4. On both these cores the bottom of the ^{137}Cs profile was not reached (e.g. Figure 2d). It must be noted that these cores were not taken in the middle of the channel due to problems with depth so they, more correctly, provide an indication of sedimentation rates close to the banks, in contrast to the entire channel.

TABLE 1. Summary of ^{137}Cs characteristics for all lower Hunter River estuarine cores. * Denotes best estimate from available data.

Core	Maximum Depth of ^{137}Cs (cm)	Mean Sedimentation Rate (mm yr^{-1})	Total ^{137}Cs Areal Activity (mBq cm^{-2})	Mean Activity (mBq cm^{-2} cm^{-1})
Fullerton Cove Core 1 (FCC1)	35	10	30.8	0.88
Fullerton Cove Core 2 (FCC2)	30	8	32.2	1.07
Hunter North Arm Core 1 (HNA1)	100	28	142.7	1.43
Hunter North Arm Core 2 (HNA2)	95	26	102.3	1.08
Hunter North Arm Core 3 (HNA3)	>150	>42	>355	2.37(*)
Hunter North Arm Core 4 (HNA4)	>100	>28	>218	2.18(*)
Hunter South Arm Core 1 (HSA1)	115	32	218.1	1.89
Hunter South Arm Core 2 (HSA2)	75	21	52.7	0.70
Throsby Creek Core 1 (TCC1)	55	15	97.5	1.77

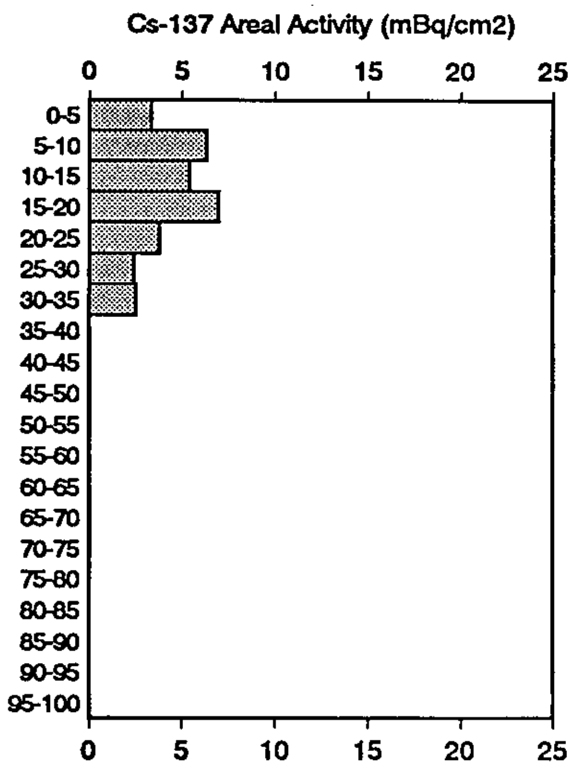

Figure 2a. Cs-137 profile from core FCC1 (Fullerton Cove).

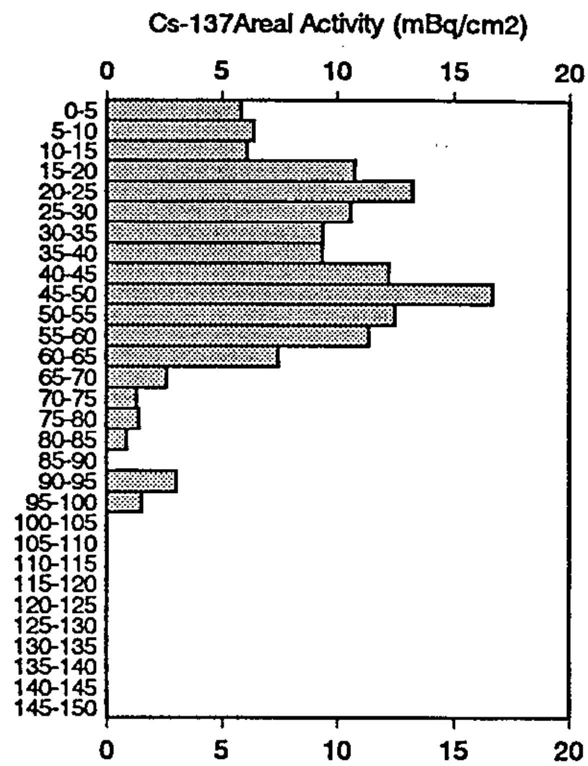

Figure 2b. Cs-137 profile from core HNA1 (Hunter River North Arm).

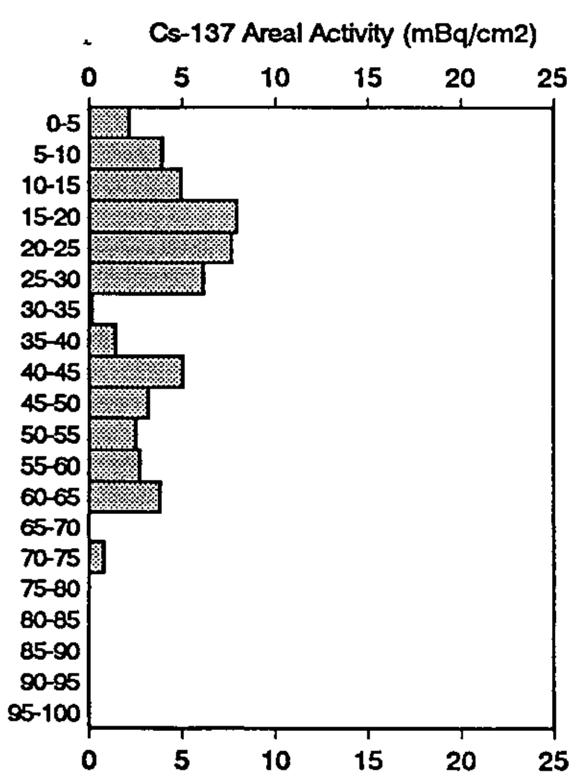

Figure 2c. Cs-137 profile from core HSA2 (Hunter River South Arm).

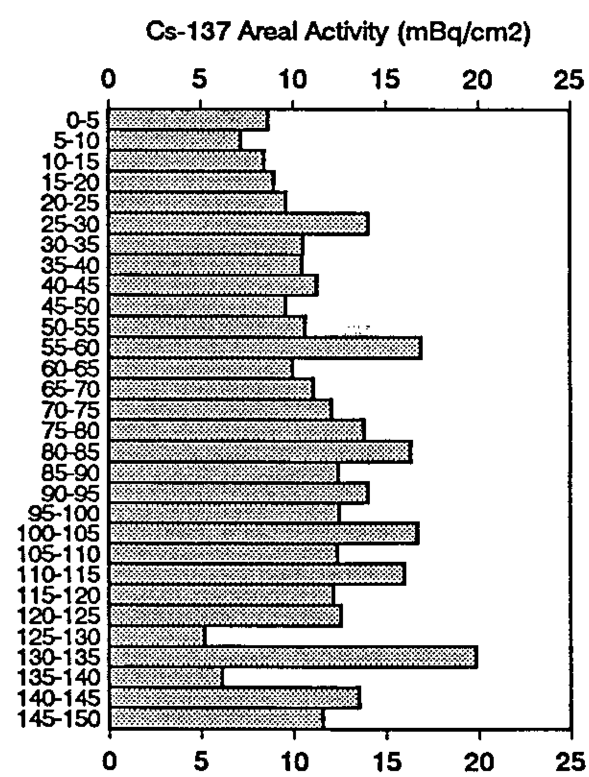

Figure 2d. Cs-137 profile from core HNA3 (Hunter River North Arm).

Sedimentation rates in the Hunter River South Channel appear to be lower than elsewhere in the open estuary (see Figure 2c). Core HSA2 shows a sedimentation rate of 21 mm yr^{-1} which may be significantly influenced by the presence of barrages (built to low tide water level) at the upstream end of the South Channel. These barrages, while originally built to reduce harbour sedimentation (Ford, 1958), are suspected of reducing tidal flushing of sediment at the harbour end of the South Channel, resulting in the higher sedimentation rate at HSA1.

The usefulness of the whole core ^{137}Cs activity values to quantitatively estimate sediment sources (e.g. Loughran *et.al.*, 1988; Peart & Walling, 1986) is limited by the unknown degree to which direct atmospheric fallout has been incorporated into the estuarine ^{137}Cs profiles. However, assuming that the atmospheric fallout incorporation rate has been constant across the estuary, inter-core comparisons can be made. The mean activity (mBq cm^{-2} cm^{-1}), shown in Table 1, is an indication of the 'strength' of ^{137}Cs labelling of the respective cores.

One conclusive observation from these results is the significant difference between the mean activities of the upper estuarine cores (HNA3 & 4) compared to the Fullerton Cove cores. Several of the other cores had a variable particle size distribution that included some significant sand layers. This may 'dilute' the ^{137}Cs due to its reduced adsorption on sand particles. Cores HNA3 & 4 and FCC1 & 2 had consistent silt/clay particle size compositions, enabling strong comparisons to be made between the two depositionary environments.

Cores HNA3 & 4 had higher mean activities compared to FCC1 & 2. This would suggest that there is preferential deposition of labelled sediments, presumably a soil source, higher in the estuary.

3. DISCUSSION

3.1. Sediment Sources

Sedimentation rates suggest that a significant proportion of sediment being deposited within the lower Hunter River estuary is deposited within the North Channel, upstream of Fullerton Cove. While it is uncertain the degree to which the channel depth is changing, there is considerable evidence to suggest that channel narrowing is occurring. Furthermore, this sediment which is being deposited higher in the estuary is more strongly labelled with ^{137}Cs (compare Figures 2a & c with 2b & d), indicating a topsoil source. There are two possible explanations for this effect. Either labelled sediment (topsoil) is preferentially deposited or deposition is occurring at this site when a greater proportion of the suspended sediment is labelled with ^{137}Cs.

NSW Dept. of Public Works (1969) suggests that the lower Hunter River estuary acts as a stratified estuary with a clearly defined salt wedge during flows of 300 to 2000 m^3s^{-1} (approximately 5% of the time). Analysis of the sediment rating curve and the flow duration curve for the lower Hunter River (NSW Dept. of Public Works, 1969) suggest that approximately 50% of the mean annual sediment load will enter the estuary under these conditions. Therefore, while the salt wedge may be operating for a relatively small amount of time it can influence a significant proportion of the suspended sediment. A salt wedge will increase the flocculation of the sediments resulting in greater sedimentation at the turbidity maximum (Knox, 1986). The results tend to suggest that this turbidity maximum, under salt wedge conditions, is usually positioned upstream of Fullerton Cove on the North Channel.

It therefore seems likely that soil sources contribute more to the suspended sediment load during periods of high flow than at other times.

3.2. Sediment Remobilisation

Fullerton Cove acts as a primary sedimentation zone within the estuary (NSW Dept. of Public Works, 1969). Sediment is deposited under conditions of high suspended sediment concentrations. During the intervening periods between these events sediment is eroded and redeposited elsewhere within the estuary, predominantly Newcastle Harbour.

Due to the shallow nature of Fullerton Cove, strong winds can cause significant turbulence within the water column that results in the re-suspension of sediments which are then removed on the ebb tide (NSW Dept. of Public Works, 1969). This would account for the greatly reduced total ^{137}Cs activity of the Fullerton Cove cores.

4. CONCLUSION

The use of ^{137}Cs within an Australian estuarine environment has been shown to yield useful information about the recent sedimentary history of the estuary. Sedimentation rates suggest that a significant amount of sediment is being deposited across the lower Hunter River estuary, with the greatest mean sedimentation rates occurring higher in the estuary. The ^{137}Cs determined sedimentation rate within Fullerton Cove was shown to match very closely to a previously determined sedimentation rate. ^{137}Cs has again been shown to be a useful tracer of labelled topsoil material within the fluvial environment.

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Floodplain Classification and its Relevance to Stream Management

J. C. Croke *

ABSTRACT: *Part of effective stream management is to integrate available knowledge on river behaviour from a wide range of locations, and apply this to the local problem. Classification schemes have an important role to play in this process by providing a logical framework in which to integrate our knowledge. To be of greatest benefit a river classification scheme needs to represent the physical processes that control river behaviour but remain simple enough for wide application. A floodplain classification is proposed here based upon the concept of stream power in relation to the resistance of the floodplain and channel sediment. The classification uses a hierarchy of floodplain types and orders, and the scheme is applicable to a wide range of floodplains, at all river scales. It is proposed that rivers move predictably from one type to another on the basis of changes to stream power or resistance, which can be modified by management.*

1.0 INTRODUCTION

Recent reports on the 'health' of Australian rivers suggest significant changes have occurred in catchments and streams throughout a very large part of the country (CSIRO, 1992). Major areas of concern include the morphological and ecological impacts of river regulation, bank erosion, changes to the stream substrate and channel siltation. While it is now generally agreed that these problems must be addressed at the catchment scale, within the framework of some Total Catchment Management (TCM) strategy, there is a lack of consensus on how this is to be achieved, and at what spatial scale. It is clear that there is insufficient data (quantitative or qualitative) available to characterise our river systems and consequently, the development of national, state or even local strategies and future management directions is virtually impossible. This task is further complicated by the problems of scale and time. Small and large catchments are likely to manifest and respond to change differently and therefore require management strategies which reflect this (CSIRO, 1992). Likewise, the state of a particular river as it exists today must be evaluated within the context of its propensity to change in the future and what the magnitude of this change is likely to be. For example, there is little point in recommending the restoration of riparian vegetation along a highly mobile river or reach of river where the dominant processes are lateral migration and/or channel avulsion. It is crucial, therefore, that river management strategies incorporate the concept of 'dynamic equilibrium' (Chorley, Shumm and Sugden, 1984).

Floodplains are important features in the landscape and it is important that their development and characteristics are understood and integrated into river management strategies for a number of reasons. Firstly, floodplains provide a major source for river sediments, and the physical and chemical characteristics of these materials may impact considerably on water quality. Secondly, floodplains which are inundated at high flow become part of the surface flow system. Even at low water, groundwater returns can be a significant component of the baseflow of river discharge. Surface forms that affect the passage of floodwaters and how they change over time are therefore important to our understanding of flood hydrology. Likewise, a knowledge of subsurface floodplain materials that affect groundwater storage, flow and quality is important. Thirdly, because floodplains are genetically associated with the river channel, they preserve a detailed record of past river activity. Understanding how river channels have changed is vital if restoration strategies which are both morphologically stable and ecologically desirable are to be developed. The purpose of this paper is to outline a relatively simple process-based classification of rivers and floodplains that can be used as a the basis for planning stream management strategies.

2.0 THE NEED FOR AND ROLE OF CLASSIFICATION

There is a need for a river classification scheme which extrapolate between sites as well as putting local sites into the broader context of riverine evolution. Determination of the position of any riverine system within the spectrum of floodplain types should make it possible to predict potential changes for the system. All river systems, at any spatial scale, expend energy; their very form and shape reflect the balance between the force of the flow and the resistance of the stream's boundary materials (Fig. 1). The location of a river within any catchment, together with the nature of its discharge, sediment load and flow characteristics are all determinants of the amount of energy available to a given river system. Australian rivers often display different and, in some cases unique processes, such as catastrophic stripping, prominent benches and pronounced levees, chains of ponds, downstream reductions in channel width/depth. There are a huge range of distinctive forms which may not appear to be related, but they can be placed in a framework of force versus resistance and over time change position predictably in this framework.

* CRC for Catchment Hydrology, CSIRO Division of Water Resources, GPO Box 1666, ACT 2601
Telephone: (06) 246 5788 Fax: (06) 246 5845 Email: jacky@cbr.dwr.csiro.au

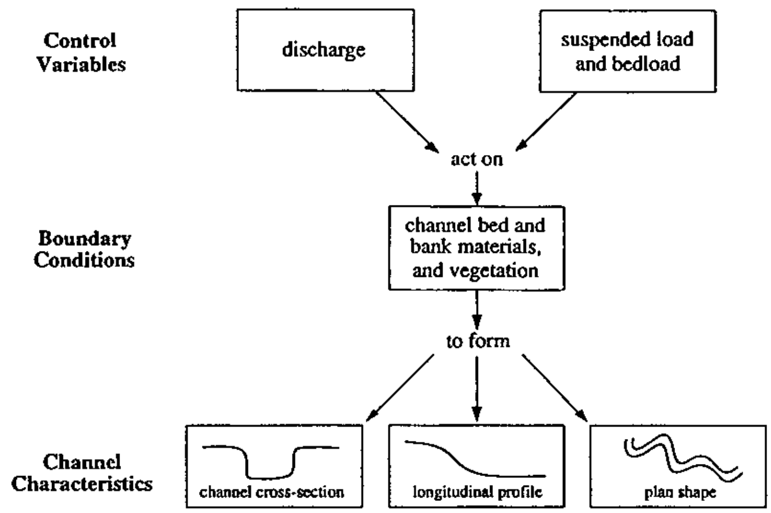

Figure 1. Equilibrium Concept for Eroding Channels (after Schumm, 1969)

River and floodplain classifications have been criticised in the past for their simplification of a complex and highly variable landform, for their resultant loss of useful information and/or for their static approach. While it is true that some classification schemes can induce unnecessary pigeon-holing, this is primarily caused by selecting criteria which are not process-based and therefore cannot reflect the natural variability of river/floodplain systems in space or time. A simple classification based solely on the morphology of the channel planform (ie meandering, braided etc) provides useful information on processes, but it provides little on where the river sits within a dynamic continuum of potential change over time. The River Murray in planform looks, and is often perceived to be, a highly mobile and active river as evidenced by the numerous scroll bars, meander cutoffs and oxbow lakes. However, over the past one hundred years or so the Murray has remained relatively stable because the present energy of the river is insufficient to mobilise the meanders (Rutherfurd, 1990). Furthermore, our understanding of the processes of channel sedimentation and hence floodplain formation have expanded considerably over the past twenty years or so. The reported dominance of a single process, namely lateral point-bar accretion, has been superseded in the literature by the identification of additional processes including overbank vertical-accretion; braided-channel accretion; oblique accretion; counterpoint accretion and abandoned channel accretion (see Nanson and Croke, 1992 for descriptions). Many of these processes are well illustrated in Australian fluvial systems.

3.0 FLOODPLAIN CLASSIFICATION

3.1 The Energy:Resistance Concept

A review of river and floodplain classifications and the principals underlying the energy:resistance concept are described in detail in Nanson and Croke (1992). In brief, the energy:resistance concept attempts to characterise the channels ability to do work, or more specifically, to entrain and transport sediment and the resistance of the channel boundary to erosion. Three categories of specific stream power are used to distinguish High, Medium and Low-energy dominated floodplains (Table 1). Specific stream power (W/m^2) is defined as $w=gQS/W$, where g is specific weight of water, Q is bankfull discharge, S is channel slope and W is bankfull flow width. Bank resistance is more difficult to quantify due to the typically unquantified control of sediment cohesion and vegetation on bank stability. Bank resistance is classified according to the size of sediment within the bank; sand and gravel banks are classified as non-cohesive and silt and clay as cohesive (Table 1). The resultant scheme produces a tripartite division of river floodplains; High-energy non-cohesive floodplains (A1-A4); Medium-energy non-cohesive floodplains (B1-B3d) and low-energy cohesive floodplains (C1-C2b). On the basis of additional geomorphological processes, for example, the presence or absence of scroll bars, counterpoint sedimentation, organic backswamp deposits, and valley confinement, a total of thirteen orders and suborders were recognised from examples reported in the literature and personal observations.

There are a number of aspects of the energy:resistance classification scheme which may be appropriate to the characterisation of Australian river/floodplain systems.

- The classification scheme is process based and can be used to characterise the energy:resistance relationship of river systems at any spatial scale, including entire river systems, reaches or specific sites.
- Stream power is an effective measure of the stream's

Floodplain Type	Order	Energy: Resistance estimate W/m^{-2}	Description
Class A: High-energy Non-cohesive Floodplain	A1: Confined coarse textured floodplains. A2: Confined vertical accretion floodplains. A3: Unconfined vertical accretion sandy floodplains. A4: Cut and fill floodplains.	> 1000 W /m^{-2} 300-1000 300-600 300	Disequilibrium floodplains which erode in response to extreme events. Typically located in steep headwater reaches where channel migration is prevented by valley confinement.
Class B: Medium-energy Non-cohesive Floodplain.	B1: Braided river floodplains. B2: Wandering gravel-bed river floodplains. B3: Meandering river, lateral migration floodplains. (There are 4 suborders within category B3.)	50-300 30-200(?) 10-60	Equilibrium floodplains formed by regular flow events in relatively unconfined valleys.
Class C: Low-energy Cohesive Floodplains	C1: Laterally stable single-channel floodplains C2: Anastomosing river floodplains. (There are 2 suborders of Category C2.)	< 10 W /m^{-2}	Floodplains formed by regular flow-events along laterally stable single-thread or anastomosing low-gradient channels.

Table 1. Summary of Major Floodplain, Orders and Energy Classes from Nanson and Croke (1992)

energy under *bankfull* conditions, a state when the potential for stream bank erosion is often most likely. Ordering stream channels according to their bankfull energy capacity provides a useful guide to the force available to that river or river reach at this magnitude of flow.

- Quantifiable values of stream power and bank stability can be collected for a range of river environments and can be then used to construct an 'inventory' of river systems at the local, state or even national scale. River systems can be placed within this energy continuum and appropriate management strategies can be devised for the specific requirements of river/floodplain type. For example, the management strategies appropriate to high energy river and floodplain systems are likely to be entirely different to those required of low energy cohesive systems.

- The classifying criteria are not static- ie if channel characteristics change this will be reflected in the energy capacity of the stream and hence floodplain type. Floodplains and channels can therefore move from high to low energy classes due to a corresponding decrease in slope, discharge and/or channel dimension etc.

3.2 Disturbing the Energy:Resistance Balance

Many of the problems encountered in our river systems today reflect the streams response to some alteration of the energy:resistance balance. Bank erosion, increased sediment and nutrient delivery to the streams, stream aggradation/degradation, and avulsion, for example, reflect the rivers disequilibrium between the amount of energy available and the resistance of the channel boundary materials. Laterally stable, single channel floodplains (C1) for example, changed to wandering gravel-bed river floodplains (B2). This followed an

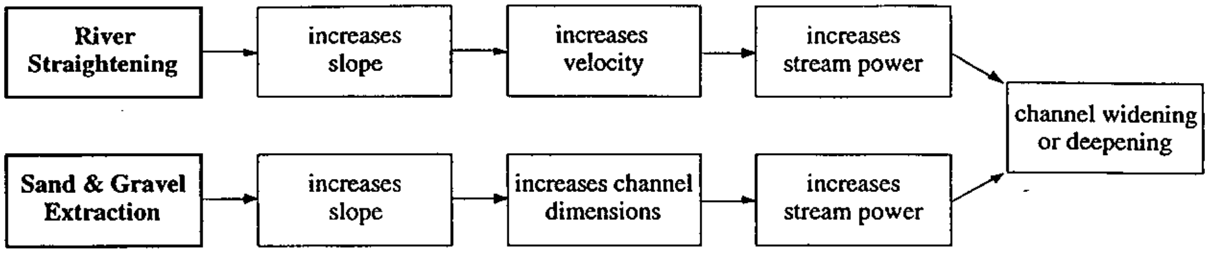

Figure 2. Adjustments to channel variables due to disturbances

increase in coarse sediment delivery in response to historic heavy metal mining (Croke, 1994). Sand and gravel extraction is likely to increase channel dimension (hence flow capacity), increase the slope of the bed and ultimately increase the available stream power (Fig. 2). This in turn is likely to increase sediment transport rates and channel bank erosion. Weir and dam impoundment will also alter the slope of the channel and the stream power / bank resistance relationship will in turn be affected (Fig. 2). Attempts to improve bank stability by artificial embankments etc may result in this available energy being applied to the channel bed, promoting increased channel incision and sediment transport. It is important to recognise the predictability of the dynamic changes within a river system.

Fundamental to the genetic classification proposed by Nanson and Croke (1992) is the recognition that a channel and floodplain will change in response to environmental factors that affect the channel. With additional data on both the range of streams powers for selected river types and bank resistance, it may be possible to identify 'thresholds' of instability for given channel and floodplain types. These can then be used in the development of management strategies appropriate for different energy classes of rivers and floodplains. It is important, therefore, that stream management strategies evaluate the potential impact of a particular disturbance within the context of the variables which will affect the energy:resistance balance of the stream.

4.0 CONCLUSIONS

Current problems in stream management highlight the sensitive balance between the channels erosive power and the resistance of its boundary materials. This energy:resistance concept of river behaviour provides a useful classification which can be used at a range of spatial scales. This variable may be particularly useful in providing a common link for river inventories and in producing a state wide or national river classification scheme. The advantages of this scheme are that it is process oriented and therefore can predict what happens through time. Furthermore, it only requires simple parameters which can be easily gathered for all rivers. It incorporates a wide range of scale of rivers and scale is important in determining appropriate management strategies; minor adjustments to resistance, for example, will have little impact on a high energy river. Further work in obtaining estimates of stream power for a greater range of river and floodplain environments, in addition to developing a quantifiable estimate of bank resistance, will contribute to the application of this scheme to river management purposes.

5.0 ACKNOWLEDGEMENTS

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An Optimisation Model for the Management of Alluvial Rivers

Robert Millar[1] and Michael Quick[2]

ABSTRACT: *A model is developed to interpret and predict the response of alluvial rivers to changes in runoff, sediment supply or bank stability conditions. The approach is based on an equilibrium analysis and uses an optimisation formulation to determine the steady-state or "regime" hydraulic geometry for a given set of input variables. The model is useful as a management tool and can be used to assess the effects of proposed land use changes or engineering projects on the geometry of alluvial rivers.*

1. INTRODUCTION

Modelling the hydraulic geometry of alluvial rivers is of interest to hydraulic engineers, hydrologists and environmental managers engaged in assessing the future response of the channel to catchment development and land-use changes. Changes in the imposed discharges, sediment load or the ability of the banks to withstand erosion can result in adjustment of the channel boundary, and the development of a new hydraulic geometry. The channel adjustments may result in changes that are determined to be undesirable for economic, environmental, or aesthetic reasons and include bank erosion and loss of riparian habitat and land adjacent to the river; degradation of the channel bed which can undermine bridge foundations and other hydraulic structures; aggradation of the channel bed which can reduce the channel capacity and result in an increased frequency of over-bank flooding; and changes in the physical nature of the channel that may impact the aquatic habitat.

In this paper an analytical model will be described. The basic goal of the model is to calculate the equilibrium or "regime" hydraulic geometry of alluvial rivers for a given set of inputs. The model is presented as an optimisation formulation. Optimisation models have been developed previously by Chang (1980), Yang *et al.* (1981), and White *et al.* (1982) among others to predict the geometry, or aspects of the geometry, of alluvial channels. The model is an extension of this earlier work.

In the companion paper (Millar and Quick, 1996b), the model is used to demonstrate the influence of the bank stability and riparian vegetation on the channel geometry.

2. DEFINITION OF EQUILIBRIUM

It is an underlying assumption of equilibrium channel analysis that alluvial rivers develop a mean hydraulic geometry in response to the water discharge, sediment load, and sediment properties that are determined by the geology and hydrologic regime of the upstream areas. Blench (1969, p. 1) refers to the "basic principle of self-adjustment" and states that:

> The fundamental fact of river science, pure and applied, is that regime channels tend to adjust themselves to average breadths, depths and slopes and meander sizes that depend on (i) the sequence of water discharges imposed on them, (ii) the sequence of sediment discharges acquired by them from the catchment erosion, erosion of their own boundaries, or other sources and (iii) the liability of their cohesive banks to erosion or deposition.

The term regime used by Blench is considered to be synonymous with alluvial. Alluvial rivers are by definition those that have bed and banks composed of sediment that is actively transported by the river.

The optimisation model is based on an analysis of this equilibrium state. Transient adjustments are not considered. A channel is defined herein as being in equilibrium when the following conditions are satisfied:

1. The mean hydraulic geometry of the representative channel reach remains unchanged over an appropriate time scale for which a steady-state equilibrium can be assumed.

2. There is no net erosion or deposition along the reach.

3. Any perturbations from the equilibrium geometry will be offset, and the equilibrium restored.

[1] Manager, Environmental Studies, Water Studies Pty. Ltd., PO Box 80, Red Hill Qld 4059.
Telephone: (07) 3369 6499 **Fax:** (07) 3368 1466

[2] University of British Columbia, Vancouver Canada.

Note that this definition applies to reach-averaged, and not local values of the hydraulic geometry. The term steady-state refers to a time-invariant equilibrium. The absolute time period over which this approximation is valid will depend upon the system being studied. It is valid where there are no significant or systematic changes in the mean annual characteristics of the discharge and sediment load, or in the competence of the bank sediment. In general the steady-state approximation may apply over engineering time scales up to 100 years or so.

3.0 MODEL BASIS

An alluvial channel is a relatively complex system with perhaps up to seven degrees of freedom (Hey, 1978). The system is indeterminate in that there are more unknown dependent variables or degrees of freedom than there are equations for solution. Even for a simplified channel geometry with only three degrees of freedom: width, depth, and slope, the solution remains indeterminate as there are only two relations, flow resistance-continuity, and sediment transport, available for solution. Being indeterminate there are an infinite number of solutions that satisfy the available governing equations.

The basis of the optimisation model is the assumption that the equilibrium or regime hydraulic geometry corresponds to an optimum configuration. This assumption allows a single, unique solution to be selected from the infinite possibilities.

3.1 Optima in Fluvial Systems

The presence of an optimum geometry in fluvial hydraulics was first demonstrated by Gilbert in 1914. In flume experiments under conditions of fixed discharge rate and channel slope, it was demonstrated that by varying the width of the flume an optimum value exists where the sediment transporting capacity of the flume was a maximum.

The mechanisms responsible for the optimum in Gilbert's experiments can be readily explained. For narrow flume widths much of the shear force is acting on the side walls, and this, together with the narrow bed widths over which sediment transport can occur, results in a low total transport rate. Conversely for the large flume widths the depth of flow and the bed shear stress both become small, and hence the total sediment transport rate also becomes small. Between these two extremes lies an optimum where the sediment transport rate is maximised.

Gilbert's experimental result can be duplicated numerically. An example of a solution curve is shown schematically in Figure 1(a). The channel slope and discharge are constant for all points on the solution curve. In Figure 1(b) a solution curve is shown where the channel slope is a variable, and the discharge and sediment transporting capacity are now fixed. In this case the optimum is the point where the slope is a minimum. This second case is considered to be analogous to most natural alluvial rivers over engineering time scales. The discharge and sediment load are imposed, and the width, depth and channel slope are dependent variables that develop in response to these imposed values.

The experimental results of Gilbert (1914) together with the numerical analyses discussed above combine to lend significant support for the actual existence of an optimum in the fluvial system. The fundamental assumption employed in the optimisation model is that a natural river channel will tend to adjust to this optimum, and that this optimum corresponds to the equilibrium hydraulic geometry.

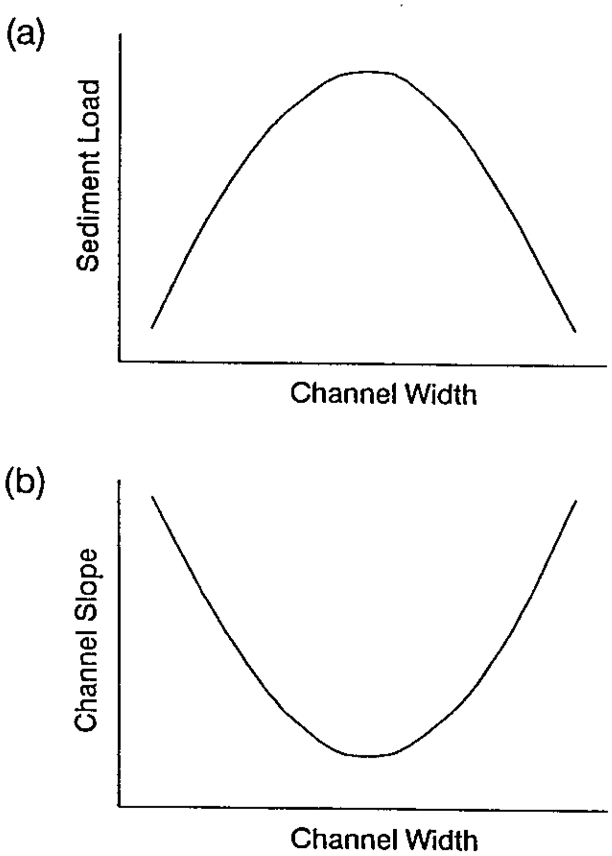

Figure 1. Schematic representation of the optimum in fluvial systems. (a) Constant discharge and slope. (b) Constant discharge and sediment load.

4.0 MODEL FORMULATION

The formulation of the optimisation model will now be discussed.

4.1 Independent Variables

The independent variables represent the known, external controlling variables which are inputs to the system. The variables which are considered independent include the physiographic, geologic and hydrologic properties of the catchment. These are the geology, relief, climate, runoff, vegetation, and the volume and calibre of the sediment yield.

Additional independent variables are related to the channel boundary, namely the bank vegetation, and bank sediment parameters such as cohesion and friction angle. The valley slope is also considered to be independent over engineering time scales. Although the valley slope can be considered to be a dependent variable over geologic time scales, any significant change in the valley slope requires the removal or deposition of large volumes of alluvium which can only occur over long periods of time.

The channel is modelled using the steady-state, mean values of the sediment yield and flow-duration data or a single representative discharge, as well as the mean bank stability parameters for the representative channel reach.

4.2 Dependent Variables

The dependent variables are the unknown channel geometry variables: width, depth, slope, bank angle, roughness, velocity, sinuosity, meander and pool-riffle wavelength, meander radius of curvature, and bedforms. In the current model a simplified channel geometry is assumed. Secondary currents and the planform variables will not be considered explicitly, however a comparison of the channel and valley slopes gives a measure of the channel sinuosity and therefore some limited information on the planform geometry.

4.3 Constraints

The principal constraints in the model are the discharge, sediment load, bank stability, and valley slope constraints.

4.3.1 Discharge Constraint

The discharge is a constraint on the channel system as it represents virtually the total energy input. The channel development and sediment transport must be accomplished with the available flows. The discharge constraint demands that the channel has a discharge capacity equal to the imposed value of the bankfull discharge. The bankfull discharge is considered to be an independent variable.

The model requires a flow resistance equation together with continuity to satisfy the discharge constraint. The discharge constraint 'sizes' the channel. The channel must have a discharge capacity equal to the bankfull discharge, Q_{bf}:

$$U A = Q_{bf} \qquad (1)$$

where U = the mean velocity, and A = the cross-sectional area of the flow. The value of U is obtained from either the Darcy-Weisbach or Manning equations.

4.3.2 Sediment Load Constraint

The sediment load constraint is a key component of the model and ensures that the amount of sediment that is imposed at the upstream end of the channel is transported without net deposition or scour. In other words the sediment load constraint demands that sediment continuity is maintained along the channel reach:

$$P_{bed}\, g_b = G_b \qquad (2)$$

where P_{bed} = bed width or perimeter, g_b is the sediment transport rate per unit channel width, and G_b is the imposed sediment load.

The value of g_b is calculated using a suitable sediment transport relation that is based on shear stress. Sediment transport relations containing a critical shear stress that must be exceeded before sediment transport commences cannot be used. The optimisation scheme is unable to handle zero transport rates.

4.3.3 Bank-Stability Constraint

A requirement of equilibrium channels is that the banks must be stable. Note that stability here applies to the reach-averaged condition of the banks. Locally, such as along the outer bend of a meander, the banks may not be stable. However the reach-average condition of the banks must be one of stability, otherwise there would be a net change in the hydraulic geometry over time, and the channel could not be considered to be in equilibrium.

The bank-stability constraint requires that the reach averaged condition of the banks be stable. The bank-stability constraint can be formulated for banks with noncohesive sediment or cohesive sediment, and is discussed in some detail in the companion paper (Millar and Quick, 1996b).

4.3.4 Valley-Slope Constraint
The valley slope forms an additional constraint or physical bound to the solution. The valley-slope constraint requires that the equilibrium channel slope is less than or equal to the valley slope:

$$S \leq S_v \tag{3}$$

where S is the channel slope, and S_v is the valley slope. S_v is considered to be an independent variable.

4.4 Objective Function

The objective function in this formulation is the maximisation of the coefficient of sediment transport efficiency, η, which was developed from Bagnold's (1966) streampower arguments (Millar, 1994). The value of η is defined as:

$$\eta = \frac{G_b}{\rho Q S} \tag{4}$$

Where G_b = the dry sediment transport rate in mass units, and ρ = the density of water, Q = representative discharge and may be the bankfull or mean annual discharge, and S = the channel slope (uniform flow is assumed). The product $\rho\ Q\ S$ is the total stream power in mass units.

Note that maximization of η is equivalent to the extremal hypotheses of maximization of sediment transport capacity (White *et al.* 1982, Millar and Quick, 1993) under conditions of fixed Q and S, and is equal to the minimisation of streampower (Chang, 1980) or minimum S for imposed values of G_b and Q. In the complete form of (4) which is not shown here, maximization of η is also equivalent to the minimisation of the energy dissipation rate of Yang and Song (1979).

The optimum solutions are shown schematically in Figure 1 (a & b). In Figure 1(a), under conditions of fixed Q and S, the optimum corresponds to a maximum value of G_b. In Figure 1(b) G_b and Q are fixed, and the optimum corresponds to a minimum value of S.

5.0 OPTIMISATION SCHEME

A computer program was developed to determine the optimum hydraulic geometry which satisfies the discharge, bedload transport and bank-stability constraints. The model uses a heuristic, iterative search routine to locate the optimum. However any non-linear optimisation technique could be used.

No evidence of local or multiple optima has been detected to date.

The optimisation model can be formulated in a number of ways depending upon the available data and the objectives. In the simplest version, the sediment transporting capacity of the channel is modelled at the bankfull discharge only. A more complex version requires the entire flow-duration curve to be discretised and used as input, and the sediment transporting capacity is modelled for the entire range of flows.

The model can be formulated as a fixed-slope model where the channel slope is held constant, and the optimum cross-section is determined by varying the channel width. The optimum in this instance corresponds to the maximum transporting capacity. Alternatively in the variable-slope formulation the imposed sediment load is fixed as an independent variable, and the channel slope is free to adjust to the optimum. In this instance the optimum corresponds to the minimum channel slope.

The variable-slope model is generally used to model natural rivers. However the fixed-slope model is useful when estimating or calibrating the bank-stability parameters. This is discussed in the companion paper (Millar and Quick, 1996b).

A version of the variable slope model is presented in greater detail in Millar and Quick (1993). The full range of models is discussed in Millar (1994).

6.0 MODEL APPLICATION

The optimisation model can be used to assess the response of a channel to any situation where there is alteration in the volume or size distribution of the imposed sediment load, the volume and timing of the flows, or the properties of the bank sediment. For example the construction of a dam will affect the sediment supply and flows. The sediment supply will be reduced dramatically, often effectively to zero directly downstream from the dam. The flows are usually affected to a large extent, typically by truncating the higher flows, and increasing the proportion of low flows. The total runoff volumes may or may not be affected. The bank stability parameters may not be affected.

Other potential applications relate to land-use changes. For instance removal of forest cover by logging or for agricultural development may increase the sediment yield from the catchment, and yet may or may not affect the runoff to any great extent. Often the riparian vegetation is affected by these developments, and as is demonstrated in the companion paper (Millar and Quick, 1996b), this can have a profound influence on the bank stability.

Urbanisation can severely alter the runoff response and sediment yield from affected areas of the catchment.

The model can be used to perform sensitivity analyses to determine the effect of a potential development on the river channel where the post-development inputs cannot be accurately determined. For instance to assess the response of a river channel to increased sediment load, the model can be initially calibrated using the observed hydraulic geometry. A sensitivity analysis can then be performed to determine the sensitivity of the channel under the range of potential increases in the sediment load.

Regardless of the type of development or catchment disturbance, the input required for the model is a flow-duration curve or representative discharge (bankfull discharge), an estimate of the volume of sediment load and grain size distribution, and estimates of the bank stability parameters. Hydrologic modelling and sediment budget studies may be necessary, together with field observations, to determine the appropriate values to use as input to the model. These values may be difficult to measure in an intact system let alone to predict the values for a disturbed catchment. Estimates of the current sediment load of a stable river system can be obtained using the observed hydraulic geometry, together with the measured or estimated flow-duration curve.

When using the optimisation model it must be realised that the optimum value is only a theoretical value which the river may show a tendency to adjust towards. The optimisation model is only an adjunct to other techniques such as air photo interpretation, and field monitoring of observed channel adjustments of the river of interest, and in nearby channels that may have been subjected to similar disturbances. Any modelling results must be tempered with sound engineering judgement, and must recognise the location of geologic controls that may further constrain the system.

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Hydraulic - Geomorphic Assessment of the Tumut River

John Paul Bucinskas BE(Civil) MEngSc *

ABSTRACT:

An hydraulic - geomorphic assessment of the Tumut River has been undertaken in order to provide an improved understanding of the processes occurring on the river and to provide a technical framework to base a revised river management strategy. This paper has been prepared to present a summary of the findings of the study and to encourage further use and research of the techniques developed as a method to quantify river behaviour.

The Tumut River has a long history of erosion and channel changes resulting from both natural and human induced changes in the catchment. The inter-catchment diversions of the Snowy Mountains Hydro -Electric Scheme and regulation of flows by Blowering Dam has caused a change in the flow regime.

The assessment technique involved an analysis of the hydraulic - geomorphic slope with consideration to channel stability. A tractive stress duration diagram was also developed in order to quantify the effect of the change in flow regime on the stability of the Tumut River. The concept of tractive stress was also investigated as a tool to assist in the design of river management works.

1. INTRODUCTION

The management of unstable rivers has traditionally been undertaken using structural means with little understanding of the processes causing the instabilities. This study provides an improved understanding of the processes occurring on the Tumut River by analysing the hydraulic and geomorphic properties of the river channel.

The aim of the hydraulic - geomorphic assessment is to quantify the effects of the changed flow regime (the hydrology) with consideration to the hydraulic and geomorphic properties of the river system to ensure that scientific and engineering judgement is integrated into the river management solutions. The hydraulic - geomorphic assessment undertaken can only be considered as a basic assessment as the river parameters used in the analysis are averaged for long river reaches and only one hydraulic and geomorphic equation was used.

The technique adopted in the study is based on the approach used by river engineers in Europe and is to the best of the author's knowledge, the first time such an analysis has been undertaken in Australia.

The main components of the hydraulic - geomorphic assessment undertaken on the Tumut River include:

- An application of the ***hydraulic-geomorphic slope*** concept to analyse the stability of the bed and bank material.
- A ***tractive stress duration analysis*** to quantify the effect of the changed flow regime on channel stability.
- To investigate the concept of ***tractive stress*** as an approach to channel stabilisation work design
- To estimate the stable channel properties of the Tumut River including width and meander geometry

This paper summarises the hydraulic - geomorphic slope and tractive - stress duration analysis components of the more detailed study undertaken by the Department of Land and Water Conservation (1995).

2. DESCRIPTION OF THE TUMUT RIVER

For the purposes of this study, the Tumut River was sub-divided into three reaches. The criteria used for the sub-division was based on changing hydraulic and geomorphic properties of the river, including the hydrology, bed slope, width, sinuosity and the grain size of the bed material. The river may have been further sub-divided to account for the anabranches (avulsions) but limited time and available data made this impractical. Information from topographic maps, gauging stations and river cross-sections were useful to quickly gain an appreciation of the river.

3. HYDRAULIC-GEOMORPHIC SLOPE

3.1 Introduction to the Concept

The hydraulic and geomorphic properties of a river channel can be described by numerical equations. The Manning equation has been used to describe the hydraulic properties of the channel and the Meyer-

* Department of Land and Water Conservation, New South Wales
P.O. Box 582, COFFS HARBOUR, N.S.W., 2450
Telephone: (066) 52 7644 Fax: (066) 52 3936

Peter and Muller (1948) bedload equation is used to describe the geomorphology.

Both the hydraulic and bedload equations can be written as a function of depth versus slope and can therefore be plotted on the same chart. The intersection of the hydraulic and bedload equations reveals the theoretical channel slope and this can be readily compared to the actual water surface or bed slope to determine the stability of the river channel.

3.2 The Hydraulics

The equation used to describe the hydraulics of the river channel is the Manning equation and it is well established to be valid for fully rough uniform flow. The derivation of the Manning equation is presented in Henderson (1966) and is defined as follows:

$$Q = \frac{AR^{2/3}S^{1/2}}{n}$$

where: Q = Discharge (m^3/s),
A = Cross-Sectional Area of flow (m^2)
R = Hydraulic Radius (m)
S = Slope (m/m)
n = Manning's Roughness Coefficient

The roughness coefficient firstly needs to be determined from gaugings of the river, using the actual cross-sections and slopes. This will provide an accurate estimation of n and will prevent having two unknowns in the analysis which follows.

In order to simplify the computations, the cross-section has been assumed to be represented as a wide rectangular section and the hydraulic radius, R, has been assumed to be equal to the depth, D. This assumption is reasonable when the width/depth ratio, $B/D>10$. That is,

$$R = \frac{A}{P} = \frac{BD}{B+2D}$$

and if

$$\frac{B}{D} > 10$$

then

$$R \approx D$$

On the Tumut River the average width B = 40 metres and the average depth D = 3 meters, giving B/D = 13 and therefore it is reasonable to consider the channel to be wide and assume $R=D$.

The Manning equation was then rewritten in terms of depth as a function of slope.

$$D = \frac{Q^2 n^2}{(B^2 S)^{3/10}}$$

and the specific hydraulic conditions in each reach were then plotted on the depth versus slope curve using the bankfull discharge. The sensitivity of changes in the estimated width, B and Manning's roughness coefficient, n were checked and the best estimate of the hydraulic conditions representing the actual reach was chosen for comparison to the geomorphic conditions.

This was achieved by firstly assuming that the water surface slope is equal to the bed slope in each reach. That is, uniform flow conditions in a prismatic channel where $S_f=S_o$. The average width of the channel was determined from the bankfull width of the channel from the cross section information. The Manning's roughness coefficient, n was then determined as the level and slope of the water surface was known at each of the cross-sections.

3.3 The Geomorphology

It is important to firstly gain an appreciation of the fluvial geomorphic aspects of the Tumut River channel before an attempt is made to quantify them.

3.3.1 The Dominant Discharge

The dominant discharge is the flow which is considered to be the channel forming flow. Although there is no universal method to estimate the dominant discharge, most geomorphologists will agree that it is best estimated as the bankfull flow.

The Tumut River however experiences bankfull flows for approximately 6 to 9 months of the year due to the inter-catchment diversions of the Scheme and regulation by Blowering Dam. It is therefore important that the prolonged duration of the bankfull flows is accounted for in the analysis.

The dominant discharge selected for the Tumut River in this study was the bankfull flow which has been considered to be equivalent to the present operational channel capacity flows which varies from 108 m^3/s upstream of the Goobarragandra River confluence

(Reach 1) to 113 m^3/s downstream of the Goobarragandra River (Reaches 2 and 3).

3.3.2 The Effect of Bedforms

The bedform of the Tumut River, as with any river, varies in both space and time. The grain size in the bed varies between the pools and riffles. The bed of the Tumut River has been observed to have an armoured layer on the riffles. It is suggested that the material in the pools however may become active bedload during bankfull flows.

3.3.3 Choice of Representative Grain Size

The representative grain size is a critical component of the geomorphic assessment in terms of the sensitivity of the bed load equation. In this assessment a single sediment size needs to be chosen to represent the highly variable nature of the reach being modelled.

For the purposes of this assessment, three different sediment sizes were chosen for each reach to represent the material in ***the armoured riffles, the pools*** and at ***the toe of the bank***. The armoured riffle material was sampled using the "grid sample" method. The material in the pools was assumed to be of the same composition as the material beneath the armoured riffles and was taken as the D_{50} of the sampled material which had undergone a standard sieve analysis. The material at the toe of the banks, which is the zone which will predominantly contribute to bank erosion, was also represented. Although the material is cohesive, a non-cohesive equivalent grain size was crudely estimated by using the grain size translation curve prepared by Hjulstrom in 1935, which is based on the threshold velocity of various grain sizes. The work by Hjulstrom is presented and discussed in Graf (1984).

Based on the methodology described above, the following grain sizes were chosen to be representative of the Tumut River reaches for the bed load computations.

	Reach 1	Reach 2	Reach 3
Riffle	55 mm	47 mm	56 mm
Pool	19 mm	23 mm	20 mm
Banks	5 mm	5 mm	5 mm

Table 1 - Selected representative Grain Sizes

3.3.4 The Bedload Equation

The equation used to describe the channel geomorphology in this study is the Meyer-Peter and Muller (1948) bedload equation. The Meyer-Peter and Muller (1948) bedload equation is based on experimental data fitting, is hydraulically backed, and is expressed in terms of shear stress as:

$$\gamma_w \frac{Q_s}{Q}\left(\frac{k_s}{k_r}\right)^{3/2} hS = 0.047\gamma_s^{"} d_m + 0.25\left(\frac{\gamma_w}{g}\right)^{1/3} g_s^{"2/3}$$

where:
γ_w = the specific gravity of water
Qs/Q = the proportion of the total flow contributing to bedload transport
k_s/k_r= a quantity that relates to the bedform roughness
h = the mean depth
S = the slope of the energy line
γ_s = the specific gravity of the bed material
$\gamma_s"$ = the specific gravity of the bedload weighed under water = $\gamma_s - \gamma_w = \gamma_s - 1$
d_m = the "effective diameter" of the bed material
g = acceleration due to gravity
$g_s"$ = the specific bedload transport weighed under water

This is equivalent to:

Shear Stress $_{(total)}$ = Shear Stress $_{(threshold\ of\ movement)}$ - Shear Stress$_{(remaining\ for\ bed\ load\ transport)}$

Since we are designing a channel for zero bed load transport then the last term of the equation is dropped and the equation becomes:

Shear Stress $_{(total)}$ = Shear Stress $_{(threshold\ of\ movement)}$

or

$$\gamma_w hS = 0.047\frac{Q}{Q_s}\left(\frac{k_r}{k_s}\right)^{3/2}\gamma_s^{"} d_m$$

The quantity $(k_r/k_s)^{3/2}$ relates the bed form roughness to the grain size roughness and can conservatively be assumed to be equal to 1. Similarly the quantity Q_s/Q=1 for a wide channel without the influence of the sides of the channel. Under these two assumptions the equation is simplified and can be rewritten with depth as a function of slope as

$$h \cong 0.047\gamma_s^{"} d_m / \gamma_w S$$

The value of 0.047 is the calibration factor (representing the Froude Number of the sediment) and defines the beginning of bedload transport. For absolute rest it is necessary to calculate with a calibration factor of 0.030.

3.3.5 Theoretical Hydraulic - Geomorphic Slope

The theoretical hydraulic - geomorphic slope was estimated by plotting the hydraulic conditions as defined by the Manning equation against the geomorphic conditions as defined by the Meyer-Peter / Muller (1948) equation. The equations are plotted with depth and slope as the axes. The curves intersect at a point which defines the theoretically stable condition. This can be compared to the actual water surface slope to determine whether or not the river is in hydraulic - geomorphic equilibrium.

The curves were plotted for all three river reaches using calibration factors of both 0.030 and 0.047. The plot using a calibration factor of 0.030 for Reach 1 is shown in Figure 1 and shows that the riffle material is on the stable side for equilibrium conditions (ie. to the left of the present water surface slope). The plot using a calibration factor of 0.047 shows that the pool material is on the unstable side and this supports the theory and observations that the pool material is active bedload during bankfull flows. The bare bank material is highly unstable as expected.

The hydraulic - geomorphic slope concept could be further used to analyse various river rehabilitation options such as channel widening.

4. TRACTIVE STRESS DURATION ANALYSIS

4.1 Methodology

The average tractive stress duration diagram is developed from flow duration and rating information which represent the average conditions on the river. The methodology involves the selection of flow duration curves which represent the average river conditions. It is then necessary to develop a rating to convert the flows into depths. The depths can then be used to estimate the tractive stress, assuming that the channel is hydraulically wide and the depth is approximated as the hydraulic radius.

The methodology is summarised as follows:

$$Flow \xrightarrow{Rating} Depth \xrightarrow{\gamma DS} TractiveStress$$

This procedure is used to convert the flows in each probability interval on the flow duration curve to form the tractive stress duration curve.

The average tractive stress is defined by the equation:

$$\tau = \gamma D S_0$$

where τ is the average tractive stress, γ is the specific weight of water, D is the depth of flow and S_o is the bed slope (which equals the energy or friction slope for uniform flow). It should be noted that the bedform and channel form roughness are assumed to be equal to 1 in this form of the equation.

The tractive stress duration curve can then be derived from the flow duration curves for the various flow duration scenarios which were taken as pre-Snowy Mountain Scheme (pre 1959), pre Blowering Dam (1959-1968) and post Blowering Dam (1968 to present).

The critical tractive stresses, defined as the tractive stress at the threshold of movement, can then be superimposed on the tractive stress duration curves to estimate the frequency that the thresholds are exceeded under the various flow duration scenarios. At this point, the factor that the banks have no recovery period due to the prolonged high flows, can be accounted for by having a lower tractive stress rating for the bare banks as compared to the vegetated banks.

4.2 Results

Figure 2 shows the results of the tractive stress duration analysis undertaken on the Tumut River.

The curves were also used to estimate the erosion potential of the Tumut River caused by the change in flow regime. The erosion potential is estimated as the area under the tractive stress duration curve and above the critical tractive stress of the material being considered. The erosion potential of the bank material was found to be presently 5 times the natural pre-Snowy channel.

5. TRACTIVE STRESS APPROACH TO CHANNEL STABILISATION DESIGN

The tractive stress approach to channel stabilisation design has been extensively used by river engineers in Europe and America and its simplicity makes it a useful tool to design river restoration works.

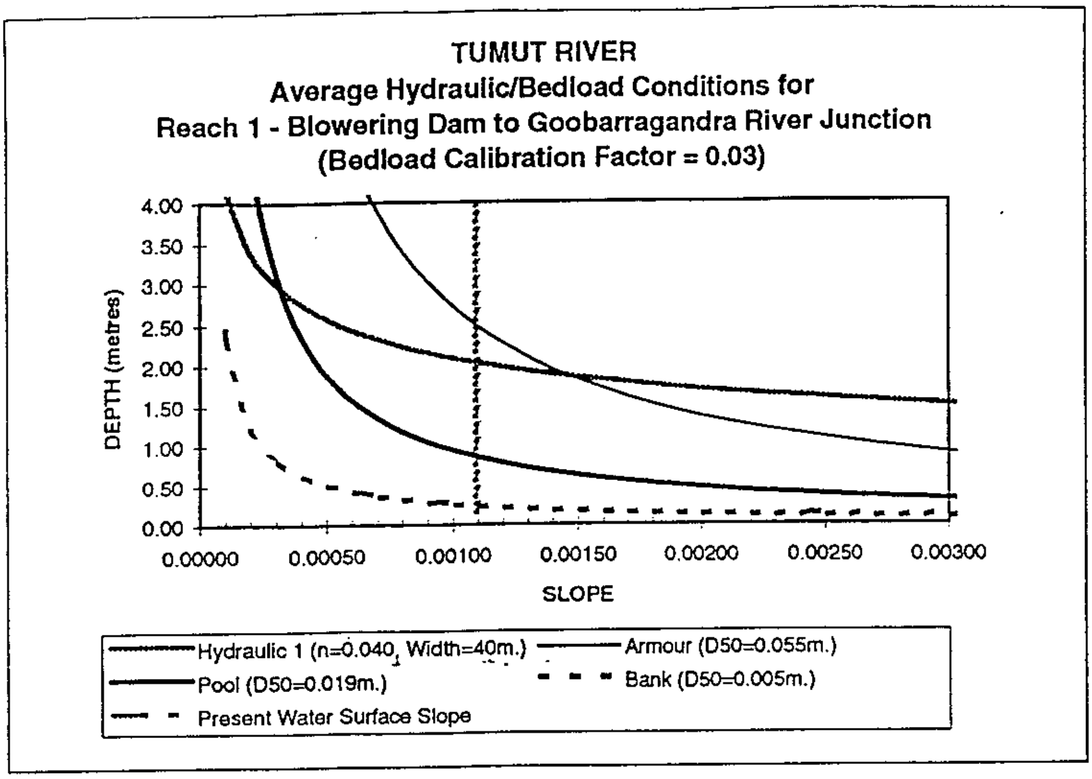

Figure 1 - Average hydraulic - bedload conditions for Reach 1.

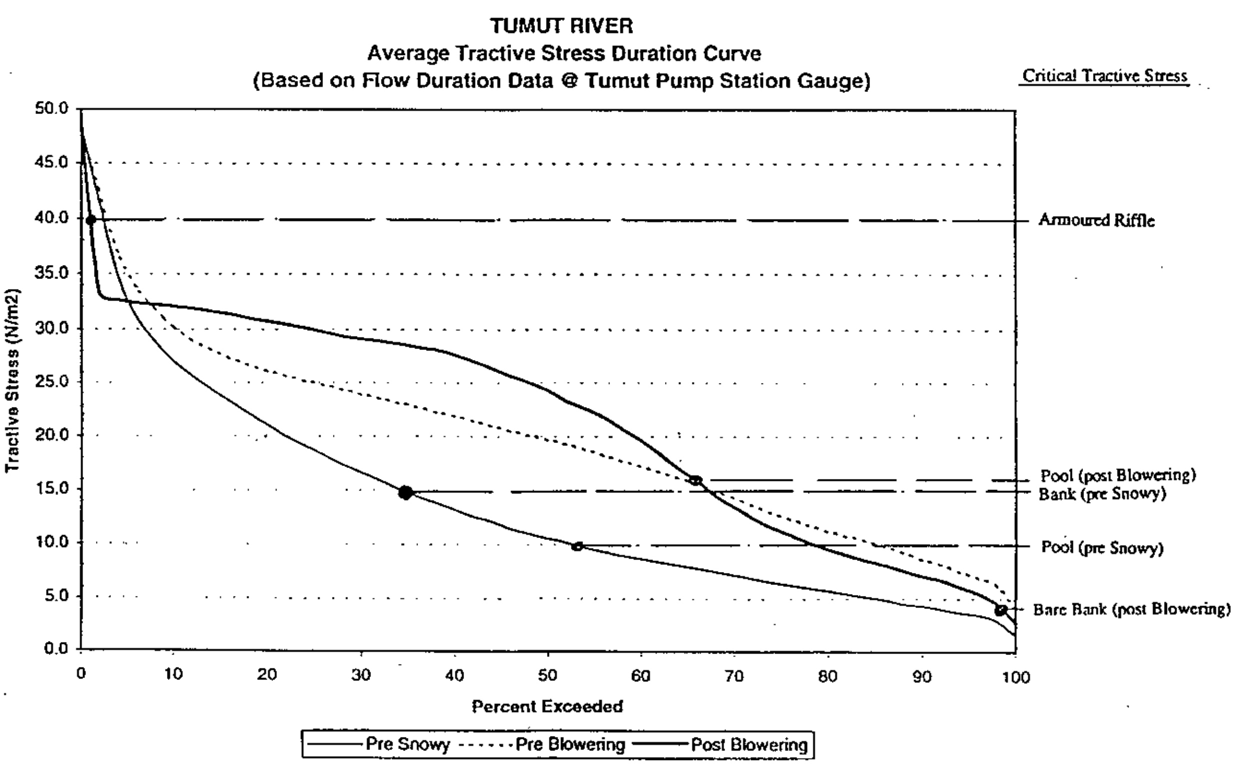

Figure 2 - Tractive Stress Duration Curves

The approach involves estimating the tractive stress imposed on the banks and comparing this with the tractive stress rating of the bank material. The ***tractive stress rating*** is also referred to as the ***bank competence*** or the ***critical tractive stress*** of the bank material. Table 2 summarises some basic tractive stress ratings used by the Bavarian river engineers.

Bank Material Type	Tractive Stress Rating (N/m^2) - (Csallner, 1984)
Bare Bank (Sand-Gravel)	10 - 15
Willow Revetment	70
Rockwork (dumped rock) with an average diameter of 0.4m. (ie. size currently used on the Tumut River)	150
Rockwork (coarse dumped rock) with an average diameter of 0.8 to 1.0m.	240

Table 2 - Tractive Stress Ratings

The average tractive stress is estimated using the equation (assuming D=R):

$$TS_{av} = \gamma D S$$

The actual tractive stress is then calculated by accounting for adverse conditions at the site by using the appropriate tractive stress multipliers summarised in Table 3.

Adverse Factor	Multiplier of the Average Tractive Stress	
	from German DIN	from Lane (1955)
Acute Angle	*2	* 1.1 to 1.7 depending on the degree of sinuosity
Right Angle	*3	
Prolonged Duration	*2	not presented

Table 3 - Tractive Stress Multipliers

The design tractive stress is then estimated by multiplying the actual tractive stress by a safety factor (1.5) to account for other variables such as unusually high stress during flood events or construction irregularities.

The design tractive stress for the Tumut River was estimated as 180 N/m^2. Bank protection works on the outside of bends will require a tractive stress rating of this magnitude to ensure stability of the works. From this basic assessment it is apparent that only rockfill protection works will stabilise the banks and the rock will require to have a minimum average diameter of 0.5 to 0.6 metres.

6. CONCLUSIONS

The hydraulic - geomorphic assessment technique was found to be a useful way to quantify and analyse the hydraulic - geomorphic processes on the Tumut River.

The analysis of the hydraulic - geomorphic slope quantified the equilibrium conditions for the bed and bank materials. The tractive stress duration analysis allowed the effects of the change in flow regime to be quantified. The tractive stress approach was also used to provide a quick assessment of the most suitable bank protection option.

There is a need to further research the technique as a viable tool for use in river management in Australia. The use of the tractive stress approach also needs to be further researched as river engineers / managers in Europe and America have found the approach useful for assessing river rehabilitation works.

This paper has been prepared to present the findings of the first basic assessment of the Tumut River and to encourage further discussions and research in this area by river managers in Australia.

7. ACKNOWLEDGEMENTS

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Streambed longitudinal gradient and unit stream power analysis of tributary streams of North East Victoria, Australia

R. E. Hardie*

ABSTRACT

This paper provides a review of surveyed streambed gradient information for 41 reaches of tributary streams in north east Victoria. The purpose of the review is to explore the data set of survey information and assist waterway managers with the identification of streambed longitudinal gradients for the design of streambed stabilisation works. Wide variability in the streambed gradients found limit the applicability of the results as a deterministic tool. However the information presented provides an indication of the typical streambed gradients and estimated unit stream power encountered for a number of streams in north east Victoria.

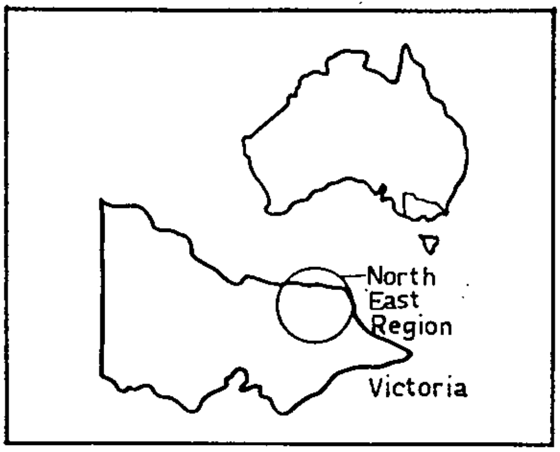

Figure 1 North East Victoria Australia

1. INTRODUCTION

Streambed and bank erosion have been identified as major issues in north east Victoria. This region includes the catchments of the Goulburn, Broken, Ovens, Kiewa, and Upper Murray Rivers (refer figure 1). The extent of streambed instability problems in the region have been described in the North East Region Landcare Plan (Anon, 1993) and in reports by I. N. Drummond and Assoc. Pty Ltd. (1984a, 1984b, 1984c, 1984d) and reports by Ian Drummond and Associates Pty. Ltd. (1986, 1988, 1989, 1990). According to these reports streambed instabilities including channel incision are present in streams throughout north east Victoria. The factors influencing channel incision in a number of streams of north east Victoria have been described by Rutherfurd (1993), Sherrard (1990) and Erskine et al (1993). According to Ian Drummond and Assoc. Pty. Ltd. et al (1988) the streambed incision is resulting in the loss of public and private assets such as roads, bridges, pump sites, fencing and agricultural land. Further, the sediment derived from the incision is contributing to downstream reductions in stream environmental conditions and reductions in channel capacity, leading to waterlogging of soils, and increased overbank flow.

Streambed stabilisation works are currently being undertaken through the region by landcare groups and waterway management authorities to arrest headward erosion and reduce sedimentation of waterways (Ian Drummond & Associates 1991, Anon 1993, Ian Drummond and Associates 1984).

According to the Standing Committee on Rivers and Catchments (1991) grade control structures are an appropriate means of achieving streambed stabilisation. According to the Standing Committee on Rivers and Catchments (1991) the location and sizing of grade control structures should be based on the selection of a design streambed longitudinal gradient identified from either an adjoining stable channel reach or from channel velocity and tractive force analysis.

This paper provides streambed longitudinal gradient information for 41 stream reaches surveyed by waterway management authorities and landcare groups in north east Victoria. The information has been reviewed to explore relationships that may assist with the design of streambed stabilisation works.

2. SURVEYED STREAMBED LONGITUDINAL PROFILES

Streambed longitudinal profile surveys have been undertaken on streams through north east Victoria and elsewhere to assist the identification of streambed instabilities, and to assist identification of longitudinal streambed gradients for the design of streambed stabilisation works. The surveys used for this investigation were undertaken between 1988 and 1993 (Hardie 1993). A total of 41 surveyed stream reaches have been included in this investigation. The surveys were undertaken by waterway management authorities and landcare groups operating in the north east Victoria. The surveys were undertaken using standard level

* I.D. & A. Pty Ltd, PO Box 165, WANGARATTA VIC 3676
Telephone: (057) 22 3300 Fax: (057) 21 9433

survey procedures. Equipment included an automatic level, survey staff and distance measuring wheel. The surveys were typically undertaken by a field party of two persons. Bench marks and reference marks were installed during surveys to assist the set out of grade control structures. Typically the surveys were tied into the Australian Height Datum (AHD). The surveys identified the bed of the stream including any irregularities including nick points, headcuts, pools and riffles. Stream cross sections were available for 24 of the 41 stream reaches reviewed.

3. IDENTIFICATION OF DESIGN STREAMBED LONGITUDINAL GRADIENT FROM STREAMBED SURVEY INFORMATION

Two methods of identifying the design streambed longitudinal gradient from the streambed survey information have been assessed. Both methods require the identification of the streambed gradient in a relatively stable reach of channel in the vicinity of the subject reach between major bed inconsistencies such as rock bars or headcuts.

3.1 Graphical method

A graphical method was used to identify the design streambed longitudinal gradients from the streambed survey information for the 41 stream reaches. The method comprises the following:

1. Project a straight line through the pools or low points of a section of stream reach between major nick points and head cuts.
2. Calculate the gradient of the line from the survey information
3. Repeat 1 and 2 above for a section of stream reach adjacent to that previously assessed
4. Compare calculated gradients and estimate the design streambed longitudinal gradient for the subject reach of stream.

3.2 Regression analysis method

The graphical technique has been compared with the use of a spreadsheet package to identify the streambed longitudinal gradient. Using regression analysis for streambed gradient data the streambed profile can be assessed for various sections of a stream reach. The estimated streambed gradients for Hodgsons Creek near Tarrawingee and lower Boggy Creek near Moyhu using the two techniques are detailed in the Table 1.

Table 1 Hodgsons Creek and Lower Boggy Creek streambed longitudinal gradient analysis.

Stream Reach	Streambed gradient by graphical method	Streambed gradient by regression analysis
Hodgsons Creek Ch2500	0.0036	0.0035
Hodgsons Creek Ch5000	0.0023	0.0023
Boggy Creek	0.0007	0.0008

For Hodgsons Creek and Boggy Creek the streambed longitudinal gradients estimated using the graphical method are similar to the estimated profiles using regression analysis. Although the limited extent of this comparison prevents any conclusive finding, the graphical method of stream profile identification used for this analysis appears to provide a satisfactory estimate of the representative streambed gradient between major nick points and headcuts.

4. DATA ANALYSIS

Lane (1957) identified streambed longitudinal gradients to be a function of sediment size, sediment load, and streamflow, other factors impacting on streambed longitudinal gradient include channel geometry, meander patterns and channel roughness.

4.1 Catchment area analysis

Hack (1957) developed a relationship between stream channel geometry and catchment area. Willgoose, et al (1991) and Tarbotton, et al (1989) have developed relationships between streambed longitudinal gradients and catchment area. The stream profile information for the 41 surveyed stream reaches has been compared with the catchment area contributing to the streamflow for the reach. The catchment area for each reach was determined using a mechanical planimeter and topographic maps. The results of the assessment are shown in figure 2. Using a regression analysis the following relationship for the data set was identified.

$$S=0.029A^{0.51} \qquad (1)$$

where S= Streambed longitudinal gradient
A= catchment area (km^2)

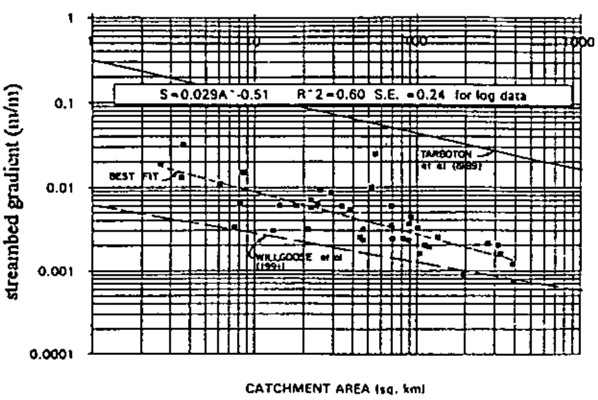

Figure 2 Catchment area versus Streambed longitudinal gradient

The data shows wide variability. For any catchment area the streambed longitudinal gradient was found to vary through a range nearing an order of magnitude. This variability is illustrated in the low coefficient of correlation ($R^2 = 0.60$) obtained for the regression analysis on the log data. However the data plotted between the theoretical results of Willgoose et al (1991) and the field results of Tarbotton et al (1989) for Big Creek Idaho (refer figure 2). The wide variability in the results is likely to be associated with factors such as catchment hydrology, sediment size distribution, cohesion of sediments channel geometry (width, depth) vegetation density and sediment supply to the reach.

4.2 Streamflow analysis

Empirical relationships that relate channel geometry and longitudinal gradients to streamflow are referred to as regime equations and according to Hinwood (1990) were first developed by British engineers working on irrigation systems through India at the turn of the century. Channels that operated without noticeable signs of aggradation or degradation were described as being in regime. Wolman (1955) proposed the following relationship for streambed gradient

$S=aQ^b$ ②

where S= Streambed gradient
Q= representative flow

Regime equations are readily applied to irrigation channels with relatively constant flows. However the variability of streamflow requires the identification or selection of a flow to represent the range of flow encountered within the stream reach. Bray (1982) describes the selection criteria for the evaluation of the characteristic discharge for a river reach as being controversial. According to Bray some researchers have used hydrological criteria such as mean annual flow or the 1.5 year flood flow. Bray cites other cases where the characteristic discharge has been defined in terms of bed load transport through a river reach. Bray (1982) concluded that the 2 year flood flow, (Q_2) based on a log normal distribution satisfied criteria for a data set under consideration.

The two year average recurrence interval (ARI) flood event (Q_2) was selected as a representative flow for this analysis to explore relationships in the streambed gradient data. Flow gauging information for the majority of streams within the data set was not available necessitating an alternate method of streamflow estimation. The rational method of streamflow estimation as outlined by Pilgrim (1987) was used for the estimation of Q_2.

The streambed longitudinal gradient for the 41 stream reaches has been compared with the estimate of 2 year ARI flood event. A plot of the results is shown in figure 3. Using a regression analysis the following relationship was identified

$S=0.018Q_2^{-0.60}$ ③
$R^2=0.60$
S.E.=0.24

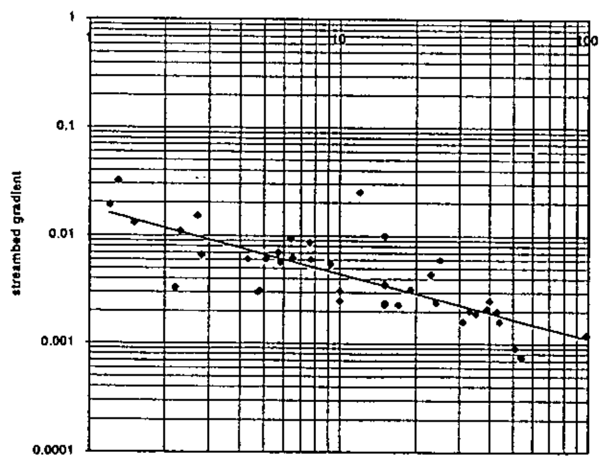

Figure 3 Streamflow versus Streambed gradient

No significant improvement in the quality of the relationship was achieved through the substitution of catchment area with an estimate of streamflow. However the use of the representative flow (Q_2) may make the results more applicable for comparison with waterways in regions other than north east Victoria.

4.3 Adjustment for Bankfull Capacity

Twenty four of the surveyed stream reaches had cross section information suitable for an analysis of cross section shape. The depth of flow associated with the estimated Q_2 streamflow for each of the 24 stream reaches was estimated using Manning's equation (refer Chow 1959). Estimates for hydraulic gradient were based on the identified streambed longitudinal gradient between headcuts and nick points and estimates of channel roughness were based on vegetation density. Q_2 flow was estimated to remain within the channel banks for the majority of stream reaches. However for five of the 24 reaches the Q_2 flow was estimated to overtop the channel banks and spread over the adjoining floodplain. For these reaches the lower of the estimated Q_2 and bankfull flow was used for the analysis. A regression analysis was undertaken to develop a relationship between streamflow and the streambed longitudinal gradient. A comparison between the data fit for Q_2 versus streambed gradient and the streamflow adjusted for bankfull flow capacity ($Q_{2/bf}$) versus streambed gradients for the 24 stream reaches with cross section information is provided in table 2. The results indicate a better fit for the Q_2 analysis without adjustment for bankfull flow.

Table 2 Regression analysis results for streamflow analysis with and without adjustment for bankfull flow

representative flow	a	b	R2	coeff
Q_2	0.022	-0.67	0.75	0.18
$Q_{2/bf}$	0.016	-0.58	0.59	0.23

4.4 Sediment size analysis

For each stream reach the A and B axis of the dominant larger sediments comprising the streambed sediments were recorded and the streambed sediments categorised. The limited data set and simple method of sediment size analysis necessitated the grouping of the sediments into the four broad classes outlined in table 3 below.

Table 3 Sediment size categories used for data analysis

Sediment class	Sediment size range
Silts and fine sands	0.02 to 0.2mm
medium to course sand	0.2 to 2mm
fine to medium gravel	2 to 20mm
course gravel to cobbles	20 to 200mm

The streambed longitudinal gradients recorded for each of the sediment size classes in the data set are shown in figure 4

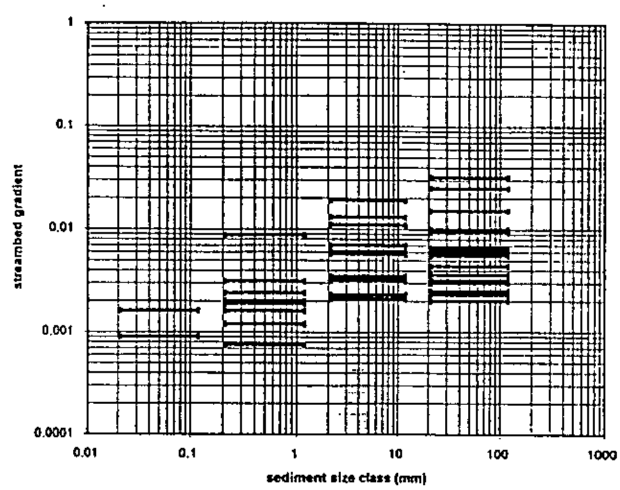

Figure 4. Sediment size analysis

The results indicate a range of streambed longitudinal gradients encountered for each of the streambed sediment categories. The limited accuracy of the analysis and variability in the results suggest further and more detailed analysis of the data set is required in order to make use of the sediment size information.

4.5 Unit Stream Power Analysis

Stream power is a measure of the energy of flowing water. Unit stream power is a measure of the energy per unit width across a stream. Unit stream power analysis enables the incorporation of a number of the variables (including streamflow, channel roughness and channel geometry) impacting on streambed longitudinal gradient to be assessed. Stream power can be written as:

Power, $(\Omega) = \rho g Q s$
where ρ= density of water
g = acceleration due to gravity
Q = flow rate
s = hydraulic gradient

Stream power per unit width of stream (ω) can be written as

$$\text{Unit stream power } (\omega) = \frac{\text{power } (\Omega)}{\text{water surface width}}$$

Stream power assessments have been used by Brookes (1987) and Simons and Richardson (1966) to the explain the bed form and channel shape. Unit stream power assessments provide an opportunity to incorporate sediment size analysis into the assessment of channel geometry and longitudinal gradient. A plot of unit stream power for the incised channel reaches in which Q_2 was estimated to remained within the channel banks is shown in Figure 5.

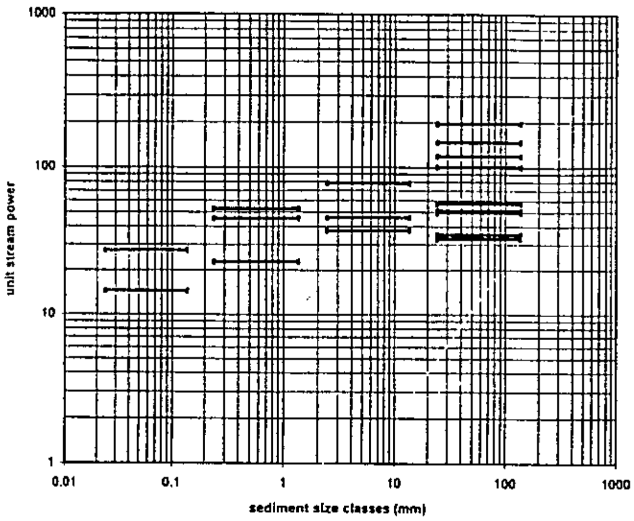

Figure 5 Unit Stream power versus sediment size class

The results of this analysis show an increase in unit stream power with sediment size. The limited accuracy of the sediment size analysis and the variability in the results prevents the development of a relationship. The variability is likely to be associated with factors such as sediment supply and inaccuracies in the estimation of streamflow. None the less the results provide a guide to the unit stream power encountered in the reaches of streams surveyed. Adoption of the lower unit stream powers encountered within each of the four sediment classes may provide a useful tool for the design of stream stabilisation works including channel geometry and streambed longitudinal gradient. The suggested unit stream powers for each sediment size class are shown in table 4.

Table 4 Suggested unit stream power for the design of stream stabilisation works.

Sediment size class	unit stream power
silts and fine sands	15
medium to course sand	25
fine to medium gravel	35
course gravel to cobbles	40

These suggested thresholds for design are in accord with the findings of Brookes (1987). Brookes (1987) found channellised streams undergoing erosive adjustments to have unit stream power in excess of 35w/m^2. Adoption of the criteria outlined in table 4 would most likely result in a conservative design of streambed stabilisation work

5. CONCLUSIONS

Wide variability was found in the streambed gradients identified from the streambed surveys included in this review. The variability in the streambed gradients found is likely to be associated with factors such as sediment size distribution, sediment supply to the reach, soil cohesion, streamflow and vegetation. The variability in the streambed gradients and the range of variables impacting on the stream reaches prevents the use of the results as a deterministic tool. However the results provide a useful indication of the streambed gradients found for a range of streams in north east Victoria. In this respect the results of the review may provide a useful check of streambed gradients identified by alternative means such as streambed surveys unit stream power analysis or shear stress assessments.

Unit stream power analysis provide a means of incorporating a number of the factors impacting on channel geometry into the assessment of streambed gradients. Some variability was found in the unit stream powers estimated for the stream reaches. This variability could be associated with quality of the streamflow estimates and sediment size analysis together with factors such as sediment supply to the reach. None the less the results of the unit stream power assessment may be a useful aid to assist design of streambed stabilisation works.

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Predicting the Limits to Gully Erosion

Bruce Abernethy and Ian P. Prosser†*

ABSTRACT: *Gully erosion in much of agricultural Australia poses problems of accelerated soil loss, erosion of structures and reduced water quality. The most intensive gully erosion occurred decades ago following clearing and the introduction of stock to the landscape. There is evidence that many of these gullies are now approaching stability and pose a low risk for future erosion. Given limited land management resources, it is important to develop techniques to distinguish those gully networks that are stable from those with considerable potential for future erosion.*

A technique that combines digital terrain modelling and a simple representation of erosion processes is explored to predict the stable extent of gully networks. The TOPOG package of digital terrain and hydrological models was used as the framework for the procedure.

The model is initially applied to a 5.5 km² cleared catchment on the Southern Tablelands, NSW, where the positions of gully heads within a stable gully network are accurately predicted. A combination of specific catchment area and local gradient proved to be the best topographic predictor of the gully network. The distribution of high boundary shear stress successfully predicts the mapped extent of the gully network and provides a process interpretation for the observed topographic limits. Realistic values of boundary shear stress were simulated using storms of one hour duration and runoff generated by Hortonian overland flow. The model is then applied to a second catchment where gullies are believed to be actively eroding. The model indicates the potential for further gully erosion in several valleys of the catchment, whilst other gully networks appear to be close to their stable limit.

1. INTRODUCTION

The introduction of European-style agriculture to south-eastern Australia last century precipitated a major phase of gully erosion. Analysis of sequential aerial photography shows that many of these gully networks are now relatively stable as they have not expanded in the last forty to fifty years (Eyles, 1977; Starr, 1989; Prosser, 1991). However, some of these systems are still extending while recently intensified landuse in other locations is resulting in further gully initiation (Prosser & Winchester, in press). In both these cases it would be useful to distinguish those sites that are most susceptible to future gully erosion, and to predict the eventual limits of the gully networks.

Assessment of the limits to gully networks can be made using techniques that range from visual assessment of sequential aerial photographs to field inspection and topographic analysis to computerised landscape modelling. In most cases it would be inadvisable to rely on one method of analysis alone. A number of erosion processes may be acting in concert within a catchment to produce a gully network and not all may be detected if reliance is placed on one analysis tool. However, the high cost of gully control structures means that assessment of the limits of the gully network is vitally important. The premise adopted here is that gullies already at their limits do not pose a threat of further erosion and do not need further control.

Dietrich *et al.* (1992, 1993) investigated linkages between erosion processes and channel network extent with a simple threshold based theory of erosion and a steady state runoff model. They were able to assess the topographic controls on channel networks and interpret them in terms of a critical shear stress for channel incision due to saturation overland flow.

In this study, we demonstrate strong topographic control on gully erosion in a catchment with a stable gully network and define topographic thresholds for the limits to gully erosion. Modifications to the Dietrich *et al.* (1992, 1993) model enabled us to predict the boundary shear stress (τ_b) applied by Hortonian overland flow. We found that mapping sites of high τ_b successfully defined the stable gully network. In applying the τ_b that defined the stable gully network, to an active gully system, we used the model to assess the spatial pattern of erosion risk within a second catchment.

2. STUDY SITES

We selected the upper 5.5 km² of the Gungoandra Creek catchment as our initial site for model testing and calibration. Gungoandra Creek is 80 km south of Canberra on the Southern Tablelands of New

* CRC for Catchment Hydrology, Dept. Civil Engineering, Monash University, Clayton VIC 3168
Telephone: (03) 9905 5581 Fax: (03) 9905 5033 Email: bruce.abernethy@eng.monash.edu.au
† CRC for Catchment Hydrology, Division of Water Resources, CSIRO, Canberra

South Wales. The site is a typical steep catchment of south-eastern Australia with an extensive gully network that has not expanded since 1944. Soils, climate and other details of the catchment are described more thoroughly elsewhere (see Abernethy, 1994; Prosser & Abernethy, subm.).

We used a second catchment, Grove Creek, to test if the parameters as calibrated at Gungoandra Creek could be used to predict gully erosion elsewhere. The Grove Creek catchment has a drainage area of 2.4 km^2 and is situated some 40 km to the north-east of Canberra near Lake George. Gullies in the catchment are known to be actively eroding. In many other respects the catchment is similar to Gungoandra Creek. It was settled and cleared in the latter half of last century and soils are similar to those of the lower hillslopes and flats of Gungoandra Creek with thin soils mantling the upper slopes. The stratigraphy of alluvial deposits in Grove Creek is further described by Coventry & Walker (1977).

3. DIGITAL TERRAIN MODELLING

Following the approach taken by Dietrich *et al.* (1992; 1993), we have relied on the TOPOG digital terrain and hydrologic modelling package (Burch *et al.*, 1986; O'Loughlin, 1986; Moore *et al.*, 1988a; Vertessy *et al.*, 1990) to link steady state erosion models with catchment hydrology and terrain. TOPOG divides a catchment into a network of irregularly shaped elements defined by upper and lower contour sections and flowlines drawn normal to the contours (O'Loughlin, 1986; Moore *et al.*, 1988b). It is assumed that both shallow sub-surface and overland flow follow flowlines with little lateral diffusion (O'Loughlin, 1986).

TOPOG requires high resolution topographic data so we commissioned a purpose drawn topographic map of the Gungoandra Creek catchment. The map was drawn from 1:25 000 colour aerial photographs using analogue photogrammetry and prepared to a scale of 1:7 500 with a 5 m contour interval. The channel network was well represented on the map, because of low vegetation cover, but we subsequently checked it in the field.

The base map was digitised and used to construct a digital terrain model (DTM) of the catchment. The Gungoandra Creek DTM consists of 9 130 discrete elements with an average element width of 40 m. A DTM of the Grove Creek catchment (Maunder & Wilson, pers. comm.) was produced from digital photogrammetry of the same series of aerial photographs as that used for Gungoandra Creek. This DTM consists of 8487 elements with an average width of 18 m.

4. TOPOGRAPHIC LIMITS

The TOPOG package calculates a number of terrain attributes for each element: upslope catchment area (a), element width (b), specific catchment area (a/b) and gradient ($\tan\theta$). Using the method described by Montgomery & Dietrich (1988) and Dietrich *et al.* (1992, 1993), graphs of a/b and a plotted against $\tan\theta$ for Gungoandra Creek showed clear separation of gullied and non-gullied TOPOG elements. For any given gradient, gullied parts of the landscape have a larger upslope catchment area than non-gullied parts of the landscape. Moreover, elements containing channel-heads plot at the boundary of the gullied and non-gullied fields. This is to be expected, as channel heads represent the transition between slope and channel processes.

The threshold line that was found to best separate gullied from non-gullied elements in a plot of upslope catchment area versus local slope is

$$a = 1420 \tan\theta^{-1.6} \quad (1)$$

which correctly discriminates 87% of elements as gullied or non-gullied. A similar relationship can be demonstrated for a/b plotted against $\tan\theta$:

$$\frac{a}{b} = 30 \tan\theta^{-1.6}. \quad (2)$$

This topographic threshold correctly accounts for 85% of elements. Equation (2) contains all the variables required to move the investigation from a purely empirical to a potential process interpretation of the channel network.

5. HORTONIAN OVERLAND FLOW

We believe that Hortonian overland flow is the dominant runoff process responsible for gully erosion in the study catchments. Hence, the algorithms presented by Dietrich *et al.* (1993; p. 263) for predicting channel incision by saturation overland flow were modified by Prosser & Abernethy (subm.) to predict channel incision by Hortonian overland flow. In the model, incision by overland flow is considered to be driven by τ_b. For non-accelerating flows

$$\tau_b = \rho g d M, \quad (3)$$

where ρ is fluid density, g, is acceleration due to gravity, d is mean depth of overland flow, and M is local slope ($\sin\theta$). To determine the τ_b applied by a given discharge requires knowledge of flow resistance, here characterised by the Darcy-Weisbach friction factor (f):

$$f = \frac{8gdM}{u^2}, \quad (4)$$

where u is mean velocity. For flow over grassed surfaces f can be expressed as a power function of Reynolds number ($f = kRe^c$). Noting that $Q = udb$ and $Re = ud/\nu$, where ν is the kinematic viscosity of fluid, equations (3) and (4) may be re-expressed, after Prosser & Abernethy (subm.), as:

$$\tau_b = \left(\frac{g^2 k \rho^3}{8 \nu^c}\right)^{\frac{1}{3}} M^{\frac{2}{3}} \left(q \frac{a}{b}\right)^{\frac{2+c}{3}} . \qquad (5)$$

Boundary shear stress is now a function of topographic parameters automatically read from the DTM (a/b and M), and user defined flow characteristics and rainfall excess (k, c and q).

For the purposes of this study we have assumed that infiltration rates and vegetative roughness are all spatially uniform. Although this may seem somewhat unrealistic we suggest that topography places some constraint on these parameters and is a stronger influence on patterns of erosion than variations in infiltration or vegetation. In any case, simulations conducted with spatial variability were not found to increase the accuracy of predictions to any significant extent. The disproportionate amount of detailed field work required to describe field variation of non-terrain parameters appears to be unwarranted in light of the only minor improvements gained. By similar reasoning, we also kept precipitation spatially uniform.

We tested the model first at Gungoandra Creek. There, the channel network has been stable for fifty years, so we chose the one in fifty years, one hour duration rainfall intensity of 42 mm/hr (Pilgrim, 1987) to represent a typical channel forming event. The steady state infiltration rate was estimated to be 20 mm/hr based on soil texture (Craze & Hamilton, 1991) and rainfall simulator experiments conducted on similar soils (Fisher, 1993). This gave q a value of 22 mm/hr.

We used the relationship of $f = 1500Re^{-0.7}$ to characterise flow resistance. This is a typical relationship for concentrated overland flow on a degraded grass surface (Prosser *et al.*, in press). Predictions of τ_b are not significantly affected by changes in the relationship of less than an order of magnitude. Therefore, using relationships from other studies will not unduly impact upon the results.

The results of simulating Hortonian overland flow, using the inputs described above and Equation (5), are shown in Figure 1. Values of predicted τ_b at the gully heads range from 100 to 590 dyne/cm^2. Referring to Figure 1, we have partitioned the catchment into three zones of susceptibility to gully erosion. The predicted τ_b of 80% of gully head elements falls within 210 and 290 dyne/cm^2 and as Figure 1 shows, elements with τ_b in this range map out the extent of the channel network very well. Elements with a predicted τ_b of more than 290 dyne/cm^2 are very likely to be incised and are found downstream of the gully heads. Elements with a predicted τ_b of less than 210 dyne/cm^2 are unlikely to be incised and are located in the unchannelled parts of the catchment.

The model underestimates the τ_b that would incise gullies in reality because τ_b is calculated as a mean across the full element width. We observed in the field that flow is usually restricted to the hollow axis, hence flow width is often much narrower than element width. Constraining flow to realistic widths in the axis of hollows, produces τ_b values up to three times model predictions for flow across entire elements. These higher values can be favourably compared to estimates of the τ_b, for incision, derived from field experiments (Prosser & Slade, 1994; Prosser *et al.*, in press).

Recognising that there are some mismatches between the mapped and predicted gully networks, the Hortonian overland flow simulation creates a reasonable representation of the channel system. Some of the scatter around the mapped network is likely to be due to variations in vegetation for which we have not accounted. Unchannelled valleys and steep slopes at Gungoandra Creek that are predicted to contain channels generally have a southerly or easterly aspect. These locations could be expected to have greater soil moisture with better vegetation cover, and presumably greater resistance to incision.

The good results of the topographic analyses, above, and those shown in Figure 1, indicate the usefulness of this approach to reliably map the headward limits of gully erosion. After calibrating the model to define the stable gully network at Gungoandra Creek, we then applied the same values of q k and c to Grove Creek, where gullies are still eroding. A simulation of Hortonian overland flow produced the τ_b distribution shown in Figure 2a.

Of the five main gully heads shown in Figure 2, the two northern-most are situated very close to their predicted limits. Field inspection revealed that these heads are now gradual, merging with the upstream hillslope hollow, and display no obvious signs of recent erosion. The model predicts high susceptibility to gully erosion in ungullied parts of the southern and eastern valleys. Gully heads are migrating upslope in the two southern valleys, and farm dams have been used to prevent gully erosion in the north-eastern valley.

The model does not predict the full extent of the eastern-most gully. Two factors contribute to this. Firstly, TOPOG produces very wide elements in the

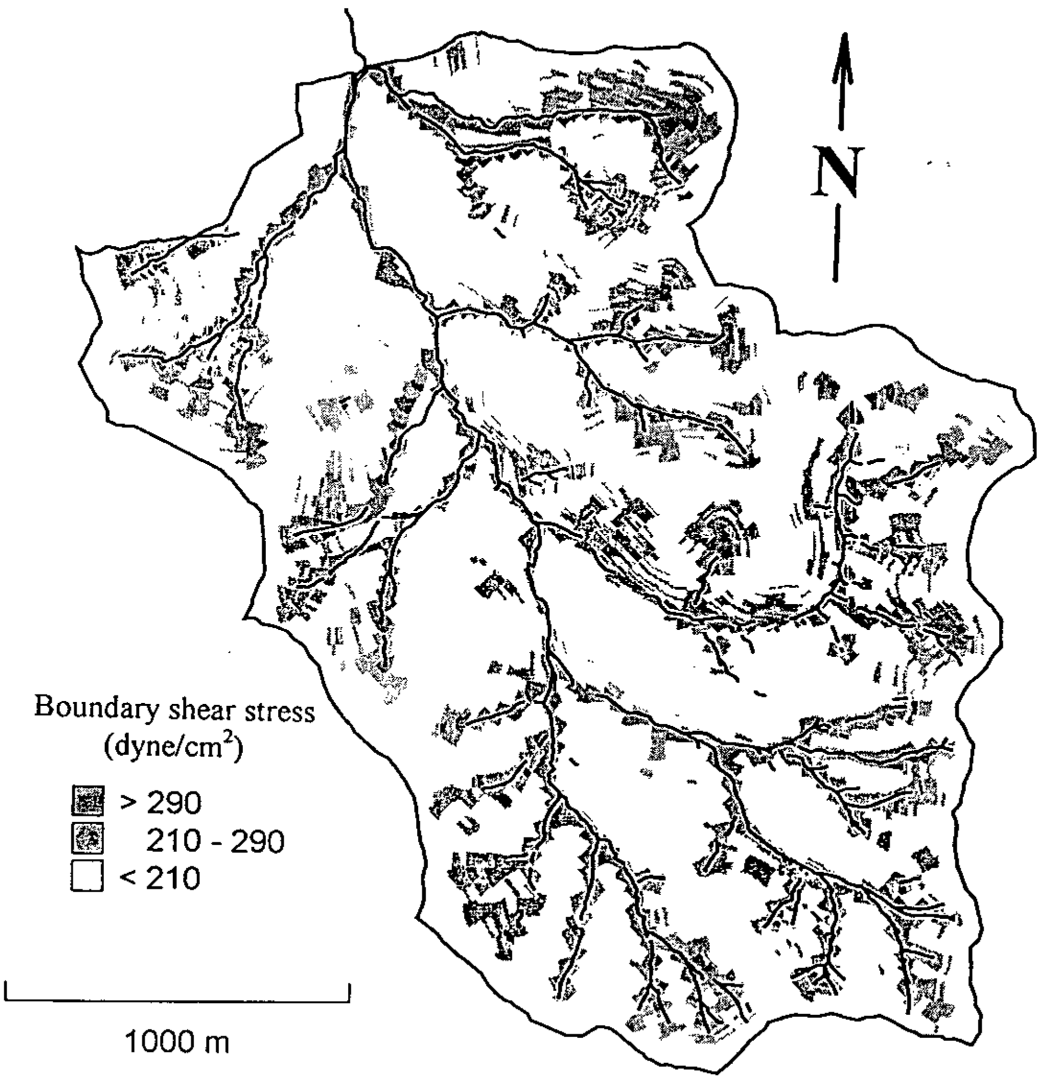

Figure 1. Comparison of the channel network at Gungoandra Creek with predicted values of τ_b applied by Horton overland flow.

axis of this valley which reduces the value of predicted τ_b. Secondly, strong seepage processes have aided in extension of the gully much closer to the divide than would otherwise be expected. In the first instance, a marked improvement of model predictions in this part of the catchment could be achieved by constraining the width of TOPOG elements to that of flow width. However, the cost of computational complexity due the addition of thousands of elements prohibits such a fine scale segmentation of the DTM. The example provided by the second point demonstrates that full reliance should not be given to any single technique to predict the limits to gully erosion. Results of all simulations should be tempered with knowledge of local circumstances wherever it is available.

6. DISCUSSION & CONCLUSIONS

Analysis of the DTM for Gungoandra Creek shows that topography is a strong control on the limits to the gully network. Good definition of the position of channel heads was achieved using a range of topographic thresholds. While the threshold of $a/\tan\theta^{1.6}$ could also be derived from field measurements at the channel heads, the DTM allows rapid analysis of the whole catchment. The DTM may also provide a more accurate method as it is difficult to define the upslope catchment area in weakly convergent terrain.

Despite its advantages, though, use of the DTM is limited by the quality of data inputs required. The fine resolution needed to accurately predict gully erosion is usually beyond that offered by commercially available digital elevation data. Indeed many of the gullied hollows at Gungoandra Creek do not appear on the 1:25 000 map sheet; the smooth contours of this scale show only the hollows

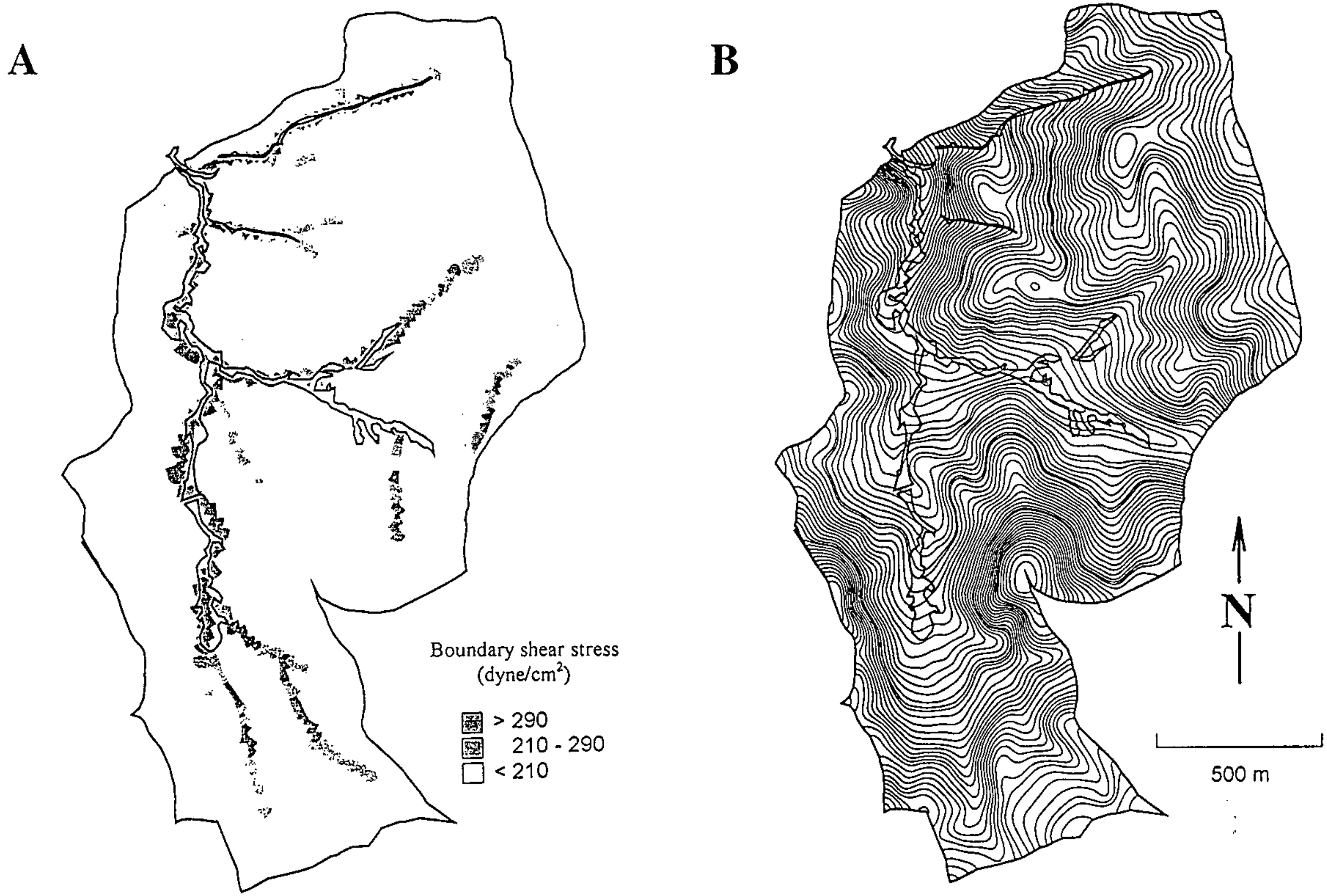

Figure 2. a) Comparison of the channel network at grove Creek with predicted values of τ_b applied by Hortonian Overland Flow. b) Topography of the Grove Creek Catchment.

that support the main trunk gullies. Also, the complexity of terrain and size of the Gungoandra Creek catchment are at about the limit of TOPOG's usefulness for the approach outlined here.

The application of topographic and process thresholds in a TOPOG framework allows a quantifiable and mappable technique for assessing gully erosion in different catchments. One should never lose sight, however, that the technique outlined here is but one approach of many available to the land manager. Field checking will verify model predictions but once validated this approach will enable managers to quickly ascertain gully erosion extent.

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SUSTAINABLE SAND AND GRAVEL EXTRACTION

The Development of a Management Plan for the Goulburn River, Victoria

*Wayne D Erskine *, Wayne K Tennant ** and John W Tilleard***

ABSTRACT: Deposits of sand and gravel within the streams of the Mid Goulburn River catchment represent a major natural resource. Extraction of this material contributes significantly to the local economy. In certain circumstances, extraction can be beneficial to the streams, however excessive or inappropriate extraction can lead to environmental and stream management problems. The North Central Waterways Management Board identified the need to develop a better understanding of the available sediment yield of the system and of the rate of resource replenishment and to produce guidelines for the management of extraction. This paper presents the results of these investigations.

1. INTRODUCTION

Sand and gravel extraction has occurred from a number of sites, over many years, throughout the 172 kilometres of the Mid-Goulburn River, Victoria between Eildon Pondage and Lake Nagambie (Figure 1). Sand and gravel are valuable economic resources but over extraction often causes many detrimental environmental impacts (Erskine, 1995).

A geomorphic investigation of the Goulburn River Basin by Erskine et al. (1993) identified extraction as a major management issue and called for a moratorium on removal of material from the Goulburn River and tributaries while further investigations proceeded. Sediment input from the upper Goulburn River catchment is limited. Erskine et al. (1993) estimated that Eildon Dam traps about 99% of the inflowing sediment load whilst regulating downstream flows to such a degree that bed load transport rarely occurs. The only minor natural replenishment of sand and gravel is by localised bed load transport, usually induced by the mining itself (Erskine et al., 1993).

Mining contributed significantly to the local economy and in some cases has been undertaken to achieve waterway diversity to meet stream management objectives (Ian Drummond and Associates, 1994). However over extraction can lead to adverse impact on the river system.

Sand and gravel extraction operations need to be undertaken at a level which is within the capacity of a river to withstand and still maintain relative stability of its geomorphic and ecological characteristics (NSW Department of Water Resources, 1992). This is only possible if the rate of extraction is less than the rate of replenishment by bedload transport (Erskine at al., 1985; Collins and Dunne, 1990). Bed degradation or erosion occurs when extraction exceeds replenishment rates causing undermining of public assets, altered bed morphology and bedforms which form important habitat; lower floodplain water tables; reduced frequency of overbank flow and wetland inundation; changed bed material size composition; bank collapse; destruction of aquatic and riparian vegetation; increased bar mobility; and greater frequency of substrate mobility (Erskine et al., 1985; Collins and Dunne, 1990).

2. DATA REQUIREMENTS FOR A MANAGEMENT PLAN

To develop a management plan based on sustainable use the following data requirements were proposed:

i) the location and rates of extraction of existing and proposed extractions;
ii) the location and extent of in-channel sand and gravel deposits;
iii) the nature and frequency of mobility of the bed material;
iv) sediment transport rates and sediment yields; and
v) extraction - induced channel changes over recent years.

The North Central Waterways Management Board and the Department of Conservation and Natural Resources commissioned the authors to undertake the necessary investigations to provide the above information. The nature of these investigations and their results are briefly outlined below.

* School of Geography, University of New South Wales, Sydney NSW 2052 Telephone: (02) 385 4603 Fax: (02) 3137878
Email: W.Erskine @ UNSW.edu.au
** I.D. & A. Pty. Ltd, PO Box 165, Wangaratta, Vic 3676 Telephone: (057) 223300 Fax: (057) 219433.

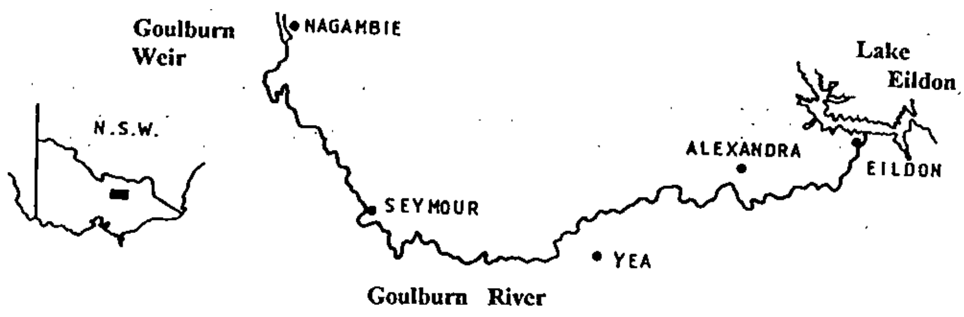

Figure 1 - Index Locality Plan and Study Area.

2.1 Rates of Extraction

While extraction has occurred at many sites on the Mid-Goulburn River for a long period of time, records are incomplete. Since 1982 an estimated 200,000m^3 (14,000 m^3/yr) have been extracted from the study area. While most operators remove relatively small amounts (<1000m^3/yr), 183,486m^3 was extracted at Seymour between 1982 and 1993. Another 10,000m^3 were extracted from one bend for the Hume Freeway construction at Seymour.

2.2 Sand and Gravel Deposits

Low level vertical air photographs were flown of the Mid-Goulburn River between Eildon Pondage and Lake Nagambie during winter low flows to determine the location and extent of in-channel sand and gravel deposits. Field inspections were also undertaken to confirm aerial photograph interpretation. There are presently no deposits within the study area where removal would result in a stream management benefit. Monitoring has been recommended to determine whether there is any future change in this condition.

2.3 Nature and Frequency of Mobility of the Bed Material

Investigations of the bed material of the Mid-Goulburn River were undertaken at Thornton, Breakaway Road, Molesworth, Trawool, Seymour and Hume Freeway (Figure 2) for the following purposes:

i) to determine whether the bed is armoured;

ii) to quantify the difference in grain size characteristics between the armour layer and substrate;

iii) to determine the frequency of mobilisation of the armour layer; and

iv) to compare the grain size characteristics of the armour layer at extracted and non-extracted sites.

An amour layer is a layer of gravel on the river bed surface that is usually one grain diameter thick and is both coarser and better sorted that the underlying substrate (Gomez, 1984; Erskine, 1992). It may be mobile or immobile under the current hydrologic regime (Erskine et al., 1985).

Armour layers are important for preventing excessive bed scour and thereby stabilising the channel and reducing sediment transport (Lagasse et al., 1980). When armour layers are extracted, bed degradation and sediment transport are initiated and continue until a partial armour layer reforms (Lagasse et al., 1980; Erskine et al., 1985).

The result of the bed material sampling are shown in Table 1. The grain size characteristics of the armour layer and the underlying substrate are significantly different, indicating that they are distinct sediment populations. The mean size (mm) of the armour layer ranges between 2.29 and 9.48 times greater than the substrate. Hean and Nanson (1987) reported similar but slightly smaller ratios on NSW rivers.

The Mid-Goulburn River is presently discontinuously armoured. A gravel armour layer is usually present on riffles and bars. Pool sediments were not sampled. Erskine et al. (1993) found that the Mid-Goulburn River exhibits nine alternating reaches of straight and meandering channels. Armouring is best developed in the meandering reaches where there are many point bars. Armouring is an important process which is currently contributing to the stability of the Mid-Goulburn River.

SITE	SEDIMENT TYPE	GRAPHIC MEAN SIZE[1] (ϕ)	INCLUSIVE GRAPHIC STANDARD[1] DEVIATION (ϕ)	INCLUSIVE GRAPHIC SKEWNESS[1]
Eildon (1)	Bedload	0.45	0.73	-0.63
Thornton (2)	Armour Layer	-5.47	0.80	0.15
	Substrate	-3.19	2.29	0.33
Breakaway Road (3)	Armour Layer	-5.45 to -5.65	0.66 to 0.78	0.14 to 0.40
	Substrate	-3.45	2.40	0.32
	Riffle Tail	2.23	0.66	-0.05
Molesworth (4)	Bed Material	1.25	0.59	0.22
Trawool (5)	Armour Layer	-4.47 to -5.37	0.43 to 0.79	0.34 to -0.05
	Substrate	-2.53 to -3.29	1.99 to 2.45	0.28 to 0.47
	Lee-Side Shadow Deposit	-1.37	2.55	-0.68
	Bedload	1.30	1.85	-0.42
Seymour Gauging Station (6)	Armour Layer	-6.80 to -6.83	0.79 to 0.83	0.04 to 0.15
	Extraction Platform	-4.72	1.01	-0.16
	Lee-Side Shadow Deposit	-2.25 to -3.10	0.98 to 1.52	0.36 to -0.02
Seymour Hume Freeway Bridge (7)	Armour Layer	-4.63 to -4.72	0.58 to 0.59	0.08 to 0.14
	Substrate	-2.45 to -3.44	1.44 to 1.97	0.28 to 0.56
	Bar Tail	-2.83	1.99	0.66

Table 1 Grain size statistics for the various sediment types at each sample site on the Mid-Goulburn River. For location of sample sites, see Figure 2.

1 - After Folk and Ward (1957)

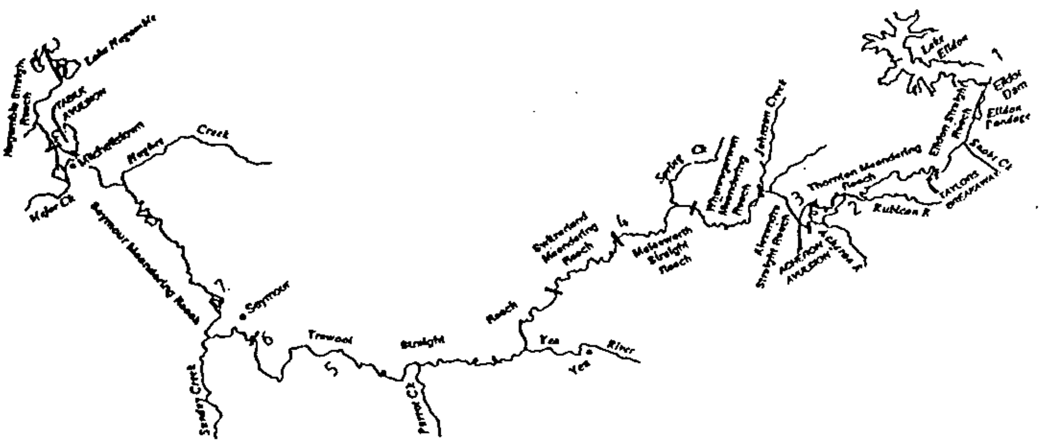

Figure 2 - Index Locality Plan of Gauging Stations.

The frequency of mobilisation of the armour layer at the Eildon, Trawool and Seymour gauging stations was determined by applying Meyer-Peter and Müller's (1948) threshold of motion criterion. Maximum irrigation flows (say 10 000 ML/d or 115.7 m^3/s) are incompetent to mobilise the armour layer at all sites (Table 2). The reason for the very high discharge to mobilise the armour layer at Seymour is that the channel impinges against bedrock resulting in the localised input of coarse gravel.

Flows well in excess of bankfull stage are clearly required to mobilise the armour layer which is a static or immobile feature on the Mid-Goulburn River.

Two extraction sites were investigated to determine whether armour layers reform following disturbance and, if they do, whether their grain size characteristics are the same as natural armour layers.

The armour layer developed on an abandoned extraction platform at Seymour and on mid channel bars at the Hume Freeway bridge was sampled (Table.1). While the two adjacent to the Hume Freeway have grain size characteristics indistinguishable from natural armour layers, the extraction platform is significantly different. This platform had been abandoned about two months before sampling and further regulated flows will rapidly modify the surficial sediment. Given sufficient time, armour layers essentially identical to natural features will be produced.

GAUGING STATION	THRESHOLD DISCHARGE FOR INITIAL MOTION (m^3/s)	FLOW DURATION[1] (%)
	Meyer-Peter and Müller - Q_M	Q_M
Eildon	697.0	<0.01
Trawool	373.7	0.2
Seymour	>1201	<0.01

Table 2. Discharges required for threshold of motion of the armour layer at each gauging station and their associated flow duration.
1 - for the period 1 January 1984 to 1 January 1994.

2.4 Sediment Transport Rates and Sediment Yields

The purpose of this section is to try to estimate the bedload yield of the River to determine what is a "safe" extraction rate. To achieve this aim, sediment transport measurements were carried out at the Eildon, Trawool and Seymour gauging stations during the winter low flow period (22 and 24 July 1994) and during the summer irrigation releases (20, 21 and 22 December 1994). Suspended sediment was sampled with the USDH 48 depth integrated sampler and bedload was sampled with the Helley-Smith pressure difference sampler (Helley and Smith, 1971). Suspended sediment concentrations were determined by membrane filtration. Bedload was collected and bagged in the field, transported to the laboratory, dried at 105°C and then weighed. One bedload sample was also combusted in a muffle furnace at 550°C to determine how much of the sample was organic matter. The results of the field measurements are shown in Table 3.

The bedload measurements at Eildon and Trawool demonstrate that irrigation flows do not transport large amounts of bedload. Furthermore, the bedload flux at Eildon for a discharge of 34.9 m^3/s is misleading. This bedload gauging was completed soon after discharge had been increased abruptly from 470 ML/d (5.44 m^3/s) to 3014 ML/d (34.9 m^3/s). During the gauging we observed rafts of macrophytes being transported following their detachment from the bed. Therefore, the bedload sample was combusted to determine its organic matter content. Only 18.2% (0.024 t/d) was clastic sediment with the remaining 81.8% (0.106 t/d) being organic matter, in particular, various parts of macrophytes.

The particle size distributions of the bedload samples collected in December 1994 demonstrate that the bedload sediment at discharges of 102.8 to 109.6 m^3/s is much finer than the substrate and other mobile sediment types (Table 1). This indicates that the measured bedload is a non-capacity load which has been entrained either from local deposits on the bed or by bank erosion.

It is often assumed that the particle size distribution of bedload is the same as the bed material. While this can be the case on some armoured gravel bed rivers it is not the case where there is selective transport of finer grain sizes. Lisle (1995) found that selective transport of fine sediment temporarily stored on the bed in patches occurs in rivers which commonly retain immobile armour layers until discharges greatly exceed bankfull. This is the situation on the Mid-Goulburn River.

Threshold of motion calculations demonstrate that bankfull flows, and usually sub-bankfull flows can transport fine gravels of 6-8 mm. Therefore, irrigation flows are certainly competent to transport small amounts of sand and fine gravel. Field measurements and calculations using the Meyer-Peter and Müller (1948) equation indicate that fluxes will not exceed 2 t/d. While bedload equations are notoriously unreliable (Hean and Nanson, 1987; Erskine et al., 1985), the checking of theoretical fluxes against measured values in the present case lends support to the results.

Based on the duration of competent irrigation flows at each gauging station and the measured and calculated bedload fluxes transported by these flows, only about 58 to 102 t/yr are transported by regulated flows on the Mid-Goulburn River.

Allowing for the duration of flood flows each year and the fact that they do not usually mobilise the armour layer, mean annual bedload yields do not exceed 300 t/yr

GAUGING STATION	DISCHARGE (m^3/s)	FLOW DURATION[1] (%)	BEDLOAD DISCHARGE (t/d)	SUSPENDED SEDIMENT CONCENTRATION (mg/L)	SUSPENDED LOAD DISCHARGE (t/d)
Goulburn River at Eildon	34.9	52.1	0.13	8	24.1
	102.8	15.0	0.84	3	26.7
Goulburn River at Trawool	21.8	87	0	6	11.3
	109.6	20.8	1.64	3	28.4
Goulburn River at Seymour	21.8	88	nd	5	9.42
	103.3	25.5	nd	3	26.8

Table 3 Results of the sediment sampling at the three gauging stations on the Mid-Goulburn River. For location of stations, see Figure 2.
nd - not determined 1 - for the period 1 January 1984 to 1 January 1994.

2.5 Extraction induced Channel Changes

Five extraction sites were resurveyed to determine channel changes caused by mining. The results showed that while there was spatially discontinuous minor erosion and deposition at most sites, little replenishment of sand and gravel had occurred since the completion of mining. The mining itself had greatly enlarged the channel. The survey results support the bed load measurements that there is little contemporary replenishment.

3. IMPLICATIONS FOR MANAGEMENT

From the investigation it is shown that the current rates of extraction is greater than the replenishment rate. Furthermore, extraction is usually removing a gravel armour layer which is important for maintaining a stable channel. If river management aims to maintain a stable channel, the disturbance of all armoured bars and riffles should be prevented. The bed load measurements and the resurvey of extraction sites demonstrate that extraction from the Mid-Goulburn River should be limited. Removal of sand and gravel at rates greater than 300t/yr will exceed the replenishment rate. The replenishment rate is so small as to raise doubt about the viability of commercial extraction. Sand and gravel mining is currently being conducted on a non sustainable basis and there are no obvious sites where extraction will benefit the river ecosystem.

4. GUIDELINES FOR EXTRACTION

In order to assist the licensing authority and extractors, guidelines for assessment of sand and gravel extraction applications have been prepared.

4.1 Site Analysis and Assessment

In the analysis and assessment of proposed extraction sites, mining should be permitted only when all the following conditions are met:

- the extraction must benefit the stream (ie. major alignment instabilities can be corrected by extraction; public and private assets can be protected; the development of channel avulsions can be delayed or prevented; heavy deposition is removed; and habitat values are maintained or increased;
- it can be demonstrated that no long term irreversable impact on the river will occur;
- the extraction is within available replenishment rates; and
- extraction must be undertaken according to approved guidelines.

4.2 Monitoring and Control of Resource Extraction

Monitoring of stream reaches subject to extraction is extremely important in influencing management of extraction operations (NSW Department of Water Resources, 1992). This can be achieved by stream surveys before and after extraction and at regular intervals to monitor changes in the stream. Monitoring creates greater awareness of stream changes. Monitoring and reporting, (NSW Department of Water Resources, 1992) will serve a number of important objectives:

- development of baseline information on the condition of the streams and inventory of the sand and gravel availability;
- identification of trends in stream condition.; and
- evaluation of the performance of management agencies and management strategies using the survey information.

5. CONCLUSIONS

Since 1982 an estimated 200,000m^3 of material has been removed from the Goulburn River and in reaches of tributary streams adjacent to the river. This represents an average of 14,000m^3/yr of material removed. The current rate at which stream deposits are extracted from the Mid-Goulburn River cannot be sustained. The replenishment rate is too small to allow continued commercial extraction. An adverse impact on stream conditions is likely should extraction rates continue at the present rate.

Conclusions drawn from these investigations are:

- that active sand and gravel resources available for extraction in the study area are limited;
- sediment yield in the Goulburn River is extremely low and;
- extraction operations which impact on the armour layer of the stream should be restricted.

Existing extraction rates on the Mid Goulburn River is not sustainable without the river system responding to over extraction. The rate of mining is exceeding the replenishment rate of material which will result in geomorphic and environmental impacts.

Extraction of sand and gravel from streams should only be undertaken with extreme care and only approved where all of the following can be demonstrated:

- extraction will assist in meeting stream management objectives for the reach;
- extraction rates are within sustainable yields; and
- guidelines and permit conditions for the operations will be enforced.

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An Investigation of Bed Scour in the Lower Mitchell River

Anthony Ladson*, Rex Candy**, Geoff Claffey**, and John Tilleard**

ABSTRACT: *Following the major floods in April 1990 there were reports of severe scouring in the bed of the Mitchell River. Our investigation of the scour included a hydraulic analysis and review of historical and field data. The investigation showed that a scour of 9m below the average unscoured bed elevation could be attributed to the combined effects of: local scour around bridge piers; scour resulting from the constriction of flood flows by bridge abutments; scour associated with bends; and scour associated with the passage of bed forms.*

1. INTRODUCTION

The April 1990 flood in the Mitchell River caused a major erosion scour up, to 6 m deep, in the bed of the river near the Princess Highway and railway bridges in Bairnsdale, Victoria. This scour could threaten the stability of the bridges and a Telecom cable laid in the bed of the river downstream of the railway bridge.

1.1 Background

The Mitchell river has a catchment of 4778 km^2 and flows from the junction of the Wonnangatta and Dargo Rivers through Bairnsdale to Lake King, a distance of approximately 120 km. In April 1990 a major flood occurred that caused extensive damage to the bed and banks of the river. In Bairnsdale, flood waters overtopped the Princess Highway and a Telecom cable in the bed of the river was washed out.

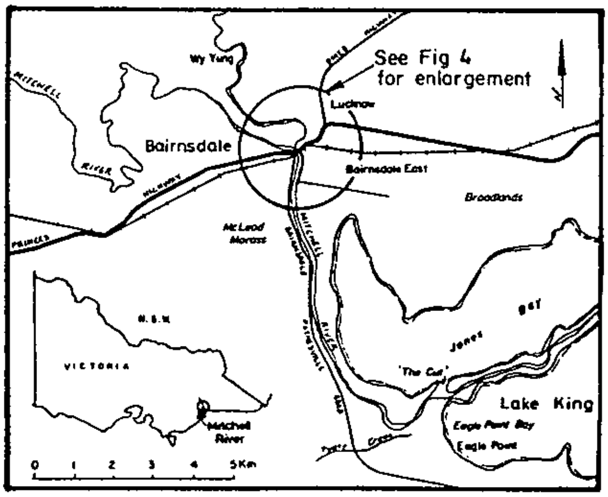

Figure 1: Locality Plan

An investigation of scour in the vicinity of the bridges was proposed by the Mitchell River Management Board and funding was contributed by the Board, Public Transport Corporation and Telecom Australia.

The location of the study area is shown in figure 1.

2. FIELD SURVEY

As part of this investigation, the bed of the river was surveyed from approximately 400m upstream of the highway bridge to 2km downstream. Eight cross sections were surveyed and selected results are reproduced herein. The bed of the river, in the area of interest, was surveyed using a boat mounted depth sounder. The boat was continuously located using a shore based tracking theodolite. Position information was telemetered to a data logger mounted on the boat that simultaneously recorded bed elevation (figure 2).

As part of a separate investigation, Vic Roads obtained bore logs from the bed of the Mitchell River. Three borings were done immediately downstream of the Princes Highway bridge, one upstream of the bridge and 2 between the railway bridge and the telephone cable.

3. HISTORICAL INVESTIGATION

A review was made of historical cross sections and longitudinal sections near the bridges, geotechnical data, and information on works at the telephone cable.

3.1 Cross Sections at the Rail Bridge

Historical evidence suggests that scour in this area has existed for a considerable period. Cross sections have been provided at the railway bridge for the years: 1907, 1914, 1915, 1916, and 1937. The Cross section was re-surveyed in 1990 following the flood. These cross sections are presented in figure 3.

The cross sections show that a major scour occurred between December 1915 and 1916 probably in association with the flood of September 1916. This flood is one of the largest on record with instantaneous maximum flows reaching 101,000 ML/d at Bairnsdale.

* Centre for Environmental Applied Hydrology, University of Melbourne, Parkville Vic 3052, Tel: (03) 9344 6646 Fax: (03) 9344 6215 Email: a.ladson@engineering.unimelb.edu.au

**I. D. & A. Pty. Ltd., P.O. Box 1372, Sale Vic 3850, Tel (051) 431 822

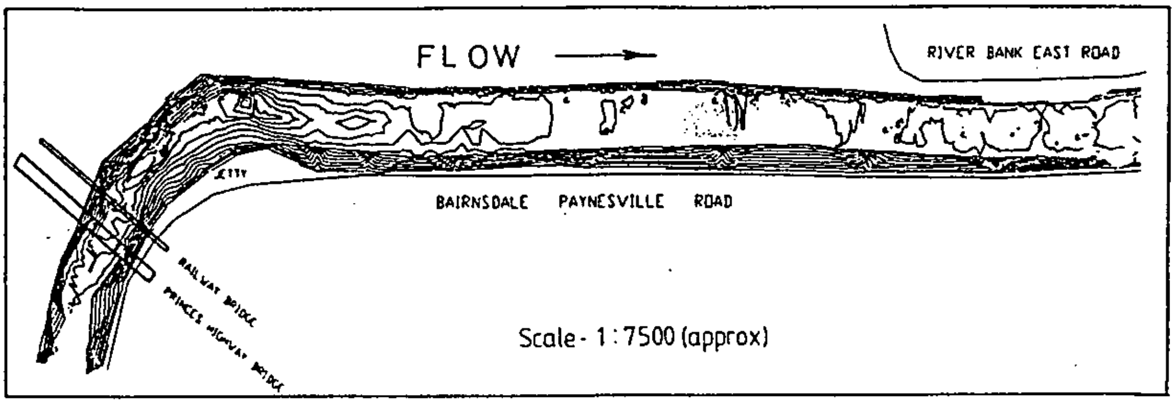

Figure 2: Survey of the bed of the Mitchell River

There is evidence of considerable scour between 1916 and 1937. In early surveys, a retaining wall is shown on the west bank. This wall was removed or destroyed between 1916 and 1937 and approximately 5 m of the bank was eroded. There have been only minor changes in the western part of the channel between 1937 and 1990 but the eastern part of the channel has deepened by about 3 m.

The cross sections show a total of about 5m of scour since 1907. The bed has deepened from -3m AHD to about -8m AHD.

3.2 1937 Mitchell River Survey

In 1937 the State Rivers and Water Supply Commission conducted a survey of the Mitchell River including occasional bed levels and cross sections (SRWSC plan 30056). The lowest level recorded immediately downstream of the bridge has an RL of -10.5 m AHD. This level is about 5 m lower than bed levels upstream of the bridges and is approximately the same as more recent survey information.

3.3 Geotechnical Investigation at Princess Highway Bridge

A report by Vic Roads (Brown 1990) suggests that scour at the Highway bridge has been aggravated since bridge construction in the 1950s. A survey of bed levels and borings of bed material was carried out to determine the extent of the changes and the threat to the bridge.

The survey shows a decrease in bed level of about 2.5m between 1955 and 1990 in the western part of the channel. The eastern part is unchanged. The maximum depth is approximately -10m AHD.

The borings show clay, sand and gravels overlaying limestone. Scourable material was found at depths down to about -15m AHD.

3.4 Destruction of Telephone Cable

The most important piece of evidence suggesting major bed movement in the recent flood was the destruction of a telephone cable placed in the bed of the river. Local reports were that bed levels dropped by up to 5 m since the installation of the cable in 1977. Further investigation showed that the cable was laid 2.5 m below bed level when installed. The cable was washed out during the 1981 floods and was re-installed 2.5 m below bed level after the flood. This was taken as evidence of 5m of scour.

This need not be the case. Investigations as part of the Vic Roads report show unconsolidated silts and sands in the bed. This material is likely to have been mobile during the passage of the flood, and re-deposited as the flood peak passed. It is likely that the cable was actually installed to similar levels before and after the 1981 floods, and that temporary scour of at least 2.5m occurred during the flood event. No survey information of the cable was taken at the time of installation.

3.5 Historical Surveys

Cross section comparisons were possible upstream of the bridge site. Three cross sections 200, 300, and 400m upstream of the Princess Highway Bridge were surveyed, in 1990, before the April 1990 flood, by the Australian Surveying and Land Information Group Victoria. These cross sections were re-surveyed during this investigation.

A comparison of the survey shows that there was little change at any of the cross sections before and after the 1990 flood.

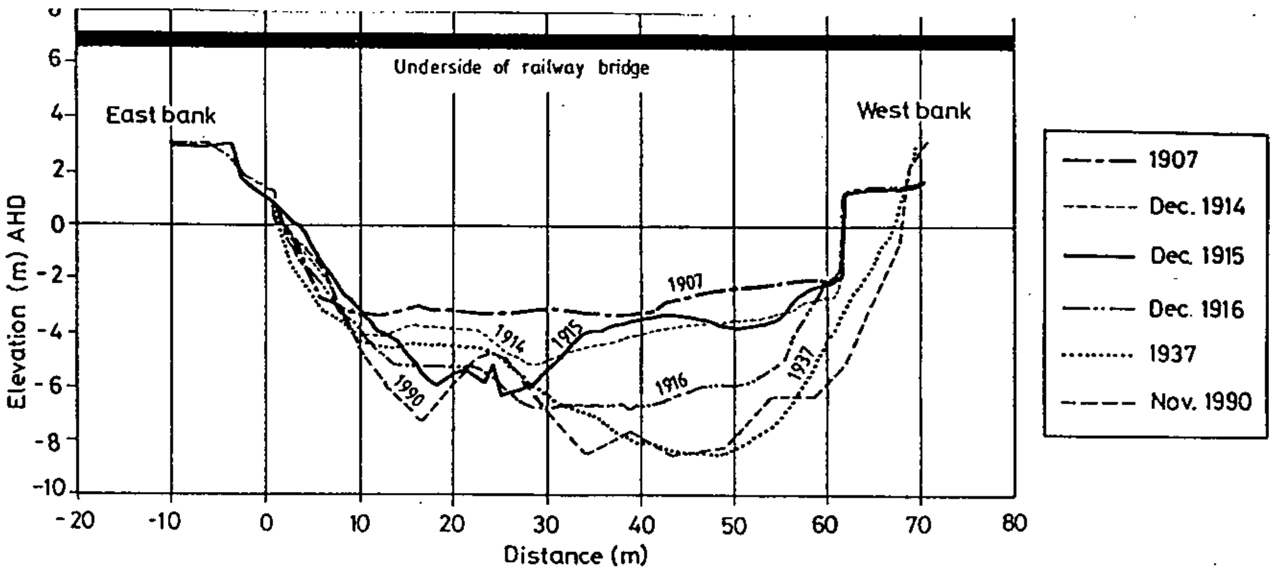

Figure 3: Comparison of cross sections at rail bridge

4. SCOUR MECHANISMS

Scour of a river bed can occur as a general process throughout the whole river system or in localised areas where there is disturbance of flow. There are four mechanisms that may cause local scour at the Mitchell river bridge. These are related to:

- disturbance of flow at bridge piers;
- contraction of flow by a narrowing of the floodplain and bridge abutments;
- secondary currents at a bend;
- migration of bed forms along the river bed.

Likely scour depths associated with each of these mechanisms can be estimated.

Calculations have been carried out to quantify the effect of these different scour processes. Scour depths are calculated for a flow of 150 000 ML/d, which was approximately the peak discharge in the 1990 flood.

4.1 Scour at Bridge Piers

Bridge piers cause high local velocities and shedding of vortices which create local scour. On the rising limb of a flood hydrograph the scour increases and reaches a maximum at the flood peak. After the peak has passed the scour hole refills as sediment drops out of lower flows. The critical time for hydraulic structures occurs at the flood peak and the depth of scour, at this time, cannot be estimated from surveys of the bed done after the flood has passed.

The component of scour attributable to bridge piers was calculated using a number of methods. Values are summarised in table 1. Scour depths show considerable variation. The average predicted scour depth is 5.2 m and the maximum is 6.2 m.

Table 1. Predicted Scour at Bridge Piers

Method	Scour Depth (m)
Laursen (1962)	6.2
Richardson et al (1987)	4.8
Shen et al (1981)	4.5

4.2 Scour at Bends

Bends associated with meandering channels cause "secondary" currents which scour sediment from the outside of the bend and deposit it along the inside. The extent of scour depends on the characteristics of the bed as well as the hydraulics of the channel. The bend in the Mitchell river at the bridges has a radius of curvature of about 500 m which could cause approximately 2.3 m of scour, at the bend apex, in flood conditions similar to those in 1990 (Breusers and Raudkivi 1991).

4.3 Contraction of Flood Plain

There is a major contraction of the floodplain in the area of the highway and railway bridges. This occurs as a consequence of the natural land form and because of the construction of bridge abutments and embankments.

Figure 4 shows the high ground on the edge of the Mitchell river floodplain. The construction of the railway embankment restricts flow capacity but three bridges were constructed, the main river crossing (figure 3) and two bridges over the floodplain with spans of 57m and 21m.

The, more recent, construction of the highway embankment further restricted waterway area. The only bridge in this section of road is the main river crossing, there are no floodplain bridges and the highway embankment effectively prevents water

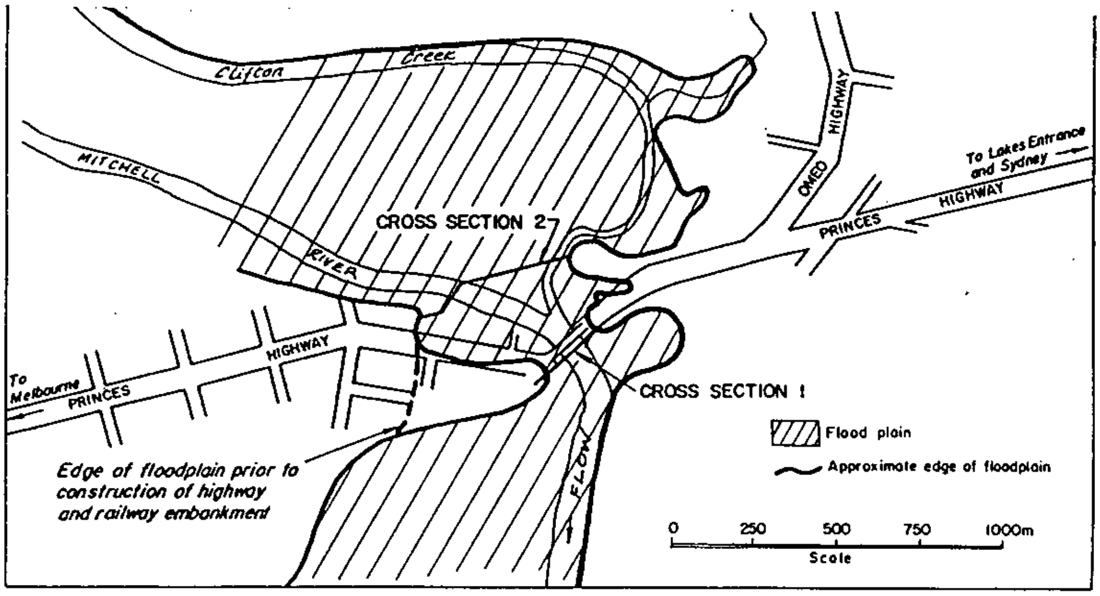

Figure 4: Contraction of the floodplain caused by highway and railway embankment

from flowing through the two floodplain railway bridges. Upgrading and construction of the east bound carriageway means the roadway is rarely overtopped.

Two cross sections were surveyed to assess the effect of the flow constriction. The locations of the cross sections are shown in figure 4. Cross section 1 was taken immediately downstream of the railway bridge and Cross section 2 was taken across the floodplain at a natural constriction upstream of the bridges. The cross sections are illustrated in figure 5 and 6.

In the 1990 flood the floodplain upstream of cross section 2 was covered with water. Under these conditions cross section 2 would be at about right angles to overbank flow. The cross section was deviated to cross the river at right angles as shown in figure 4.

Figure 5 and 6 shows waterway areas and average velocities for the two cross sections for 1990 flood levels. There is a significant reduction in waterway area at the bridge site and a large increase in velocity. More material will be transported through the contracted section and the bed will tend to scour until there is a balance between sediment supply and transport.

Scour depth attributable to the contraction in the floodplain is estimated to be approximately 3m (Farraday and Charlton 1983).

4.4 Migration of Bed Forms

There is evidence of dune or antidune bed forms in this reach of the Mitchell river. Figure 2 shows regular changes in bed elevation downstream of the bridges. It is likely that these represent bed forms. Dune or antidune bed forms are known to exist approximately 10km further downstream near "The Bluff".

The migration of bed forms along the river bed causes bed elevations to vary with time. The worst case is where the flood peak occurs at the same time as the trough of a dune is passing through an area of high local scour. Studies have shown that scour depths can be up to 30 percent greater as a consequence of bed form migration (Garde and Ranga Raju 1978).

4.5 Combined Scour

Scour depth caused by piers, bend curvature, contraction of the floodplain and migration of bed forms may have combined to create the scour hole existing downstream of the bridges. The actual depth of scour is a function of discharge with a maximum occurring during flood peaks.

Adding the estimate of scour attributable to contraction of the floodplain and the bridge piers gives a total of 8.2m. Similar scour depths are calculated using the method described by Blench (1969).

A further 2.3m of scour could be attributed to flow disturbance at the bend giving a total of 10.5m. The migration of bed forms could increase this by 30% to 13.7m. The upstream bed elevation is approximately -5.5m AHD so if the processes are considered to be additive an maximum scour depth of -19.2m would be predicted for a flow of 150,000 ML/d.

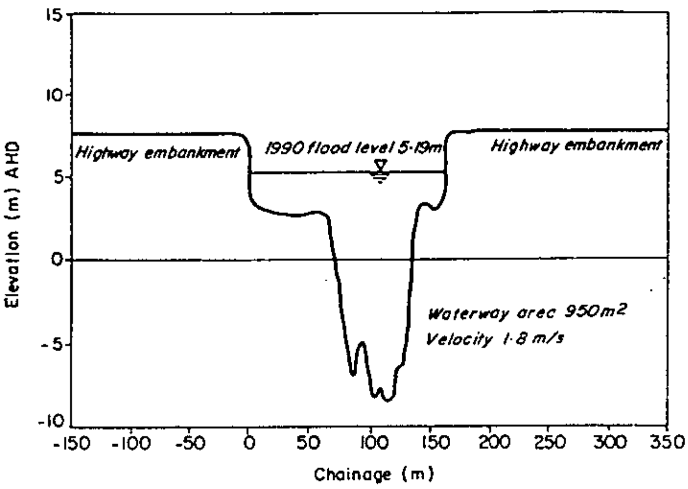

Figure 5: Cross section at bridges. Cross section 1 (looking downstream)

It is acknowledged that scour depths are probably overestimated by adding the results of these equations. The likely extent of scour is discussed below.

5. CONCLUSIONS

In making a judgement on likely future scour during large floods the following factors have been considered.

- The telephone cable was washed out in the 1990 flood indicating temporary scour depths of at least 2.5m.
- Vic Roads bore logs show scourable material, sands, silts, and clays, to depths of -15m AHD at the Princess Highway Bridge and -16m AHD at the telephone cable.
- If scour mechanisms are additive then calculations predict scour depths to -19.2m AHD.
- The longitudinal profile shows an existing hole in the bed of the river down to -10.1m AHD downstream of the bridges (see figure 7).
- Historical cross sections at the rail bridge show 5m of scour since 1907 with depths to -8m AHD.

Considering all these factors, bed elevations of -10m AHD at the Princess Highway Bridge are likely and -15m AHD are possible. -15m AHD is approximately 9m below the unscoured bed elevation as shown in figure 7. A greater depth of scour is expected near the rail bridge as the bridge is closer to the large scour hole at the apex of the bend in the river.

If the telephone cable is to be placed in the bed of the river and made secure against scour in a flood of similar magnitude to 1990 then it must be installed at or below -16m AHD.

Even on a relatively small river, scour depths during a major event can be limited only by the depth of erodable material. Scour depths during floods could be up to 9m below the general bed elevation in this area. This has profound implications for river stability and for the security of bridge foundations.

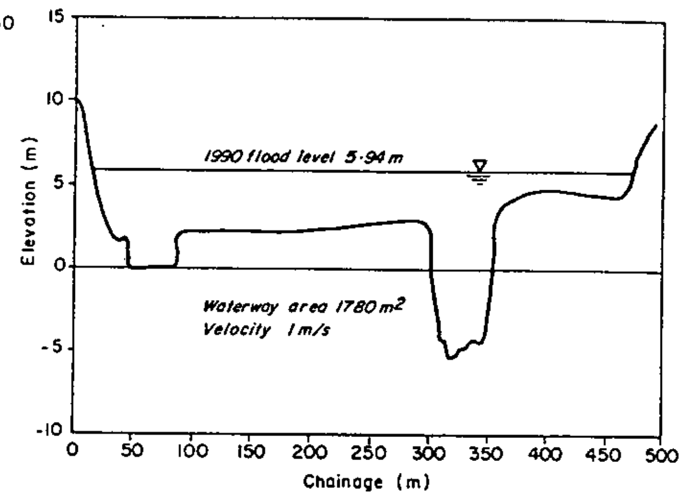

Figure 6: Cross section at restricted section upstream of bridges. Cross section 2 (looking downstream)

6. ACKNOWLEDGMENTS

Review of the history of scour at this location involved inquiry from many agencies. The cooperation of all officers is acknowledged with appreciation. In particular we thank staff of the Public Transport Corporation who provided valuable historical information at the railway bridge site and the Port of Melbourne Authority for their assistance with surveying the bed of the Mitchell river.

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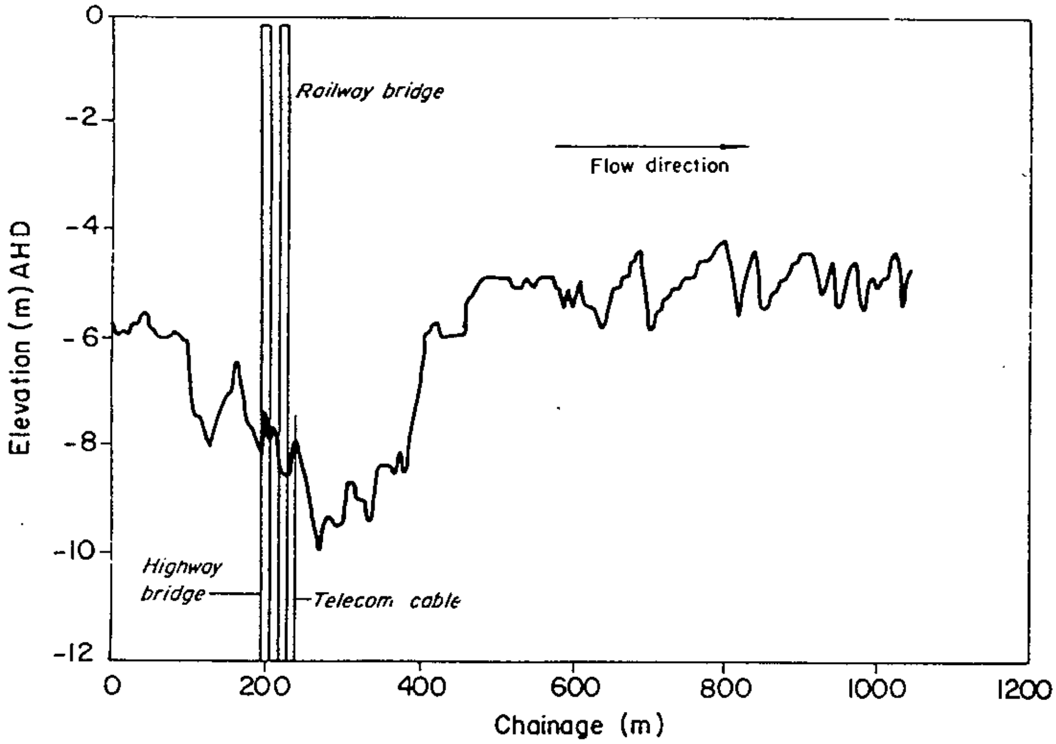

Figure 7. Long section in the vicinity of the highway and railway bridges and telephone cable.

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Downstream Increasing Flood Frequency On Australian Floodplains

Jacky Woodfull, Ian Rutherfurd** and Paul Bishop**

ABSTRACT: *Unlike most rivers described in the international literature, numerous Australian streams display a downstream decrease in channel dimensions that is matched by an increase in flood frequency. In many of these streams, the phenomenon is explained by human impacts such as channelisation, gullying, and artificially increased sediment loads. However, in many streams, the downstream increase in flood frequency is a natural phenomenon caused by channel avulsion, or, most interestingly, by other processes that we have not yet identified. The recognition of this class of streams has implications for managing floods and for understanding the evolution of floodplains.*

1. INTRODUCTION

One of the corner-stones of fluvial geomorphology is that stream channels maintain an equilibrium between the magnitude and frequency of discharge and channel dimensions. That is, with increasing catchment area, stream discharge increases, and channel size increases so as to maintain a channel that floods, on average, every one to two years. Positive exponents in downstream hydraulic geometry relationships have been found for numerous Northern Hemisphere streams; average exponents are 0.5 for width, 0.3 for depth and 0.2 for velocity (Leopold & Maddock, 1953; Park, 1977; Rhodes, 1987). These same hydraulic geometry relations are often used for defining stable stream dimensions for stream engineering in Australia.

Nanson and Young (1981) described a group of streams flowing from the Illawarra escarpment of NSW that dramatically decrease their channel dimensions, and increase their flood frequency, downstream. This reduction takes place across the lower floodplain tract, after the streams have left their confined bedrock gorges. We have observed that many Australian streams decrease in channel dimensions downstream, and increase in flood frequency. This is true of streams of all sizes, from the large Herbert River in northern Queensland, and the Macalister River in Gippsland, down to small gullies.

This paper describes examples of Australian streams that increase in flood frequency downstream, and considers the various causes of the phenomenon. We should stress that, although we are mostly discussing downstream decreasing channel dimensions, the most important characteristic of these streams is their downstream increase in flood frequency.

The two most common types of stream that decrease in area downstream are 'losing streams' and anabranch systems. 'Losing' streams lose discharge to evaporation and seepage in karst, arid and semi-arid areas. Although their dimensions reduce downstream (eg. Dunkerley, 1992), we suspect that their flood frequency does not. We have found no references that discuss flood frequency in 'losing' streams. Similarly, although anabranching streams decrease their dimensions as they lose water to effluents, the flood frequency in separate channels remains reasonably constant (Rutherfurd, 1992). In the streams we consider here, the channel dimensions decrease downstream but the discharge either increases or remains constant, producing a downstream increase in flood frequency. We have called these 'DIFF' (downstream increasing flood frequency) streams.

2. DISTRIBUTION OF DOWNSTREAM INCREASING FLOOD FREQUENCY (DIFF) STREAMS

This study has concentrated on Victorian streams, but we are able to report some DIFF streams in other states. Table 1 lists the names of major streams we have identified that decrease in dimensions and increase in flood frequency downstream. The table is not the product of an exhaustive search, so there are likely to be many more DIFF streams than shown here. These streams were identified from published cross-sections, from gauging records, or from descriptions in the published literature. Most of the examples discussed in this paper are drawn from streams in Gippsland, Victoria.

It is noteworthy that many of these streams occur in the coastal strip, extending from Melbourne, around the SE coast to Wollongong. The downstream increase in flood frequency (downstream decrease in bankfull capacity) can be caused by several processes. These are listed in Table 1 and discussed in the following section.

3. DESCRIPTIONS AND CAUSES OF DOWNSTREAM INCREASING FLOOD FREQUENCY

DIFF is most commonly the product of erosion (deepening and widening) in one reach of the river, coupled with deposition downstream. This occurs in discontinuous gullies, incised streams, channel avulsions, or with catastrophic widening. We will describe examples of DIFF that are obviously caused by humans, and then move to examples that predate human impact.

* Dept. of Geography and Environmental Science, Monash University and Victorian Institute of Earth and Planetary Sciences.
** CRC Catchment Hydrology, Civil Engineering, Monash University

Table 1. Some streams with downstream decreasing channel dimensions in Australia

State	Name of Stream	Source of information	Possible cause of DIFF
Victoria	Latrobe	Gauge data and cross-sections	Mostly channelisation
	Macalister	Gauge data and cross-sections	Channel avulsion
	Avon	Gauge data and cross-sections	?
	Snowy	Gauge data and cross-sections	?
	Tarwin	Gauge data and cross-sections	?
	Avoca	Rutherfurd & Smith, 1992	?
	Rainbow Ck	Brizga & Fabel, 1993	Channel avulsion
	Piccaninny Ck	Gauge data	Aggradation by mining sediment (Peterson, 1995)
	Bendigo Ck	Gauge data	Aggradation by mining sediment (Peterson, 1995)
South Australia	Gawler	Paul Harvey, Co-ord. Mt. Lofty Ranges Catchment Program, pers. comm.	?
	Inman	" "	Channelisation
	Bremer	" "	?
Queensland	Herbert	I.D. Drummond & Assoc., 1994	?
	Barron	Kapitzke *et al.* (this volume)	?
	Mulgrave	Kapitzke *et al.* (this volume)	?
	Burdekin	Kapitzke *et al.* (this volume)	?
	Proserpine	Kapitzke *et al.* (this volume)	?
	O'Connell	Kapitzke *et al.* (this volume)	?
	Mossman	Kapitzke *et al.* (this volume)	?
NSW	Bega	Brooks, 1994	Channel aggradation
	Illawarra escarpment streams	Nanson & Young, 1981	?
	Tantawangalo	Gauge data	Channel aggradation
	Brogo	Gauging data, confirmed by Martin Thoms, pers. comm.	Aggradation downstream of dam?

3.1 Stream Aggradation

European landuse has increased the sediment yield to many streams in SE Australia. Mining, gullying and general catchment erosion (especially in granite catchments) have led to the storage of sand in the downstream reaches of streams. The sand is typically moving through the stream system; the rate of movement decreases downstream, so that the lower reaches of many streams are now choked with sand (see Rutherfurd, this volume). This increases the flood frequency. For example, sand-slugs in the Glenelg River in western Victoria have reduced channel capacity by between one third and one half for over 100 km of river. Other examples include the Tantawangalo River in southern NSW, which has aggraded with sand in the downstream reaches since clearing for agriculture and forestry occurred in the upper catchment (Brooks, 1994), and the Brogo River which shows a notable decrease in downstream channel capacity. According to M. Thoms (pers. comm.), channel capacity has decreased by 30% since a dam was constructed on the river. Mining is another activity that has reduced channel capacity. Huge quantities of sludge, more than 1.7 million m^3 annually, were deposited on floodplains in the Bendigo region, Victoria, as a consequence of gold mining in the 1850s (Peterson, 1995). The decrease in channel dimensions of Piccaninny and Bendigo Creeks in the area is attributed to the deposition of this sludge.

3.2 Incised Streams

"Incised Streams" exhibit the most dramatic decrease in channel dimensions. These are streams that have catastrophically deepened, often since European settlement, and include gullies and larger valley-floor incised streams. It is not uncommon to find incised streams that, within one to two kilometres, decrease from 10m deep and 30m wide to a broad 'floodout' with poorly defined channels. The large upstream channel is never filled by floodwaters, whilst the downstream channel is filled every time the channel flows. The numerous examples of such streams in SE Australia (Bird, 1985; Rutherfurd, 1995) include Eaglehawk Creek in Gippsland and Fernances Creek in NSW (Melville & Erskine, 1986).

3.3 Channelisation

Attempts to increase flow conveyance by desnagging, and cutting drains and bends, have led to many examples of downstream increasing flood frequency. A good example is the Latrobe River in Gippsland (Reinfelds *et al.*, 1995). The floodplain tract of the Latrobe has been straightened by nearly 70 artificial cutoffs, and the channel desnagged up to five times. Even though the channelisation was fairly uniform along the channel, the river response was not. The channelisation produced up to a doubling in width in the upstream reaches of the river, but almost no erosion in the lower reaches. The result is that the river channel now has twice the bankfull capacity at Thoms Bridge (20,000 Ml/d) at the upstream end of the floodplain, than at Rosedale, 70 river kilometres downstream (9,000 Ml/d). The 1937 (pre-channelisation) widths show that the Latrobe did have a natural downstream decrease in channel dimensions (from 34 m wide at Thoms Bridge, to 27 m wide below Rosedale), but this tendency has been greatly increased by channelisation (Figure 1).

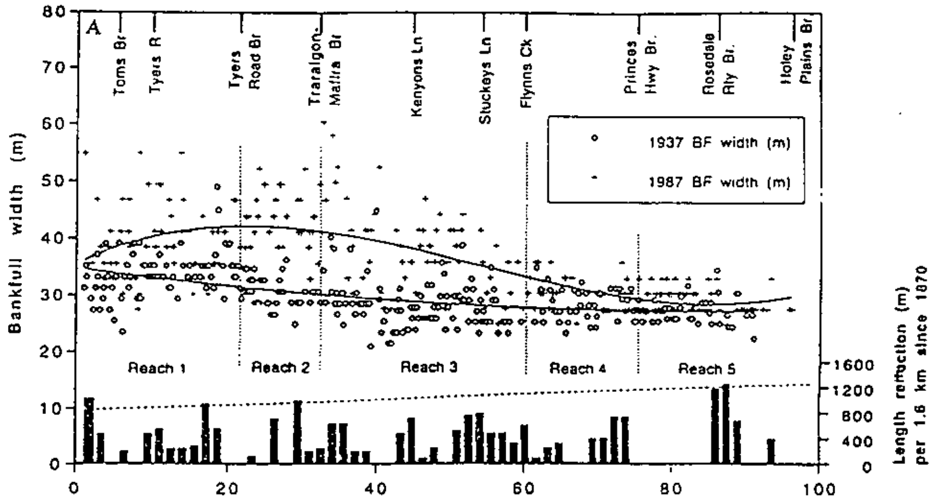

Figure 1. Downstream trends in the effect of channelisation on bankfull width in the Latrobe River. Channel length reductions due to artificial cutoffs for each 1.6 km of river channel are illustrated in the histogram (Reinfelds *et al.*, 1995 p 63).

3.4 Channel Avulsions

Channel avulsions, the sudden abandonment of one channel for another, produce a pronounced downstream increase in flood frequency. During a large flood in 1952 the Thomson River in Gippsland cut a new channel: Rainbow Creek across its floodplain. The new course is 15 km long. Its dimensions decrease downstream from a bankfull width and depth, respectively, of 60 m and 6.7 m at Rice's Bridge, below the off-take from the Thomson, to a bankfull width of 46 m and a depth of 4 m, two kilometres above its junction with the Thomson River.

Channel avulsion may also explain the Macalister River, another DIFF in Gippsland. The Macalister is a large river (catchment area 2,330 km^2) that has a flood frequency of 1 in 20 years (60,000 Ml/d) close to the mountain front. This decreases to a 1 in 1 or 2 year flood (7,500 Ml/d) downstream near Maffra. Whilst channel dimensions decrease downstream, channel sinuosity and wavelength increase. An 1831 map (No. 8198, RWC) shows that the Macalister had its present planform, and probably its present width, before the construction of Glenmaggie Weir. Thus the dimensions of the river are not a product of erosion below the dam.

Note also that the Macalister cannot be interpreted simply as an anabranching stream or as a bifurcating branch around an island. Flood waters do leave the Macalister at defined points, but the effluent points are just slight depressions in the bank, not true anabranches. Most importantly, the channel dimensions of the Macalister do not increase again when the effluents return to the trunk stream. Thus, we interpret the modern Macalister as a pre-historic channel avulsion not unlike Rainbow Creek.

The original Macalister probably occupied Newry Creek, which is still preserved to the North of the modern Macalister (Figure 2). The present Macalister abandons Newry Creek at the mountain front (ie. the apex of the alluvial fan) and rejoins Newry Creek at Bellbird Corner, some 30 river km downstream. Newry creek above Bellbird corner, and the Macalister just below Bellbird Corner share very similar cross sectional areas and channel sinuosities. This suggests that, like Rainbow Creek, the channel avulsion was the cause of the increase in channel capacity upstream of Bellbird Corner.

3.5 DIFF Streams With no Simple Explanation

Of most interest to us are the group of streams that have DIFF, but do not fall into any of the above categories. That is, the DIFF is not caused by stream aggradation, or any other obvious human induced erosion and sedimentation, or by channel avulsions. The streams originally described by Nanson and Young (1981) fall into this category as does the Tarwin River.

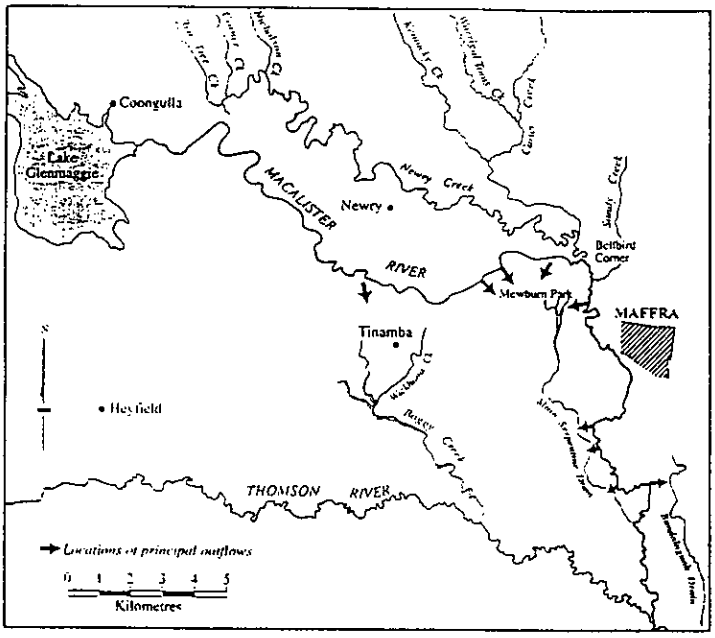

Figure 2. Map of the Macalister River area below Lake Glenmaggie (adapted from I. Drummond and Assoc., 1992, p. 22 & 31).

In their study of five small streams, Nanson and Young (1981) found that downstream flood frequency increased as channel capacity decreased. Anecdotal estimates of flood frequency suggested that overbank flows in the lower reaches occurred approximately 1 - 2 times per year, compared with once every 3 - 8 years at the upstream edge of the floodplain.

The Tarwin River in Southern Gippsland is another example of DIFF. In its upper reaches, the Tarwin's cross-sectional area initially increases until it reaches a maximum at about 15 river kmfrom its headwater (Figure 3). Over the next 20 km, the channel capacity decreases from a bankfull area of 75 m^2 to only 25 m^2, an average decrease of 2.5 m^2/km.). There are no obvious benches within the channel that could be defined as some surrogate bankfull level as is found in many NSW streams (Woodyer, 1968). The reduction in channel capacity is the result of decrease at a similar rate of both width and depth (Figure 4).

What is the explanation for these examples of DIFF? Nanson and Young (1981) explained the downstream decrease in channel size in the Illawarra streams by 'a sudden decline in slope and associated stream power, the cohesive nature of the downstream alluvium, its retention on the channel banks by a dense cover of pasture grasses and the availability of an extensive floodplain to carry displaced water' (Nanson and Young, 1981, p. 239). The problem with this explanation is that these characteristics are shared by most streams as they leave the confined, bedrock portion of their courses and enter the floodplain: slope and stream power decrease, bank cohesion increases, and there is a broad floodplain. Yet the vast majority of streams maintain their channel dimensions, and maintain a reasonably consistent flood frequency downstream. This is shown by the consistency of downstream hydraulic geometry exponents world-wide (Park, 1977; Rhodes, 1987).

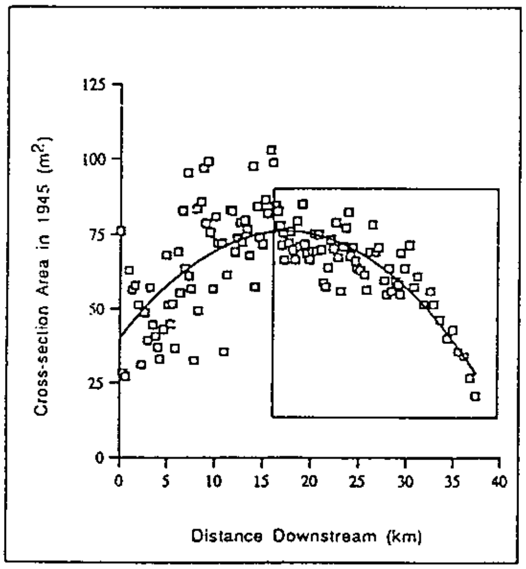

Figure 3. Changes in cross-section area along the Tarwin River, Gippsland. Boxed region highlights where the decrease in dimensions occurs.

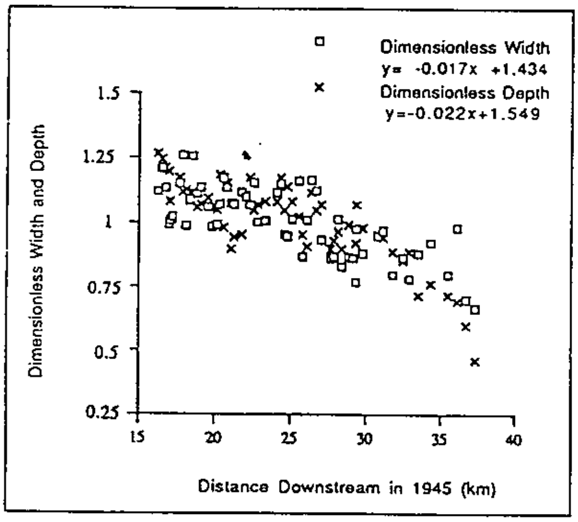

Figure 4. Downstream rates of decrease in width and depth on the Tarwin River for the length of river highlighted in Figure 3. (N.B. width and depth have been non-dimensionalised by dividing each value by the mean value).

It is true that all of the coastal DIFF streams that we have identified in Victoria (excluding anabranching streams) build their floodplains mainly by vertical accretion, rather than by lateral meander migration. The downstream decrease in channel area could be explained by differential overbank deposition. That is, more material is deposited at the upstream end of a reach where a flood first goes overbank, so that levees are deposited first at the upstream end and are progressively built downstream. Although this effect may contribute to DIFF, it is not the whole explanation. First, levee deposition cannot account for the downstream changes in width. Overbank deposition should, if anything, narrow the channel in the upstream reach, as well as deepen it, as material is deposited on the banks. Second, in the streams that we have considered, the downstream difference in the height of levees is not enough to account for the change in channel capacity. For example, on the Tarwin, the difference in levee height is less than a metre, whilst channel depth decreases by 3 m downstream. There may be some streams in coastal NSW (eg. the Macdonald) that have such well developed levees (up to 10m high) that the levees could explain DIFF, but it is not a universal explanation.

Another possible explanation for these DIFF streams could be 'inherited' low valley slopes. Floodplain slopes are often considered to be a product of the erosion and deposition of the modern stream. Yet, in many cases, the slope of the modern floodplain is a product of the underlying depositional surfaces. This surface is likely to be Pleistocene in origin. Deposition from a low energy stream is more likely to be plastered over the former surface than to modify that surface by erosion. Although we have not yet investigated this hypothesis, we may find that DIFF streams are associated with a lower inherited floodplain slope than other streams of similar size that maintain constant downstream flood frequency.

4. DISCUSSION

4.1 Downstream Rates of Change in DIFF Streams

We have discussed the distribution of DIFF streams, and their possible causes. It is interesting now to note two characteristics of DIFF streams: flood frequency and downstream hydraulic geometry.

The flood frequency of the DIFF streams suggests that the upstream reaches are over-large, rather than that the downstream reaches are too small. The downstream reaches of all of the rivers considered above have a 1 in 2 year bankfull flow, whereas in the upstream reaches bankfull flows are much more rare. If we accept a 1 to 2 year bankfull flood frequency as being 'normal' (Dury, 1976; Wolman & Leopold, 1957), then downstream reaches of these streams are 'normal' and the upstream reaches over-large.

It is important to note that we cannot strictly apply hydraulic geometry relationships to these DIFF streams because the basic presumption of hydraulic geometry, that bankfull flood frequency is constant downstream (Leopold & Maddock, 1953), is not true. However, it is noteworthy that the down-stream change in channel dimensions occurs at the same rate in the Macalister River as it would in a normal stream but in the opposite direction. Thus, although the **discharge** in the Macalister increases downstream, the **size** of the channel decreases downstream at the same rate that other streams would be expected to increase, from hydraulic geometry relationships. This is shown by a comparison of exponents. A review of exponents from numerous rivers around the world (Park, 1977) found that, on average, width tends to increase as the square-root of discharge downstream, whilst depth increased to the 0.3 power. On the Macalister, by comparison, the width decreases downstream with an exponent of 0.52, and depth decreases with an exponent of 0.36. This result could be just a coincidence on the Macalister so we are investigating other DIFF streams to see if the same relationships holds.

4.2 Importance of DIFF Streams

What is the significance of DIFF streams? Leaving aside incised streams and smaller streams, DIFF streams are important for three reasons. First, the simple fact that these streams have higher flood frequencies in their downstream reaches helps to explain flooding patterns on many floodplains. The lower flood frequency of the upstream end of these streams means that flooding is less frequent along these channels than one would normally expect. Second, DIFF streams are also important for our understanding of floodplain deposition and destruction. For example, the changing downstream flood frequency leads to differential levee deposition and anabranch development. Down-stream anabranches are likely to develop at a faster rate with more frequent flow. Third, it requires us to consider what is happening to bedload transport. Assuming that there is a balance between supply and transport of bedload in the lower reaches, that is, supply and transport are in 'equilibrium', then the discharge in the upper reaches is able to transport in excess of its supply of bedload. If this is so, where is the sediment deposited? This question is also under investigation as part of this study.

5. CONCLUSIONS

There is a class of streams in Australia in which channel dimensions decrease, and flood frequency and discharge increase downstream.. Even in large rivers, the downstream decrease in channel dimensions can be dramatic, with up to a four times decrease in channel area. The purpose of this paper has been to describe the various types of these streams, and offer some preliminary explanations for this phenomenon. Streams of all sizes display DIFF, but from our preliminary work it appears that large DIFF streams are most common along the coast, particularly between Melbourne and Wollongong, and in Far

North Queensland. The identification of such streams is important for three reasons. First, they differ from the well-accepted model of consistent downstream flood frequency. Second, erosion and sedimentation processes in these types of streams can contribute to our understanding of floodplain evolution. Third, an appreciation of this type of stream explains flooding patterns.

Many of the DIFF streams are a product of erosion of one portion of a stream, often with deposition downstream. The result is that the upstream portion of the channel is usually over-large (ie. low flood frequency) rather than the lower reaches being too small. In most of the examples described, much of the erosion is a result of human interference, usually by channelisation, or by accelerated runoff and erosion from catchments. In other cases, a natural DIFF can be increased by human intervention, for example by channelisation. Other examples of DIFF are explained by natural channel avulsions. Finally, there is a group of DIFF streams that cannot be explained either by human intervention or channel avulsion. We have no satisfactory explanation for these streams' decrease in channel capacity downstream, but it may be related to both levee development and inherited floodplain slope. Finally, we should acknowledge that the 'explanations' we have suggested for DIFF streams are, to some extent, descriptions rather than explanations. For example, we state that channel avulsions tend to be much larger at the upstream end of the avulsion, but why is this so? DIFF streams still require more research.

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Hydraulic Characteristics of Retards

B.G. Dyer[*], *A.W. Western*[**], *R.B. Grayson*[**]

ABSTRACT: *Retards have been widely used for river bank protection and stream alignment in Victoria. To date little analytical information has been available for use in the design of retards. This research outlines how retards affect flow. The effect of rail spacing, retard height, and the longitudinal spacing of the retards was investigated. These results provide designers with some analytical inputs for the design process and should lead to a better understanding of how retards work to prevent erosion and encourage deposition.*

1 INTRODUCTION

Retards are low fences that extend from the river bank into the stream and are typically constructed of log rails attached to steel or timber piles. The intention of constructing retards is to stop erosion of the toe of the bank and to encourage the deposition of sediment, which in turn will encourage the establishment of vegetation. Generally the design will be such that the deposition of sediment will result in the formation of a new bank line. Thus retards are effectively used for flow alignment works.

To date the design of retards in Victoria has largely been based on experience and general guidelines published in 1991 (Drummond and Tilleard, 1991). This research aimed to extend these guidelines and to develop some analytical relationships for use in design of retards. The areas covered include:

- how retards work;
- retard porosity (rail spacing);
- retard height and the effect of submergence;
- zone of influence;
- angle of the retard to the flow;
- multiple retards;
- sediment stability.

The laboratory research was carried out at the University of Melbourne using scale models. The flume used was 36 m long, 0.925 m wide, and set at a slope of 1:1500. Velocities were measured at regular depths and intervals across the flume using a 10 mm diameter propeller style current meter. Some sediment studies were carried out to provide quantitative answers to some of the hydraulic theories. Dye traces were also injected into the flow to allow visual studies of how the flow was affected by the retards.

The model retards used were 300mm long and 150mm high, constructed from 6mm steel rod. The spacing between the rods was varied to give different porosities. Tests were carried out for Froude numbers ranging from 0.5 to 0.1 and flow depths of twice, one and half, and one times the height of the retard.

2 HOW RETARDS WORK

Originally it was thought that retards worked by providing a backwater effect upstream, reducing velocities and allowing sediment to deposit. While retards do cause a minor afflux and associated backwater affect, this was found to only have a minor contribution to the success of retards in stopping bank erosion and providing the suitable hydraulic conditions for the deposition of sediment. Primarily retards protect a bank and cause sediment deposition by providing a resistance to flow in a section of the channel. This slows the flow in the immediate vicinity behind the retard and causes the flow to concentrate in the unaffected (no retards present) section of the channel. This velocity reduction is mainly downstream of the retard (Figure 1).

Given that retards have their greatest influence downstream, it is possible to site a series of retards such that the downstream retard is within the area of influence of the upstream retard(s). This allows a cumulative velocity reduction to be developed.

3 RETARD POROSITY

The effect of the retard porosity on the downstream velocity was examined. Retard porosity, or percentage open, is defined as the percentage of the frontal area of the retard that is open (see Eqn. 1).

The results from this section of the research indicated:

- that the relative downstream velocity (see Eqn. 2), was independent of the upstream velocity and varied with depth of flow. Hence, at a given flow depth, the one set of results is applicable to all flow velocities. This finding agrees with hydraulic theory (Dyer et. al, 1995) and allows the results determined from scaled hydraulic modelling to be directly applied to the field situation; and
- that as the porosity decreased, so did the relative velocity.

[*] *Murray-Darling Basin Commission, GPO Box 409, Canberra, ACT, 2601 ph (06) 279 0100*

[**] *Centre for Environmental Applied Hydrology, University of Melbourne, Parkville, VICTORIA 3052 ph (03) 9344 6641*

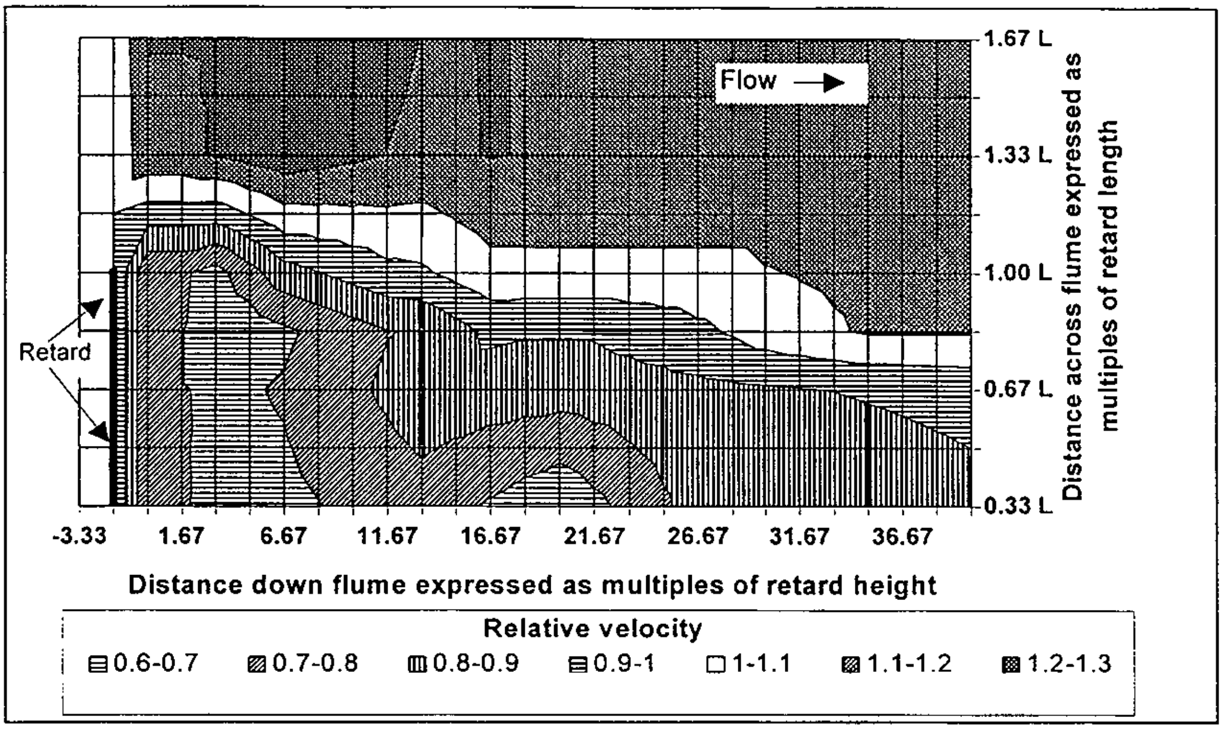

Figure 1 Plan view of relative velocities behind a retard of 50% porosity. Note that these results are for a straight flume and are unlikely to be applicable to flow around a bend. Also note that the plot does not go to the edge of the flume (as this area it is influenced by edge effects and is not typical of general flow conditions).

$$\text{Percentage open} = \left(1 - \frac{\text{frontal area of bars}}{\text{frontal area of retard}}\right) * 100 \quad (1)$$

$$\text{Relative Velocity } \% = \frac{\text{velocity behind retard}}{\text{original velocity}} * 100 \quad (2)$$

The results for the effect of porosity on the relative velocity are given in Figure 2. These results allow the designer to determine the effect of different retard construction on the downstream velocity and hence determine the economic benefit of each design. For example the cost of closer rail spacing

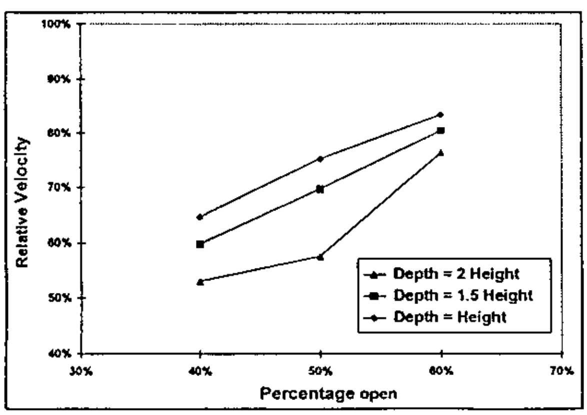

Figure 2 Average results indicating the effect of porosity on relative velocity at a point 1.5 times the height of the retard downstream of the retard. The different curves are for different flow depths which have been expressed as multiples of the retard height.

(ie. a reduction in the porosity) may be outweighed by the associated decrease in the relative velocity. Thus while the overall cost of the project increases, the risk of the retards failing can be reduced.

4 SUBMERGENCE

Retards are constructed in river beds and are exposed to a wide range of flow depths. Figure 2 shows that the relative velocities varied with the depth of the flow. As the depth of flow increased the relative velocity decreased because it was easier for the flow to divert over the top of the retard.. The implication for design is that as the flood magnitude increases, the relative velocity decreases. The designer should be able to relate the velocities associated with flood stage to the relative velocities associated with that depth of flow over the retard and hence determine how the absolute velocity behind the retard varies with flood stage and magnitude.

It must be appreciated that when the retard is submerged, the velocity profile of the flow is severely affected by the retard. Figure 3 shows the velocity profiles recorded in the laboratory for flow over a single retard. The two profiles recorded downstream (d/s) of the retard have much lower velocities in the area affected by the retard, ie. the area below the top of the retard. The velocity of the flow that passes over the retard is higher than the velocity that would have existed had the retard not been in place (the control velocity). The designer needs to consider how this high velocity will affect

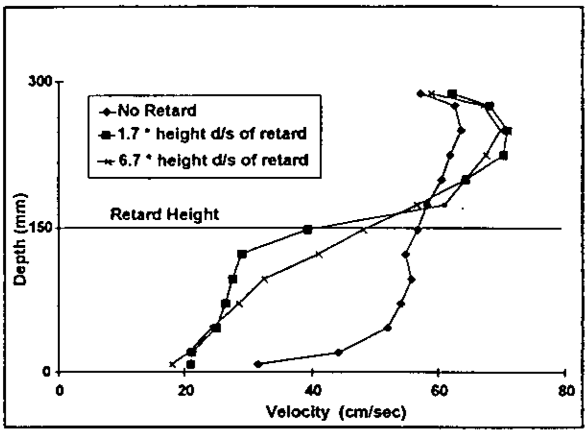

Figure 3 Velocity profiles recorded in the laboratory. Note how the velocity profiles downstream of a retard have higher velocities for the flow above the retard than occur for no retard.

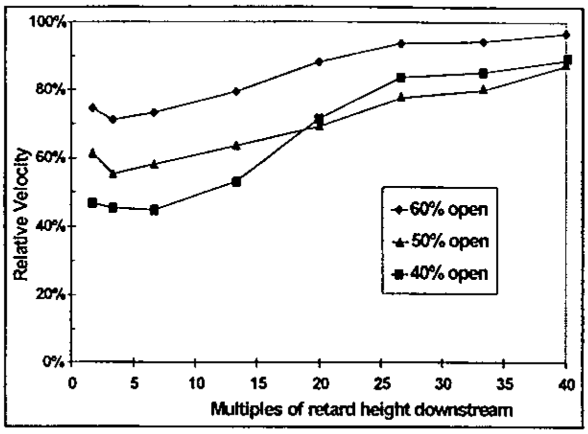

Figure 4 Relative velocity versus the distance downstream of the retard, expressed as multiples of the retard height.

the bank above the retard and include this consideration in determining the height of the retard.

5 RETARD HEIGHT AND DOWNSTREAM INFLUENCE

As discussed above retards reduce the velocity of the flow behind the retard but do not reduce the velocity of the flow over the retard. The reduction in the flow velocity behind the retard can be observed for a considerable distance downstream. Figure 4 shows the relative velocity for three different values of retard porosity and how the relative velocity increases downstream of the retard. The designer can use these results to determine how far downstream the retard provides effective protection (ie. reduces the velocity sufficiently) for the site under consideration. This can then be used in determining the location of the next retard. The designer will need to recognise that the downstream effect is a function of the height of the retard. Thus the design height of a retard can be adjusted to achieve a suitable downstream effect.

An interesting result is that the lowest relative velocity occurs not at the retard but a short distance downstream of the retard (Figure 4). The retard creates a uniform velocity profile which initially results in much higher energy losses to bed friction and hence a decrease in velocity. Furthermore this zone, immediately downstream of the retard, is subject to high shear stress. Therefore some scour can be expected immediately downstream of the retard.

The results in Figure 4 are for the situation where the increase in the velocity of flow behind the retard is due to the mixing with the high velocity flow above the retard with minimal lateral mixing from the high velocity water flowing in the channel, hence the results in Figure 4 are not applicable to locations near the channel end of the retard. A better understanding of this can be obtained from Figure 1 which shows a plan view of relative velocity contours behind a 50% open retard.

The results presented in Figure 1 were obtained in a straight flume and are unlikely to be directly applicable to flow in bends. At present the area of influence of a retard on a bend is determined by the angle of attack (a line tangential to the inside bank of the stream, passing the tip of the retard and extended downstream to the outer bank. The area between this line and the retard is defined as protected). This is not considered to be a particularly accurate method although it is believed to be conservative and the designer may wish to determine the area of influence as a compromise between the angle of attack and the results in Figure 1.

6 RETARD ANGLE

There was a general belief amongst those who had experience with retards that retards streamed flow across the river to the opposite bank and that this was partially due to the angle of the retard. This was based on the observation of a wave angling downstream of the retard towards the opposite bank. Dye tests in the flume determined that this wave was a surface feature only and that there was no streaming of flow from a retard. It is important to recognise that surface features do not indicate the true characteristics of the flow.

A question of considerable interest to designing engineers is what affect does the angle of the retard have on the relative velocity? The laboratory experiments showed that the angle of the retard to the flow has a minimal effect on the relative velocity. Thus the angle of the retard is free to be adjusted by the designer.

When setting the angle of the retard it is necessary to consider the possibility of the retard collecting debris and the porosity being severely reduced. In this situation the retard will act as a groyne and the diversion of the flow will be considerable, greatly increasing the potential for scour. Thus the retard should not be angled to point into the flow.

The effect of the angle of the last two panels at the channel end of the retard was found to influence the location of the scour hole (this forms immediately downstream from the tip of the retard). Angling the last two bays of the retard at approximately 30° and 60° to the line of flow results in the scour hole being located further out in the main channel.

7 MULTIPLE RETARDS

The main effect of retards is to slow the flow by providing additional resistance. They influence the flow for a considerable distance downstream (see Section 0). As such it is possible that the flow approaching a retard may be influenced (ie. had its velocity reduced) by the retard(s) upstream of it. Hence with correct retard spacing, interaction between retards can result in a cumulative decrease in velocity. To obtain a large decrease in velocity the upstream retards should be closely spaced, with larger spacing downstream to maintain the velocity below the desired level (Figure 4 indicates how velocity increases downstream of a retard).

The majority of the laboratory modeling was carried out using a single retard. The applicability of these results to multiple retards was tested and it was found that the response of multiple retards could be determined by analysing each retard as a single retard subject to the flow conditions from the retard(s) upstream of it. Thus to determine the relative velocity behind a retard that is influenced by an upstream retard the following steps need to be applied.

1. For a given depth of flow and retard porosity determine the relative velocity behind the upstream retard (use Figure 2)
2. Based on the distance to the second retard, and the relative velocity behind the first retard determine the actual velocity in front of the second retard (use Figure 4). This is the control velocity for the second retard.
3. Based on the selected porosity of the second retard and the selected depth of flow determine the relative velocity applicable to this retard (use Figure 2).
4. The actual velocity behind the second retard is the product of the control velocity (from 2) and the relative velocity of the retard (from 3).

8 SEDIMENT MOVEMENT

Retards are used to form an artificial bankline and hence train the river to a different course. The expected life of a retard is 10 - 20 years and thus for a long term solution it is necessary to have sediment deposit in the embayments and form an artificial bankline. When considering sediment movement within an embayment there are two points to consider. The first is the retention of the original bed material. Once this is eroding the retard can be considered to have failed. The second point is the deposition and retention of fine sediment which is important for the establishment of vegetation.

There are four fundamental considerations to achieving stable sediment deposition. These are:

- risk management and the failure flood;
- velocity of flow;
- berms; and
- vegetation.

8.1 Risk Management and the Failure Flood

The successful implementation of retards is fundamentally a procedure in risk management. The first point to recognise is that it is uneconomic, if not impossible, to build a structure that can successfully protect the bank and deposit sediment in all possible flow conditions. However the retard design can be varied to adjust the risk of failure.

Failure is defined as the flow at which the bed material (as distinct from the deposited fines) within the embayments is eroded. By use of a flood frequency relationship and hydraulic consideration of the reach, the designer should be able to estimate the velocity and stage of flow associated with floods of different annual exceedence probability. From this and the velocity information in Section 8.2 the designer can determine what is the annual exceedence probability of the failure flood for a given design. It should be noted that the magnitude of the failure flood will increase as the vegetation becomes established and assists the retards in protecting the bed material from erosion. Hence the most critical period for failure of retards is the period from construction until the vegetation becomes established.

Considering the deposition of fines, if the embayments are higher than the low flow channel, then there will be a continuum of events that cause the embayments to become inundated. Directly related to this will be a range of velocities over the embayment; extending from near zero when the embayment is just inundated to the velocity associated with the failure flood. Linked to these velocities is a range of erosion and deposition outcomes. These will range from minor freshes that will barely cover the embayment and deposit very fine material, to moderate events that will erode fine material but deposit coarser material, to the failure flood that will erode all material sizes in the embayment, including the bed material.

The implication of this for designers is that by adjusting the berm height and the design of the retards the designer can influence the magnitude of the failure flood and the impact of the more frequent events. This is where the risk management concept comes in as the designer has to weigh up the cost of some additional works against the decrease in the risk in failure associated with the works.

8.2 Velocity of Flow

Research has shown that the erosion of a particle can be related to the mean stream velocity. Hence when designing retards it is possible to determine whether the flow velocity behind the retard will be sufficient to move particles, or whether they will remain stable. Table 1 relates the hydraulic radius, particle size (based on median sieve diameter), and velocity at which particles of that size begin to move. This table is based on the results of Yang (1973). These results can be used in conjunction with the estimated flow velocity, the relative velocities from Figure 2 and the downstream effects from Figure 4 to determine a suitable layout and porosity of the retards such that the desired sediment size will remain stable.

To assist with this analysis the designer should consider the particle size distribution of sediment carried by the river at that location. The simplest way to obtain this information is to carry out a basic sieve analysis of the bed material and material from a site where sediment has deposited. With the bed material the designer should consider the following points.

- Could the bed material form an armour layer. If so what size material would form this armour layer and is there enough of this material to form an armour layer quickly.
- What size material needs to be eroding such that the bed can be considered to be fully mobile and hence the retards have failed.

By considering these the designer should be able to obtain an estimate of the particle size that is considered representative of the bed material. The velocity associated with this can then be used to determine the failure flood magnitude and hence the annual exceedence probability of the failure flood.

The sieve analysis of the deposited material will give the designer some indication of the material that is being carried and hence what is available for deposition. Using this information and the velocities from Table 1 the designer can determine what proportion of this material will be trapped and held in a stable manner for a given design of the retards and a given flood magnitude. Alternatively the designer can use empirically derived sediment transport relationships to relate velocity to the size of sediment being transported. If necessary, the design can be adjusted to improve on this. Again the cost of the design will have to be considered against the amount of sediment that is expected to be trapped.

The velocities in Table 1 are for incipient motion (ie. the first particles beginning to move) and thus slightly higher velocities will cause some movement of the particles, but not sufficient to result in significant erosion. It is not known by how much the velocities in Table 1 can be exceeded before the erosion rate becomes significant.

8.3 Berms

A berm is a raised area on which retards are built. They are usually constructed to allow the retards to be built on dry land. Berms have several other advantages which are outlined below.

- The berm diverts the low flow channel away from the retards and the eroding bank, reducing erosion of deposited sediment.

Table 1 Critical velocities for different particle sizes and different hydraulic radii. Note that on a wide berm the hydraulic radius is approximately equal to the depth of flow.

Critical Velocity m/sec		Hydraulic radius m							
		0.1	0.15	0.2	0.25	0.30	0.35	0.40	0.45
Particle diameter mm	1	0.32	0.31	0.30	0.29	0.28	0.28	0.28	0.27
	2	0.46	0.44	0.43	0.42	0.41	0.41	0.41	0.41
	3	0.53	0.51	0.51	0.51	0.51	0.51	0.51	0.51
	4	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.62
	5	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70
	6	0.74	0.74	0.74	0.74	0.74	0.74	0.74	0.74
	7	0.82	0.82	0.82	0.82	0.82	0.82	0.82	0.82
	8	0.84	0.84	0.84	0.84	0.84	0.84	0.84	0.84
	9	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87
	10	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90

- The berm provides a location, above water level, on which revegetation can commence.
- If the berm is uneven, then during the recession of an event sites where there is deeper water will have lower velocities, allowing finer sediment to deposit, which will in turn assist in the establishment of vegetation. This process can be assisted by deliberately creating gentle hollows in the berm (approximately 300 mm deep). It is important that these hollows be laid out such that they do not form a potential flow path.
- The elevation of the berm needs to be determined with respect to the flow regime of the river, the stage discharge relationship, and the vegetation to be planted. The lower the berm is, the longer and more frequently it will be inundated.

8.4 Vegetation

Vegetation has a major role in trapping and stabilising sediment in the embayments. Velocities for incipient motion (Table 1) are very low, and for fine particles, economically unachievable by the use of retards alone.

By combining vegetation with retards sediment trapping can be greatly enhanced. Vegetation has the following advantages.

- It increases the hydraulic roughness of the area between the retards and hence lowers the velocity. The velocities within dense vegetation (eg. grasses) can be very low, sufficient for the deposition and retention of very fine sediment.
- Careful choice of vegetation can give plants with an extensive root system which will mechanically bind particles, effectively creating a composite material of much greater strength.
- Grasses provide a surface cover to protect underlying soil.
- Fine material deposited on the recession limb of the hydrograph (when there are lower velocities) will, over time, be bound by the vegetation and stabilised against erosion in further events.
- In small events the vegetation will act like a sieve and trap floating debris. This in turn will provide humic matter for the vegetation.
- As vegetation becomes established it decreases the annual exceedence probability of the failure flood and thus decreases the risk of failure of the retards.

Key properties for vegetation for use with retards are:

- fibrous root systems;
- able to survive in poor soils (eg gravel from the river bed); and
- able to cope with periods of inundation.

The necessity of vegetation in the successful implementation of retards in a long term river training strategy can not be over emphasised. Field surveys indicated that the greatest deposition of material occurred where vegetation was successfully established. Several highly successful rehabilitation works have been based solely on the use of lines of willows (vegetative retards) although it should be noted that the use of vegetative retards is a higher risk option than the use of retards and vegetation.

9 CONCLUSION

This research has developed a series of analytical relationships which can be used in conjunction with the general guidelines for the design of retards. These have been combined in a report "Retards and Groynes: Design Guidelines" available from the Division of Catchment and Land Management, Department of Conservation and Natural Resources, Victoria.

10 ACKNOWLEDGMENTS

This research was funded by Department of Conservation and Natural Resources, Victoria with in kind contributions from Ian Drummond and Associates and the University of Melbourne. John Oates and John Tilleard provided valuable assistance in the supervision of this project. Thanks are extended to Ian Drummond and staff of the Ovens, Avon—Macalister, and East Gippsland River Management Boards for their assistance in viewing and understanding the behaviour of retards in the field.

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MECHANISMS OF STREAM BANK EROSION

The Results of Five Years Of Bank Profile Monitoring - River Murray

Judy Frankenberg*, Wayne K. Tennant** and John W. Tilleard**

ABSTRACT: *Detailed monitoring of river banks is contributing to a greater understanding of stream processes on the River Murray near Albury-Wodonga. This paper will present a summary of the results of five years of stream bank profile monitoring at eight sites on the river. The paper also presents some preliminary interpretation of the results but much remains to be learnt from more detailed analysis.*

A consistent pattern of retreat of unvegetated banks is identified, dominated by parallel retreat of the mid-bank facet up to a bank height corresponding to summer release levels. Notching of the upper bank occurs at summer release levels which causes collapse of the overlying vertical upper bank facet. Vegetated banks are shown to retreat at slower rates than unvegetated banks.

1. INTRODUCTION

This paper presents the results of a detailed stream bank monitoring program at eight sites on the River Murray, Australia. The sites are focused on the river near Albury-Wodonga, 30-40 river kilometres below the Hume Dam (Figure 1). This dam, as the major storage on the River Murray, regulates irrigation flows for the Murray Valley irrigation areas in Victoria, New South Wales and South Australia, and ensures a water supply for Adelaide.

The Murray River is a special case in river management. It is a large river by Australian standards, and is highly regulated. The Hume Dam was constructed between 1919 and 1936, and enlarged to its present size (3040GL) in 1961 (Jacobs 1990). The catchment above the dam, while covering less than 1.5% of the Murray-Darling Basin, contributes 37% of the total inflow.

Construction of the Dam has altered the natural flow regime (Close 1990). In the reach between the Hume Weir and Yarrawonga, a distance of about 230 river kilometres, the seasonal flow regime has been almost reversed, with high flows in summer and autumn, and low flows in winter. Small annual floods have been virtually eliminated and moderate (5 year ARI) floods often modified. by pre-releases.

The total annual flow has also been modified by diversions from the Snowy River catchment through the Snowy Mountains Hydro-electric Scheme. For the period 1892 to 1974, the natural flow model run by the Murray-Darling Basin Commission indicates that the average annual flow has increased from 4670 GL/year to 5110 GL/year (Close 1990).

The reach of the river where the study was carried out carries more water than any other section of the Murray. The annual discharge has increased over the last forty years, since the diversions from the Snowy River commenced, and as regulation has increased, a greater proportion of the flows are confined within the channel, rather than occurring as overbank flows during small floods (T. Jacob *pers. comm.*).

The floodplain and river banks have been greatly changed by clearing and grazing, The river bank vegetation was probably once dominated by the Common Reed (*Phragmites australis*), wattles (*Acacia dealbata*), bottlebrushes (*Callistemon seiberi*) and River Red Gum (*Eucalyptus camaldulensis*). It is now grazed over much of its length, there are few shrubs, annual grasses and adventive weeds occur on the top of the bank and the face is bare. The bank sediments are therefore exposed to the effects of the long duration bank-full flows which occur as a result of regulation. A high proportion of the river banks appear to be eroding. By contrast, some banks, generally those which are covered with reeds, appear to be stable (Frankenberg 1992).

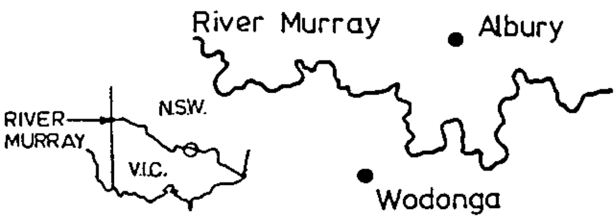

Figure 1. - Locality Plan

* Murray Darling Freshwater Research Centre P.O. Box 921 Albury 2640 Phone (060) 431002 Fax (060) 431626
** I. D. & A. Pty Ltd. P.O. Box 165 Wangaratta 3677. Phone (057) 223300 Fax (057) 219433

2. RIVER EROSION PROCESSES

The Murray in the study area is a meandering stream with a wide alluvial floodplain. Bank erosion associated with meander processes is to be expected.

European settlement has introduced potential for additional episodes of erosion and bank instability. Likely causes are changed bank conditions, catchment clearing, changes in seasonal flow regimes, headward erosion and removal of bank vegetation.

Prior to selection of survey sites, four major categories of bank erosion were tentatively identified from preliminary observations in the field. (Frankenberg and Tilleard 1990).

- Upper bank fretting apparently associated with wave action during prolonged periods of regulated flows. Fretting can occur on both inside and outside bends, wherever the bank material is susceptible. Within the study reach, fretting is particularly noticeable on unconsolidated deposits of alluvium kept bare by grazing. It was also observed on any bare bank unprotected by vegetation.
- Undermining and collapse associated with meander development and movement. Secondary currents circulating in river bends remove material from the toe of the bank, generally on the outside of the bend, causing undermining and collapse.
- Slumping associated with saturation of the river bank profile, leading to a loss of soil structure. Within the study area, slumping failures are typically associated with saturation of the bank profile by subsurface drainage from the adjacent floodplain, or rapid drawdown of the river level, which leaves the saturated bank unsupported by water in the channel.
- Gradual attrition on bare banks where material is lost from the face of the bank. This causes a continual retreat of the bank, which does not batter back to a stable alignment.

Often individual banks display a combination of processes

3. METHODS

3.1 Selection of sites

Following a general survey of the river banks in the vicinity of Albury-Wodonga, eight sites were chosen for monitoring activities.

The sites represent the range of different bank types within the study area. Considerations included erosion modes, types of bank material, channel alignment (ie. inside/outside of bend), grazing regime, existing vegetation; suitability for vegetative treatment and accessibility for monitoring program.

At the selected monitoring sites two survey datum bases were established where regular detailed measurements could be repeated.

- The 'top-of-bank' survey identifies the location of the top edge of the river bank in three dimensions, relative to a base line.
- Vertical bank profiles were established at several locations along the bank. The bank shape was measured from the top of the bank to below water level.

All survey work was undertaken to Australian Height Datum. Permanent marks have been established to ensure that base lines can be re-established in the future.

3.2 Survey Techniques

Following a review of alternatives for monitoring river bank movement, techniques using electronic distance measurement were adopted. Measurements were taken from the same or the opposite bank of the river, depending on the height and shape of the bank. Surveys were repeated annually, during winter when river levels are low, in the years when funding was available.

Surveys employed to monitor the rate and mechanism of erosion included:

- top of bank surveys at seven of the eight sites; and
- a series of detailed bank profiles at six sites. Sites were pegged so that exactly the same profile was measured each year. A total of 40 profiles have been measured five times, in 1988, 1989, 1992, 1993 and 1994. An additional survey of five profiles at one site was carried out in 1987.

Survey data were processed and stored on computer using the reduction and plotting software "Geocomp".

3.3 Water Level Records

Gauging boards were installed at four of the survey sites, and surveyed to the same datum as the bank profile surveys. The gauges were read regularly, and the results for each site were correlated with the daily gauge readings at Albury or Doctors Point to allow an estimate of daily river levels at each site during the study.

The record of daily river levels at each site has been analysed to give a frequency analysis of river heights. These results have been plotted to the same scale as the river bank profiles to facilitate comparison of the erosion pattern with dominant flow levels.

3.4 Erosion Control Structures.

At one site (Site H) erosion control structures were installed in 1992. These needle groynes were used to enable the establishment of vegetation at the site. Their position was recorded with respect to the profile survey datum.

4. RESULTS

Forty profiles and seven 'top of bank' surveys have been measured at eight sites. A representative selection of these are discussed in this paper. Analysis of the data is not yet complete.

4.1 Top of Bank surveys.

All Top of Bank surveys showed some retreat of the bank during the survey period. The results from representative Sites B, F and H are shown in Table 1 and Figures 2 and 3. Sites F and H were situated on an outside bend and experienced a regular rate of retreat throughout the survey period. Site B, located on an inside bend, also showed a consistent although slightly lesser retreat during the period.

YEAR	*SITE H OUTSIDE BEND AREA*	*RETREAT PER METRE OF BANK* m^2	*SITE B INSIDE BEND AREA*	*RETREAT PER METRE OF BANK* m^2	*SITE F OUTSIDE BEND AREA*	*RETREAT PER METRE OF BANK* m^2
1988						
	15.81	0.25	34.27	0.33	16.03	0.11
1989						
	41.14	0.66	36.44	0.35	85.09	0.60
1992*						
	17.29	0.28	19.21	0.18	65.38	0.46
1993						
	2.7	0.04	2.25	0.02	4.6	0.03
1994						

Table 1. - Top of Bank Surveys - Area of Retreat (Total area and rate per linear metre of bank).
* Three year period (1989 - 1992).

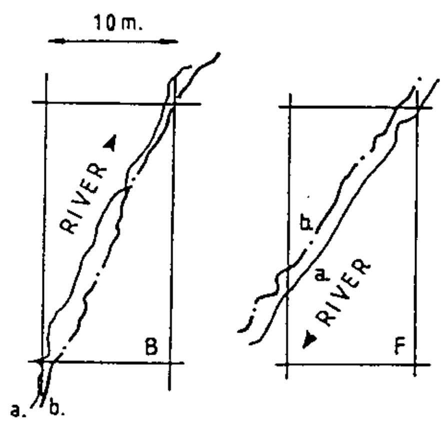

Figure 2. - Top of Bank Surveys, Sites B and F.

Figure 3. shows the results of all surveys at Site C, which was a top of bank site only. This bank is the upstream end of a slight outside bend. It was fenced from grazing in 1984 when trees were planted but by the end of the project was grazed again as the fence was not maintained once the trees gained some height. Two small patches of the Common Reed (Phragmites australis) spread during the fenced period but the extent of the stand was reduced once grazing recommenced. The survey shows a constant rate of retreat, greater at the downstream end, closer to the outside bend.

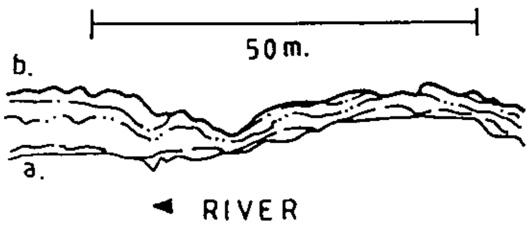

Figure 3. - Top of Bank Survey, Site C. a - Survey details 1988, b - Survey details 1994

4.2 Bank Profiles

The profiles show a consistent pattern of erosion. This can be related to the duration of flow levels, and demonstrates that the steady irrigation supply levels have a significant influence on the erosion pattern and rate.

The un-vegetated banks have a characteristic shape, with a sloping lower bank, a notch at the summer irrigation flow level (noted as HWM on the Figures 4.) and a vertical upper bank. The degree to which the notch will develop before collapse of the upper bank depends on the type of bank material involved. Clay banks will maintain a notch up to 40cm deep before bank collapse, while more sandy sediments suffer more frequent collapse.

To assist in understanding erosion processes the record of daily river levels at each site was analysed to give a frequency analysis of river heights. This allowed plots to be prepared showing the number of days that the river was at each height during the period (Figure 4).

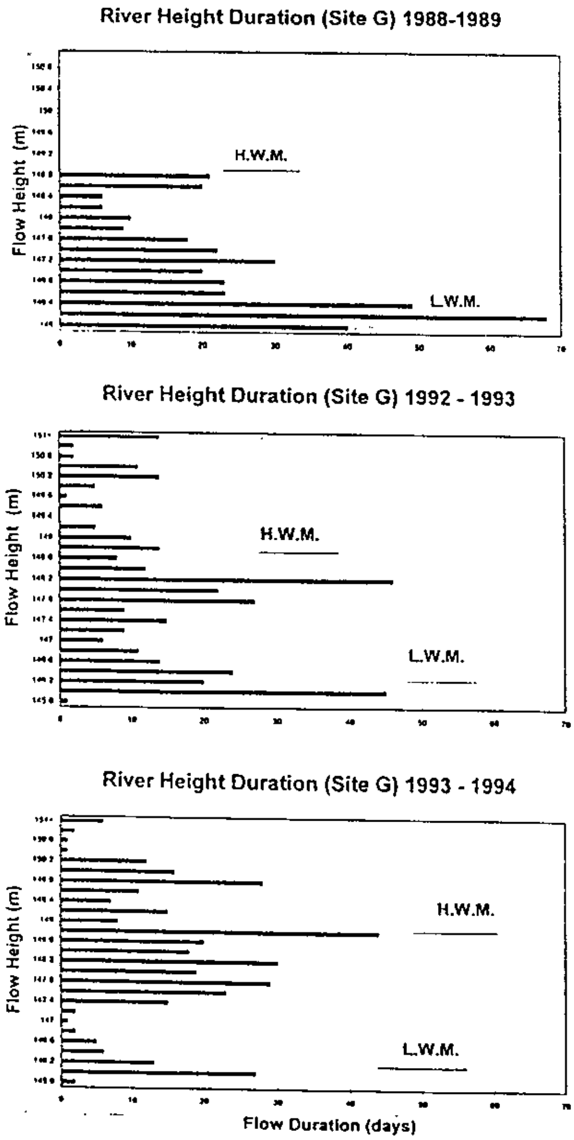

Figure 4. - Examples of River Height Duration Plots (1988/89, 1992/93, and 1993/94)

The profile data document the process of undercutting of the upper bank at the notch, the subsequent collapse of the upper bank, the removal of this material from the lower bank, and the re-instatement of the notch over the next couple of years. This can be seen clearly on the profiles A - C at Site G (Figure 5).

This site is on a slight outside bend just downstream from a 1940's cut-off, with a hard clay bank. The profiles at the upstream end of this Site, (H - J) (not shown) are protected by willows and Phragmites and are closer to an inside bend. Erosion rates on these profiles are less.

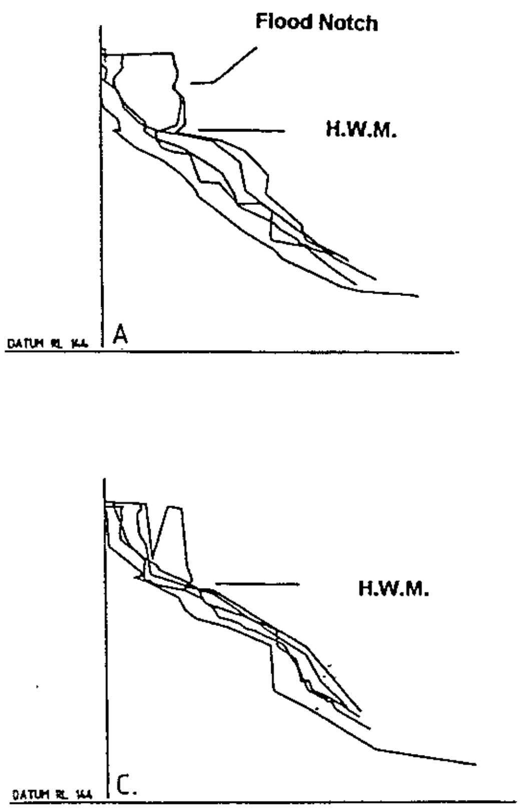

Figure 5. - Site G, Profiles A and C.

Floods cause a change in the pattern described above. The level of the flood can be recognised by a notch higher on the bank, which persists until the original bank shape is reset by the next bank collapse over the irrigation notch. At Site G, the evidence of flood flows prior to the survey in 1988, a notch on the upper bank, persisted for two years until that section collapsed.

An important observation is that on most banks the lower sloping bank consistently moves back, maintaining a constant batter angle. This consistent "parallel bank retreat" on both sides of the river means that the river appears to be widening.

No significant accretion of the bank has been measured at any site to date. On inside bends, the lower bank is very mobile and sand and gravel beds are constantly moving, but there is consistent attrition of the upper bank at the summer flow level.

	Above Maximum Regulated Flow Level		Between Maximum and Estimated Minimum Flow Level		BANK	RETREAT
	CUT AREA m^2	FILL AREA m^2	CUT AREA m^2	FILL AREA m^2	Top of Bank m	Maximum Regulated Flow Level
AVERAGE (per annum)						
Unvegetated Profiles	1.61	0.18	3.71	0.59	1.64	1.16
Vegetated Profiles	0.18	0.32	0.87	0.27	0.19	0.12

Table 2. Erosion Rates of Vegetated and Unvegetated Profiles at Site E.

On banks covered by Phragmites, the profiles have a different shape. The bank tends to be convex, without a notch at irrigation supply level. Accurate profile measurement is more difficult on these banks, but over a period of years, any changes can be detected. The profiles at Site E (Table 2 and Figure 6 and 7), demonstrate the contrast between the bare banks and those partly or wholly covered by Phragmites.

Figures in Table 2 represent the average erosion rates per annum for three vegetated and five unvegetated profiles at the site. A gradual increase in Phragmites cover on Profile C (Figure 8) was reflected by an increasing stability of the upper bank.

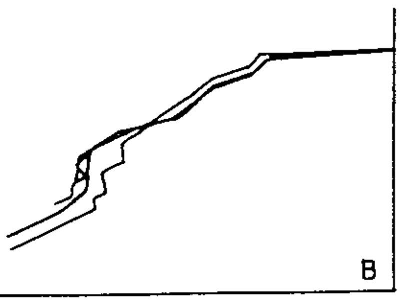

Figure 6. - Site E, Bank Profiles B, Vegetated Bank.

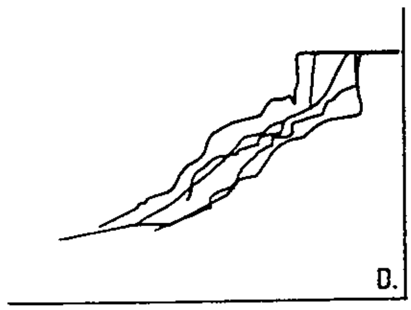

Figure 7. - Site E, Bank Profiles D Unvegetated Bank

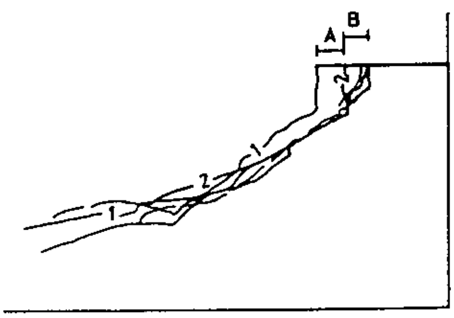

Figure 8 Site E Profile C, Establishment of Phragmites,
A - Bank retreat 1988 to 1989, B - Bank Retreat 1989 to 1994

5. DISCUSSION

The bank profiles show that during the period of the survey there has been a consistent retreat on all unvegetated banks measured. The rate of retreat has varied from site to site and year to year, and is greater at sites on outside bends, as would be expected. However no sites have stable banks, except possibly those which are well covered by Phragmites. On these profiles the bank shape is more difficult to measure accurately, and results are less clear. Unfortunately some of the sites which were fenced from grazing at the beginning of the project did not remain so, and the Phragmites which had begun to thicken and spread at the top of the bank was grazed and weakened by the end of the survey period. Despite this, the erosion rate on the vegetated banks was markedly less than on comparable bare banks (Table 2).

Analysis of the surveys is not yet complete, and relationship between flow and erosion rate cannot be drawn across all sites. It appears that floods can increase the loss of bank material on bare banks, and can cause some slumping of Phragmites covered banks. However the most consistent pattern of erosion shown by the profiles is the loss of material at the regulated flow level, which continually undercuts the upper bank and causes bank collapse. This process can be recognised on every unvegetated bank surveyed. The rate depends on the type of bank material, but the pattern is the same.

It is also apparent from the profiles that this loss from the upper bank is accompanied by a general retreat of the lower bank, so that the angle of the bank remains constant. A battering process which would ultimately reach an angle of equilibrium does not seem to be occuring.

This "parallel bank retreat" appears to be the dominant erosion process. It is the retreat of the sloping section of bank that actually drives the overall bank movement. The notching and subsequent collapse of the upper bank, while visually impressive to casual observation, is not the primary cause of bank retreat. If it were, banks would exhibit extensive upper bank benches, instead of the progressive parallel retreat of the whole bank face.

The complete set of forty bank profiles, each measured five times over a period of six years, represents an invaluable data set. Much is yet to be learnt from further interpretation.

6. ACKNOWLEDGEMENTS

The funding for this research was provided by the Australian Water Resources Advisory Council (now the Land and Water Resources Research and Development Corporation) between 1987 and 1989, and the Murray-Darling Basin Commission through the Natural Resources Management Strategy between 1992 and 1994.

Daily flow data for the study period was provided by the Murray-Darling Basin Commission.

The data manipulation on GEOCOMP was carried out by Geoff Claffey.

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Potential for the restoration of aquatic macrophytes in billabongs

*Ralph Ogden**

ABSTRACT: *Aquatic macrophytes greatly enhance the conservation value of billabongs (floodplain lakes), but many billabongs are devoid of macrophytes. Evidence from the fossil record and a limnological survey suggests a regional decline in macrophytes since the mid 1800's, and supports a hypothesis of 'switching' in the dominance of aquatic macrophytes and phytoplankton. It may be possible (and practical) to switch the plant dominance back to the macrophytes. To do so would involve improving the light conditions for macrophytes by temporarily lowering water levels. Once macrophyte dominated, the billabongs should remain so unless further unnatural perturbations occur.*

1. INTRODUCTION

Aquatic macrophytes are an important component of shallow lakes. They provide substrate for a variety of organisms, contribute enormous amounts of organic matter to food chains, and create diverse physicochemical conditions that often differ markedly from adjacent open-water regions (Carpenter and Lodge 1986; Carignan and Neiff 1992). Besides harbouring large invertebrate communities (Timms and Moss 1984; Cyr and Downing 1988), macrophytes provide protection for small fish, including fish fry (Zaret 1984; Timms and Moss 1984; Nichols 1991), and increase the waterfowl carrying capacity of a lake (Bellrose et al. 1979; Scheffer et al. 1993).

Thousands of shallow floodplain lakes, known as billabongs, fringe the lowland rivers of the south east Murray Basin (Pressey 1986). Most of these are abandoned former river courses or related depressions formed as rivers migrate across their floodplains. Billabongs along river tracts are practically the only natural freshwater lakes found over vast areas of inland Australia, so that their ecology is of special importance.

Aquatic macrophyte cover is highly variable between billabongs; some are choked with vegetation and others are almost entirely devoid of higher plant life. It is noteworthy, though, that most of the large, abandoned channels have little submersed macrophyte cover, in spite of having extensive shallow water regions that seem suitable for the development of beds of submersed plants. Many of these billabongs are fringed by emergent plants such as sedges and rushes, but these provide less structural diversity for aquatic biota than some of the common submersed plants such as *Myriophyllum*, and submersed and emergent plants differ in their effects on billabong limnology (Boon et al. 1990).

The ecological importance of aquatic macrophytes makes factors underlying variation in plant cover of considerable interest, and in particular whether plant cover is affected by land use or other factors that offer management opportunities.

The landscape surrounding the Murray River and its tributaries has changed vastly since settlement in the mid 1800's (Buxton 1974). Farming, mainly the grazing of cattle and sheep, is practised throughout the south east Murray Basin. The Murray River and several of its tributaries have been dammed well up their tracts. Carp are widespread in the river-flood plain system (Shearer and Mulley 1978).

The aim of this paper is to demonstrate the relationship of land use or other human-related impacts (e.g. fish introductions) to regional patterns of aquatic macrophytes. The results are discussed with reference to potential management avenues for the enhancement of submersed aquatic macrophyte cover.

2. STUDY SITES

The study region encompasses the eastern Murray River and the lower Ovens River (figure 1). This region includes stretches of unregulated river (Murray River above the Hume Dam, Ovens River) and regulated river (Murray below the Hume Dam). Farming intensity on the floodplain is variable but generally decreases downstream for both rivers.

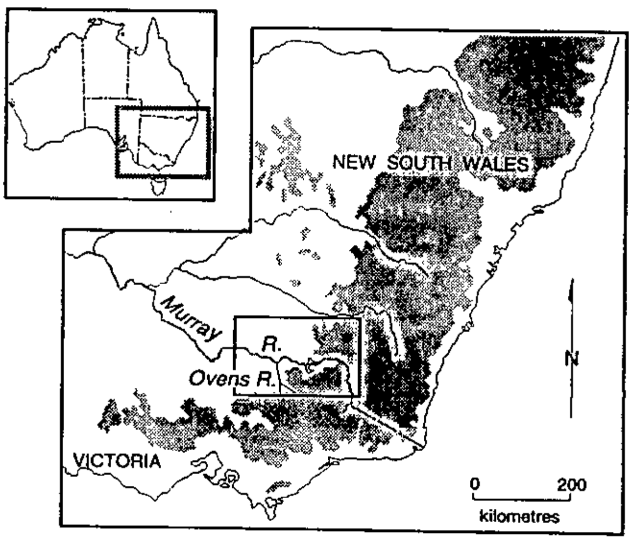

Figure 1. The study region. Stippled area is above 600 m.

*Division of Archaeology and Natural History, RSPAS
Australian National University, Canberra, 0200

site	location	area (ha)	max depth (m)
9	U Murray	3.6	1.5
Hogan's	M Murray	5.4	4
21	Ovens	3.4	1.9
23	Ovens	1.6	2.0
25	Ovens	1.3	1.5
32	L Murray	4.8	3.6
38	L Murray	5.4	3.1

Table 1. General features of billabongs from which sediment cores were obtained. All are either sublinear abandoned channels or cutoff meanders. U, M, and L refer to upper, middle and lower sections of the Murray in the study area.

Forty two billabongs were surveyed for their limnology. Billabongs were selected using a stratified sampling method so that unregulated sites and sites with low farm exposure are adequately represented (Ogden 1996). A strictly random sampling in the study region would be biased towards intensely farmed and regulated billabongs, reflecting the predominance of land use practices in the region. Thirty one billabongs were randomly selected within farming and regulation strata and a further 11 billabongs were added to the survey to bolster the representation of billabongs that are less intensely farmed. Farming intensity was gauged by the density of trees and saplings, and observations of stock, dung, stock trails and billabong bank collapse.

The number of billabongs surveyed on each river reach is 11 on the Murray above the Hume Dam, 8 on the Murray between the Hume and the confluence with the Ovens River, 14 on the Murray below Lake Mulwala, and 9 on the Ovens River.

Sediment from 6 billabongs in the limnological survey and one other billabong were examined for their fossil record (table 1).

3. METHODS

This section provides an outline of the methods used in this study. A more detailed description of the methods is found in Ogden (1996).

3.1 Present day patterns

A 15 month sampling program was undertaken to the correlate physicochemical and plant cover data from each of the 42 billabongs in the survey. Sampling trips were carried out every 2 months starting in January 1992 and finishing in March 1993. Billabongs were not sampled if they were dry or were experiencing a substantial flood.

Macrophyte abundance was visually estimated and a score was recorded corresponding to < 5%, 5-25%, 25-50%, 50-75% or 75-100% plant cover. Maximum depth was recorded and physicochemistry was measured from the deepest point in the billabong, preferably in open water. pH was measured at 1 m depth and 3 integrated samples of the top 2 m of the water column were pooled for chemical analyses. Bicarbonate was measured on site by titration and the remaining measurements (turbidity, major ions, total nitrogen, total phosphorus) were made on stored samples by standard methods.

3.2 Historic patterns

It is possible that pristine control billabongs no longer exist for gauging the impact of land use on macrophytes since farming occurs throughout the region (Walker and Hillman 1977). The relative amount of fossil remains of two families of Cladocera with contrasting habitat preference, Bosminidae which prefers open water, and Chydoridae which are mainly littoral species, is used to estimate the past extent of the littoral zone in the billabongs (cf. Korhola 1992). The percentage of Chydorids in billabong surface sediments has been shown to be positively related to aquatic macrophyte cover estimated as outlined above (Ogden 1996).

A single sediment core recovered from the deepest point in each of seven billabongs was sampled every 20 cm. Three surface sediment samples (top 1 cm) from the profundal zone were also pooled for analysis. The silt fraction, including cladoceran remains, was isolated from dispersed sediments by sieving and the fossils separated from inorganics by running the sample through a water column. The sample was dewatered, put in silicon, and slides prepared. Fossils were counted at 100x magnification. Estimates of percent chydorids are based on 200 - 300 remains.

Billabong sediments deposited after ca. 1870 are differentiated on the basis of the presence of pollen from the introduced tree genus *Pinus*, which has been confirmed as a valid post settlement marker by ^{210}Pb dating in two cores (Ogden 1996). The *Pinus* pollen was isolated in the same manner as Cladoceran remains, and counted using a dissecting microscope.

4. RESULTS AND DISCUSSION

4.1 Historic macrophyte levels

There is a sharp decline in the percentage of chydorids around the first appearance of *Pinus* pollen, in 6 of the 7 sediment cores examined (figure 2; table 2). The timing of the decline is interpreted as ca. 1870 (see above), just after settlement of the region by Europeans.

About half the decrease is due to taphonomic processes; the percentage of chydorid remains in surface sediments is higher than sediments immediately below this in a number of billabongs, including several with very low aquatic macrophyte

site	present day submersed macrophyte cover	depth in profile of first *Pinus* pollen	depth of 'step' decrease in % chydorids	nature of pre settlement record
9	nil	75	between 65 and 45 cm	poorly preserved in parts but macrophyte cover appears to be variable
Hogan's	nil though few observations	95	between 105 and 85 cm	macrophyte cover high throughout
21	some seasonal cover at margins	35	between 45 and 25 cm	poorly preserved
23	extensive cover	25	none: possible decrease at 35 cm not sustained	few sections examined; poor preservation in most of the sections
25	some seasonal cover at margins	55	between 85 and 65 cm	not extensively examined
32	nil	62	between 65 and 55 cm	macrophyte cover high throughout

Table 2. Present-day and historic levels of aquatic macrophytes in 6 billabongs. The 'step decrease' in chydorids corresponds to decreasing macrophyte cover, and the appearance of *Pinus* pollen to European settlement (see text).

cover. Therefore, higher percent chydorid remains do not reflect a recent expansion of macrophyte beds, but relatively less preservation of chydorid than bosminid remains in samples below the surface zone of accumulation.

In spite of historic changes in preservation potential, the fossil cladoceran profiles still indicate a decrease in aquatic macrophyte cover since settlement. Taphonomic processes consistently account for less than 50 % of the decline in percentage chydorids. The remaining decrease is interpreted as indicating a contraction in the extent of aquatic macrophyte beds.

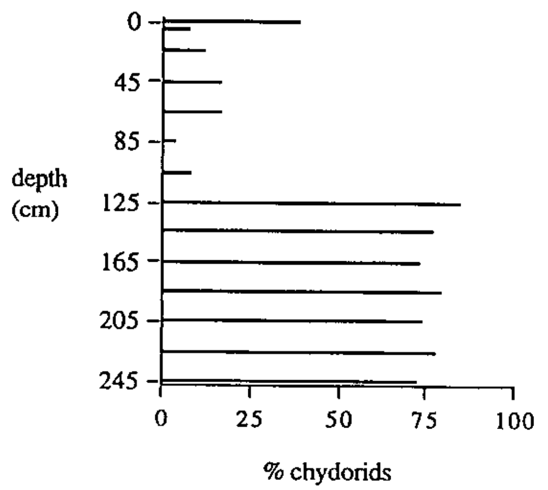

Figure 2. The profile of percent chydorids in a sediment core from site 38. The first appearance of *Pinus* pollen is at 115 cm. Present day macrophyte cover in site 38 is nil. See caption to table 2 and text for explanation.

Supporting this, the one billabong with extensive, persistent macrophyte beds (site 23; table 2) does not show a marked decrease in percentage chydorids. Lower organic inputs to sediments from macrophytes since settlement have increased the oxidation of sediments (Ogden 1996), which has also affected the percentage of chydorid remains preserved.

The historic contraction of macrophyte beds is likely to be related to submersed rather than emergent macrophytes. Present-day billabongs often have a fringe of emergent vegetation but lack submersed macrophyte beds. Much less commonly, both emergent and submersed macrophytes occur. The emergent macrophytes appear to colonised to the same depth in both instances, suggesting that they would not have colonised a greater area in the past. Furthermore, the historic decrease in macrophytes is as apparent in billabongs with fringing emergent macrophytes as ones with more limited development of emergent plants.

It is noteworthy that in cores with continuous preservation of Cladocera, for example cores from sites 32, 38 (figure 2) and Hogan's Billabong, the levels of percent chydorids vary little within either the pre settlement or post settlement period.

The patterns and timing of macrophyte decline are at odds with several theories for explaining macrophyte abundance. The decrease in macrophytes is not gradual enough to invoke succession as the mechanism, and in any case is the opposite pattern to what is expected from succession (Korhola 1992). Carp are clearly not the agent underlying this variation. The major period of carp expansion is in the 1960's (Shearer and Mulley 1978), nearly a century after the decline in macrophytes. Tench (*Tinca tinca*) and Redfin (*Perca fluviatilis*) were introduced during the time period corresponding to the decline in aquatic plants (Weatherly and Lake 1967). However, the comparative effects of these species and native fish on billabong macrophytes are unknown.

River regulation is not responsible since regulation began in the 1930's, which post dates the decline in macrophytes, and the decline also occurs on unregulated sections of floodplain.

Early farming, mainly grazing, was concentrated on the floodplain since alternate water sources did not exist (Williams 1962). Cattle and sheep may have eaten macrophytes or increased turbidity levels in billabongs. Extensive tree clearance in the early days was carried out to provide fuel for riverboats (State Pollution Control Commission 1987). This may have affected billabongs via litter inputs, protection of banks and wind exposure. However, since the grazing and tree clearance on the floodplain have decreased this century (Ogden 1996), why have aquatic macrophytes not recovered to their pre settlement levels of abundance?

The 'step' decrease in chydorids suggests that two alternative stable states (Scheffer et al. 1993) exist for macrophyte cover in billabongs and that the billabongs have 'switched' to phytoplankton dominance in the post settlement period. Rapid switching of shallow lakes between macrophyte dominated, clear water phases and turbid phytoplankton dominated phases has been documented in other parts of the world (Scheffer et al. 1993). In Australia, Douglas-Hill (1995) recently suggested that these two stable states are found in New South Wales farm dams.

Scheffer (1990) and Scheffer et al. (1993) have developed a theory to explain the phenomenon of switching in the dominance of macrophytes and phytoplankton with a number of assumptions and predictions that can be examined in the context of south east Murray Basin billabongs.

4.2 Alternative stable states?

Scheffer (1990) and Scheffer et al. (1993) have proposed that in certain situations it is possible for alternative equilibria between macrophytes and phytoplankton to exist from the same initial lake conditions. The alternative states are stable due to a number of feedback mechanisms. A variety of disturbances may lead to a switch from one stable state to another, but the proximal reason for switching is turbidity (see below).

It appears that the same set of initial conditions has lead to different endpoints of macrophyte cover in the region's billabongs. Conditions in billabongs dominated by macrophytes are only consistently different from phytoplankton dominated sites with respect to water clarity (Ogden 1996). Mean nutrient levels are lower in macrophyte dominated billabongs but medians are not appreciably lower (table 3), suggesting that general levels of nutrient loading are the same but phytoplankton dominated sites have occasional periods of high nutrients. pH is circumneutral in all sites, waters are fresh at all times, and patterns of macrophyte dominance are not correlated with maximum site area (Ogden 1996). However, this conclusion must be tempered by the fact that a number of potentially important factors (e.g. trace elements) were not measured.

The theory of alternative stable states is only applicable to lakes where nutrient limitation of macrophytes is not a primary factor (Scheffer 1990). Nitrogen and phosphorus often limit plant growth but this is almost certainly not the case in the regions billabongs. Average annual levels of nitrogen and phosphorus in the billabongs surveyed are eutrophic by OECD standards (table 3 and Ogden 1996; Rast et al. 1989).

Another assumption is that sections of the water column in the shallow lakes are at or near a critical light level for photosynthesis to take place (Scheffer et al. 1993). The euphotic depth of the regions billabongs was not measured in the limnological survey but can be roughly estimated from the levels of turbidity and secchi depths observed (table 4). The precision of such estimates is poor (Kirk 1994) but adequate enough to indicate that the regions billabongs have euphotic depths near to maximum site depth, as was found for Ryans 1 billabong in the centre of the field area (Oliver 1990, table 4).

Alternate equilibria should only be found in shallow, relatively even-bottomed lakes (Scheffer 1990). In such lakes, normal fluctuations in turbidity will prevent photosynthesis in a relatively large section of the water column since turbidity levels are already near critical levels for photosynthesis. At some point, as turbidity levels increase, a catastrophic decline in macrophytes will occur since nearly all of

site	total N mg/l			total P mg/l		
	med	mean	max	med	mean	max
1	.42	.52	1.11	.05	.11	.42
5	1.40	1.28	1.60	.14	.14	.25
6	1.15	1.17	1.48	.09	.13	.42
7a	.45	.61	1.40	.09	.19	.62
22	1.20	1.41	2.80	.13	.14	.23
23	.97	.99	1.40	.09	.13	.32
all 42 sites:	1.36	2.05	19.6	.16	.30	5.2

Table 3. Levels of total nitrogen and total phosphorus in well vegetated sites and all sites in the limnological survey.

	mean depth (m)	turbid. (NTU)	mean secchi depth (m)	Z_{eu} (m)	Z_{col} (m)
this study:					
42 sites	1.6	34 (mean)	.44		1.1 (T) 1.3 (S)
Oliver 1990:					
Ryans1		5 - 12		.9-2.3	1 - 2
Ryans2		7 - 90			.2 - 2

Table 4. The light environment in the regions billabongs. Z_{eu} is euphotic depth and Z_{col} is potential depth of colonisation by macrophytes (Kirk 1994). (T) and (S) are estimates based on turbidity and secchi depth, respectively.

the macrophytes occupy the same position in the water column. Once the majority of the water column is only habitable by phytoplankton, feedback mechanisms help stabilise this state. In deeper lakes with gradually sloping basins, the relative area that can be colonised by macrophytes does not change as drastically as turbidity levels increase, and the decline in macrophytes is more linear with increasing turbidity levels.

The billabongs with the clearest evidence of switching (sites 32, 38, Hogan's Billabong) are the deepest billabongs examined for their historic plant cover, but are also the largest sites and probably have the most gently sloping bottoms. The billabongs in the survey that are macrophyte dominated mainly seem to fall into two groups: shallow sites and deep sites that have fairly steeply sloping basins, which supports Scheffer's hypothesis.

The patterns of aquatic macrophytes in the region are consistent with the theory of alternative stable states. Such evidence cannot be construed as proof that switching is the dominant mechanism in billabongs, but stands as a useful starting point for management initiatives and a hypothesis for further research.

4.3 Restoration of macrophytes

The restoration of aquatic macrophytes in billabongs is desirable because of their ecological importance. Very shallow billabongs tend to be macrophyte dominated, but are generally ephemeral and poor habitat for longer lived species such as fish (cf. Bonetto et al. 1969). This discussion is therefore restricted to consideration of deep water billabongs.

Attempts at the restoration of aquatic macrophytes in billabongs previously dominated by phytoplankton has been successful in a number of instances (Moss 1990; Hosper and Jagtman 1990). A variety of methods have been employed, but several general trends are apparent that have differing applicability to billabongs.

A reduction of nutrient loadings is, depending on nutrient levels, necessary or helpful if macrophytes are to be restored (Jeppesen et al. 1990; Moss 1990; Scheffer 1990). However, a reduction in nutrient loadings is probably not required in this situation since there are deep billabongs in the region that are macrophyte dominated which are about as nutrient rich as phytoplankton dominated billabongs (table 3). Jeppesen et al. (1990) also found lakes the size of billabongs remained macrophyte dominated at phosphorus levels encountered in this study. In any case, nutrient reduction is probably not feasible in the shorter term due to the extensive use of fertilisers in the region and the diffuse source of nutrients carried by floods.

Food web manipulations have successfully restored macrophytes by encouraging the growth of large bodied Cladocera (e.g. *Daphnia*) which effectively keep phytoplankton populations in check (Moss 1990). These often involve introducing a piscovore, which puts pressure on planktivorous fish, releasing the populations of *Daphnia* from predator control. However, piscovores undoubtedly gain access to billabongs during floods and if they have not reduced the populations of planktivorous fish already there is no reason to believe artificial introductions will have any more success. Nevertheless, the emplacement of artificial shelters for *Daphnia* is one possible way that their populations may be encouraged (Moss 1990; but see Irvine et al. 1990).

With respect to restoration by food web manipulations, it is noteworthy that the only human related impact other than farming and tree clearance that corresponds to the timing of the decline in macrophytes is the introduction of Tench and Redfin. It would be interesting to know if these fish directly or indirectly affect *Daphnia* abundance differently than native planktivores. If so, the abundance of these exotic fish may have to be taken into account in the restoration of aquatic macrophytes.

Perhaps the most promising method involves directly improving the light environment for macrophytes. This can be achieved by temporarily lowering water levels (Scheffer et al. 1993). Currently, low water in billabongs corresponds to the late summer and winter during macrophyte senescence, and high water to the spring when maximum growth of macrophytes occurs, which is the opposite of what is desired to restore macrophytes (Ogden 1996). Water could be pumped out during the spring so that macrophytes receive maximum sunlight during their growth phase. Once restored, the macrophyte beds should be stable unless another unusual disturbance occurs, so that ongoing water level manipulations are not required.

The billabongs chosen for restoration should be as remote from farm activities as possible and have a good cover of trees to faithfully recreate the pre-settlement conditions. They should be isolated from large-scale water level fluctuations that characterise billabongs with connections to the Murray River during irrigation flows (Pressey 1986; Ogden 1996). Seeding with plant propagules is desirable, and the abundance of carp may have to be taken into account.

5. CONCLUSION

The evidence presented above lends support to the hypothesis by Scheffer et al. (1993) that two alternative stable states exist in the billabongs; one that is macrophyte dominated, and one that is phytoplankton dominated. Phytoplankton currently dominate most of the large, deep billabongs in the study region. The restoration of aquatic macrophytes is desirable in light of their ecological importance, and it may be possible to switch billabongs from phytoplankton dominance back to macrophyte dominance. Projects that aim to restore aquatic macrophytes in the regions deeper billabongs offer a good opportunity to meld management and science. The process of the restoration of macrophytes can be used as an experiment to test the general hypothesis of alternate stable states and uncover the mechanisms involved.

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Hydrological impact of water use and regulation in the Barwon - Darling River

*Neeraj Maini * and Hugh Cross**

ABSTRACT: *The flow regime of the Barwon-Darling River has changed markedly over the last century, and especially the last 30 years, through construction of weirs, regulation of streams upstream and a continued increase in water abstractions. A model developed by the Hydrology Unit, Water Resources, of NSW Department of Land and Water Conservation was used to compare simulated natural flows at five stations with simulated current conditions which corresponds to irrigation development in 1993/94. New and infrequently used hydrological methods are developed to analyse the impact of water abstraction on the riverine environment. Water Resource development has significantly reduced daily and annual volumes of flow. Increases in rates of fall, or a steepening of the recession limb of flood hydrographs, have occurred for events that occupy up to 50% of river channel capacity. Further, the frequency and size of in-stream flood flows have been significantly reduced at all stations. These hydrological changes have had a profound impact on ecology and the long term utility of the river as a resource.*

I. INTRODUCTION

The Barwon-Darling River is a large low land river draining most of the semi-arid inland of NSW north of the Lachlan valley, and southern inland Queensland up to Charlesville (Figure 1). Despite the river and its tributaries draining an area of 650,000 square kilometres, the Darling contributes, on average, less than 10% of the mean annual flow of the Murray River at Wentworth. Climatic variability, especially rainfall, is a feature of the catchment with occasional periods of intense rainfall over much of the catchment interposed by periods of long drought. This is reflected in long term variations in mean annual flow volumes at Bourke which can range from 6.34 % to 286 %.

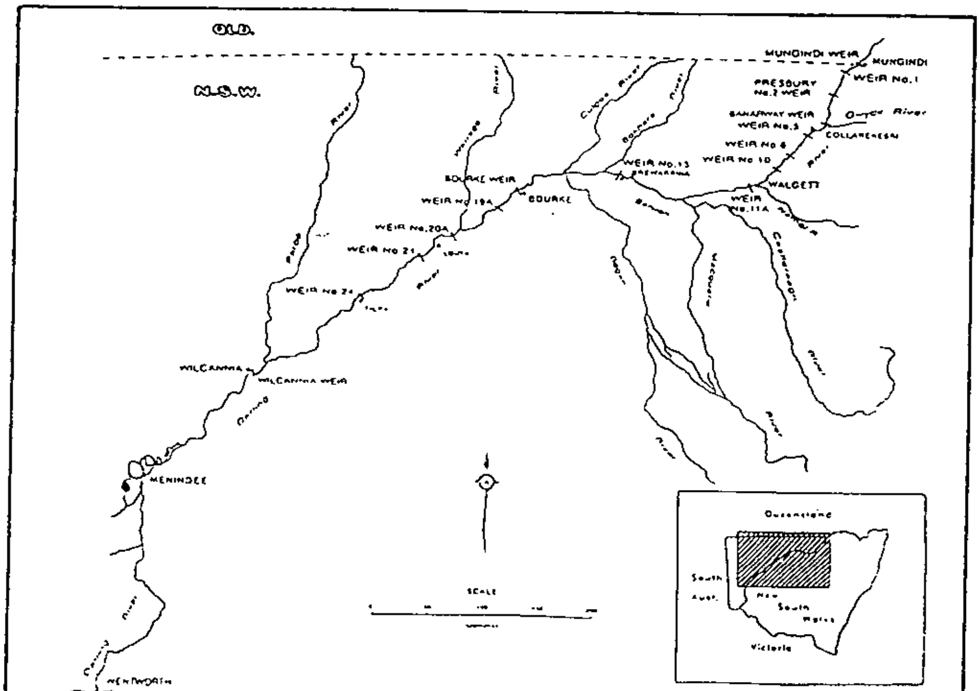

Figure 1 The Study Area Barwon-Darling River System

* *Ecological Services Unit, Water Resources, NSW Department of Land and Water Conservation, P.O Box 3720 Parramatta 2124. Telephone: (02) 895 7471 Fax: (02) 895 7867*

The purpose of this paper is to analyse the change in specific hydrological variables that have resulted from flow regulation and water use. These results were used by the Barwon-Darling Expert Panel to investigate changes to the flow regime and assumed linkages with ecological and geomorphological processes (Cross *et al.* (in press) ; Thoms *et al.*, (in press)). The approach differs substantially from that used in the study of six regulated rivers of the Murray-Darling Basin by NSW Fisheries and the former NSW Department of Water Resources (Swales and Harris, 1995).

The study area covered the unregulated section of the Barwon-Darling River, from Mungindi at the Queensland border, to the upstream end of Lake Wetherill at Menindee. The Barwon-Darling River upstream of Menindee is highly impacted by water extraction, both from regulation of upstream tributaries and from pumping of unregulated flows along the river. For example, the median monthly flow at Mungindi is now only 40% of its natural value. Seventeen weirs constructed between Mungindi and Menindee over the past 100 years which now impound about 40% of the length of the river in this reach. The resulting changes in the flow regime from all these changes has significantly contributed to in-stream environmental deterioration reflected in declining fish populations (Harris, 1992) and an increase in the frequency and severity of algal blooms, especially blue-green blooms (Blue-Green Algal Task Force, 1992).

2. METHODS

To analyse the impacts of water abstraction on the riverine environment we have used new and infrequently used hydrologic "tools". In particular, the frequency, duration and recession limb slope of individual flow events appeared from the panel's assessment to be critical to ecological functioning. Water resource elements having an influence on ecosystem components (fish, invertebrates, macrophytes, trees and geomorphology) were identified as: total discharge; flood frequency; frequency of drought; flow duration; seasonality; velocity; frequency of stage height variation and rate of rise and fall. Hydrological data were analysed for annual and mean daily volumes, peak flows, duration of flows, event duration and rate of rise and fall. The panel conducted their own analysis of the frequency of stage height variations in a separate study.

Simulated data were used for five key sites along the river at Mungindi, Collarenebri, Walgett, Bourke and Wilcannia. Simulated data for pre- and post development (natural and current) conditions between 1966 and 1992 were obtained from output of NSW Department of Land and Water Conservation's Integrated Quantity/Quality Model (IQQM). The IQQM is a daily time step, generic river basin flow simulation package and was configured to simulate different processes and water management rules in the Barwon-Darling system (Black et al., in press). Simulated natural (ie. pre development) data refers to flows in the river in its natural state without any regulation or abstraction, and the simulated current (ie. post development) data refers to water resource development conditions existing during 1993/94.

The following methods were used in the assessment of hydrological changes in the River system:

2.1 Flow Duration Curve (FDC) Analysis

FDC analysis was performed to compare the percentage of time during which specified discharges were equalled or exceeded in simulated current and natural conditions. Monthly flow duration curves are derived by simply ranking the daily flows from all the months of that particular month, and extracting the flow values corresponding to exceedence values of 1%, 2%, 3%-------98%, 99%. This approach was used to derive monthly FDCs for all months from simulated flow data (1966 to 1992) under current and natural conditions. The major limitation of these curves is that they do not give any indication of the length of individual events. The percentile values plotted were selected by the panel to represent the range of most commonly occurring flows, that is low flows.

2.2 Flood Frequency

Flood frequency analysis is based on the annual exceedence series (Chow, 1964). It would be, in fact, more appropriate to use partial-duration series. For instance, in this series the recurrence interval is the average interval between floods of a given size regardless of their relation to the year or any other period of time. But in the annual series the recurrence interval is the average interval in which a flood of given size will recur as an annual maximum. Modelled data for the period 1966-1992 was used for this analysis.

2.3 Flow Exceedence Frequency Duration Analysis

The flow exceedence frequency duration is derived by scanning the daily flow record and noting the number of times and the length of period during which the streamflow exceeds the four given thresholds (ie. 80%, 50%, 25%, 10%) of mean daily natural flow recognised by the Panel as important in-channel threshold flows. These frequencies are then accumulated to provide information on the number of times that the flow exceeded the given thresholds for periods of 10 day intervals 1 - 10, 10 - 20, 20 - 30,----------,190 - 200 days and greater than 200 days.

2.4 Rates of fall and rise

This analysis attempts to quantify any changes in slope of the rising and the falling limbs of individual flow event hydrographs. Simulated data for the period (1966-1992) were used for this analysis.

2.4.1 Rates of fall

The number of days for which daily discharge dropped by greater than 100, 500 and 1000 ML/D from the preceding days was calculated for various flow ranges. These flow ranges were selected by the expert panel on the basis of surmised interactions between river flows and geomorphic processes. The percentage occurrence of discharge dropping by more than the nominated rates of flows in each range, was determined by dividing the number of days flow dropped by more than 100, 500 and 1000 ML/D by the total number of days that the flow dropped within that range.

2.4.2 Rates of rise

The rates of rise were calculated in a similar manner to the rate of fall for nominated daily changes up to 500, 1000 and >2000 ML/D for all flow events at Bourke. Flows were not directed into the flow ranges used for the falling limb analysis due to the panel's conclusion that ecological and geomorphic processes are less sensitive to changes in the slope of the rising limb.

3. RESULTS AND DISCUSSION

The results presented in this paper have been limited to Bourke for some analysis due to space constraints.

3.1 Flow Durations

Table 1 shows discharges for 80, 50, 25 and 10 percentile flows at each site. Figure 2 gives flow exceedence values for all months at Bourke. This analyses demonstrates that in all months simulated current FDCs for all five stations are below the simulated natural curves except for the 97th to 100th percentile flows which are now higher. This indicates an overall reduction in total flow value and the cumulative duration at all but the very lowest flows in the Barwon-Darling River. The difference is more noticeable for larger flows that occur less than 25 percent of the time. Seasonal variability is also seen by a reduction in flow durations which are more prominent during the summer months, corresponding to higher water demand in summers. This shows that current conditions are affecting seasonal distribution (magnitude of flows in different seasons during a year) and 'seasonality' (the relative variation of flows from one season to the next).

3.2 Flow Exceedence Frequency Duration

Results are reproduced in Table 2 as the ratio of the number of simulated current and natural flows events exceeding threshold levels. The percentage of natural events exceeding each flow threshold for different durations were also calculated. The duration ratios for the 80th and 10th percentile flows are presented in Table 3.

Table 1: Flow duration analysis (simulated data ; 1966-1992)

Station	Discharge in ML/D for different flow percentiles							
	10%		25%		50%		80%	
	Natural	Current	Natural	Current	Natural	Current	Natural	Current
Mungindi	5250	3250	2250	1000	510	340	110	70
Collarenebri	8750	6250	3250	1500	720	550	180	160
Walgett	14500	9000	5500	2250	1390	590	370	200
Bourke	24500	20000	9750	5500	2930	1350	780	510
Wilcannia	25250	21000	10500	6000	2600	670	500	240

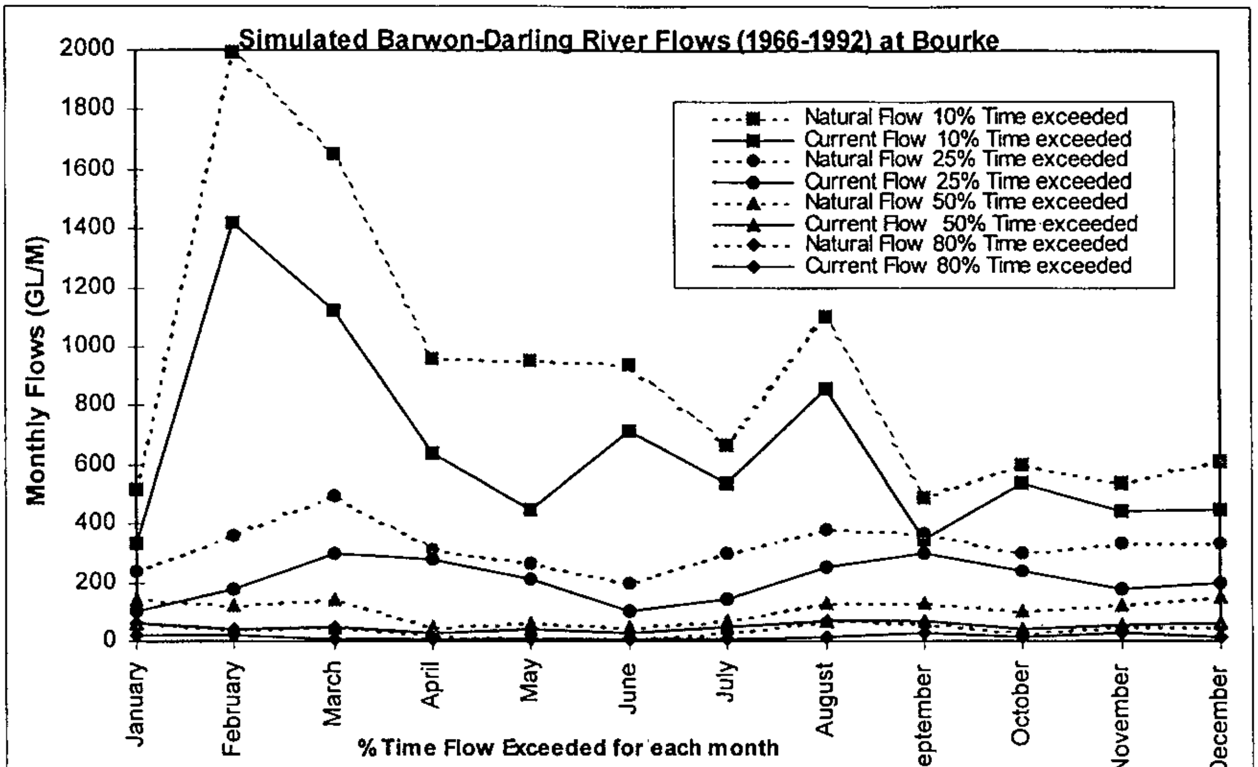

Figure 2: Flow exceedence values by month (Monthly Volumes)

Table 2: Ratio of the number of simulated current and natural flows

Station	The number of events exceeding the following flow percentiles (expressed as a ratio of simulated current: natural)			
	80 th	50 th	25 th	10 th
Mungindi	2.13	1.88	0.63	0.71
Collarenebri	1.16	1.19	0.88	0.74
Walgett	1.47	0.88	0.63	0.72
Bourke	1.29	1.57	0.78	0.97
Wilcannia	1.40	0.60	0.71	0.81

Table 3: Duration ratios for the 80th and 10th percentile flows.

Station	The number of events with the following durations (expressed as a ratio of simulated current: natural)									
	1-10 days		11-20 days		21-30 days		31-40 days		----->120 days	
	80th	10th	80th	10th	80th	10th	80th	10th	80th	10th
Mungindi	2.62	**0.69**	3.89	**0.72**	1.28	**0.70**	4.50	**1.00**	0.61	**0***
Collarenebri	1.25	**0.68**	1.23	**0.57**	1.60	**0.82**	0.80	**1.50**	2.43	**0***
Walgett	1.46	**0.92**	1.83	**0.60**	3.60	**0.50**	0.50	**1.00**	0.70	**0***
Bourke	1.44	**0.66**	2.00	**1.20**	1.83	**0.66**	0.37	**0.86**	0.82	**0***
Wilcannia	2.00	**2.00**	1.60	**0.25**	8.00	**3.00**	0.70	**0.50**	0.66	**0***

* No events greater than 120 days

Table 2 shows that the frequency of events exceeding higher flows (ie. 25th and 10th) is less than natural by up to about 35%. This is consistent with the reduced flow durations under current conditions for same thresholds observed using the FDC analysis (Table 1).

The lower flow events (ie. 80th and 50th percentiles) display a contrary trend, ie. they have increased in frequency despite the FDC analysis showing an overall decline in flow duration under current conditions for all flows. The apparent contradiction is a result of fragmentation of events under current conditions relative to natural conditions, ie. single large events have been broken up into a number of smaller events that intersect the flow thresholds more frequently but for less total time.

The duration analysis of each threshold exceedence shown in Table 3 indicates that the greatest changes have taken place for events of 30 days duration or less, for 80th percentile flows these changes have been positive, whilst for higher flows (ie. 10th Percentile) the frequency has decreased. Longer duration events generally correspond to higher flows which have been less impacted by flow regulation.

3.3 Flood Frequencies

Table 4 shows changes in flood flows for various average annual recurrence intervals at Bourke. Flood flows up to the 5-10 year return interval have been significantly reduced at all stations under current conditions. Reductions generally decrease with an increase in the average return interval. The size of flood flows and reduction in their frequency are greatest at Bourke. This shows that water resource development has reduced the frequency and size of in-stream flood flows in the Barwon-Darling River system, up to events of about 1 in 10 years average recurrence interval.

Table 4: Changes in flood flows for different ARI at Bourke

ARI (years)	Natural	Current	% Change
1 in1	18,000	10,000	-44.00
1 in 2	30,000	20,000	-33.30
1 in 5	110,000	70,000	-36.40
1 in 10	180,000	180,000	0
1 in 20	200,000	200,000	0

3.4 Rates of fall

A comparison of the number of days the river fell by nominated rates of flow at Bourke is presented in Table 5. Comparing the two indicates whilst number of events have fallen considerably the relative proportion of steep events to total number of falling days has remained almost the same. This is further confirmation of the fact that the significant reduction in flows has been achieved without any significant change in rate of fall.

3.5 Rates of rise

At Bourke the rates of rise (Table 6) in daily flows have generally decreased under current conditions. A reduction in flows upstream will have tendency to reduce rate of rise (and fall) at downstream locations due to channel routing effects. Under certain circumstances this effect could be compounded by progressive increase in pumping rates during the rising limb along the Barwon-Darling River.

Table 5: Frequency of days exceeding nominated rates of daily reduction in discharge at Bourke. The number of days and the percentage of occurrence are given.

Number of days exceeding nominated rates of fall at Bourke at each flow stage								
Nominated rates of fall	0 - 1000 ML/D Natural	Current	1000 - 3000 ML/D Natural	Current	3000 - 10,000 ML/D Natural	Current	10000 - 30,000 ML/D Natural	Current
> 100 ML/D	30 (13%)	83 (7.9%)	235 (62.5%)	284 (58%)	586 (94.5%)	329 (81%)	333 (96.3%)	243 (91.4%)
> 500 ML/D	0	7 (0.7%)	5 (1.4%)	30 (6.2%)	134 (21.6%)	136 (33.5%)	211 (61%)	193 (72.6%)
> 1000 ML/D	0	3 (0.3%)	0	4 (0.8%)	36 (5.8%)	49 (12.1%)	105 (30.4%)	132 (49.6%)

Table 6: Number of days exceeding nominated rates of daily increases in discharge (ML/D) at Bourke:

Nominated rate of increase in daily flow	Number of days (simulated data 1966-1992) Natural conditions	Current conditions
Up to 500 ML/D	2876	3174
500 - 1000 ML/D	656	472
> 2000 ML/D	291	234

4. CONCLUSIONS

The analysis shows that daily flows have been significantly reduced for flows having an average annual recurrence intervals less than about 1:10 years and that this reduction is greatest for flows in the 25 to 50th percentile flow range. For example, at Bourke these flows which equate to 9750 and 2930 ML/D respectively, have been reduced on an average by 56% to 46% respectively. Although the changes has been less dramatic for flows less than the 50% flow on a cumulative basis, the effect on individual flow events has been to fragment larger events into smaller ones with respect to the flow thresholds. This has led to a reduction in the duration of individual flow events even though the total number of events is generally now greater.

The Barwon-Darling Expert Panel have addressed the ecological and geomorphological significance in detail (Thoms *et al.*, in press). The analysis of the above results by the Panel, together with other data, such as, water quality, fish and field observations, indicates that the reduction in peak flows and flow fragmentation are likely to have contributed substantially to the observed deterioration in river health. These impacts occur via direct (first order) effects on biota such as via velocity and depth and also via indirect (second and third order) effects. The latter occur by ecological changes to processes, such as changes in competition or predation, and through geomorphic and structural habitat changes.

The rate of fall analysis does not seem to conclude that the observed hydrological changes are likely to increase bank erosion arising from more rapid or frequent steep drawdown in river flows. However, similar more powerful analysis might be performed using stage-height data which may more directly reflect the relevant mechanism of bank erosion by mass failure. It may also be appropriate to repeat the above analysis using shorter or longer time scales than the daily rates used here.

5. ACKNOWLEDGMENTS

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The Importance of Channel Complexity for Ecosystem Processing: An example of the Barwon-Darling River.

M.C Thoms[1] *and F Sheldon*[2]

ABSTRACT: Interactions between flow, channel morphology and the retention of organic matter in the Darling River are outlined. Data from a preliminary study indicate the presence of in-channel horizontal surfaces, at various elevations, influence organic matter accumulation and retention within the channel. Each morphological feature is associated with a specific flow band. Flow regime changes in the Darling Basin, via flow regulation and diversions, is indicated to have the potential to: reduce in-channel habitat complexity which leads to a decrease in the quantity of organic matter trapped; and, thus a reduction in the quantity and quality of organic matter available as a food source for aquatic organisms.

INTRODUCTION

River channels in semi-arid environments are often characterised by highly variable or compound cross-sectional shapes (Graf, 1987). Compound channels generally have several modes of operation: a high flow channel or 'trough', shaped by high magnitude, low frequency flood events and a series of lower flow channels within the larger 'trough'; which represent adjustments to a highly variable hydrological and sedimentological regime (Thoms and Walker, 1993). Prolonged flows at different levels within the larger 'trough', which have the ability to erode and transport sediment, shape the cross section to form a series of inset low flow channels. Compound channels have also been reported by Graf (1987) to occupy a single meandering channel at low flow whilst having a wider 'braided' channel at high flow. This low flow meandering channel is nested inside the larger braided component. Complex cross sectional morphology is a response to highly variable hydrological and sediment transport regimes; a feature of semi-arid river systems (Davis et al, 1994).

Discharge and channel complexity are known to influence the ability of a lotic (river) system to retain and process organic material (c/f. Speaker *et al.*, 1992; Sandon *et al.*, 1992). The retention and processing of allochthonous organic matter is important in structuring aquatic assemblages (cf. Rounick & Winterbourn, 1986; Cummins *et al.* 1984; Prochazka, 1991) as it provides a complex habitat and a vital food source. In small, low-order, temperate streams which experience regular overbank flows a large proportion of the allochthonous organic biomass enter river channels from the surrounding floodplain environment. However, floodplain inundation in semi-arid river systems does not occur as frequently (Walker et al 1995). Thus, in-channel features are relatively more important for ecological processes. In-channel features, such as concave benches act as minor floodplains; in the sense that they increase the habitat complexity of the main channel, provide surfaces for organic matter accumulation, retention and transformation, and promote invertebrate colonisation and productivity (Sheldon and Thoms, 1995).

The effects of riverine and water management are catastrophic for semi-arid riverine ecosystems. Semi-arid systems are adapted to highly variable flow and sediment regimes and complex habitat structure (channel morphology). Channel maintenance activities and flow regulation often reduces this natural variability. In the River Murray for example, flow patterns have been fundamentally altered with a five fold reduction in the frequency of monthly flows and an increase in flows maintained at or near bankfull capacity (Thoms and Walker, 1993). Moreover, decades of snag removal has significantly reduced available habitat for native fish (Lawrence, 1988). Effective management of these systems requires the recognition and acknowledgment of the importance of the inherent variability of these systems.

This paper presents the preliminary results of an investigation into the importance of in-channel complexity for ecological processes in the Barwon-Darling River, a major semi-arid river system in central Australia.

STUDY AREA

The Barwon-Darling catchment (650 000 km2) drains the inland slopes of the Eastern Highlands of Australia (Figure 1) and spans 11 degrees of latitude and longitude. The headwaters of the major tributaries of the catchment originate in south-east Queensland and flow inland in a south-westerly direction before joining the Murray River, near Wentworth. It is subject to a vari-

[1] School of Natural and Environmental Science, University of Canberra
[2] Department of Zoology, University of Adelaide

ety of climates, but most of the rainfall occurs in a small part of the catchment; average annual rainfall and evaporation ranges from 200-1000 mm and 500 and 1800 mm respectively.

The Barwon-Darling catchment is arid to semi-arid with significant areas contributing no runoff. Mean annual runoff is derived from less than 10 percent of the catchment and only less than 3 percent of average annual rainfall (MDBMC, 1987). Flow variability is a feature of the Barwon-Darling River. Long term variations in average annual flow for selected stations throughout the basin range from 0.04 percent to 911 percent (MDBMC, 1987). In general, discharges for the major rivers in the basin are highly skewed with a large proportion of average flows occurring in very wet years and during major floods. In-channel flows in the Barwon-Darling system are important with over 90% of all flows retained within the main channel (Walker, 1992).

Secular changes in the catchment's hydrological regime further influence natural flow variability. It has been demonstrated that the hydrological regime of the period 1900-1946 differs from the preceding and succeeding periods (Riley, 1988). Periods prior to the 1900s and that from the mid 1940s have been wetter and hence have produced greater runoff than the period 1900 to 1945.

Regulating structures, notably headwater dams and weirs, and water diversions have had a large impact on the flow regime of the Barwon-Darling. The median monthly flow at Mungindi and Menindee, for example, is now only 40 and 50 percent, respectively, of its natural value.

The Barwon-Darling is a suspended load river; it is deep, highly sinuous and has a 'complex' river channel cross section (see Woodyer, 1968; Woodyer *et al.*, 1977; Riley and Taylor, 1978). Similar complex channels have been reported along the lower River Murray in South Australia by Thoms and Walker (1993).

THE APPROACH

Two reaches were chosen along the Barwon-Darling River. An 'unregulated' reach at Culpaulin Station, downstream of Wilcannia and a 'regulated' reach at Studley Station downstream from Pooncarie. A series of cross sections from each reach were surveyed, to AHD (Australian Height Datum), to investigate the presence of in-channel morphological structures and assess in-channel complexity.

At selected sites within each reach the extent of organic matter accumulation within the channel was investigated. Coarse organic matter (CPOM - >2mm) and the percent organic content of the <2mm fraction were determined from material collected from the surfaces of various in-channel morphological features. Ten samples were collected randomly from each surface feature using a 25 cm2 quadrat. Sediment in each quadrat was sampled to a depth of 5 cm and returned to the laboratory for processing. Material was collected from both the vertical and corresponding horizontal surface of each feature and processed according to the methods outlined by Aloi (1990). Differences in the weight of CPOM and the percent organic content between the surfaces of each identified in-channel feature were explored using the Mann-Whitney U test.

RESULTS AND DISCUSSION

1. In-channel habitat complexity

A series of cross sections from the two reaches are illustrated in Figure 2. A notable feature of the unregulated reach cross sections are five distinct morphological features located at different elevations within the channel. Identification of these horizontal features was largely a matter of subjective field assessment along with the verification of the morphometric index employed by Riley (1975). Not all the morphological features were present on any one cross section, although all five were present within the unregulated reach.

There are a lack of in-channel morphological features in the 'regulated' reach of the Darling River in comparison to the 'unregulated' reach. Cross-sections of the Darling River near Pooncarrie depict the channel as being relatively shallower with few horizontal in-channel features present compared to that near Wilcannia (cf. Figure 2). The cross sections indicate the presence of features at relatively high elevations in the channel (ie, Level 1 and 2 features) but features at relatively lower elevations (Level 3, 4 and 5) appear to be absent. Old photographs of the river, taken at the turn of century near Pooncarrie do show the presence of many morphological features, at various levels within the channel, which may suggest a once complex cross-section.

Bank erosion is common in highly regulated rivers. Rates of bank retreat in excess of 1.5 metres a year have been recorded in the regulated sections of the River Murray (Thoms and Walker, 1989). In the Murray most of this retreat occurs following rapid falls in water level. For example, water levels may drop by

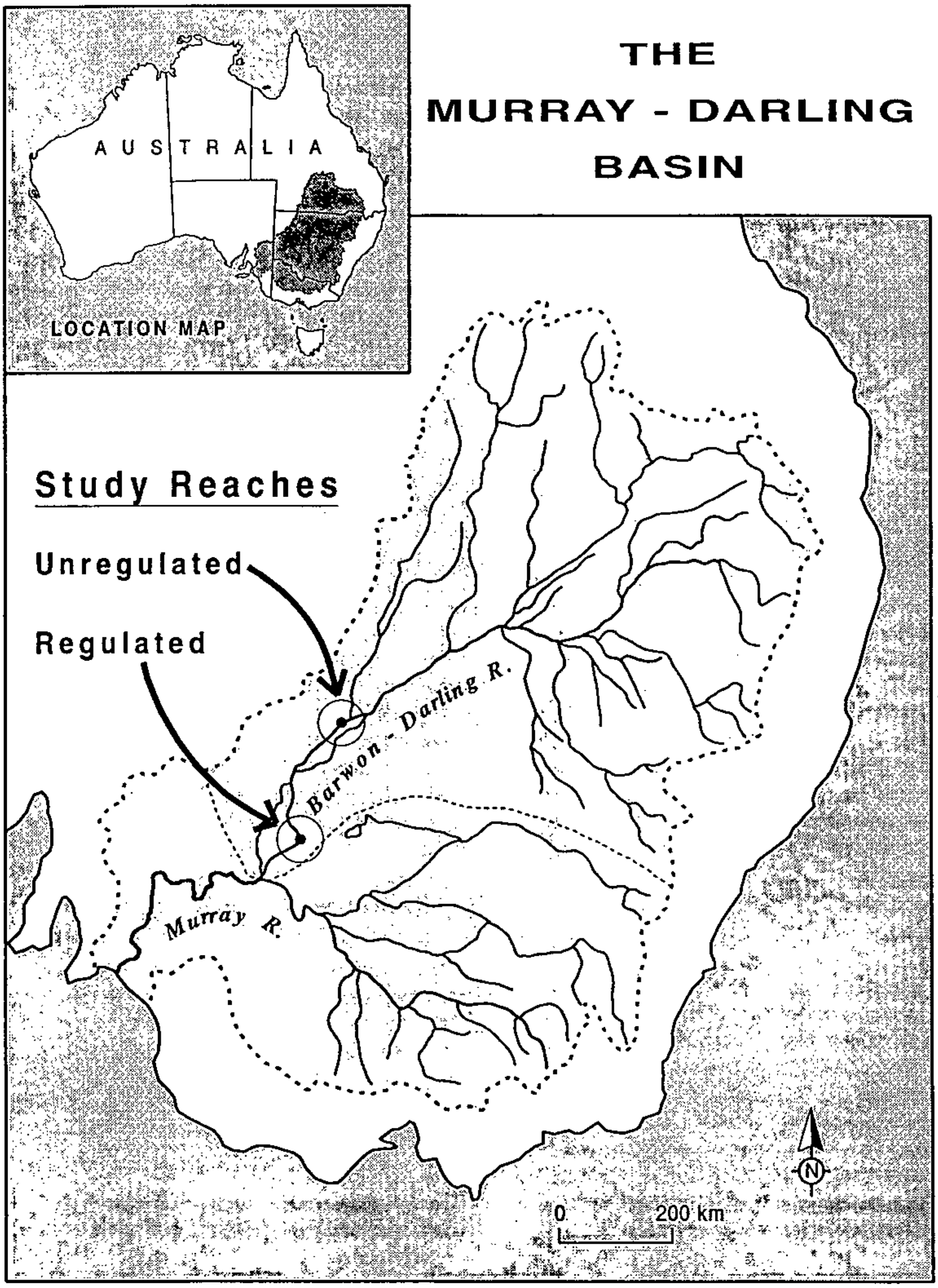

Figure 1. The Barwon-Darling Basin. Location of study reach are indicated.

2.5 m in a week downstream of some regulating structures, leaving saturated banks prone to sliding. The relatively steep slopes and general morphology of the channel banks of river in this reach of the Darling River, below Menindee, suggest that abrupt block failure is an important erosion mechanism. Furthermore, smaller more frequent changes associated with routine weir operations may also undermine the toe of the bank, leaving it vulnerable to larger falls. Changes in bank morphology and the subsequent loss of in-channel benches is a feature of highly regulated sections of the River Murray.

The geomorphology of in-channel features in the Barwon-Darling is not well known. However, depositional benches have been reported by Woodyer et al (1979) to be a prominent feature of the Barwon-Darling river channel. These benches are defined by horizontal sections of a cross section, excluding the bed. Woodyer et al (1979) identified and described the stratigraphy underlying four surfaces within the channel of the Barwon River, near Walgett. The two lower surfaces were considered to be formed by suspended-load deposition. These surfaces form as point, concave, convex and lateral benches and are composed of laminations of fine inorganic sediments and enriched organic mud. These muddy laminae range in thickness from 0.1 to 14 cm (Woodyer et al 1979). The upper surfaces, also termed benches, were identified by Woodyer (1968) and Riley (1975) as part of the present floodplain. It is postulated that they are relic surfaces, being inundated about once in every 15 years, although on a number of the high surfaces sand laminae were identified. Nevertheless each bench surface in the channel is considered to be a response to change in flow regime (Woodyer, 1968; Riley 1975; Woodyer et al, 1979).

Observations of the stratigraphy of a number of the in-channel features were made at various sites within each reach. The stratigraphy and sediments contained within the upper four features concur with the observations of Woodyer et al (1979). Each morphological feature contained a series of fine sand-mud laminations. The extent of the deposits and individual laminae were dependant upon the size of the in-channel feature. A continuous banding of fine sand and mud up to 4-5 metres in thickness was noted at several sites.

The lower most feature (Level 5) was easily recognised as a distinct break in slope near the base of the channel. This feature resembled an erosional or cut bench similar to that reported by Partheniades (1965) in channels with highly cohesive bed sediments. The formation of these features was suggested to be independant of bed material shear strength and more a factor of geomechanical processes resulting from prolonged low flows.

2. In-channel habitat complexity and flow variability

There is an apparent banding of flows at five distinct stage heights in the 'unregulated' reach of the Barwon-Darling River. Figure 3 is a frequency histogram of stage heights at the Wilcannia gauge, for the period 1972 to 1994. The height (AHD-m) of these bands correspond to the levels of the various in-channel morphological features. The highest number of flows occurs between 0.5 and 1.5 metres, corresponding to the low water mark on the channel banks and the location of the Level 5 feature. There is a grouping of levels between 3.25 and 3.75 metres, within the range of the Level 4 feature; another between 5.5 and 6 metres, the Level 3 feature; another group around 7.5 metres or the Level 2 feature and another at approximately 9.75 metres in the range of the high Level 1 feature. This apparent banding of lows was not evident in the 'regulated' reach of the river.

This preliminary analysis suggests there is an apparent association between flow regime and the presence of morphological features which contribute to in-channel complexity. Thus an interaction between flow and morphology; the nature of this interaction requires further investigation, particularly the impact of changes in the flow regime on in-channel complexity.

3. In-channel habitat complexity and organic matter retention

The quantity of organic matter on the horizontal and corresponding vertical surface of each morphological feature were determined at sites in the 'unregulated' and 'regulated' reaches. Four features were identified at Culpaulin (unregulated) and only one at Studley (regulated). The overall aims of this section of the study were to:

- assess the amount of large course particulate organic matter (CPOM), >2 cm, retained on each surface;
- assess the percent organic content of the fraction < 2 cm, providing an indication of the ability of the different surfaces and features to retain organic matter.

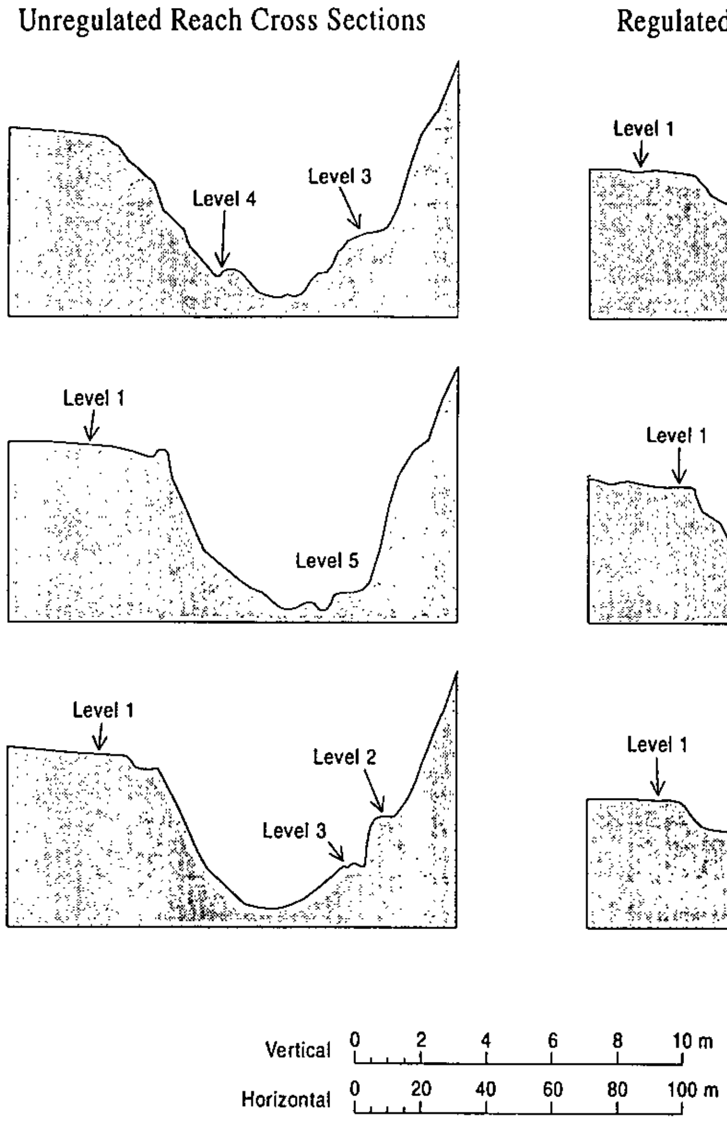

Figure 2. Representative cross sections for the Barwon-Darling River. A: cross sections from the 'unregulated' reach downstream of Wilcannia; B: cross sections from the 'regulated' reach downstream of Menindee.

Mean weights of organic material collected from the quadrats and standard errors for both surfaces for each feature at the two sites are given in Table 1. The horizontal surface only was sampled for the Level 4 feature as the corresponding vertical surface was inundated. Results of the Mann-Whitney U tests for each feature are given in Table 2.

For the CPOM fraction (>2 cm) statistical differences were found between both surfaces for all features sampled at each site (Table 2). Horizontal surfaces retained a greater weight of CPOM than vertical surfaces. This difference was repeated for the percent organic content, with significant differences between both surfaces for all features except Level 3 (Table 2).

In-channel morphological features do accumulate and trap significant quantities of organic material. However some appear to accumulate more than others. Differences in the ability of the in-channel morphological features to trap organic matter may relate to one or a combination of the following: the mode of formation of the feature, the surface roughness of each feature and the relationship between input of organic matter and the time of deposition. It is also apparent that the horizontal and vertical surfaces of each morphological feature differ in their ability to accumulate

Site	Feature	Surface	COM>2cm (g)		% Organic Content	
Culpaulin (unregulated)	Level 1	Horizontal	62.47	*(10.49)*	11.18	*(0.67)*
		Vertical	4.23	*(1.17)*	3.53	*(0.19)*
	Level 2	Horizontal	21.29	*(5.69)*	8.38	*(0.58)*
		Vertical	0.57	*(0.31)*	4.99	*(0.16)*
	Level 3	Horizontal	61.87	*(15.14)*	3.68	*(0.57)*
		Vertical	4.11	*(1.26)*	2.59	*(0.28)*
	Level 4	Horizontal	11.09	*-2.55*	7.28	*-0.15*
Studley (regulated)	Level 2	Horizontal	63.62	*(11.19)*	9.79	*(0.32)*
		Vertical	11.47	*(3.95)*	6.25	*(0.15)*

Table 1. Means (SE) for the CPOM fraction >2 cm (g) and the percent organic content for both surfaces of each feature sampled at the two sites.

Site	Feature	COM>2cm (g)	% Organic Content
Culpaulin (unregulated)	Level 1	U=100, p<0.001	U=100, p<0.001
	Level 2	U=98, p<0.001	U=100, p<0.001
	Level 3	U=90, p<0.001	U=58, p<0.05
Studley (regulated)	Level 2	U=86, p<0.001	U=90, p<0.001

Table 2. Results of the Mann-Whitney U comparisons between the horizontal and vertical surfaces of each feature for CPOM >2 cm and percent organic

CPOM of a size range greater than 2 cm; twigs, leaf litter and other woody debris. The horizontal surface of each feature accumulated a greater weight of CPOM. Differences in the amount of CPOM accumulated on the horizontal surfaces for the range of features may reflect differing proximity's to overhanging riparian vegetation. This analysis, however, clearly indicates that horizontal surfaces have a greater ability to collect woody debris than vertical surfaces.

The horizontal and vertical surfaces also differed in the quantity of organic matter (% organic content of <2 cm fraction) retained within the sediment; with the horizontal surfaces retaining greater quantities of organic matter than vertical surfaces. The Level 3 feature at Culpaulin Station was the only feature in which there was no significant difference in the percent organic content between horizontal and vertical surfaces. Interestingly, the sediment composition of both surfaces of this feature was predominantly sand, whereas the sediment composition of all other features was dominated by silt and clay.

The lack of horizontal surfaces in 'regulated' reaches of the Barwon-Darling River may limit the in-channel trapping of organic matter. Horizontal surfaces not only provide a site of deposition, hence the accumulation and retention of organic matter, but also influence the form roughness of the channel. Increased roughness enhances in-channel deposition. Changes in river morphology have occurred in the Murray-Darling Basin resulting in the erosion of in-channel features such as depositional features (cf. Thoms and Walker, 1993). The influence of flow regulation and channel maintenance activities on the stability of river morphologies is well documented. These activities are common through out the basin.

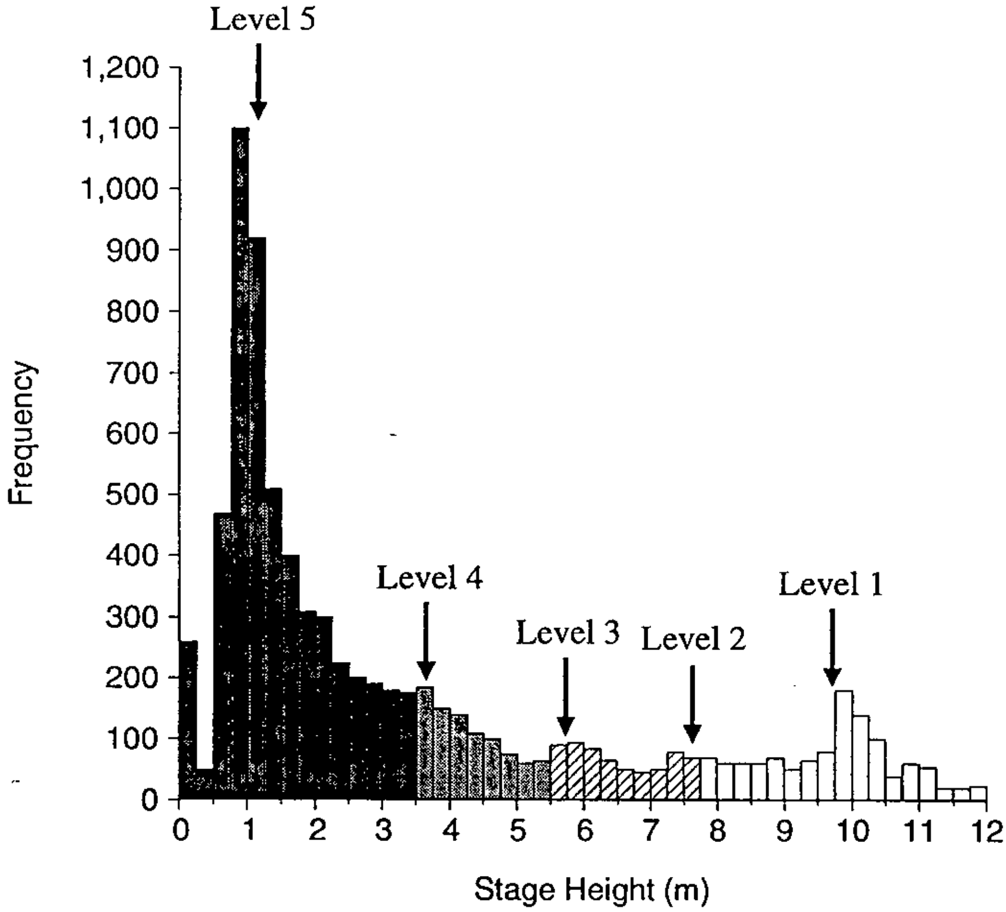

Figure 3. Frequency histogram of stage heights in theDarling River at Wilcannia (1972-993) with levels of the in-channel features observed in the cross sections.

SIGNIFICANCE

There is a growing body of opinion that channel complexity in rivers such as the Barwon-Darling is critical for ecosystem health. In-channel morphological features play an important role in the energy transfer throughout the system. During low flow periods, litter accumulates on these flat features. When flow levels rise, inundating the accumulated organic matter, it becomes available to certain aquatic organisms whereupon it is processed and becomes part of the food chain. In effect, the function of these features is similar to wetlands, except that they would be inundated more frequently.

The greater the complexity of the channel, the greater the surface area available as a food source and as habitat for lower order aquatic organisms such as macroinvertebrates. Conversely, if the degree of complexity is reduced, this could have repercussions for overall ecosystem health. A hypothetical association between in-channel complexity, hydrology and food source availability is presented in Figure 4.

Water resource development can give rise to dramatic changes in the character of riverine ecosystems. In order to assess the environmental flow requirements for a specific ecosystem it is important to understand how aspects of the physical environment impact various components of the ecosystem. For the Barwon-Darling River it is imperative to maintain both the natural flow and habitat variability.

Ecological sustainable development of Australia's inland rivers requires sound environmental knowledge. However, the character of riverine ecosystems is the result of many interacting parameters, and it is difficult to discuss individual factors in isolation. Indeed, physical, chemical and biological, factors operate in conjunction with each other to produce unique systems, both in terms of their character and functioning. The

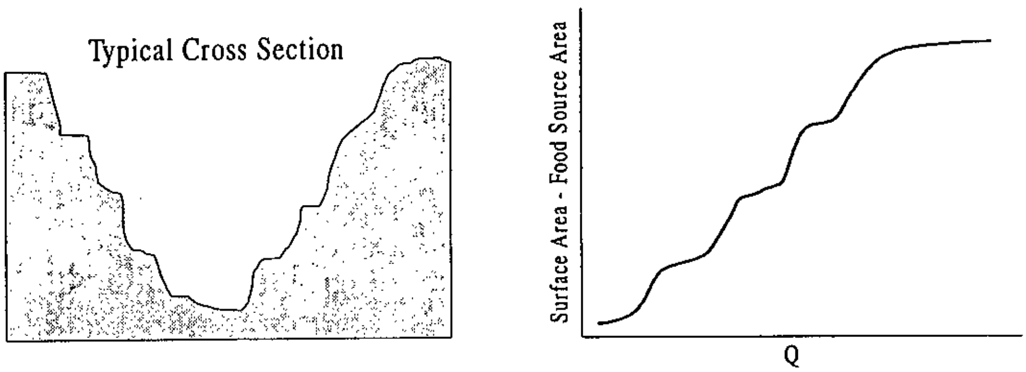

Figure 4. Hypothetical association between available habitat-food source area and discharge.

integrity of river ecosystems relies on a balance between all parameters. This fact is often neglected with a tendency for a focus on 'flows' in the management of our rivers.

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A Schematic History of Waterway Management in Victoria

*Patricia Geraghty and Peter Vollebergh**

ABSTRACT: *This paper presents a brief overview of the development of the institutional framework for waterway management in Victoria and discusses some of the major paradigms which have driven its development. Table 1 summaries the chronology of major milestones in waterway management. These milestones illustrate some of the changes in the attitudes of organisations, government and non-government, and of the community regarding the management of rivers and streams in Victoria.*

1. IN THE BEGINNING — CENTRALISED CONTROL

From the 1850s on through to the early 1880s, **river frontages were reserved as public land** as the adjoining land was settled. This was to ensure access for stock watering, river boats and for recreation, especially for fishing. In England, by comparison, land up to the water's edge is private to this day. Because land started to be settled far more quickly than frontages could be surveyed and reserved, a general proclamation of May 1881 declared that all remaining frontages were to be reserved as Crown Land.

The provisions of the *Water Act 1905* established the State Rivers and Water Supply Commission (SR&WSC), which was the forerunner to the Rural Water Corporation of the early 1990s. The Act reinforced the concept of State ownership of water resources and of the bed and banks of waterways. However, the SR&WSC did not have river or floodplain management responsibilities, nor could this organisation raise revenues for these functions. **So the prevailing paradigm for river management in Victoria at that time was that of State ownership and State responsibility.**

There was a significant shift in the way the environment was perceived following **recognition through the 1930s and 1940s of environmental degradation of both rivers and streams and of soil.** This heightened public awareness of the environmental consequences of many hitherto socially accepted land and water management practices was the trigger for a number of initiatives.

One of these initiatives was the establishment of the Rivers and Streams Fund in 1931, whereby licence fees collected from the grazing of water frontages were paid into a central fund. Grants were made to councils for works on rivers such as clearing obstructions from streams and treating bank erosion. The fund was administered by the Public Works Department with advice from the SR&WSC.

A further example of this concern for better management of natural resources in this State was the *Soil Conservation Act 1940*.

Even though there was increasing acknowledgment that natural resources were not being managed well, there was no fundamental change in the way river management was administered for the first forty or so years of this century, that is, from centralised organisations with a single statewide funding source.

2. THE 1940s — DECENTRALISATION

The next significant step was the move to placing the responsibility for local river management problems with locally-based organisations. This was the recommendation from a 1945 Parliamentary Inquiry which enquired into the "action necessary to provide for the efficient maintenance of river improvement and drainage works". This inquiry resulted in the *River Improvement Act 1948* and the subsequent formation of many river improvement trusts (RITs) during the 1950s. These RITs generally formed following flood damage and were most interested in local flooding and severe erosion problems.

The SR&WSC became the primary authority for river improvement at the State level. It is fascinating to note that there was much concern about the state of our rivers and corresponding uncertainty about who should pay for river management during the parliamentary debate on the River Improvement Bill. The same questions are raised today.

The 1945 Parliamentary Committee seemed to anticipate later attitudes in that it recommended that river management, drainage and flood protection should be managed as a complementary suite of functions. The Dandenong Valley Authority formed in 1963 and its powers were in line with these recommendations. This authority had waterway management, regional drainage and floodplain management functions and the ability to raise revenue by charging municipalities in the Dandenong Creek catchment.

The Joint Select Committee on Drainage, established in 1969, endorsed the conclusions of the 1945 Parliamentary Committee and further recommended that these functions should be managed by catchment-based authorities.

*Department of Conservation and Natural Resources, PO Box 41, East Melbourne Vic 3002
Telephone: (03) 9412 4043 Fax:(03) 9412 4049

Selected chronology of some of the major milestones in waterway management in Victoria

1850s to 1880s	Reservation of river frontages for public use
1905	*Water Act* - State Rivers and Water Supply Commission established
1931	Rivers and Streams Fund established - Public Works Department
1940	*Soil Conservation Act*
1945	Parliamentary Public Works Committee
1948	*River Improvement Act*
1950s	Formation of many River Improvement Trusts
1958	*River Improvement Act*
1963	*Dandenong Valley Authority Act*
1969-70	Joint Select Committee on Drainage
1975	Standing Consultative Committee on River Improvement
1980	Public Bodies Review Committee (PBRC)
1983	PBRC Eighth Report (recommendations related to river management)
1983	*The State of the Rivers* report
1984	State of the Rivers Task Force
1984	Department of Water Resources (DWR) and Rural Water Commission (RWC) established
1984	Regional Drainage and Stream Management Task Force
1987	*Better Rivers and Catchments* report
1987	First catchment-based RMA: Mitchell RMB. State Conservation Strategy
Late 1980s	Mergers and catchment-based River Management Authorities (RMAs)
1989	DWR takes over the administration of RMAs from RWC
1989	*Water Act*
1990	First multi-functional authority: Latrobe Region Water Authority
1994	Water sector reform: separation of commercial and public good functions
1994	*Catchment and Land Protection Act.* Catchment and Land Protection Council and Boards
1995	Directions for Waterway Management in Victoria policy

By contrast with this, the districts of RITs existing in the 1970s, mainly located in the eastern part of the State, were usually small and comprising just the downstream reaches of major rivers. These authorities only had river management powers, not drainage nor floodplain management powers.

3. THE 1970s & 1980s — THE RISE OF ENVIRONMENTAL CONCERNS, CATCHMENT-BASED MANAGEMENT AND LOTS OF REPORTS

By the 1970s, community concern about environmental matters was again on the rise. Among various targets were the RITs, which were perceived by some people to be "river destruction trusts". In response to this, the Standing Consultative Committee on River Improvement was set up. It achieved the following:

- established an institutional and legal framework;
- developed guidelines on revegetating streams; and
- released *The State of the Rivers* (Standing Consultative Committee on River Improvement, 1984).

The State of the Rivers was an important vehicle for the promotion of catchment-based river management and it outlined, in quantitative terms, the degraded state of Victoria's rivers and streams. The Standing Committee recommended that a further group, the State of the Rivers Task Force, be established to investigate:

- how catchment-based river management could be established;
- the costs of river restoration in each catchment; and
- ways whereby these costs could be met.

At the same time the Task Force was operating, the Public Bodies Review Committee (PBRC), an all party committee, started a review of the entire Victorian water sector. The PBRC identified a number of major problems related to river management. These were:

- board members were mainly frontage landowners;
- Trust districts were confined to short reaches of rivers;
- limited funding for river management (both State and local);

- outdated legislation;
- deficiencies in the river management knowledge base; and
- little recognition of the wider values of rivers (e.g. environment, recreation, tourism).

The final PBRC report (PBRC, 1983) **recommended that all RITs cease to exist and that their functions be undertaken by a total of twenty-three different agencies**, namely nine water boards, nine catchment boards and five municipalities.

This arrangement continued to endorse **the concept of decentralised river management**, a recurring theme in the Victorian water sector, compared with the more centralised situation in some other States.

However, the PBRC's recommendations were not seized upon wholeheartedly. For example, the water boards did not want river management responsibilities. Hence the Regional Drainage and Stream Management Task Force, which was appointed in 1984, reviewed the recommendations of the previous review (Regional Drainage and Stream Management Task Force, 1984).

The Task Force reinforced the concept of the existing system of RITs, recognising the critical importance of local knowledge, commitment and responsiveness. **It recommended the establishment of catchment-based river management authorities** (RMAs), as in the previous *The State of the Rivers* report. The subsequent *Better Rivers and Catchments* (State of the Rivers Task Force, 1987), estimated the costs of correction works for each catchment and also discussed possible management arrangements for river management throughout the State. **The major paradigm operating at that time and for some years following was that of catchment-based RMAs, responsible for the condition of all the rivers and streams within an entire catchment.**

Simultaneously, changes in the administration of river management at the statewide level were occurring. In 1984, the Department of Water Resources and the Rural Water Commission (successor to the SR&WSC) were established. The Department became the focus of river management policy in the State, with the goal of implementing the recommendations of both the State of the Rivers and the Regional Drainage and Stream Management Task Forces. The Commission had a continuing role in river management in those areas without RITs or RMAs, a minimal role which persisted until 1989. There were some funds expended on works as part of the Commission's role.

Ultimately these activities led to a commitment by the Government, both in Cabinet and via the State Conservation Strategy (Government of Victoria, 1987) to **"achieve a significant and visible improvement in the condition of the State's waterways by the year 2000" and to achieve this through, amongst other activities, the establishment of catchment-based RMAs.**

It is thus apparent that through the 1980s the community's environmental awareness was becoming stronger by the year and therefore increasingly powerful as a political factor. This is reflected in the current Water Act in the description of the functions of RMAs (e.g. "to identify and plan for . . . environmental values of land and waterways") and how they must perform these functions ("an Authority must perform its functions in an environmentally sound way)". Such explicit requirements are indicative of an environmentally aware community and a responsive Government. It also gives a measure of statutory strength to the concept that river management activities must be environmentally responsible and so reinforces the continued application of that concept in future arrangements. **The shift from the view of RITs as "River Destruction Trusts" in the 1970s to that of RMAs being in the vanguard of environmentally proactive organisations has been a very significant one.**

4. INTO THE 1990s

The first catchment-based RMA was the Mitchell River Management Board (RMB), formed in 1987, followed by the Ovens, the East Gippsland and the Tarwin RMBs. During the early 1990s, many RITs extended their districts to the whole of their catchments or merged with neighbouring authorities and new RMAs formed in catchments where there had not been a history of river management. The area of the State thus covered by RMAs has increased from about 7% to 40% since 1987 and is anticipated to be up to about 60% by the end of 1996.

A short-lived concept, which was a driver in relation to reform for the water sector in its entirety, was that of the multi-functional authority. Such an authority was designed to deliver an integrated water management approach to water supply, sewerage provision, waterway management plus, eventually, all of the other functions related to the management of the water resources in a district. The first such authority established was the Latrobe Region Water Authority, which encompassed a number of small Water Boards plus a river management authority. Several other multi-functional authorities were formed but the impetus for their establishment disappeared with the current Government's reform agenda (Office of State Owned Enterprises and Office of Water Reform, 1994).

Once again, the nature of RMAs is undergoing radical change. The driving force for the last ten years or so has been the establishment of whole of catchment RMAs. This has not led to the solution of all of the concerns raised a decade ago by the PBRC. Certainly, the issue about outdated legislation has been largely overcome through the *Water Act 1989* and the existence of a few small, fragmented authority districts is no longer a problem, since none of these is expected to continue by the end of 1996. But the issues related to limited funding, to RMA members being largely landowners, to deficiencies in the knowledge base and to a narrow view of what river management encompasses persist. For each of these issues, there has been a discernible improvement, but they do persist.

So the establishment of catchment-based RMAs has not been the panacea some of us hoped, perhaps naively, it would be. Other changes have also contributed to this conclusion. First, the Water Industry Reform initiatives introduced by the current Government (Office of State Owned Enterprises and Office of Water Reform, 1994) reduced the number of non-metropolitan water and sewerage authorities from 83 to 13. These new regional water authorities, which have replaced both the older style water boards as well as the few multi-functional regional water authorities, have a strong commercial focus and will generally steer clear of public good activities such as waterway management.

Second, the *Catchment and Land Protection Act 1994* established the Victorian Catchment and Land Protection Council and ten catchment-based regional boards across the State. The Council advises the Government on the condition of the State's land and water resources and priorities for action across Victoria. It also assists in the coordination of other resource management agencies at the statewide level. The Catchment and Land Protection Boards oversee and coordinate the management of land and water resources at the catchment and regional levels. Each Board is responsible for developing a regional catchment management strategy for its area.

Statewide policy development and the river management grants program have been concentrated in a small group which has moved from the Department of Water Resources (DWR) to the Department of Conservation and Environment, back to a revamped DWR and, since October 1993, to the Department of Conservation and Natural Resources.

5. THE FUTURE

These various events have led to opportunities for RMAs to extend their activities into new areas. A document titled "Directions for Waterway Management in Victoria" was in a draft form as of December 1995 and undergoing a targeted consultation phase. This policy document articulated **the goal for future waterway management in Victoria, from the Government's perspective, as:**

> **"To establish catchment-based authorities which will be responsible for the management of all waterways throughout the State and which will play an important role in the integrated management of all activities impacting on waterway condition and water quality".**

Perhaps the most significant reform recommended in this document relates to the suite of functions that are undertaken by what are now called waterway management authorities (WMAs). It is proposed that WMAs progressively take on those functions that will minimise the impact of the major waterway related problems in their region, in a "strategic alliance" relationship with their Catchment and Land Protection Boards.

These potential new functions include:

- floodplain management;
- regional drainage management;
- frontage and riparian zone management;
- sand and gravel extraction;
- water quality monitoring; and
- environmental flow management.

Other changes relate to the funding of WMAs, board selection and composition, accountability and so on. **Hence it is apparent that: one of paradigms currently fighting for favour appears to be for catchment/regional authorities that are responsible for a suite of public or mixed good activities.** These activities comprise those with major impacts on both waterway condition and water quality, and seem to be grouped in terms of integrated catchment management, albeit a restricted definition of this concept.

This is a definite shift from the prevailing integrated water management concept of the late 1980s and appears to largely be the result of **the separation out of public from private goods throughout the water sector,** both at the Federal and State levels. It is relatively easy to isolate the commercial functions and establish appropriate institutional arrangements for them. However, the "left over" public or mixed good activities in both land and water resource management, which are perceived to be the foundation of an integrated catchment management approach, also need to be housed appropriately. The institutional separation of various aspects of the water sector, described as water resource management, standard setting, regulatory enforcement and provision of service, is required by the Council of Australian Governments by 1998 (Council of Australian Governments, 1994). In addition, the Hilmer concept of competition has led to the clear separation of private good functions, such as water supply, sewerage provision and irrigation management, with focussed organisations providing these functions in an increasingly competitive environment.

So right now, there appear to be two very different driving forces which are shaping the way waterways are managed in this State. The first, by defining the commercial, competitive components of the water sector, has really excluded waterway management, plus various other public or mixed good activities, from its considerations. Hence this separation philosophy has clearly described how one portion of the water sector should manage its business and totally ignored how the remainder should operate.

The second underlying philosophy is a **modified integrated catchment management approach**, which certainly incorporates the new Catchment and Land Protection Act perspective, but which has yet to develop an accepted institutional framework. Perhaps then this is one of those "exciting" times when two rather different views are competing. Inevitably, one paradigm will prevail, but this may well be an amalgam of the two competitors or even something quite new.

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No involvement, no commitment, no change! - Involving the community in watercourse management

Michael Good* and Jim Burston*

ABSTRACT: *A plethora of natural resource management plans exist that have failed to achieve any change in on-the-ground management because of poor community involvement. A project funded by the National Landcare Program in the Mt. Lofty Ranges (S.A.), is developing management plans for watercourses in four catchments, by actively involving rural landholders. Establishing meaningful landholder participation, has been a key driver behind the project design, including the manner of data collection and use of geographical information systems. A collaborative, community participation process was used, where landholders developed community goals and used these to evaluate watercourse problems in a structured, equitable and effective manner. The outcome was a plan of priorities for watercourse works, which was used to allocate project funds and provide long-term community direction.*

1.0 BACKGROUND

The Mt. Lofty Ranges, covering around 3500 km^2, lie immediately to the east of Adelaide. They contain a great variety of land uses; are a major tourist destination; produce, on average, about 60% of Adelaide's water and over $200 million annually in farm-gate agriculture income (Anon, 1993).

In 1993 the National Landcare Program funded the "Mt. Lofty Ranges Healthy Catchments Program" for three years, with the aim of implementing actions to achieve integrated natural resource management and sustainable development in the Mt. Lofty Ranges. This program consists of seven major projects, one of which is the Riparian Zone Management Project (RZMP).

This project aims to improve water quality and ecological health in the watercourses of four Mt. Lofty Ranges catchments - Inman, Torrens, Onkaparinga and Tookayerta. Watercourses that are unfenced, infested with woody and annual weeds, actively eroding and have poor habitat value are the rule, not the exception, in the Mt. Lofty Ranges.

The project brief was to:

- survey the current condition of these watercourses
- prepare plans for improved watercourse management
- assist the community to improve watercourse management by providing technical advice and financial assistance.

2.0 COMMUNITY INVOLVEMENT IN THE RZMP

Involvement of the rural community in this project has been a very high priority and has driven many of the decisions taken in formulating the direction of the project.

2.1 Science or Art ? - Getting Change On The Ground

There is a plethora of natural resource management plans in South Australia, and probably elsewhere) that failed to achieve any change in on-the-ground management because of a failure to involve the local community. If change on the ground, in this case, improved watercourse management, is the desired outcome, then the "science" of watercourse management is of less importance than the "art" of working with the watercourse managers.

In the Mt. Lofty Ranges, the vast majority of watercourses flow through freehold agricultural land. If agency staff do not work with these landholders in a way that is meaningful for the landholders, to produce improved management practices, then little or nothing will change on the ground - the ground they own! In South Australia there are no Crown frontages (or similar) as in Victoria. Most land titles show a total disregard for land capability classes. Property boundaries and internal fencing are commonly placed so that riparian zones are managed by landholders as part of the whole paddock, ignoring their special ecological functions.

The authors have a strong belief that only by working with landholders and taking a collaborative problem-solving approach, will management really be improved. This is not without its risks - things can

* Mt.. Lofty Ranges Catchment Program,
Department of Environment and Natural Resources (Water Resources Group),
2/85 Mt. Barker Rd, STIRLING 5152 S.A. Phone: (08) 339 7111 Fax: (08) 339 7112

go "off the rails". Our observation is that this means that the objectives of agencies and landholders are often not the same, and the landholders are saying so! Agency staff have less control of the process and risk uncertain outcomes. Resource management agency staff typically have a science background. The chaos of subjective, interrelated and "fuzzy" community information and interactions is not always a comfortable place for those wanting hard scientific answers.

2.2 So Why Involve The Community?

Firstly and most importantly, the community have a right to have input into decisions that could effect them, now or in the future.

Second, nothing will change on the ground unless the process involves landholders. In South Australia there are no clear legislative mechanisms to force landholders to improve their watercourse management. We believe that a regulatory approach would fail and engender community hostility. It is no good enforcing watercourse fencing if the landholder leaves open the gates!

Thirdly, watercourse management involves value-driven subjective decision-making, especially when done on a catchment wide basis. For these types of decisions, it should be those who will have to live with the consequences, that make the decisions.

Fourthly, the project collected information about properties that could portray poor management in the eyes of "outsiders". This is a particular issue when the data will be stored on a geographic information system (GIS). There is considerable potential for future misunderstandings and misuse of GIS data, when the original project staff have moved on. It is important for landholders to have a clear idea of what data will be collected, why and how it will be used. To do otherwise is to invite suspicion, mistrust and lessen the chance of the adoption of improved management practices.

Fifthly, landholders have a wealth of observations about their watercourses. Older landholders, needless to say, have a great deal to offer. It is possible, indeed sometimes likely, that landholders will misinterpret these observations and have misunderstandings about watercourse processes and the importance of the riparian zone. However, to assume that their "fuzzy" information is of no value does them and ourselves a disservice. Two way information flow is critical to achieving better on-ground management.

2.3 What Type of Community Involvement?

The "con" in community consultation is an old joke but sadly, is sometimes a reasonably accurate description of the process. It begs the question "What does community involvement mean?". We take a public participation approach. "*Public participation is a two-way process of communication between planners and the community which promotes the exchange of information and encourages problem solving and the resolution of conflict in order to produce plans and policies which are acceptable to the community and which can be effectively implemented*" (Dugdale and West, 1991).

One of the most important points that Dugdale and West (1991) make is that the level of power that the community is being offered must be clear to both the community and the agency staff. We have taken an approach that gives the landholders a direct input into the creation of a plan of on-ground works in their catchments.

Part of effective community involvement is listening to landholders' concerns, fears, aspirations and ideas and not being locked into only seeing the agency's objectives. A recent attitudinal survey of a diverse range of stakeholders within the Mt. Lofty Ranges, showed that although all groups ranked poor landcare practices as the biggest barrier to natural resource management, producer groups ranked streambank erosion as the least important of eight landcare issues considered (AACM, 1994). Government agencies, however, ranked it second highest. Only by looking for the common links in the right manner, it is often possible to move forward toward some common goals.

2.4 What Community?

One of the critical issues is to define the community that needs to be involved in the process. For this project, the community of concern was defined by their ownership of watercourses of interest. It was decided to only survey and prepare management ideas for streams of third order and greater (as defined by Strahlers method on 1:50000 scale maps). This was done for two reasons. Firstly and most importantly, any attempt to improve the management of the first and second order watercourses (many of which are seasonal in the Mt. Lofty Ranges) needs to be dealt with through a property management planning approach. Without this property level integrated approach any changes to the management of these small watercourses may either not be implemented, or if they are, they may lead to frustration and difficulties with farm management.

Secondly, the sheer logistics of surveying more than 700 kilometres of watercourses was beyond the scope of the project.

2.5 Community Participation Objectives & Evaluation

Five key objectives for community participation were established:

- to provide an opportunity for landholders to have direct input into the production of a table of priorities for watercourse works for their catchments.
- to give the local community as much ownership of the project as possible.
- to provide project staff with an understanding of landholder knowledge of watercourse processes and the role of riparian zones.
- to facilitate two-way sharing of information useful to each party.
- to improve landholder awareness and understanding of watercourse processes and the role of riparian zones.

Evaluation of community participation projects must be considered from the start. To do otherwise, is to, assume that what you are doing is adequate. Flexibility and an openness to change is essential.

2.6 Outcomes and Purpose of Community Participation Process

The production of a plan of prioritised watercourse works for each catchment is the key outcome of the process. This serves two purposes. Firstly it is a mechanism for equitable and effective allocation of the project funds available for that purpose to landholders in each catchment. These funds will only address the most significant issues in each catchment. Secondly, these plans will provide catchment groups, landcare groups, local government and Catchment Water Management Boards with a long-term, comprehensive plan to be used in accessing other funding sources in order to continue future works.

The role of Catchment Water Management Boards may be significant in the near future. Under the Catchment Water Management Act (1995), these Boards must produce and implement catchment plans to improve the management of the water resource in each catchment. To fund the implementation of works under these plans the Boards will raise a levy from all ratepayers. This may provide considerable funds for future watercourse works.

2.7 Design of Survey Methods

Most riparian survey methods seem to favour a stratified sampling approach where small reaches are surveyed. However, for the purposes of the project, it was essential to have detailed information, recorded continuously, along watercourses because:

- of the need to implement management changes with all landholders along these larger watercourses. It has been our experience that landholders are not particularly receptive to generalised information. This is especially so when they are being asked to take part in a process that may ultimately involve them changing the layout or management of their property.
- the vast majority of the watercourses flow through many properties with different landuse (historically and current) which has resulted in different current watercourse condition. A common sight in the Mt. Lofty Ranges is adjoining properties with watercourses in very different condition.

2.8 The Use of Geographic Information Systems (GIS)

The opportunity to utilise GIS for the storage of data was seized upon as much for its power in the community participation work as any other advantage. The greatest power of GIS in this project has been the ability to produce, in particular, maps (but also diagrams and statistics), of a variety of information for use in landholder meetings and field days.

One of the simple barriers to better watercourse management, for communities, is the lack of an easily understandable "picture" of watercourse condition at a catchment scale. The need for the community to work in a coordinated way on watercourse issues makes the maps an essential part of community planning.

3.0 CASE STUDY: THE INMAN RIVER CATCHMENT

We will now consider the application of this approach in the first catchment tackled in this project - the Inman River catchment.

The Inman River catchment is located in the southern Fleurieu Peninsula, approximately 70 kilometres south of Adelaide. It is an area of mixed landuse - predominantly grazing and dairying. Watercourse condition has been a community concern since last century.

A diverse mix of concerned residents formed the Inman River Catchment Group (IRCG) in mid 1993, with the aim of raising awareness of the catchments' health and improving its management. In July 1993, the IRCG surveyed all of the catchments' residents, and found that water quality and erosion were amongst the community's greatest concerns. Having experienced two 1-in-100 year floods in successive years (1992 and 1993), concern about the condition of watercourses was to be expected.

Against this background, the authors commenced the Mt. Lofty Ranges Riparian Zone Management Project with work in the Inman catchment, in June 1994.

3.1 Community Participation Process used in the Inman River Catchment

The community participation process was based around the use of a modified version of the model established by Craigie (1990). A three stage process was used to develop a plan of prioritised watercourse works for three sub-catchments, and ultimately the entire catchment. The model enabled landholders to evaluate all watercourse management issues against social, economic and environmental impacts, and then rank them in order of priority. The outcomes from the three sub-catchments were combined to produce a list of on-ground works for the entire catchment.

The Craigie model was chosen to build upon as it has the following positive characteristics:

- it does not rely on detailed financial assessments,
- it explicitly requires social, economic and environmental factors to be considered,
- it is consistent in its application to diverse problems,
- it takes into consideration what could happen in the future if no action is taken, and
- it assigns a numerical value to each watercourse management issue being assessed.
- it allows quite diverse management problems to be ranked
- it lessens the risk of vocal or influential individual landholders hijacking the process and hence biasing the outcomes.

It was important to have a consistent procedure so that at the end of the process the three sub-catchments' plans could be combined into an overall catchment plan of watercourse works.

Problems were treated on an issue-by-issue basis, rather than on a stream reach basis. This allowed the application of the Craigie model in prioritising watercourse remedial works. Dealing with problems on a reach basis would have inevitably lead to large landholders obtaining a large share of the funding, guaranteeing that large sections of the community would not be involved. Allocating funds on an issues basis ensures a greater spread of money throughout the sub-catchment (and catchment), thus facilitating greater involvement and activity by local landholders in the long term.

The community participation process (in chronological order) consisted of:

1) Build up contacts in the local community

Contact was made with all relevant local people - IRCG members; District Councillors and local government staff; Department of Primary Industries staff; the local Soil Board and landcare group members. This revealed information about the social networks and the way information moves in the district.

2) Identify all the landholders & their catchments

All landholders whose properties contain $\geq 3^{rd}$ order watercourses, were identified from local government records and the community network established in step 1. This revealed 124 landholders to try to involve in the process.

The Inman catchment was split into three smaller catchments on the basis of watershed and social networks. This was done for several reasons:

- working with smaller groups would promote greater local input,
- greater involvement of all landholders attending meetings, (people in the Mt. Lofty Ranges only really identify with small local catchments (AACM, 1994)),
- logistical ease in running smaller meetings.

3) Contact landholders

Contact was made by letter and telephone. Importantly all correspondence was jointly signed by the project leader and the chair of the IRCG. Also much of the telephone work involved members of the IRCG. This local input made a huge difference to the way landholders reacted to a project coming out of an agency that has not always had a good relationship with the rural community in South Australia.

4) Media

During the early part of the Inman work radio and local press articles were used to try to raise local community awareness of the project and watercourse issues in general.

5) Each of the three sub-catchment groups then individually took part in a 4 part process.

5.1) Meeting 1

All meetings were opened and closed by an IRCG member. The first meeting was used to:

- identify landholders' concerns and visions for watercourse management,
- identify the extent of landholder knowledge pertaining to watercourses,
- illustrate that watercourse management should be viewed from both an individual and community perspective (ie some issues affect many people),
- illustrate that some problems can only be addressed on a reach basis, and this may involve two or more landholders,
- target information required in the management guidelines,
- develop an itinerary for field days,
- gain permission to enter properties.

Small group discussions were conducted around four questions to achieve some of these outcomes. The information from the small groups was summarised and mailed to all target landholders. Providing prompt feedback allows everyone, including those who did not attend, to see the results of the meetings' efforts.

5.2) Field survey work

All watercourse management issues were identified by the field survey work. Some landholders participated in the survey work. This was encouraged, as it provides another opportunity for sharing of knowledge and building of understanding.

5.3) Field day

These were conducted on different properties in each sub-catchment. Properties were selected to illustrate a range of issues, and importantly where those landholders were happy to talk publicly about their ideas and the history and problems of their watercourses. The purpose of these days was two-fold. Firstly, to show landholders a range of issues and give them some understanding of the processes that have contributed to the current condition of watercourses and how they might be rehabilitated. This was a two-way process. Wherever possible landholders were encouraged to voice their management ideas. Secondly, to give landholders information and knowledge to prepare them for the process in the second meeting.

5.4) Meeting 2

This meeting was conducted in two parts. The first session used the landholders inputs from the first meeting to develop general "themes" of concern and then goals for each of those themes. The goals used in the original Craigie (1990) model were used as a starting point. The group (landholders and project staff) deleted some goals, added others and modified the wording as they saw fit until they were happy that the goals adequately addressed their concerns.

In the second part, small groups, prioritised watercourse management issues using the new **joint** goals in the modified Craigie tables. To assist them in this process every small group had GIS generated maps. Each small group was facilitated by someone involved in the survey which allowed for explanation of issues and maps. The process was considerably assisted by the local knowledge of landholders especially in regard to the rate of change of some processes.

6) Summary of information

All issues were then ranked by the numerical scores produced in the meeting. The three tables from each sub-catchment were combined into one for the entire catchment by the project staff using the modified Craigie tables and landholder goals that evolved throughout the process.

3.2 Outcomes

The material product of this process was a report containing:

- a detailed history of changes to watercourses of the catchment
- recommendations aimed at Local and State government; the IRCG and other community groups
- table of 185 watercourse management actions for the entire Inman catchment, ranked in order of priority by that catchments community.

A very tangible outcome was the handing over of $60,000 "action money" from the project to the IRCG. This money, to be administered by the IRCG, will address the highest priority actions identified by the project through the community participation process.

3.3 Evaluation of Inman community participation process

Evaluation was done in several ways, during and at the end of the project work, to determine how well we had achieved our five community participation objectives. This included on-going reviews based on IRCG member feedback and landholder feedback; a "focus group" evaluation and a questionnaire of all landholders after the completion of the process. In summary these evaluations showed that landholders were broadly comfortable with the entire process; felt that strong efforts had been made to really involve all landholders; that the outcome (ie the table of prioritised watercourse works) were sensible and broadly representative of community opinion. The major concern was the difficulty of the voting process in the second round of meetings.

One of the most obvious measures of success is that approximately 50% of the overall target community took part in some or all of the process. This is a reasonable figure but importantly some very large landholders who own long stretches of watercourse and who are "influentials" in the district took part. This bodes well for future outcomes.

Perhaps the best evaluation was the attendance of approximately half the target landholders to the public handing over of the $60,000 "action money" from the project to the IRCG by the Minister for Environment and Natural Resources. This was on a bitterly cold, windy day when many would have had better things to do.

We believe we achieved all five community participation objectives.

4.0 CONCLUSION

Although there is a lot of science behind watercourse management it is insufficient and sometimes irrelevant in improving the management of watercourses. This is particularly so in catchments of agricultural landuse on freehold land.

Only by actively seeking community participation will effective long-lasting change be achieved on the ground. This means being open, really listening and looking for the common ground between the objectives of landholders and agencies.

Ultimately only by a personal commitment to change will landholders change their watercourse management. This commitment is only built if landholders gain an understanding of technical information and the importance of better watercourse management for themselves (as well as the wider community). This commitment is only achieved by the landholders having a real input into decision-making and by having a real ability to implement those decisions, which means access to resources.

All of these only occur by taking the considerable time and effort to work with landholders. No involvement, no commitment, no change !

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The Management of Stream Erosion and Sedimentation - An Interactive Community Driven Process

John Gardiner *

ABSTRACT: *"RIVERCARE" is an initiative of the Manning Catchment Management Committee and the Department of Land and Water conservation (DLWC formerly DWR). It was devised as an interactive process with landowners as part of the LANDCARE program to address the Manning Valley's number one areas of concern; bank erosion, floodplain stripping, sedimentation and stream/riparian vegetation management.*

Through a series of overlays placed on enlarged aerial photographs the necessary information is collected by landowners and their perceived management options are listed. This information is melded with Departmental technical input, an on-site inspection, consultation with other authorities to form a FINAL PLAN which forms the basis of management of the river for about five years.

The concept won the Australian Water and Wastewater Association's Federal "WATER ENVIRONMENT MERIT AWARD" for 1995.

1. ABOUT THIS PAPER

This paper describes in a general way the development and implementation of the RIVERCARE planning process as part of the LANDCARE program on the mid-North Coast of New South Wales. I have deliberately not set down quantities of technical process and data in this paper because this is readily available elsewhere in such publications as Newbury and Gaboury (1993), Raine and Gardiner (1995).

2. THE REQUIREMENTS OF THE MANNING CATCHMENT COMMITTEE

From its inception the Manning Catchment Committee designated its number one area of concern to be streambank erosion, floodplain stripping of the mid-river area, sedimentation in the estuary areas, and vegetation management.

It was generally accepted by the Committee that the sediment deposits in the lower section of the Manning River came from upstream during flood events, and they were the result of bank erosion and floodplain stripping. Some contribution, particularly to the wash load, came from gully erosion. Problems with lack of growth of vegetation on the river channel banks or overgrowth in the channels indicated an overall plan was needed to set management strategies.

3. HOW THE DLWC MET THE COMMITTEE'S REQUIREMENTS

The Logic behind the assessment process.
After a deal of soul searching a system of rating the Manning River was devised for the non-tidal areas. Two parameters were used to highlight the most highly degraded areas.

Firstly the geomorphic state of the river was divided into three categories indicating, high, medium or low ***(red, yellow, green)*** levels of degredation. A number of gradations had been bandied about but it became apparent that a three cell subdivision was sufficiently accurate for the purpose at hand.

When this was combined with a three category state of vegetation rating a nine cell matrix was formed which gave nine management ratings. These are set out in *Figure 1*.

The geomorphic rating was devised to tell us about the river's stability and is related to the dominant, bankfull or characteristic flow - the 1 in 18 month flood flow.

The vegetative rating was used because vegetation is the second most important factor in controlling a channel's stability, width, etc. Hey and Thorne (1983) give seven variables which define the hydraulic geometry of rivers, and note *"Discharge has a major effect on channel width, through the continuity equation, while bank vegetation appears to dominate the process of bank erosion"*. This is confirmed in Hey and Thorne (1986).

Experience in the Manning Catchment has shown that bank erosion can largely be controlled by vegetative means with minimal structural input if the channel is close to being in a regime state.

*New South Wales Department of Land and Water Conservation, P O Box 297, Muswellbrook NSW 2333
Telephone: (065) 421 216 Fax: (065) 434 164

STATE OF BANK VEGETATION

DEGREE OF DEGRADATION OF RIVER		DEGRADED (RED) RATING	DEGRADED (RED) MANAGMENT	POOR (YELLOW) RATING	POOR (YELLOW) MANAGEMENT	GOOD (GREEN) RATING	GOOD (GREEN) MANAGEMENT
DEGREE OF	DEGRADED RED	•River channel is in an advanced stage of disintegration •Vegetation on the banks is either missing, banks are bare or are falling into the channel.	•There is a need for extensive general repair of the channel and its vegetation and to apply the RIVERCARE planning method, with follow up design plans. Check to see if this plan needs to be part of a **TOTAL CATCHMENT PLAN**	•River channel is in an advanced stage of disintegration. •Vegetation on the banks is sparse, or the wrong kind or has excessive growth within the river channel.	•There is a need for extensive general repair of the channel with extensive replanting of its vegetation. Apply the RIVERCARE planning method. Detail design plans needed in some area. Check to see if this needs to be part of the **TOTAL CATCHMENT PLAN.**	•River channel is in an advanced stage of disintegration. •Vegetation on the banks is generally sound with good species diversity.	•Although there is good bank cover an unstable channel points to a wider catchment problem which may need an **TOTAL CATCHMENT MANAGEMENT PLAN.**
DEGRADATION	POOR YELLOW	•River channel starts to enter a state of decline and physical instability. •Vegetation on the banks is either missing, banks are bare or are falling into the channel.	•Prepare a RIVERCARE plan. Later probably also a design plan for capital works. Check to see if this plan needs to be part of the **TOTAL CATCHMENT PLAN**	•River channel starts to enter a state of decline and physical instability. •Vegetation on the banks is either sparse, or the wrong kind or has excessive growth within the river channel.	•Prepare a RIVERCARE plan for the river channel and its vegetation and implement that plan.	•River channel starts to enter a state of decline and physical instability. •Vegetation on the banks is generally sound with a good species diversity.	•Undertake a RIVERCARE plan for the channel and retain existing vegetation management style. Check for wider catchment degradation.
OF RIVER	GOOD GREEN	•River channel is stable from erosion. •Vegetation condition is degraded, maybe contains exotics, or noxious weeds for example.	•Inspect after flood events and rectify any minor instability •Get advice on bank and channel vegetation, planning and management.	•River channel is stable from erosion/. •Vegetation on the banks is sparse, or the wrong kind or has excessive growth within the river channel.	•Inspect after flood events and rectify any minor instability. •Get advice on bank and channel vegetation, planning and management.	•River channel is in a good stable state. •Vegetation on the banks in good condition with a good diversity of Australian native species.	•Seek extension advice on maintaining existing condition. Keep up the good work!

Figure 1. River stability and vegetation rating with management options.

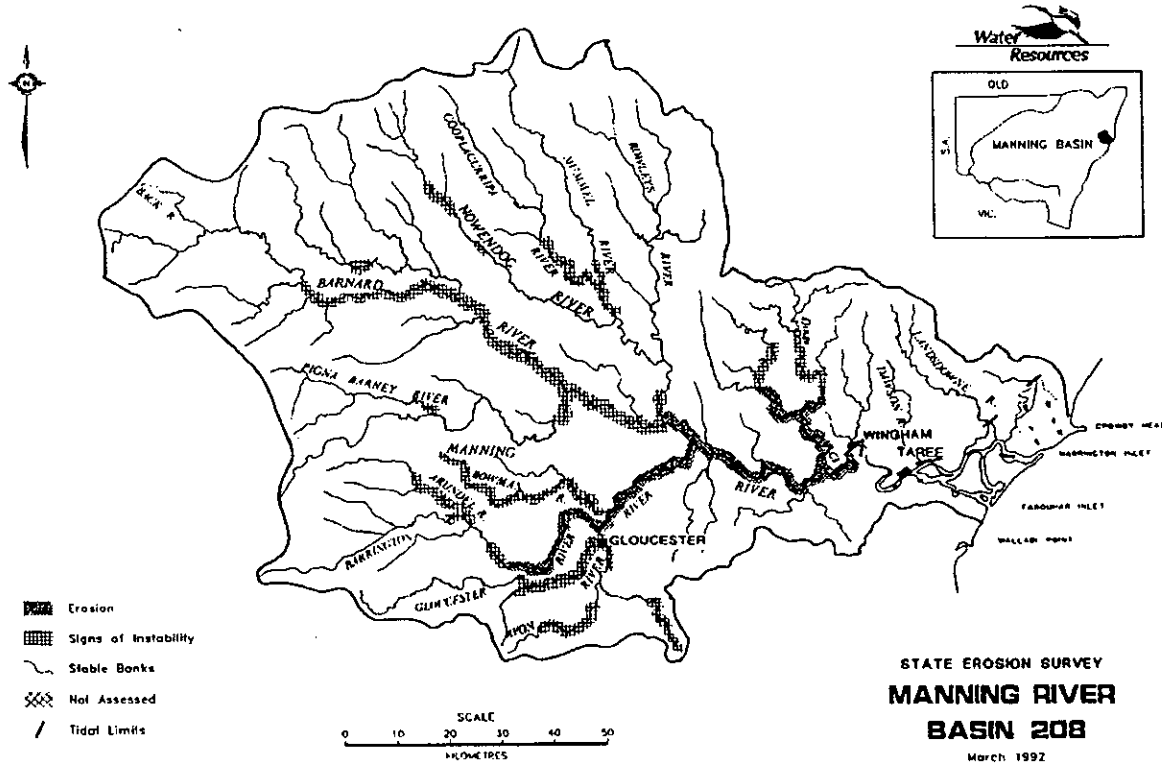


Figure 2. Channel Stability Map used in the initial assessment of the Manning Valley 1992.

4. THE PROCESS DEVISED

Initially the catchment was assessed according to the categories described above to determine the areas of greatest importance and as set out in Raine and Gardiner (1992). These largely coincided with the areas where people were asking for assistance - see the generalised map at *Figure 2*.

It became apparent that we were going to need a large amount of data about the rivers if we were to manage them effectively. Resources to have departmental people go along the rivers and collect this data were not available. After discussion with the Committee it was decided to adopt an approach similar to that being used in property planning. Enlarged aerial photographs were obtained to form the base and acetate overlays to form the data layers. The size adopted was A1. A type of manual GIS, if you like.

This system was put in place with explanatory notes. It has been undergoing constant modification since that time, mainly in format, but in essence the procedure has remained the same. The layers are shown at *Figure 3* which sets out the layer arrangement used in the most recent plans we have been undertaking, - The Nambucca River Valley. This plan focuses on problems associated with extensive gravel extraction and bank erosion. The geomorpic layer is designed to pick up this information.

An abridged step-by-step process and the approximate time required for a five layer five sheet RIVERCARE plan is set out in a box at the end of this paper.

5. THE INITIAL TRIALS

The very first plan was evolved on the Gloucester River at Gloucester NSW. This River had been subject to river management in the late 1960s and early 70s. The works put in place then were designed to correct a River that was in a highly degraded state. The work, which consisted at that time of mesh/rock training walls and willows planted behind, was seriously in need of maintenance. Many of the original works were damaged, washed out or just plain ineffective. The plan sets down action which needs to be taken to consolidate these old works and bring them into line with current methods and practices.

Further problems were arising from the growth of river oaks and bottle brush consolidating the point bars and islands in the river. Alignment widths were set to provide a guide to Landowners on how to manage this pioneer vegetation before it blocked the main channel.

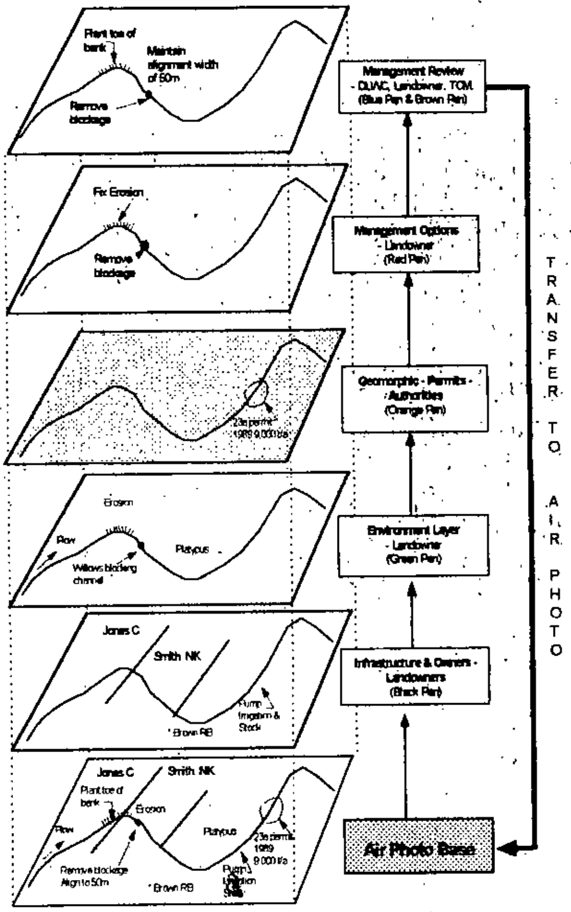
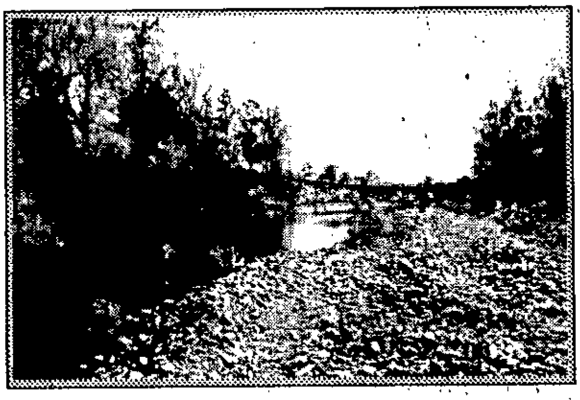


Figure 3. Graphical representation of the RIVERCARE planning process, for a five layer plan.



Photograph 1. BARRINGTON RIVER, GLOUCESTER, NSW, showing a section of River looking d/s from a point-bar cleared of brush and oak to relieve flow concentration on a downstream eroding bank. This is part of the Barrington RIVERCARE plan.

6. LANDOWNER INPUT

By the use of an overlay process similar to that in *Figure 3* the landowners put down details about their ownership, their property boundaries, environmental features, problem areas and proposed management schemes.

This is then consolidated during a "walk-through" phase with Departmental Officers, who walk along the river and discuss the information on the plan layer with the relevant landowner.

A management proposal is drawn up from this.

7. TECHNICAL INPUT

The Department's input consists of:

a) Initial liason - advice on setting up a RIVERCARE plan.
b) Assistance in applying for National Landcare Program grants to access funds for the project.
c) Ordering of aerial enlargements.
d) Setting up the photos and acetate overlays on backing boards, providing pens, rubbers etc.
e) Producing the Landowner Activity Guide.
f) Working out channel dimensions.
g) Putting together the management strategy for the river.
h) Liaising with other Government Departments such as Fisheries, National Parks & Wildlife, etc.
i) Arranging for the finalised plans to be vetted and signed off by the Group, Catchment Committee, the Department etc.
j) The issuing of permits to the Group at the end of the process.
k) Follow on/up activities into the future.

8. THE ON GROUND ASSESSMENT

This is part of the walk through process, whereby the information on the overlays is assessed in relation to the on ground conditions existing at the time of inspection.

The width of the channel is measured to see how it lines up with the calculated widths as set out in Raine and Gardiner (1994). This provides a clue to the extent of channel degradation or widening. Other factors such as vegetation type, style and density are considered along with environmental factors.

Agreement is sought from the individual landowners and the Landcare Group to the proposed management style.

9. ACCEPTANCE OF PLANS

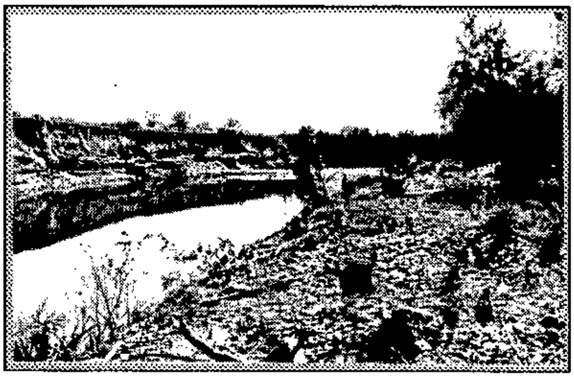
Once the plans reach the final stage they are signed off by the Landcare Group, and the Catchment Committee after approval has been obtained from such bodies as the Department of Fisheries and the National Parks and Wildlife Service and the Department of Land and Water Conservation.

Permits for works are issued on a whole plan basis to the responsible Landcare ("RIVERCARE") Group.

10. ON GROUND WORKS

The RIVERCARE plans enable a planned works program to be put in place. As the plans are accurately scaled it is possible to quantify the amount of work that needs to be done to achieve the objectives set down as part of the implementation process.

In some areas desirable results can be obtained by simply controlling channel vegetation growth as below.



Photograph 2. Bottle brush cleared to alignment opposite eroding bank which is to be planted along the toe. BARRINGTON River, NSW, looking downstream.

In other instances structural works of various types may be needed. The degree and nature of these depend on the extent of degradation being addressed. Photographs 3, 4 and 5, for instance, depict the construction of log sills in the Nambucca River, New South Wales, as part of a restoration program to stabilise erosion, re-establish the pool-riffle system of the River as well as the health and habitat of the River.

11. EXPECTED OUTCOMES

By undertaking a RIVERCARE plan Landcare members become part of a cohesive interactive group with a common purpose, namely restoring and maintaining the common river channel adjacent to their properties.

To date, there have been some very positive outcomes. The extent of works undertaken by RIVERCARE groups has been beyond expectation, particularly where they have been initiated with seed funding from the NSW RIVERCARE 2000 program.

Photograph 3. NAMBUCCA RIVER, NSW. The construction of a log sill to recreate the pool/riffle sequence in a highly degraded sandbed river. NAMBUCCA River Stabilisation Task Force.

Photograph 4. Placing a geotextile membrane upstream of the log sill to reduce undersill seepage and raise the water table level in the river channel.

Photograph 5. Securing log sill timbers to vertical piles with friction pins. Banks of the stream are subsequently planted out with trees.

Photograph 6. Gravel build up reclaiming a degraded area in the MANNING River at TIRI resulting from "manipulation" of the channel vegetation - Mt George RIVERCARE plan.

Photograph 7. A recently placed log sill in the NAMBUCCA River, starting to re-develop the pool/riffle sequence of the River. Sills are placed to parameters set by the NSW Department of Fisheries to promote fish passage. Surplus sand and gravel are initially removed from the pool upstream of the sill and the downstream plunge pool. This material is sold to pay for the cost of the works.

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PROCEDURE FOR UNDERTAKING A RIVERCARE PLAN

Below is an abridged list of steps currently being used (Feb 1994). They are constantly under review as is the time involved in producing the Rivercare Plans. The assumption here is that five (5) aerial enlargements with five (5) overlays are used for the plan. At a scale of 1:5000 it will cover 25 to 30 km of river.

	ITEM	APPROX DLWC TIME PLUS TRAVEL
STAGE 1	**INITIAL DISCUSSION**	
	DLWC talks to Landcare group about procedures, extent, commitment, costs, funding options.	20 hours
STAGE 2	**FUNDING APPLICATION, SETTING UP BASE PLAN**	
	Apply for funding (NLP). When obtained order aerial photograph enlargements, maps, look at catchment parameters, catchment areas, flow hydorgraphs, work out river widths, set up photographs on backing sheets with overlays, set up package for handover to Landcare group.	60 hours
STAGE 3	**INITIAL HANDING OVER OF PLANS, COLLATION OF INFORMATION**	
	Arrange meeting, present "Activity Guide," set direction, landowners collect information, return plans to DLWC for assessment.	23 hours
STAGE 4	**SITE DISCUSSION, FINALISE INFORMATION, PERMITS**	
	LANDCARE GROUP arranges program for site discussion with DLWC Officers. Assessment and agreement on management transferred to aerial photo base. Organise approvals for clearing vegetation, moving sand and gravel, for example.	180 hours
STAGE 5	**FINAL ACCEPTANCE OF PLAN**	
	Landcare group views and comments on final plan. Final comments from Fisheries, National Parks and Catchment Committee sought. Make changes, have Landcare group, Catchment Committee, DLWC sign-off plan - laminate.	35 hours
STAGE 6	**HANDOVER COMPLETED PLAN**	
	Present plans, approvals and associated material to LANDCARE group. **START IMPLEMENTATION PHASE.**	7 hours
		TOTAL 325 hours

Riverwise: Educating the Community About River Management

David Outhet[*]

ABSTRACT: *The NSW Department of Land and Water Conservation has implemented the "Riverwise" program for educating people about rivers. This has been done to help meet the long-term goal of getting the community to look after their own rivers. The Riverwise program complements the Rivercare program of incentive grants to community groups. These programs serve to get people interested in "owning" the problem of management of their local streams and experienced in doing river restoration. It is hoped that, armed with this new knowledge, experience and interest, the community will carry on without major government funding and without frequent technical advice. This paper reveals the details of the strategies in the Riverwise program.*

1. INTRODUCTION

A long-term goal of the Department of Land and Water Conservation (DLWC) is to have land owners and community groups managing all the streams in New South Wales in an ecologically sustainable way without major government funding or frequent technical advice. This assumes that the present relatively low level of government funding and staffing in this area will not be significantly increased. It is expected that the situation of "seed" money grant schemes and a few staff giving advice will continue indefinitely. This concept of the community managing its own rivers will require a major change in attitudes for many people. It will also require that "river carers" be empowered with the knowledge they need to carry out their task. Riverwise is the name of the DLWC program for educating the community about ecologically sustainable river management.

Other similar DLWC programs have similar aims. For example, the Streamwatch program is concerned with educating the community about water quality.

The Riverwise program runs in parallel with the Rivercare program of incentive grants. This is the main force for sowing the seeds of change in attitudes and getting community ownership and involvement in river management. It is a way of encouraging community groups to work together to plan their river restoration and construct works. These can be for erosion or sediment control, revegetation of the riverine corridor, artificial wetlands and other nutrient control works. In addition, there is a Rivercare 2000 Award Scheme. This is a way of rewarding community groups and individuals for their work on streams, especially those who do things for themselves.

2. OBJECTIVES

The objectives of the Riverwise program are to educate the "river caring" people in the community to:

- understand the behaviour of rivers and identify the causes of problems
- successfully obtain Rivercare grants and other funding
- successfully obtain permits for river restoration works
- assess the effects of proposed developments and land use changes on rivers
- be aware that mismanagement on one property can affect many others upstream and downstream
- control accelerated river erosion and sedimentation
- revegetate the riverine corridor
- control stock access to rivers
- strike a balance between flood mitigation and erosion control
- control the input of nutrients
- consider the big picture when planning river restoration projects
- counter the popular misconceptions about rivers
- use legislation to stop river damage by the ignorant and exploitative

3. COMMUNITY EDUCATION STRATEGIES

The Riverwise program includes a full range of community education strategies. These are implemented whenever the resources of staff and funds are available.

3.1 Workshops

Workshops on river erosion control are often conducted by DLWC advisory staff for localities where erosion is a major problem. All people in the local area who are interested in the problem are invited to attend. The people who attend can be diverse, including Landcare groups, Landcare coordinators, local government engineers, gravel extractors and teachers. These people learn about the

[*]NSW Department of Land and Water Conservation, PO Box 3720, Parramatta NSW 2124
Telephone: (02) 895 7816 Fax: (02) 895 7834 Email: douthet@dlwc.nsw.gov.au

main fluvial processes and the various options for erosion control. They also learn how to apply for grants and how to start making a plan for the restoration of their river.

3.2 River Walks

A river walk is conducted by a community group which has invited a technical adviser from the DLWC. The group walks along their stream bank with the adviser. Problem sites are marked on a map or air photo. The cause of each problem is determined and a range of options is listed for solving the problem at each site. This is the best way of educating the community about rivers. However, it requires a high level of DLWC resources.

3.3 Construction Days

Many river restoration works are now constructed by the members of community groups during a construction day organised by the group. They invite a DLWC adviser to show them the best construction techniques and advise on any design details that come up on the day. The group can then continue to build similar works without the adviser attending every time.

3.4 Field Days

A field day is organised by a community group that wants to show off their completed river restoration works to other invited community groups. A DLWC adviser is usually invited along to help explain why each particular type of work was selected to suit the erosion cause at each site. This strategy expands the number of people educated by the adviser.

3.5 School Talks

DLWC advisory staff have been invited to give talks on caring for rivers at many different schools at all levels throughout NSW. This is one of the most effective ways of changing the attitudes of future land managers. In addition, the young people are educating their parents to some extent if they discuss the topic at home.

3.6 Displays at Public Events

The DLWC has several high quality multimedia displays which are erected at public events such as agricultural shows, fairs and fetes. Staff attend the displays to answer any questions, show videos, organise activities and hand out printed material in show bags.

3.7 Water Week Activities

Many DLWC regions run river tours during Water Week (held during October). For example, the Sydney South Coast Region organises an annual canoe "discovery" tour of the Nepean River in conjunction with the Hawkesbury Nepean Catchment Management Trust. During this tour, experts show people all the various features of the riverine environment and evidence of changes.

3.8 Videos

Three educational videos have been produced by the DLWC and are available for purchase by institutions or available for loan to community groups:

- Rivercare - For the Good of Your Country
- Rivercare 2 - Restoring the River Corridor
- River Processes in Action

3.9 Riverwise Advisory Notes

The following Riverwise Advisory Notes have been published to date for free distribution:

- Rivercare - Community Groups Looking After Our Rivers
- Extractive Industries on River Bars - Best Management Practices
- Extractive Industries on Floodplains - Best Management Practices
- Livestock Control Near Rivers
- Controlling Willows
- Restoring Urban Streams - Treatment Option: Reconstructing Vegetated Meander Bends in Straightened Channels
- Works to Control Stream Bank Erosion - Treatment Option: Planting the Common Reed, *Phragmites Australis*
- Works to Control Stream Bank Erosion - Treatment Option: Recycled Tyres and Revegetation
- Works to Control Stream Bank Erosion - Treatment Option: Log Wall and Vegetation
- Works to Control Stream Bank Erosion - Treatment Option: Rock Revetment and Vegetation
- Works to Control Stream Bank Erosion - Treatment Option: Car Body Revetment and Vegetation
- Works to Control Stream Bank Erosion - Treatment Option: Brush Groynes and Vegetation
- Works to Control Stream Bank Erosion - Treatment Option: Rock Groynes and Vegetation
- Works to Control Stream Bank Erosion - Treatment Option: Timber Groynes and Vegetation
- Works to Control Stream Bank Erosion - Treatment Option: Jacks and Vegetation
- Works to Control Stream Bank Erosion - Treatment Option: Heavy Duty Mesh Fencing and Vegetation

- Works to Control Stream Bank Erosion - Treatment Option: Gravel Mesh Sausages and Vegetation
- Works to Control Stream Bed Erosion - Treatment Option: Boulders
- Works to Control Stream Bed Erosion - Treatment Option: Log and Rock Bed Control and Road Crossing
- Works to Control Stream Bed Erosion - Treatment Option: Log/Timber V Weir (Horizontal or Vertical Logs)
- Buffer Zones Along Rivers and Creeks
- Wetlands On Your Farm
- Small Farms and Septic Tanks
- Blue-Green Algae in Farm Dams
- River Recreation
- Disposal of Farm Chemical Containers
- Filter Zones for Farm Dams

Several more are scheduled for publication in 1996, depending on funding:

- Restoring Native Riverine Vegetation
- Weed and Pest Control in the Riverine Corridor
- Management of Large Woody Debris (Snags) and Willows in Rivers
- Guidelines for Small Stream Crossings, Causeways and Bridges
- Controlling Sediment in Rivers by Vegetation Management
- Creating Pump Holes in Rivers Using Flow Jumps
- Fish Habitat Restoration
- Constructing Farm Dams and Small Weirs on Streams
- Works to Control Flood Scour on Floodplains
- Works to Control Stream Bank Erosion From Overbank Drainage
- Works to Realign River Channels
- Prevention and Control of Saturated River Banks
- Protecting Streams During Housing and Drainage Construction
- River Fill and Reclamation - Best Management Practices

Most of the Riverwise Advisory Notes are written by several DLWC staff along with external staff from other agencies and universities where additional expertise is required.

4. STAFF EDUCATION STRATEGIES

The DLWC staff who educate the public and provide technical advice on river problems must be educated themselves. This is a highly specialised field and no university provides the level of practical training to enable a recent graduate to proceed straight out to advise a Rivercare group. Accordingly, the Riverine Corridor Branch of the DLWC runs the following in-house courses for new staff.

- Policies, Procedures and Legislation (with manual)
- River Processes and Behaviour (with manual)
- River Restoration Works Design Principles
- Riverine Vegetation
- On-Site Design and Works Construction Practice
- Group Facilitation

Staff who have taken the courses are kept up to date by means of regular additions and revisions to their manuals along with a newsletter, Rivercare Update.

5. QUALITY CONTROL

The quality of the community education and technical advice produced by the DLWC is audited internally by senior staff in the Riverine Corridor Branch. This involves annual visits to all the DLWC's regions and extensive field visits to accompany regional staff during their work.

6. FUTURE ACTION

6.1 Performance Measurement

The Riverine Corridor Branch will be monitoring the level of community education and stakeholder input in each region by maintaining a database of the river restoration works carried out each year. (Permits are usually required for works). This will be analysed to determine the ratio of works funded and designed partly by the government to those funded and designed solely by the community group or landowner/manager. An increase in the proportion of works done without government aid should indicate:

- that the community knowledge of rivers and river restoration works is increasing and
- that there are more people with the attitude that they own the problem and that they should be doing something about it themselves.

This database has only recently been established and there is insufficient information from previous years to allow any conclusions to be drawn about trends. However, the nominations for Rivercare 2000 awards and anecdotes from newspaper clippings indicate that many groups and land owners have recently designed and funded works themselves.

A typical example is Mr David Suttor, owner of a grazing property, "Brucedale", on Winburndale Rivulet and Clear Creek near Bathurst, NSW. He has fenced off eight kilometres of bare creek bank. This was done to control stock access and allow regeneration of native vegetation. Although he started with a small grant from the former Green River Banks program (the predecessor of Rivercare), most of the work was done using his family's resources. He saw the benefits from the effects of the first fencing work and plans to fence off all of the riverine corridors through his property. The benefits he mentions include:

- a reduction in the bank erosion rate and loss of land (4 to 6 hectares in the last 2 floods)
- streamlined stock management with a cell system using the creek fences as boundaries
- improved look and value of the property
- a filter for water running off the paddocks, improving water quality in his creeks and in Burrendong Dam (on the Macquarie River near Wellington) if everybody followed his example
- a filter for flood water "so that we won't have to pick up sticks from the lucerne paddock every time the creeks overflow"

6.2 Internet Access

The DLWC intends to have much of its community education material and public-access data available to internet users by the end of 1996. This will also include newsletters, newsgroups and email addresses for "River Wizards" (expert staff who can answer technical questions). Some of this information is already available through the DLWC home page (http://www.dlwc.nsw.gov.au/). The Streamwatch home page is coming soon.

7. CONCLUSION

A program is in place for educating the New South Wales community about river management. If it is a success, we should see a gradual increase in the proportion of river management works designed and carried out by community groups and land owners themselves.

Land Development and Stream Management in the Tully and Murray Rivers Catchment, North Queensland.

Rob Lait, Mike Merrin**, and Bruce Gaydon****

ABSTRACT:

The Tully-Murray Rivers catchment of North Queensland is located in one of the highest rainfall areas in Australia and has the highest average annual discharge per catchment area in Queensland. The catchment has considerable economic potential and is an important fish habitat area.

More than 9000 hectares of grazing and forest lands within the catchments floodplain have been targeted for sugarcane expansion under the joint community, industry and government-sponsored Sugar Industry Infrastructure Package.

The expansion of the sugarcane industry in the catchment would significantly boost the local and state economies but is contingent on removal of residual floodwater to minimise inundation times. It is the basic requirement of the Package that any development will proceed in a planned and environmentally responsible manner.

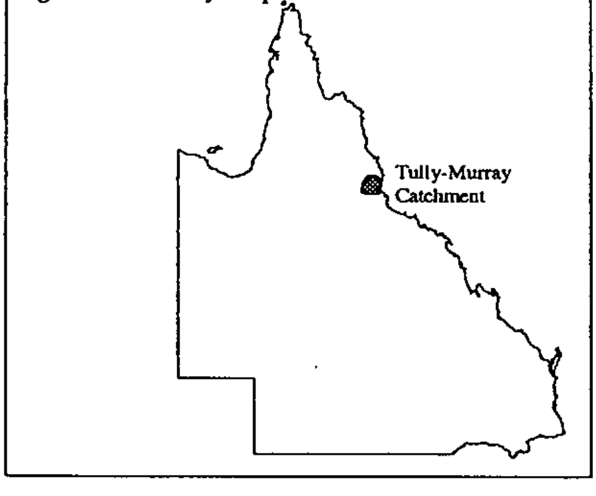
Strategic management of the waterways which traverse the floodplain is fundamental to the success of the Package.

1. THE TULLY-MURRAY RIVERS CATCHMENT

1.1 Location and Climate

The Tully-Murray Rivers catchment (Latitude 18°S, Longitude 146°E) is located in the wet tropical coast of North Queensland (Figure 1).

Figure 1 : Locality Map



The catchment experiences humid summers and mild relatively dry winters. Rainfall is concentrated in the period between October and March and is monsoonal. There is a strongly declining rainfall gradient from north to south with the town of Tully - to the north of the catchment receiving a mean annual rainfall of 4287mm over 151 wet days, and the town of Cardwell - to the south of the catchment receiving a mean annual rainfall of 2127mm over 135 wet days. It is not unusual for little or no rain to fall from April to September.

Mean monthly temperatures range from 14°C in June to 31°C in December. The prevailing summer winds are northeasterly and are monsoonally influenced. During winter much drier southeasterly winds prevail (Cannon, Smith and Murtha, 1992).

1.2 Catchment Hydrology

1.2.1 Surface Hydrology

The two main drainage features of the catchment are the Tully and Murray Rivers. The Tully River rises in the ranges immediately inland of Tully and has a total length of only 80km. It is classified as a Wild and Scenic River and flows through World Heritage listed area for the first 30km of its course. In this section the Tully River has steep bed gradients. Where it enters the floodplain, gradients flatten remarkably and the river becomes meandrine.

The mean annual discharge of the Tully River is 3401 521 ML with a range of between 4972 953 ML (1973-1974) and 2 003 425 ML (1977-1978) (QWRC, 1980). The area of the catchment above the measuring point is only 1475 km^2. Consequently the Tully River has the highest mean annual discharge per catchment area of any river in Queensland.

By contrast, the Murray River has a much smaller catchment area with a mean annual discharge of 226 240 ML ranging from 420 041 ML (1973-1974) to 86 508 ML (1977-1978). The total length of the Murray River is only 45km. It , too, rises in steep World Heritage listed land only 30km from its mouth.

For the purposes of this paper discussion will be limited to the Tully-Murray Rivers floodplain. Figure 2 shows that section of the floodplain which is being considered for expansion of the sugarcane industry. A number of smaller, but nonetheless

Queensland Department of Primary Industries * PO Box 20, South Johnstone Q 4859 Phone: (070) 643 911 ** PO Box 1756, Innisfail Q 4860 Phone: (070) 616 477 * PO Box 3180, Toowoomba Q 4350 Phone: (076) 319 200**

important, streams traverse the floodplain. The majority of these enter the Murray River.

Several major lagoons, up to 6m deep, are present in the floodplain. These have resulted as the major watercourses have abandoned their channels with time.

During moderate and high floods the Tully and Murray Rivers merge and that section of the floodplain between their courses may remain inundated for days or weeks, depending on the intensity of the flood event. Potential development of the grazing lands in the western section of the floodplain will probably increase runoff and may exacerbate the flooding problem if unplanned.

1.2.2 Subsurface Hydrology

The floodplain contains two significant aquifers (Herbert and Lait, 1994). The older and deeper aquifer is a semi-confined alluvial aquifer which extends beneath the majority of the floodplain. It is used mainly by landholders adjacent to the Tully River. This aquifer is generally found at depths of between 20 to 40 metres below the surface and is mainly recharged laterally in areas around the periphery of the catchment where it is exposed at the surface. It is overlain by 10 to 15 metres of clayey sediments.

Perhaps the more significant aquifer of the floodplain underlies the area between Porter Creek, the Murray River and Dundonald Creek (Figure 2). This aquifer is unconfined, only 6 metres thick, and very dynamic - completely recharging and rapidly draining each climatic year. This aquifer is heavily exploited for domestic, stock watering and irrigation purposes. It is also in direct hydraulic connection with the floodplain lagoons. Unco-ordinated drainage of the floodplain has the potential to impact heavily on the availability of groundwater in this section of the floodplain.

1.3 Soils

Cannon, Smith and Murtha (1992) provide a comprehensive description of the soils of the floodplain. Generally, the soils are of two main types - those which are derived from the granite hills which form the catchment rim and those which are deposited as flood overbank deposits. The former are generally sandy and the latter silty. Both soil types are suitable for agricultural production.

Associated with the Tully and Murray Rivers are heavy, clayey, potential acid-sulphate soils in a strip which extends for several hundreds of metres either side of these watercourses. Unco-ordinated drainage of these areas could generate acidic leachate.

1.4 Land Use

There are three main types of land use on the floodplain. These are banana production along the Tully River, beef cattle grazing in the King Ranch area west of the Murray river, and sugarcane production in the remainder of the catchment.

The floodplain is also recognised as a major fish breeding area (Hogan and Graham, 1994). The importance of this area to the fisheries of North Queensland has been recognised by the Queensland Government and, following a period of community consultation, the majority of the Tully and Murray Rivers, the floodplain lagoons and any lands which landholders wish to be included will probably be gazetted as a Fish Habitat Area.

2. THE RIVERSDALE - MURRAY VALLEY WATER MANAGEMENT SCHEME

Sections of the Tully-Murray Floodplain are already a major sugarcane producing area in the Wet Tropical Coast region of Far North Queensland with the potential for sugarcane expansion to occur in more than 9000ha of grazing land in the Murray Valley area.

The Riversdale-Murray Valley Water Management Scheme is an approved project under the Sugar Industry Infrastructure Package (SIIP). The Package is a joint initiative developed by the Queensland and Federal Governments in conjunction with the Sugar Industry in 1993, to enhance productivity in the sugar industry on an ecologically sustainable basis.

The purpose of the Water Management Scheme is to enhance productivity of existing and potential agricultural lands in the Riversdale-Murray Valley area through the provision of infrastructure and associated strategies to reduce the period of inundation from the frequently occurring high intensity rainfall events in the area. Measures to mitigate the potential for sustained waterlogging of canelands, and the ensuing yield decline, are seen to be critical in this area due to the likely impacts of the current rates of more intensive agricultural development which is occurring in the Murray Valley area.

It is important to emphasise that the Scheme is not essentially a flood mitigation scheme, but rather a scheme to improve residual drainage in the area, thus reducing the period for which lands remain inundated. The Scheme will need to address the impacts of future agricultural development in addition to infrastructure deficiencies in existing areas. Strategies to minimise the generation of increased rates and volumes of runoff, and to secure adequate outlet capacity in the lower catchment will be key elements of the scheme. These strategies have focussed on preserving the benefits of existing drainage infrastructure in the developed area of the floodplain while also addressing the impacts of future development.

To achieve the overall purpose of the scheme and to ensure its ecological integrity, the SIIP Central Review Committee has developed Terms of Reference to guide the development of the preferred scheme. These Terms of Reference identify a range of environmental considerations and constraints which the scheme needs to address. These relate to the maintenance of essential ecological processes and natural systems, the protection of key natural resources and the management of potential adverse impacts on these systems.

2.1 Scheme Objectives

Based on the overall purpose of the proposed scheme and the issues to be taken into consideration in the project Terms of Reference, a number of objectives have been developed for the scheme, as follows:

Water Management Objectives

- To reduce the period of inundation of existing and potential agricultural lands after flooding;
- To improve residual drainage to allow removal of floodwaters more rapidly from the area after the peak has subsided;
- To ensure that runoff from developing areas does not increase to the point of adversely affecting existing development;
- To maximise the use of the existing drainage system and other existing infrastructure in implementing the scheme;
- To have drainage infrastructure across the area developed and co-ordinated with the natural system capacity.

Environmental Objectives

- To protect and enhance the significant environmental features of the area;
- To maintain and where necessary improve the water quality of the waterways of the floodplain and downstream environment;
- To protect the quality and quantity of the existing groundwater reserves;
- To maintain and enhance land and water habitat for wildlife.

Land Management Objectives

- To encourage the use of suitable soils for agricultural production and avoid the development of marginal or unsuitable lands;
- To ensure the viability of existing farms is not compromised by new land development;
- To ensure the scheme is acceptable to the majority of landholders and other stockholders on the floodplain.

2.2 Strategic Approaches

A number of strategies have been developed to ensure the preferred scheme meets the above objectives. Essentially, these strategies encompass four broad approaches which form the basis for the preferred scheme. They comprise:

- Establishment of an arterial drainage network to maintain and enhance the hydraulic capacity and biological functions of the floodplain;
- Reinstatement and enhancement of natural flowpaths across the floodplain and catchment outlets in the lower floodplain;
- Development of structural and non-structural measures to reduce the adverse impacts of existing and future farm development on downstream lands and systems through:
  - minimising increases in post development runoff
  - co-ordinating drainage inputs to drainage network capacity;
  - establishment of consistent drainage design criteria throughout the area;
- Incorporation of environmental enhancement measures into scheme elements.

2.3 Environmental Considerations

In addition to productivity benefits, the environmental impacts of the elements of the preferred scheme have also been assessed, as required under the project Terms of Reference. Where required, measures to mitigate adverse environmental effects have been incorporated into the works proposed for implementation of particular elements. In some instances, individual elements of the preferred scheme exhibit inherent benefits to the natural systems and ecological processes upon which they impact.

Key environmental issues addressed by the scheme elements, either inherently or by measures incorporated into the works, include:

- Maintenance and enhancement of water quality;
- Protection of groundwater reserves;
- Avoidance of potential acid-sulphate soils and marginal lands for agricultural development;
- Enhancement of instream habitats and riparian corridors;
- Provision for fish passage where required;
- Preservation of significant terrestrial habitats including Mahogany Glider habitat;
- Protection and enhancement of floodplain lagoons and wetlands complexes;
- Protection of significant cultural heritage and archaeological sites;
- Minimising erosion from agricultural development and subsequent sedimentation of waterways and lagoons.

2.4 Elements of the Scheme

Following an extensive period of consideration of engineering, agricultural and environmental factors nine elements of the scheme have been designed. These are:

- Boundary-Brick Creek Improvements
- Boar Creek Natural Detention Area
- King Ranch Wetlands
- King Ranch Detention Area
- Lower Murray Outlet Improvements
- Murray River - Barretts Lagoon Overflow
- Murray River Improvements
- Upper Murray Overflows
- Scheme Area Drainage Improvements

The location of each of the elements is shown on Figure 2.

Each element is a combination of engineering and non-engineering works designed to improve the effectiveness of drainage of floodwaters in an ecologically sustainable manner. It is beyond the scope of this paper to detail these elements and the reader is referred to Connell Wagner (1995) and Department of Primary Industries (October, 1995) for further information.

3. STREAM MANAGEMENT

The success of the Package will depend on establishment and preservation of an arterial drainage network, installation of a network of arterial lagoons, and rationalisation and co-ordination of existing drainage infrastructure.

The establishment of an arterial drainage network will effectively provide a Drainage Master Plan for the area. Key features of the network include Preferential Flow Paths and Arterial Lagoons.

3.1 Preferential Flow Paths

Figure 2 shows those waterways which will be declared Preferential Flow Paths to ensure their preservation as essential features for the discharge of runoff flows from the upper catchment and throughout the floodplain to the outlets at the bottom of the catchment. It is intended that these waterways and their riparian zones will be managed to secure their hydraulic and biological integrity for the future. Reinstatement and upgrading works will be undertaken on waterways where investigations have indicated the need. In addition to these identified works, it is proposed that the functions of all Preferential Flow Paths be preserved and enhanced by on-going management, including the enhancement of their riparian zones. Management measures for Preferential Flow Paths and their adjacent riparian zones will include:

- Prevention of unauthorised modifications or works to the waterways and controls on the erection of buildings or structures which could disrupt flows, eg. access crossings;
- Controls on the discharge of farm drains to Preferential Flow Paths eg. number and spacing of outlets, water quality controls, drainage complying with natural catchment, etc;
- Revegetation of damaged riparian areas in accordance with the value based assessment criteria developed for the scheme (in preference to a "standard" width of vegetation along all waterways). (Malcolm, Lait, Smith, Brownrigg and Merrin, 1995).

3.2 Arterial Lagoons

Arterial lagoons have been included in the scheme to improve water quality. Studies undertaken as part of the preliminary design phase of the scheme have highlighted the need to improve the quality of runoff flows in the area, particularly in those areas where rapid and substantial agricultural development is occurring, to ensure satisfactory water quality is maintained in the waterways and natural lagoons which are important habitats for fish, crocodiles and other aquatic organisms. Recent scientific studies which have monitored the sediment levels in the off-shore flood plume from the 1994 runoff event in the Tully-Murray system have confirmed this need in relation to the great Barrier Reef lagoon (Steven and others, 1995).

In addition to the measures proposed to preserve and enhance the remaining natural lagoons on the floodplain, it is proposed to construct artificial lagoons at strategic locations on Preferential flow Paths throughout the area to help trap silt and nutrients from agricultural runoff, thereby improving water quality. These arterial lagoons will also be capable of providing additional aquatic habitat, replacing many of the natural areas which have been lost to development in the past. They will be appropriately sized and configured to allow sufficient retention time to trap silt and nutrients from frequent runoff events and to meet aquatic habitat needs where required. Appropriate vegetation in the form of wetland sedges and melaleuca species will be incorporated into lagoon features. Arterial lagoons will be used because:

- There will be a time delay before on-farm measures are implemented on properties with existing development;
- On-farm measures will not be practicable in many situations to manage the quality of all drainage flows to Preferential Flow Paths;
- Arterial lagoons will be controlled by the Water Management Board and can therefore be assured of regular maintenance.

Typically, arterial lagoons will have a surface area of at least one hectare and have a variety of depths to a maximum of eight metres. It is proposed that they be located in low lying areas to minimise loss of productive land as well as excavation cost. Excavated material can be used to "build up" adjacent lands to improve the productivity of these areas.

Once lagoons are established, monitoring will be undertaken to evaluate lagoon performance so that design modifications can be incorporated into future lagoon design, if required.

3.3 Rationalisation and Co-ordination of Existing Drainage

Mapping and analysis of the extensive farm drainage systems currently existing in the Riversdale-Murray Valley area have highlighted the need for rationalisation works to address some of the major deficiencies identified in the system. As a result of the ad-hoc nature of the system development over a long period of time, the result is a system with wide discrepancies in drainage capacity and very little co-ordination.

Drain capacities vary widely, from a minimum of 5 litres per second per hectare, (L/S/ha), up to 150 L/S/ha. In addition, many drains are excessively deep, with several identified being between two to three metres deep. Such deep drainage has the effect of depleting groundwater supplies in the shallow aquifer which underlies much of the area.
If drainage continues to develop in such an ad-hoc, unco-ordinated manner, it will result in serious consequences in terms of increased runoff and inundation of productive lands, loss of valuable groundwater supplies and water quality problems in waterways and lagoons. For example, when the area is developed to its full potential, landholders along the Murray River could expect to be subject to a full extra day of inundation under the 3 year/3 day design event adopted for the scheme. These impacts have the potential to seriously affect the productivity and viability of many existing farms in the area.

It is proposed to adopt a design modulus of 10 litres per second per hectare (L/S/ha) for all drainage works in the scheme area. This rate is sufficient to remove the runoff from the 3 year/3 day design rainfall event in a 3 day period. Studies by Bureau of Sugar Experimental Stations and others have concluded that yield losses from canelands in the Wet Tropics are not significant where this time requirement is met (Rudd and Crardon, 1977). These studies have shown, however, that where caneland is inundated for periods extending beyond 3 days, losses of the order of 0.5 tonnes per hectare can be expected for each additional day of inundation.

Modifications are proposed to reduce the capacity of existing drains where capacity exceeds the design drainage modulus. This will ensure that all drainage is rationalised on an equitable basis consistent with the capacity of the arterial network. This will involve partial filling of drains over a short distance (say 10 metres) at intervals along the drain.

In addition, control structures will be installed in excessively deep drains which have the potential to deplete shallow groundwater reserves. These structures will consist of a small weir in the bed of the drain, with a control crest set to a level sufficient to prevent excessive groundwater loss.

4. MANAGEMENT ROLES

The Riversdale-Murray Valley Water Management Scheme involves the following key stakeholders:

- The landholders of the Tully-Murray Rivers floodplain;
- Cardwell Shire Council;
- Cardwell Shire River Improvement Trust;
- Department of Primary Industries;
- Department of Environment and Heritage;
- Bureau of Sugar Experiment Stations;
- Tully Sugar Mill;
- Mourilyan Sugar Mill;
- South Johnstone Mill.

Each of the stakeholders has a management role with the leading stream management roles being shared by the Cardwell Shire River Improvement Trust and the Department of Primary Industries. Cardwell Shire Council are in the process of adopting a Development Control Plan at the time of writing. This Plan links strongly with the objectives of the River Improvement Trust which essentially implements works in the waterways on the floodplain. The River Improvement Trust will share responsibility for the improvement and maintenance of the schemes Preferential Flow Paths with the Sugar Mills and landholders.

5. CONCLUSION

The catalyst for co-operative water management on the Tully-Murray Rivers floodplain has been the desire for ecologically sustainable development on behalf of all of the stakeholders.

The proposed Riversdale-Murray Valley Water Management Scheme is a good example of a community-driven planning, research and management effort. Waterway management is a key component of the Scheme. The Scheme has raised awareness in the community and management agencies of the vital link between agricultural production, habitat values and environmental needs. The ultimate success of the Scheme will depend on a co-operative approach to floodplain management generally and waterway management in particular.

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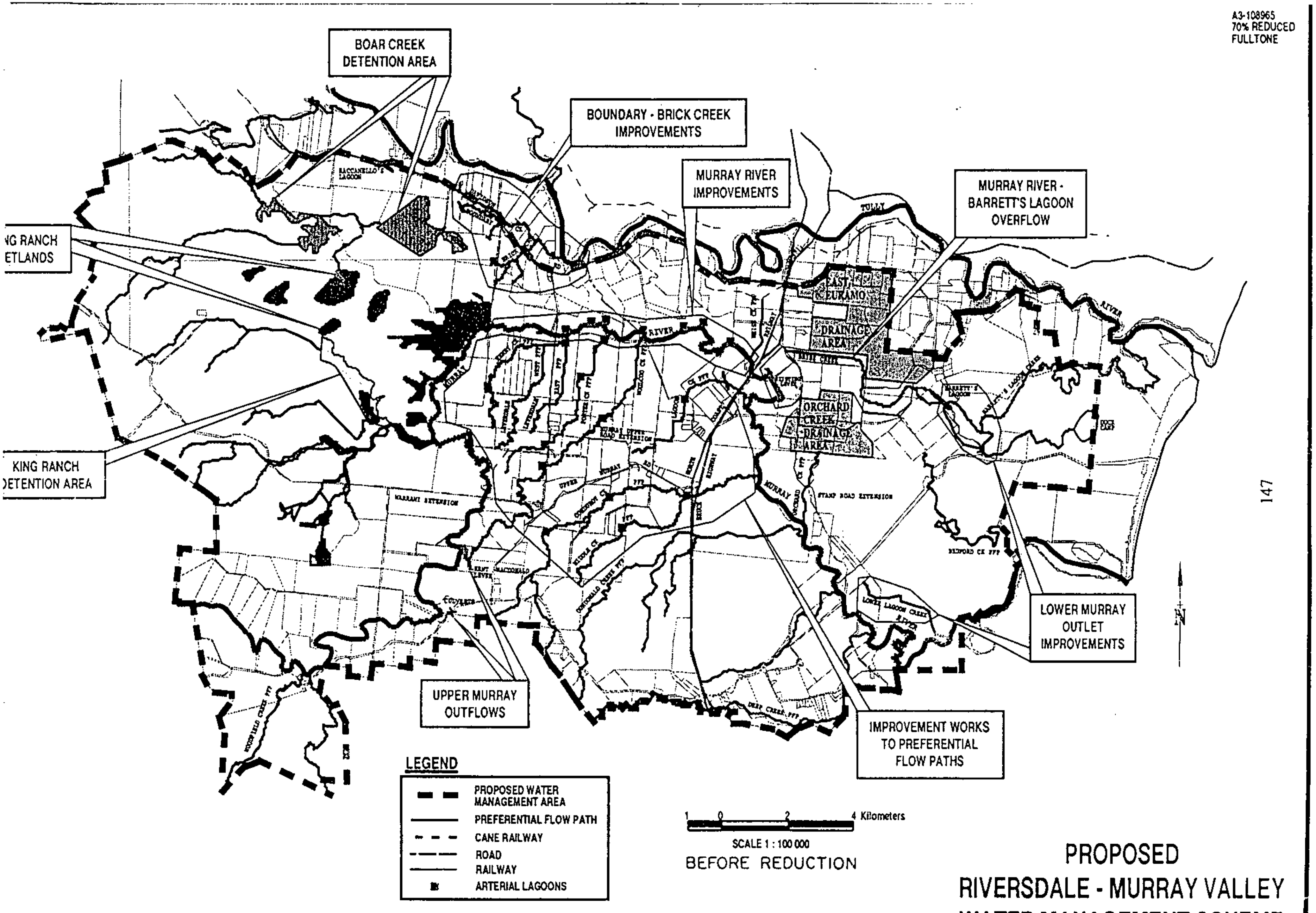
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70% REDUCED
FULLTONE
BOAR CREEK DETENTION AREA
BOUNDARY - BRICK CREEK IMPROVEMENTS
MURRAY RIVER IMPROVEMENTS
MURRAY RIVER - BARRETT'S LAGOON OVERFLOW
NG RANCH ETLANDS
KING RANCH DETENTION AREA
EAST EURAMO DRAINAGE AREA
ORCHARD CREEK DRAINAGE AREA
TULLY
RIVER
MURRAY
LOWER MURRAY OUTLET IMPROVEMENTS
UPPER MURRAY OUTFLOWS
IMPROVEMENT WORKS TO PREFERENTIAL FLOW PATHS
LEGEND
PROPOSED WATER MANAGEMENT AREA
PREFERENTIAL FLOW PATH
CANE RAILWAY
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PROPOSED
RIVERSDALE - MURRAY VALLEY

Management Plan for the Upper Condamine River and Tributaries

Bruce P. Gaydon*, Greg A. Murphy*, Lyall E. Hinrichsen and Andrew J. Markham****

ABSTRACT:

The Warwick and Clifton Shire River Improvement Trusts, with the support of the Department of Primary Industries and the Commonwealth National Landcare Program, funded the preparation of a River Management Plan which provides the framework for addressing key management issues impacting upon the Upper Condamine River, its tributaries and associated riparian zones within the Shires of Warwick and Clifton, Southern Queensland. The process used in preparing this plan involved field assessment, community participation and co-operation from various agencies. The Study was the first of its kind for a river system in inland Queensland.

The Upper Condamine River, within the Shires of Warwick and Clifton has a catchment area of over 5300 km^2. The combined length of the Condamine River and its main tributaries in the Study Area is approximately 1050 km. Land uses comprise intensive agriculture, grazing, forestry, intensive livestock, meat and dairy processing, other industries, National Parks and Urban Centres. Furthermore, recreation and the environment are important values for the area.

The Study process involved the assessment of the physical and environmental condition of the river system and riparian zones, the description of the processes impacting on that condition and the identification of stakeholders and beneficiaries and their relationships with the river system.

Key management issues identified included the management of riparian vegetation, stream siltation, erosion, flood break-outs, water quality, accelerated rates of runoff, perceived threats to riparian lands and water rights, inadequate public awareness on stream management issues and the lack of funding for river management.

1. INTRODUCTION

The Condamine River forms part of the upper-most headwaters of the Murray-Darling River System.

The Study Area comprised the upper part of the Condamine River Catchment, within the Darling Downs Shires of Warwick and Clifton (refer Fig. 1)

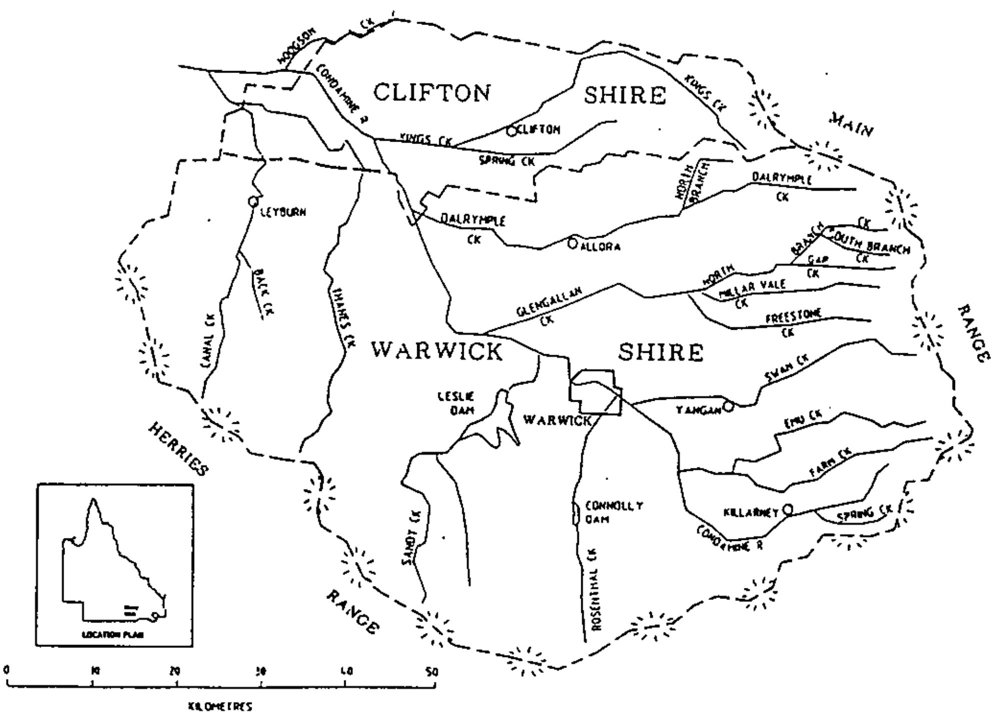

Figure 1: Locality Plan: Upper Condamine River Catchment

* *Queensland Department of Primary Industries, P.O. Box 3180, Toowoomba Qld. 4350.*
** *I.D. & A. Pty. Ltd, P.O. Box 631, Townsville Qld. 4810.*

2. HISTORY AND DEVELOPMENT

2.1. Discovery and Settlement

The area was 'discovered' by explorer and botanist, Alan Cunningham, on an expedition from the Hunter Valley, in 1827. Cunningham, even then realised the importance of his discovery, writing in glowing terms of the area's rich soils and the luxuriance of the pastures. Though only some 100km from the coastal settlements around Brisbane, the area was initially inaccessible from the coast due to the rugged nature of the Great Dividing Range.

Cunningham returned to the Downs in 1828, trekking west from Brisbane and travelling via a 'Gap' in the Dividing Range, which he had recorded during his first journey.

Twelve years later, a trail was blazed through Cunningham's Gap and the first settlers arrived with their large flocks of sheep. By 1847, the entire area had been taken up by squatters (Power, 1993).

The area was more closely developed in the period from 1860 to 1870, with the larger pastoral holdings being sub-divided into smaller parcels for agricultural use. By the late 1800's, some 20,000ha in the Warwick District was under cultivation.

2.2. Agriculture

The Darling Downs area is renowned as being one of the best agricultural areas in the nation. Approximately 124,000ha of land is cultivated within the Study Area (Carberry, 1995), producing a variety of crops including sorghum, sunflowers, barley, maize, wheat, lucerne and fodder crops.

The area also supports significant numbers of beef and dairy cattle, sheep and pigs.

2.3. Urban Development

The major urban area within the Study Area is the City of Warwick, with a population of 10,000. Including surrounding rural areas and other smaller centres, the total population of Warwick Shire is 19,000 and 5,800 for Clifton (Carberry, 1995).

2.4. Water Resources

As is typical for most inland river systems, stream flows are extremely variable. Flow gauging records for the period from 1961-1991 show annual runoff rates ranging from 0.9 to 261ML/km^2, with an average of 43.5ML/km^2.

Associated with the intensive agricultural development is a high demand for irrigation supplies. Groundwater sources supply the bulk of this demand due to the relative unreliability of surface flows. Department of Primary Industries' estimates indicate that annual water consumption from groundwater sources is 30000ML with 7000ML per annum being drawn from 'unregulated' surface water sources.

Major water conservation works are limited to a 107,000 ML Storage on Sandy Creek (Leslie Dam) and a smaller storage on Rosenthal Creek (Connolly Dam). Leslie Dam provides both irrigation water supplies (80% of yield) and urban supplies. Connolly Dam is utilised entirely for urban water supply purposes.

Sandy and Rosenthal Creeks are minor tributaries of the Condamine River, that drain catchments principally of granitic origin.

In the lower parts of the Condamine River system, below the Study Area, there is also a substantial amount of private development involving the 'harvesting' of flood flows. Within the Study Area, there is only limited waterharvesting.

2.5. History of River Management

River Improvement Trusts have operated in the Upper Condamine Area since 1956.

The catalyst for the formation of the area's River Improvement Trusts was the heavy infestation of the Condamine River and many of its tributaries by Weeping Willows.

In 1950, a major flood event resulted in massive break-outs at a number of locations along the Condamine River and some of its major tributaries. These break-outs caused severe soil erosion and waterlogging of cropping land.

At the time, there was a prevailing view that such break-outs were simply the result of a flood event of exceptional magnitude.

In subsequent years, however, further break-outs were reported. In many areas, it was feared that these break-outs would ultimately result in major stream course changes. It was then recognised, that the prolific growth of Weeping Willow trees within and adjacent to these streams had significantly reduced the flow capacity of the streams.

It was concluded that the Willow trees needed to be removed to alleviate this flooding problem. This culminated in the 1956 formation of the Condamine Trust, which covered part of the current Study Area.

* *Queensland Department of Primary Industries, P.O. Box 3180, Toowoomba Qld. 4350.*
** *I.D. & A. Pty. Ltd, P.O. Box 631, Townsville Qld. 4810.*

In the following years, River Trusts, in various forms, were eventually created and expanded to cover the entire Study Area.

The 'principles' under which the Condamine and other Trusts operated were simply:

- To clear Willow trees selectively.
- To undertake an experimental program of poisoning Willow trees.
- To clear the river and creeks of flow obstructions.
- To attempt to prevent flood break-outs (through the construction of levee banks).

By the mid 1970's, the majority of the Willows and major snags had been successfully removed in each of the Trust areas. From this time, the Trusts devoted most of their resources towards paying-off past debts. Only limited works involving regrowth control and the removal of major snags, caused by fallen gum trees and the like, were performed.

To date, the focus of the Trusts has remained on regrowth control and clearing debris obstructing stream flows. Various works have also been performed in order to prevent potential avulsions and protect eroding stream banks.

3. BACKGROUND TO STUDY

The study was borne out of a recognition by the Warwick and Clifton Shire Trusts and the Department of Primary Industries that a strategic approach to river management was required.

This recognition corresponded to community and Government expectations for river managers to broaden their focus beyond just physical stream attributes to include also biological and social values associated with stream systems.

Furthermore, it was clear management strategies needed to be based on a firm understanding of stream processes. Prior to this Study, very little was understood about either physical or ecological stream processes, and particularly how these processes have been affected by catchment development and past stream management practices.

4. GEOMORPHOLOGY OF THE UPPER CONDAMINE RIVER SYSTEM

The Condamine's tributaries are characterised, to a large degree, by the nature of the soil and geological units they drain. A number of tributaries drain westwards across thick alluvial deposits of volcanic origin overlying Tertiary volcanic and Jurassic sandstone and other sedimentary material. These are referred to as the **Alluvial Streams**.

Those streams to the west of the Condamine and draining eastwards are referred to as the **Western Streams**. These drain across Jurassic and older Carboniferous sediments, granites and other intrusive rocks. Alluvium is much thinner in the western streams. The western streams are, therefore, better controlled by resistant bedrock outcropping.

4.1. Alluvial Streams

The alluvial streams include Hodgson, King, Spring, Dalrymple, Glengallan, Freestone, Swan, Emu and Farm Creeks.

Most of these streams are severely incised for much of their course. Incision is evident from perched gullies, trenching or terracing of the channel bed and banks, and active bank erosion (triggered by deepening). Upland sediment storage zones were also observed and severe gullying on some streams. Active incision in the form of upstream-progressing nick-points were also observed.

4.2. Western Streams

The Western streams include Rosenthal, Sandy, Greymare, Rodgers, Thanes, Canal and Back Creeks.

The western streams are in better physical condition than the alluvial streams. This is largely because their form is controlled by frequent bedrock outcrops, unlike the alluvial streams where the streams erode easily through the unconsolidated alluvial and colluvial material. Sandy Creek carries a high sand load as it drains from granitic material. Large sand deposits were observed in a tributary of Sandy Creek upstream of Leslie Dam. Downstream sites show no signs of degradation although re-working of bed material is likely during higher flows.

Many reaches of the Western streams are characterised by snags and vegetation in the channel.

4.3. The Condamine River

The Condamine River rises east of Killarney and flows west across Tertiary volcanics through Killarney and across older sedimentary material, before turning north-west at the Elbow Valley Fault. It continues, thereafter, through Warwick in a north-westerly direction before branching downstream of the Hodgson Creek confluence and flowing out of the Study Area.

Below Warwick, the Condamine's alluvial deposits are more extensive, forming vast plains that have been intensively developed for agriculture. Oxbow lakes are visible around the Dalrymple and Kings Creek confluences. Numerous break-out channel

* *Queensland Department of Primary Industries, P.O. Box 3180, Toowoomba Qld. 4350.*
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paths are also evident throughout these alluvial plains.

Inspection of the long-profile of the river shows a classic concave-upwards shape. Generally, concavity increases as the degree of resistance or outcrop control decreases as would be expected.

Unlike many of its alluvial tributaries, the main river is in good physical condition. This is mainly because it is controlled, throughout much of its length, by bedrock outcrops. The numerous relic channels and floodplain channels, however, potentially could capture the main channel.

5. A MODEL FOR AUSTRALIAN RIVER CHANNEL CHANGE

Erskine, (in Ian Drummond and Associates, 1993) developed a 4-stage model to account for changes before and since European settlement in the Goulburn River catchment which has been adopted as a general model for the Condamine River. The model is described, briefly, below. The four stages are as follows:

- Pre-European;
- Depositional;
- Incising;
- Present.

5.1. Pre-European

The pre-European conditions of the rivers was one of dynamic equilibrium, over a time-scale of, say, 1000 years. In general, sediment supply was equal to sediment delivery while processes such as meander development and slope changes continued as a result of natural processes.

5.2. Depositional Phase

With the arrival of Europeans, large-scale clearing of floodplain and other catchment areas released huge quantities of sediment to the river systems. This is referred to as Post-Settlement Alluvium (PSA). This PSA is delivered towards the river and deposited over much of the inner floodplain to a thickness of around 1m, but particularly around confluences with main stream stems as deltas or alluvial fans.

5.3. Incising Phase

Following delivery and deposition of the immediately-available new sediment, supply rates slowed as upstream sediment supplies became exhausted and increased runoff increased the streams' sediment transport capacities. Streams began to incise back through the PSA deposits. Increased runoff resulted from better drainage and clearing which increased overland and shallow subsurface flow. In recent times, improved soil conservation and farming practices helped reduce the supply of sediment to the streams.

However, rapid incision and deepening caused further channel instabilities which, in turn, caused widening and terracing through width adjustment and bank erosion. Freshly-worked deposits became transported and deposited further downstream.

5.4. Present Phase

The present phase in many stream systems is characterised by relative stability. Sediment loads have reduced and streams have adjusted their form to suit. Some floodplain vegetation has been re-established and banks stabilised.

6. EFFECTS OF EUROPEAN SETTLEMENT IN THE CONDAMINE CATCHMENT

The following section documents the history of land-use change in the Condamine catchment and develops a specific application of the model described above.

6.1. Pre-settlement conditions on the Condamine River

From historical accounts, It is clear that the tributaries, particularly the alluvial streams, were less-well developed than they are today. Cunningham refers to Glengallan Creek as "a chain of deep ponds" from observations on 5th June 1827. The relevant quotation from his diary is as below:

"Deep ponds, supported by streams from the highlands, immediately to the eastward, extend along their central lower flats; and these, when united in a wet season, become an auxiliary to the Condamine's River, a stream which winds its course along their south-western margin."

6.2. Effects of European Development

It can, reasonably be assumed that gully development commenced in the Condamine catchment soon after European settlement, particularly given the poor resistance of the alluvial soils found there. Early pioneers allowed the fertile flood plains to be heavily grazed (Carberry, 1995). Intensive agricultural development also occurred rapidly following settlement.

6.3. Hydrological Response

Clearing of native vegetation for agricultural development, similar to that which occurred immediately after European settlement, is known to have major impacts on the drainage network and sediment transport. These include:

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- Changes to the hydrological balance (decreased evapotranspiration and increased overland flow);
- Loss of floodplain storage area for floodwaters;
- More frequent higher flows and less frequent lower flows;
- Reduced resistance to erosion of both the river bank and floodplain; and
- Salinity and high water tables.

The sediments released from the catchment by the different methods of erosion were either re-deposited on the floodplain during overland flow events or delivered to the tributaries. In the early years, sediment volumes may have been very large; the streams conveying a slurry of water and sediment during floods, particularly downstream of gully confluences.

6.4. Incision and re-working of sediments

Following the dramatic sediment releases immediately following European settlement, coinciding with a period of decades of above-average rainfall, it is likely that sediment loads declined. This was, to some extent, due to the realisation of the problems, improved practices and the spread of Willows in the streams and riparian zones.

There then followed a period of incision in the streams and reworking of sediment. Incision probably worked upstream from the base of the tributaries, and back from the banks of the tributaries as headcuts or gullies. This occurred because as the upstream supply of sediment declined, the streams were able to transport material that had been recently deposited on the beds.

However, the spread of Willows eventually began choking the streams and encouraging deposition. Following removal of the Willows in the 1960's, a second phase of incision has occurred. Material deposited in alluvial fans along the Condamine is gradually being eroded and transported downstream. The rate of sediment yield thereafter decreased rapidly from this second peak through time. Most of the post-Willow incision may have happened within a few years. It is reasonable to assume, therefore, that the second incision phase is nearing completion. Bank erosion, however, is ongoing in most of the alluvial streams.

6.5. Bank Erosion in the Alluvial Streams (Present Day)

The second phase of incision following the removal of Willow trees has been accompanied by channel widening and meander migrations on most of the alluvial tributaries as the streams adjust to increased discharge, decreased boundary resistance (removal of vegetation), and, to a lesser extent, a change in long-term flood frequency.

Bank erosion is manifest through meander migration and channel widening. Meander migration is caused by different hydraulic processes but achieved through bank erosion. Meander migration may be ongoing and, is a more complex channel response, incorporating longitudinal instabilities.

7. COMMUNITY INVOLVEMENT

The success of any stream management strategy will depend, ultimately, on the level of community ownership and support. With this in mind, the Study involved a significant community consultation program. This involved stakeholder participation in both formal workshops and in on-site field discussions.

Out of this process, the following key issue areas were identified:

- Riparian Zone Vegetation Management;
- Stream Capacity and Stability;
- Water Management;
- Landholder Rights, Resources and Support Systems;
- Land Management; and
- Water Quality.

The specific concerns relating to each of these categories are detailed in the following table.

Table 1: <u>Summary of Key Management Issues</u>

Management Issue	Key Areas of Concern
1. Riparian Zone Vegetation Management	• Spread of the weed Lippia. • Growth of exotic vegetation. • Loss of native vegetation. • Grazing within the riparian zones. • The possibility of restrictions on land-use • Growth of water weeds.
2. Physical Capacity and Stability of Streams.	• Channel obstructions. • Stream siltation. • Bank erosion. • River course changes. • Flooding.

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3. Water Management.	• Lack of groundwater recharge. • Over use of groundwater reserves. • Lack of water storages. • Inadequate regulation of water consumption.
4. Landholder Rights, Resources and Support Systems.	• Threats to existing water and land rights. • Lack of guidelines defining best practice. • Lack of finance for stream management. • Lack of community awareness and education programs.
5. Land Management.	• Inadequate on-farm moisture retention. • Deficiencies in runoff control. • Soil erosion.
6. Water Quality.	• Poor water quality.

8. FUTURE MANAGEMENT APPROACH.

The project Steering Committee recognised that the Trusts should take-on a lead agency role for the first two issue categories identified above. The other, issues, though in themselves important, were considered to be outside of the Trusts' core activity area. Indeed, many of these areas were already covered by agencies or groups with well-established and recognised lead agency roles. The Trusts' roles relating to these non-core issues will focus largely on improving inter-agency co-ordination on stream management. This process will be facilitated through a community-based, Catchment Co-ordinating Committee that has formed for the Condamine River Catchment in recent years.

The roles that will be adopted by the Trusts relate closely to the traditional Trust roles. However, there is also recognition of the need to manage for a much broader suite of stream values. Apart from the Trusts, there is no alternative agency with lead-agency status in managing the physical integrity of the streams or the riparian vegetation.

8.1. Elements of Management Strategy.

Pro-active and thoughtful management will be necessary for the rehabilitation of the physical and biological condition of the Upper Condamine River System.

This will require a combination of in-channel stabilisation works and changes to land management practices. To fulfil the required role, the Trusts will need significantly increased resourcing. They will also need a broadened expertise base amongst Trust membership and technical and operational staff. However, of probably more importance is raising community awareness of the processes that have resulted in stream degradation and then encouraging the adoption of land management practices that are sensitive to stream values.

This Study has been an important first step in raising community awareness of the problems that exist and in encouraging community participation in addressing such problems. On-going community involvement in strategy implementation will be an integral part of the Trusts' future management approach.

Key elements of the management strategy therefore include:

- an emphasis on community education programs;
- increased community involvement in Trust planning and strategy implementation;
- involvement with other agencies in the preparation of guidelines defining best-practice in land and riparian zone management;
- interaction with other agencies on issues affecting the physical or ecological values of the area's watercourses;
- actively pursuing increased funding for river management;
- support for and participation in research projects relevant to stream management;
- actively supporting and participating in soil conservation and gully-erosion control projects.
- managing flooding problems through both works implementation and involvement in land management planning;
- performing stabilisation works on those streams where erosion is of concern;
- undertaking riparian zone revegetation works;
- ensuring the protection of riparian vegetation by encouraging the adoption of appropriate management practices or by statutory means where necessary;
- actively participating in the control of problem exotic weed species; and
- managing snags to provide a balance between preserving habitat values and maintaining the physical integrity of the stream.

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** *I.D. & A. Pty. Ltd, P.O. Box 631, Townsville Qld. 4810.*

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** Queensland Department of Primary Industries, P.O. Box 3180, Toowoomba Qld. 4350.*

*** I.D. & A. Pty. Ltd, P.O. Box 631, Townsville Qld. 4810.*

The Identification, Conservation and Management of Wild Rivers in the Kimberley Region of Western Australia

P.J Williams*; L.J. Pen*; J.A Stein**; J.L Stein** and B. Prince***

ABSTRACT: *A project identifying Australia's wild rivers is presently being undertaken. A specially developed G.I.S. has identified possible candidates and been proven to give a reasonably accurate indication. A pilot field study and verification exercise was undertaken in the Kimberley Region where excessive grazing pressure is the major cause of riverine degradation. All 65 of the Region's rivers were inspected, compared and assigned to one of five categories ranging from wild to degraded. Seventeen were found to still be in a wild condition and conclusions reached as to how their values might be conserved.*

1. INTRODUCTION

The Australian Heritage Commission (AHC), on behalf of the Commonwealth Government, is undertaking what is known as the Wild Rivers Project . Its aims are to identify all wild rivers throughout Australia, to work with the States and Territories to develop guidelines for their management, and to make the whole community aware of their existence and special values.

Wild rivers are defined by the AHC as rivers which are relatively undisturbed by the impacts of modern technological society. Wild rivers remain undammed and exist within catchments where biological and hydrological processes continue without major interference. They occur within a variety of landscapes and may be permanent, seasonal, or dry water courses which flow only occasionally. The first phase of identification at the national level is being undertaken through a Geographic Information System (GIS) analysis being conducted for the Commission by the Centre for Resource and Environmental Studies (CRES) at the Australian National University (ANU).

At the same time, Western Australia has embarked upon a process of allocating all of the State's water resources, both divertible and in-situ, to all of the various consumptive and non-consumptive uses that society requires of them. The riparian zone is the most extensively degraded natural resource zone in Australia (CEPA 1992). As a part of the process of allocation, Western Australia is seeking to identify rivers that are 'outstanding' from various possible viewpoints. These include rivers with special cultural significance to both Aboriginal peoples and more recent settlers; rivers with unique topographical, geological or biological features; and the finest, best preserved examples of rivers across the full range of hydrologic, physiographic, vegetation association and other variables.

These shared interests provided an opportunity to establish a collaborative project between the AHC and the Water Authority of Western Australia (WAWA) to assess the rivers of the Kimberley Region, testing the preliminary results of the CRES study and providing direction for similar verification studies which may be required in other parts of Australia. A joint field study was undertaken in June 1995. Its aim was to confirm the primary cause of riverine degradation in the Region, and to identify rivers in wild, and a range of less well preserved conditions. In doing so it has provided the basis of a future State Government riverine resource allocation, to be augmented by studies of Aboriginal significance, recreational, scientific and educational use, as well as diversion potential. It has also helped formulate ideas regarding future conservation and management of both the 'wild' and the somewhat degraded rivers of the Region.

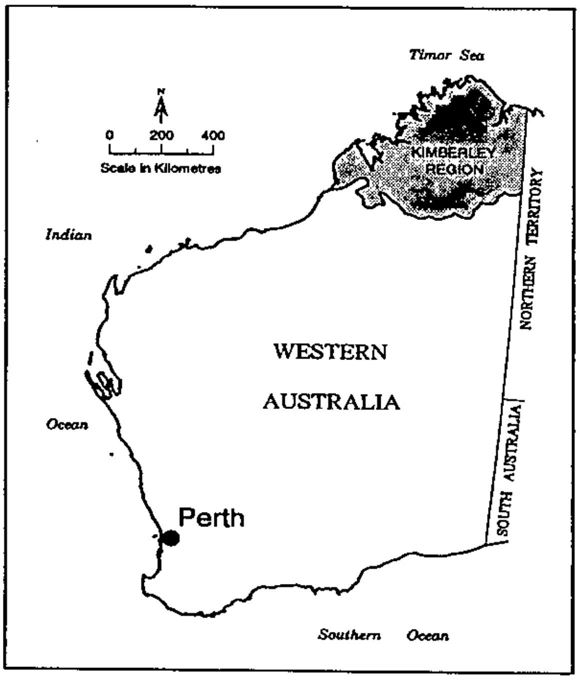

Fig. 1. Location Plan

*Water Authority of Western Australia, PO Box 100, Leederville WA 6007. **Australian National University
Telephone: (09) 420 2645 Fax: (09) 420 3174 ***Australian Heritage Commission

2. THE KIMBERLEY REGION

The Kimberley Region is located in the extreme north of Western Australia, between latitudes 14° and 22° S (Fig. 1). It constitutes the portion of the AWRC's Timor Sea Drainage Division that comes within the State. It is 277 230 sq. km in area.

2.1 Climate

The Region experiences only two distinct seasons. The wet, tropical rainfall season extends over the summer months from April to October. Summer rainfall is monsoonal, resulting from cyclonic activity. Rainfall varies from over 1 400 mm per annum, received within a belt extending along the north-west coast from Admiralty Gulf down to the Prince Regent River, to less than 400 mm along the Region's southern boundary., Rainfall is relatively reliable in northern coastal areas, but not at all so in southern inland areas. Daily maximum temperatures vary little throughout the year. On the coast they range from about 30°C in July to about 33°C in January. Inland the corresponding figures are 27°C and 39°C respectively. Similarly, minima range from 12°C in July to 20°C in January at the coast, and from 9°C to 24°C inland.

2.2 Landform and Soils

While not mountainous, the highest point being the centrally located Mount Hann at 776 m AHD, the Kimberleys are rocky and rugged, with steep-sided ranges and gorges. The north-western portion, approximately half of the entire Region, consists of a broad and irregularly dissected plateau. This is flanked to the south and east by the rugged King Leopold and Durack Ranges. Beyond these lie the sand plains, dune fields and tidal flats of the Dampier Peninsula and the broad alluvial Fitzroy Valley to the south, while to the east lie the Ord Plans, the rugged Lamboo Hills and the Cambridge Gulf lowlands.

A wide range of soil types occur. However, over most of the Region there is mainly bare rock with small areas of shallow skeletal soils. Deep red or brown sandy soils occur on the sand plains and dune fields of the south and east. In addition, there are widely scattered areas of red and yellow earths, and the grey and brown cracking clays known as 'black soils', the latter being the backbone of the pastoral industry as well as holding the most potential for irrigated agriculture.

2.3 Vegetation

Most of the northern Kimberley is covered in an open forest or woodland formation, dominated by Eucalyptus or Acacia species (Beard, 1979). This becomes progressively more open as rainfall diminishes towards the south, where trees become sparse and grasses become the most characteristic component. The Kimberley ground flora is dominated by grasses from a wide range of genera while shrubs are typically scarce. The World Conservation Strategy (IUCN, 1980) states that tropical grassland ecosystems, such as those of the Kimberley are under-represented in conservation reserve systems worldwide.

Two vegetation types of relatively limited extent deserve special mention. The first is the relatively numerous but small patches of rain forest, located mainly in heavy rainfall northern coastal areas, but with a few extending inland and as far south as Broome. The second is the mangrove communities forming extensive low closed forests on tidal flats at the mouths of most rivers. These are particularly diverse and rich in species composition.

2.4 Rivers

The Kimberley has a well defined and extensive network of surface water courses. Mean annual run-off to the ocean is an estimated 36 000 million cubic metres, 75% of that of the whole of State. Streamflow is irregular; however, all major rivers do flow every year. Only a few rivers in the extreme north-west are perennial. Peak floods are very high by world standards and flooding can be severe. All rivers are fresh flowing. However, seawater penetrates up to 100 km inland in places as a result of low stream gradients, low dry season flows and very high tidal ranges. A total of 65 rivers and creeks (see Fig. 2) were identified for field inspection and assessment.

2.5 Population and Land Use

The Kimberley Region has a total population of 30 000 (DRDN/DPUD 1990) of which two-thirds live in 5 small urban centres: Broome; Derby; Fitzroy Crossing; Halls Creek; Wyndham and Kununurra. Approximately 45% of the population is of Aboriginal and Torres Straight Islander descent, compared with 3% for Western Australia as a whole. The main use of land in the Kimberley is for pastoral purposes. There are also a number of large national parks and nature reserves, a number of Aboriginal reserves and significant areas of Vacant Crown Land.

The very limited system of roads has ensured that most of the Region has remained remote and inaccessible. There are two main roads from west to east. The southerly paved Great Northern Highway passes through or close to the urban centres listed in the previous paragraph. The Gibb River Road to the north is unpaved, generally suitable for 4 wheel drive vehicles only, and is closed for a long period each wet season. A third road runs north from the Gibb

Road, providing access to a few pastoral stations and the Aboriginal settlement at Kalumburu.

3.0 METHOD OF ASSESSMENT

The Kimberley was first settled by pastoralists in the 1880s. With pastoralism the only form of land use over nearly all of the region, the most widespread cause of riverine degradation was thought likely to be vegetation damage and loss, and soil denudation resulting in sheet and gully erosion. A programme of inspection was planned based on this assumption.

A two-level aerial survey was undertaken. In the first instance, the rivers were inspected from a light aircraft flying at between 300 and 600 metres. Most rivers were flown from source to sea, covering all major tributaries. They were subsequently reflown and viewed from a helicopter, flying generally at between 30 and 60 metres. Landings were made at a number of locations in order to confirm the aerial impressions, and make a detailed on-the-ground inspection and analysis. The survey was made after the end of the wet season, when most of the rivers were still flowing, but at relatively low volumes. At or close to peak flows it would not have been possible to see much of the necessary detail.

There was not considered to be any point in taking water samples for analysis. None of the rivers would be conveying any quantity of any polluting substance. A detailed sediment load analysis would have been of benefit in many instances. However, such an analysis, to be of any value, needs an extremely lengthy, detailed and carefully planned programme for which neither sufficient time or money was available.

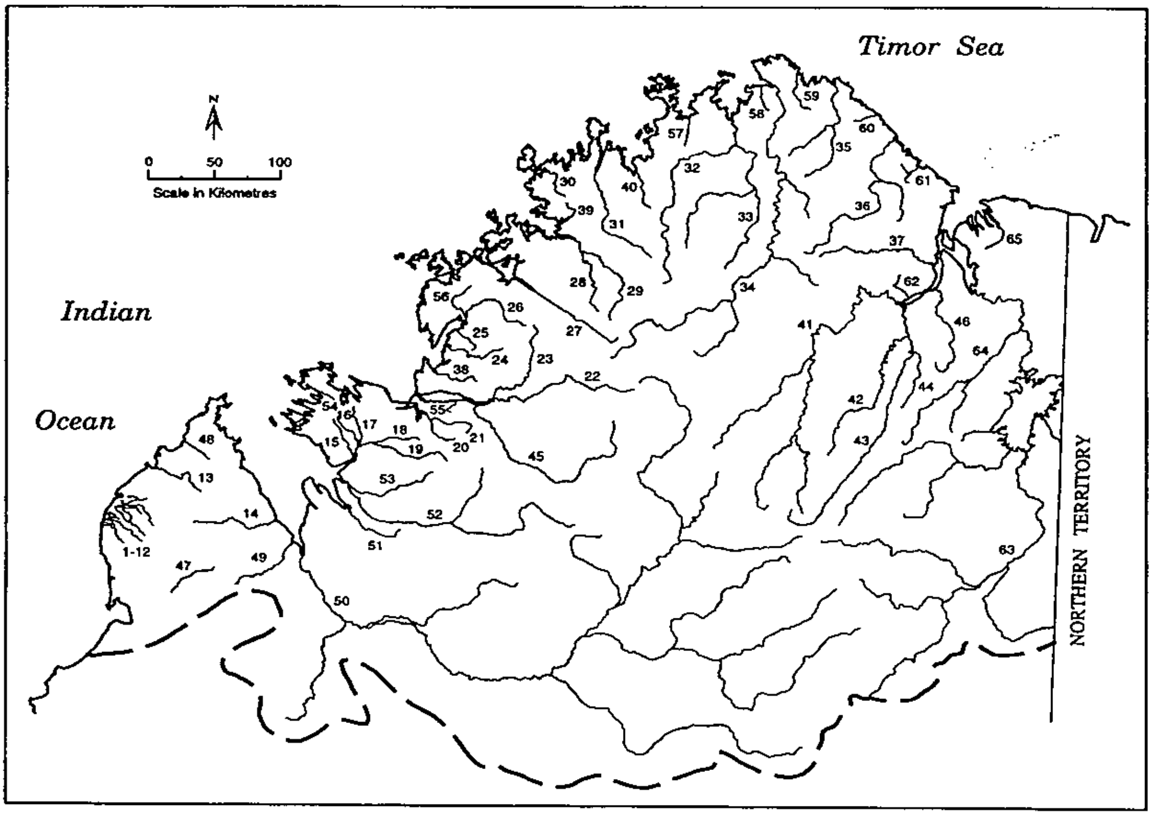

Fig. 2. Kimberley Region Rivers

4. CLASSIFICATION SYSTEM

The rivers inspected were assigned to one of the following categories:

A1 Wild and undisturbed
A2 Wild though modified
B1 Relatively Natural
B2 Altered
C Degraded

Rivers assigned to category A1 (wild and undisturbed) have had no alterations to their water courses or to their catchments since European settlement. There has been no significant:

- clearing or other alteration to the landscape.
- road or track construction;
- increased fire frequency;
- introduction of foreign plants or animals;
- introduction of plant diseases;

Rivers assigned to Category A2 (wild though modified) have had no significant changes to their natural ecosystems, despite some past or present human activity within their catchments. However, there may be:

- some seldom-used minor foot and vehicle tracks;
- some increase in fire frequency;

- v. limited introduction of plant or animal species;
- minor evidence of grazing but no soil exposure.

Rivers in both Categories A1 and A2 fit the AHC project definition of 'wild'.

Rivers assigned to Category B1 (Relatively Natural) are still essentially dominated by native species throughout their catchments, and though they have been changed to some extent, it is considered that with the removal of grazing pressure, they would quickly return to a wild state. They may be experiencing:

- some, but not extensive problems of erosion and sediment deposition
- relatively constant use of tracks;
- some loss of vegetation as a result of grazing;
- increased fire frequency;

Rivers assigned to Category B2 (Altered) have been significantly changed in one or a number of ways. They may have received:

- fairly heavy grazing;
- regular use of fire, degrading some plant communities;
- a moderate number and fairly heavily-used vehicular tracks;
- some unnatural bare patches, sheet erosion and gullying;
- considerable sediment deposition in river floodways, but mainly on point bars.

Rivers in this category have been degraded to such an extent that it would not be possible or practical to return their catchments to a wild state. However, with appropriate rehabilitation measures and proper management, they could be made stable, healthy functioning ecosystems.

Rivers assigned to Category C (Degraded) have been very extensively and radically changed by post European settlement land use. They have been subject to all or most of the following:

- heavy grazing pressure, particularly on sedimentary plains and along water courses;
- frequent fires and related damage;
- many frequently-used stock and vehicle tracks;
- many bare patches, sheet and gully erosion;
- river channels and floodplains heavily silted and eroded;
- trampled river banks and fouled billabongs;
- widespread infestation of weed species;
- impoundments and regulation of river flows.

Though rivers in this category would be capable of being rehabilitated to a considerable extent, it is considered that they could never be returned to anything approaching their undisturbed state.

While there is a distinct theoretical difference between rivers in Category A1 and those in Category A2, there is not between A2 and B1. Also, there is a distinct theoretical difference between rivers in Category B1 and those in B2, but there is not between B2 and C. Rivers in Category A1 are unmodified and have not been changed in any way, as far as is known, since the time of European settlement. All the rivers in A2 and B1 have been changed, and from the best of those in A2 to the worst of those in B1 there is more or less a continuum. The dividing line between B1 and B2 is drawn on the basis that rivers in Category B1 would revert to a wild state, if the land uses causing change were to be removed. In contrast, in the case of rivers in Categories B2 and C, if the land uses causing alteration and degradation were to be removed, the river conditions would improve, but they would not be able to return to near their original undisturbed state. These rivers have been radically and permanently changed.

5. RESULTS

The pastoral potential, or rather the soil condition that gives rise to it, was found to be the determining factor in relation to the condition of rivers in the Kimberley Region. In general, the areas with high potential are the sedimentary river plains with deep productive soils. The bare rock and skeletal soils over most of the Plateau Region have little or no pastoral potential.

Continuous uncontrolled grazing by cattle and feral animals is the major cause of damage to, and decline of, the vegetation, and subsequently of the soil supporting it. Fire has also undoubtedly contributed to the decline, and continues to do so. High intensity rainfall, common throughout the Kimberley, the over use of land and susceptible soils predispose large areas to soil erosion. Reports have shown that a large proportion (30%) of pastoral land has been subject to excessive grazing pressure and is in poor condition. It is generally the most productive valuable areas that are in the worst condition (Payne et al., 1972).

The rivers and creeks numbered 1 to 45 in Figure 2 were identified as possible or potential 'wild' rivers in the CRES study. All were given a detailed field inspection throughout their length. Most of the remainder (46 to 65) were flown over and inspected for a portion of their length, providing sufficient information, together with what was already known, to place them in their appropriate category. The rivers found in each of the 5 categories are listed below.

The creeks marked with an * are representative of a number of other creeks in their vicinity. The two un allocated water courses, both located towards the northern end of the Dampier Peninsula, remained so because no defined channel could be discerned from the air, except within tidal mud flats.

The rivers in Categories A2 and B1 in the table below are listed in their order of condition from best to worst. As stated in Section 4, there is more or less a continuum between the best of A2 (Jinunga River) and the worst of B1 (Chamberlain River). The line has been drawn where, for the moment, we believe the cut off should be made. However, at some time in the future, when the rivers over the remainder of the country have been examined in detail, and the line between wild though modified and relatively natural defined for other parameters or types of change, the rivers of the Kimberley will need to be looked at again, and the position of the dividing line perhaps redrawn.

<u>A1 Wild & Undisturbed</u>
55 Mt Page Creek
38 Doubtful River
56 Mt King Creek
27 Prince Regent River
39 Hunter River
30 Scott Creek*
60 Cape Whiskey Ck*

<u>A2 Wild though Modified</u>
54 Jinunga River
25 Gibson Creek
26 Glenelg River
61 Thurburn Creek*
62 Bulla Nulla Ck*
57 Wade Creek*
59 Londonderry Ck*
44 Pentecost River
42 Salmond River

<u>B1 Relatively Natural</u>
40 Lawley River
58 Placid Creek*
36 Berkeley River
35 King George River
24 Sale River
28 Roe River
23 Calder River
37 Forest River
22 Charnley River
29 Moran River
32 King Edward River
43 Chamberlain River

<u>B2 Altered</u>
47 Deep Creek
1-12 Complex N of Broome
14 Fraser River
49 Logue River
53 Alexander Creek
16 Keightley River
17 Townshend River
18 Tarraji River
20 Swift Creek
21 Humbert Creek
45 Isdell River
31 Mitchell River
33 Carson River
34 Drysdale River
41 Durack River
65 Emu Creek

<u>C Degraded</u>
50 Fitzroy River
51 May River
52 Meda/Lennard River
19 Robinson River
46 King River
63 Ord River
64 Dunham River

<u>Un allocated</u>
13 Beagle Creek
48 Pender Creek

6. COMPARISON WITH MODEL PREDICTIONS

Potential wild rivers in the Kimberley had been identified by CRES in their GIS analysis. A Wild River Index (WRI) was derived for each stream section. WRI is a dimensionless rating on a 0 - 1 scale, with 0 representing the undisturbed, or pristine end of the continuum. The index is made up of two components, a Catchment Naturalness Index (CNI) and a Naturalness of Flow Regime Index (NFRI). These are computed by accumulating values calculated for individual stream sections from data relating to the location of settlements, infrastructure, extractive industries, cleared areas, dominant land use and alterations to the flow regime such as dams or diversions. This was obtained from the AHC's National Wilderness Inventory and supplemented from AUSLIG's GEODATA database.

The WRI for each streamline were mapped using 6 classes and plotted in different colours:

Class	Index Value	Colour
1	0	dark blue
2	0 - 0.025	light blue
3	0.025 - 0.05	green
4	0.05 - 0.15	brown
5	0.15 - 0.25	purple
6	> 0.25	red

It was necessary to interpret the plots and to allocate an anticipated potential or degree of wildness based on them. It was concluded that:

- rivers entirely dark blue were assumed to be A1;
- rivers mainly dark blue but with some reaches in light blue were assumed A2;
- rivers mainly dark and light blue but with significant areas in green and a few reaches extending into brown were assumed B1;
- rivers in the B2 and C categories were not differentiated in a definitive fashion, largely because there were not sufficient numbers of them covered. However, it follows that they will be indicated by reaches in browns and reds in increasing proportions of the whole.

When the comparison between the model predictions and the field assessments were made, it was seen that the CRES model gave a reasonably good indication of which rivers are in a 'wild' condition. In the 42 instances where comparison was possible, in 16 cases river condition was found to be the same as that predicted by the model, in 7 cases it was found to be better and in 19 cases worse. Of the seven instances in which the rivers were found to be in better condition than predicted, five were one grade and two were two grades better. Of those found to be worse, fourteen were found to be one grade, four two grades and one three grades worse.

7. IMPLICATIONS FOR RESOURCE ALLOCATION

Major potential development (dam) sites have been identified on all of the large rivers in the Kimberley, and in the case of the Fitzroy Rivers (50) on each of its major tributaries. Looking at the long-term future, the huge resources of the degraded Ord (63) and

Fitzroy Rivers are the most conveniently located to be in demand for export outside the Region, to the arid interior of the country, should such a scheme ever be economically feasible. Also, towards the downstream end of these two rivers, plus the degraded May (51) and Meda/Lennard Rivers (52), lies land with the greatest potential for irrigated agriculture. The Ord has already been, and the others could at some time be developed for such a purpose. It is difficult to envision any of the existing urban areas growing sufficiently in size to need a significant proportion of the Region's theoretically divertible water resource. However, it is worth noting that all of them are located within or adjacent to the Ord and Fitzroy River catchments.

All of the best preserved rivers, those in the A1, A2 and B1 categories, are located in the remote northern and north-western portions of the Region. It is difficult to imagine much demand for use in these areas, other than the development of small tributaries for any mining venture that might proceed. When it comes to allocating the in-situ resources of the Kimberley, it would appear that there are unlikely to be many conflicting demands. It should be possible to allocate the best preserved to the environment and ecosystem maintenance, and to Aboriginal significance and traditional use. Thus, in doing so, their wild nature will remain undisturbed and protected.

8. IMPLICATIONS FOR CONSERVATION AND MANAGEMENT

Pastoral activity, plus the grazing pressure from animals that have become feral over the last century, are by far the most significant causes of river degradation in the Kimberley. In the northern Kimberley the pastoral stations are large, all over 500 000 hectares. There are no boundary or internal fences. Consequently, the cattle are not prevented from straying into adjacent national parks, nature or, Aboriginal Reserves. Also, the cattle are not prevented from concentrating in the small portions of each station or other area that offer the greatest prospect for nourishment. Thus the small areas of river sediments supporting the palatable grasses and shrubs are the first and most heavily grazed, leading to denudation and erosion. Pastoralism in the area equates, more or less, to the periodic culling of what is in effect a feral cattle population.

The rivers found to be A1 all have catchments that are so isolated, rugged and rocky that they would not be at all attractive to cattle, and stock movement would be more or less impossible. The catchments are generally contained entirely within existing national parks, nature reserves and other areas of land afforded status and protection, but not in all cases. A number are within areas of Vacant Crown Land or have portions within parts of pastoral leases that are less susceptible to damage from over use by cattle. The A2 catchments, generally, have increasing proportions within pastoral leases, though little or no areas with high pastoral potential and susceptibility to damage.

The management of wild river catchments in the Kimberley Region, and probably other regions across the country, will need to look specifically at forms of degradation or damage associated with pastoral activity. There is no doubt that in catchments of rivers in Categories B1 (Relatively Natural) and B2 (Altered), degradation is progressing continuously, and perhaps accelerating. In particular, consideration should be given to implementing some form of control of grazing pressure on areas highly susceptible to damage, and also to determine the likely long-term effects of the deliberate and frequent (annual) use of fire.

The north-west Kimberley, comprising, say, the catchments of all rivers discharging to the coast from Walcott Inlet to the West Arm of Cambridge Gulf, constitutes one of the last great, remote isolated and virtually unscathed wilderness areas of the country, and perhaps of the earth as a whole. The area constitutes an eco-tourism resource of great potential value to the future of W.A.. Figures are not easy to arrive at, but the value of the area to tourism may well already exceed any income from pastoralism. The impact of grazing needs to be considered in relation to maintaining conservation values, in particular the wild river values.

The impact of tourism development also needs to be assessed in relation to the conservation of wild river values. The major natural tourist sights of the Kimberley happen to be located on less well (overall) preserved rivers. These include Mitchell River Falls, the King George River Falls, the Bungle Bungles Region of the Ord catchment and spectacular gorges along the Isdell, Charnley and Chamberlain Rivers. The values of these areas will best be maintained if access to view these sights and the beauty of the wild river catchments continues to be mainly from the air, by sea or on foot.

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Identifying And Redressing The Ecological Consequences Of River Regulation in the Lower River Murray

*Anne Jensen**

ABSTRACT: *The broadscale consequences of river regulation and increasing water diversions from the Murray-Darling Basin have been highlighted in the 1990s. In response, there is a strong impetus towards definition of effective measures to rehabilitate river and floodplain ecosystems.*

Experiences in the Lower River Murray indicate that reinstatement of key elements of the hydrological regime is critical to maintain natural regeneration processes. However, other factors inhibiting these processes also need to be identified before successful rehabilitation of river and floodplain ecosystems can occur. For example, further understanding is required of germination cycles, factors affecting seedling survival, the effects of soil salinity, groundwater salinity and depth to groundwater.

Measures to redress the ecological consequences of river regulation must integrate water management, land management and protection of riparian zones. Trying to get the hydrological regime right is just the first step in determining the complete suite of management actions required to achieve sustainable rehabilitation and management of river systems.

1. INTRODUCTION

A recent comparison of flow management in the Murray-Darling Basin with practices in the basin of the Aral Sea in Uzbekistan drew the startling conclusion that the proportion of water diverted from the Murray-Darling Basin rivers is of the same ratio as diversions which have resulted in the reduction of the world's largest freshwater lake to one-third of its natural size (Blackmore pers comm 1995). In the case of the Murray-Darling, the serious impacts resulting from river regulation are masked by the marine waterbody at its outfall. However, the recent Water Audit report highlights the gravity of ongoing impacts caused by river regulation and unchecked diversion of water (Murray-Darling Basin Ministerial Council 1995). The resulting moratorium on further diversions gives an opportunity to incorporate measures to redress the ecological consequences of river regulation.

The ecological consequences of river regulation in the Lower River Murray (Figure 1) are well documented. The particular impacts are summarised briefly below:

- naturally highly varied flows with a wide range of salinities have been replaced by a series of very stable elongated pools of relatively stable salinities, with former low summer flows eliminated, through the effect of 10 weirs below the Darling junction
- riverine-adapted species such as crayfish and river mussels have declined in the mainstream, being replaced by floodplain-adapted species yabbies and billabong mussels (Walker 1986)
- mean flow to the Lower Murray has been reduced by 37%, although the seasonality of flow peaks (spring) is unchanged (Close 1990)
- retention of flows in upstream storages can remove up to 50% of River Murray flow peaks upstream of Wentworth
- except in high flow conditions, river flows in the Lower Murray are now relatively stable throughout the year, with no significant seasonal variation
- the mixing pattern of Murray and Darling water has been changed through storage and slow release of higher flows in Lake Victoria, extending the natural flow period of highly turbid Darling water from approximately 2 months to 7 months (Suter et al 1993)
- Lakes Alexandrina and Albert have been converted from fluctuating estuarine habitats to stable permanent freshwater lakes, with seawater excluded from the estuary by 5 barrages
- the estuary of the Murray-Darling Basin is now confined to short channels below the barrages and dominated by the marine influence
- extended periods of no flow at the barrages are becoming more frequent, with drought flow conditions now occurring 1 year in 2, and frequencies of severe flow restrictions increasing (MDBMC 1995)
- minor to medium floods have been eliminated (up to the 1 in 7 year event) (Caldwell Connell 1981), with drought frequencies on the floodplain now increased from 1 in 20 to 1 in 2 (MDBMC 1995)

* Department of Environment and Natural Resources, GPO Box 1047, Adelaide 5001
Telephone (08) 204 8730 Fax (08) 204 8889

- floodplain inundation frequencies have been very significantly reduced, for example inundation of the Chowilla floodplain has been reduced from 1 year in 4 to 1 year in 13 (Sharley 1992)
- recruitment of native fish is significantly reduced, with no recruitment of Murray cod since the floods of 1974-75 until overbank flows in 1989-1993 produced four strong year classes of native cod (Pierce pers comm 1994)
- regeneration of key vegetation species such as river red gum is poor and lacking in vigour on the regulated floodplain below Wentworth (Margules et al 1990)
- extremely rapid flood recessions (eg 2m fall in level in 2-5 days), are causing accelerated large scale bank slumping (Thoms, Walker & Sheldon 1992)
- rapid flood recessions may interrupt waterbird breeding cycles, leading adults to abandon unfledged chicks (Jensen 1983)
- peak levels of some medium floods are actively reduced by diversion of water into Lake Victoria to protect key infrastructure on the floodplain in South Australia (eg Berri-Loxton causeway, Loxton Caravan Park) (Figure 2)
- only once floods reach approximately 110 000 ML/d are they largely uncontrolled and a relatively natural pattern of inundation of the floodplain occurs.

This long list of environmental consequences associated with river regulation in the Lower River Murray highlights the major threats to the long term health of the riverine environment and the sustainable use of its resources. Clearly, significant changes must occur in river management to redress these impacts.

2. DEFINITION OF ENVIRONMENTAL FLOW REQUIREMENTS

2.1 Defining Key Elements of Hydrological Regime

A return to a pre-regulation hydrological regime cannot be accommodated within the current social and economic dependency on the water resource (Jacobs 1990). Therefore, the key to rehabilitation and sustainable water resource management will be in the smart use of any opportunities to restore key elements of the hydrological regime. What are these key elements?

The preferred approach for the Lower Murray is to concentrate on restoration of broadscale processes, rather than to define the needs of individual species or to attempt to address each of the separate impacts listed above (Jensen et al 1994).

This process-targeted approach is very similar to the holistic approach described by Arthington et al (1992), which advocates identification of key elements in the hydrological regime, such as the timing, peak, duration or rate of recession of floods. It avoids the difficulty of having to define environmental flow requirements in terms of the needs of individual species, which can require significant investigation time. The species-targeted approach may lead to delays, conflicts between the needs of different species or lack of flow provision for some species because of lack of data.

For the process-targeted approach, the Lower Murray Flow Management Working Group has defined a general management aim in riverine rehabilitation as follows:

> *to achieve broadscale inundation of the floodplain environment that will stimulate regeneration and revitalisation of native aquatic and terrestrial plant communities and breeding in waterbirds, native fish and aquatic invertebrates. Inundation should occur on a natural cycle. In the case of a natural drought, inundation of the floodplain would not be required.*

For the Lower Murray, a number of key elements of the hydrological regime have now been identified for inclusion in a package of environmental water requirements. The package should address one or more of the following environmental management aims:

- inundation of the floodplain during spring peak flows to reinstate as many as possible flood events up to 1 in 7 year frequency
- inundation of the floodplain for a minimum of two months and maximum of four months for waterbird and fish breeding
- minimum inundation of the floodplain for two weeks or more to water stands of floodplain vegetation and to replenish freshwater lenses in the groundwater for future water reserves
- inundation of the floodplain for two to six weeks to stimulate flowering of floodplain vegetation

- inundation of waterbird rookeries for a minimum of two months to ensure completion of fledging
- slower rate of recession after flood peaks to prevent bank slumping
- drying of permanent and semi-permanent wetlands for a minimum of two months at least once every three years
- minor variations in mainstream river levels to favour increased diversity in food chains
- maintenance of a relatively natural pattern of flow variations in the mainstream, and seasonality, frequency and duration of high flow peaks
- reduction of the influence of turbid Darling flows to near-natural patterns.

Clearly, the package of measures to redress the impacts of river regulation and identify environmental water requirements must be a flexible mixture which outlines options for varying river conditions and climatic cycles. The objectives outlined above would only be met over a period of time, which might be many years, depending on climatic cycles.

2.2 Defining Opportunities for Changed Management of Hydrological Regime

In defining opportunities to implement delivery of environmental water requirements, two major groups of constraints must be considered. Engineering constraints include the physical constraints of operation and safety of the structure (dam, weir, size of outlets, etc) and the consumer demands for water delivery.

Social and economic constraints include the demand for irrigation and domestic supplies to be delivered in a different sequence to the natural flow regime, and requirements for specific, usually stable water levels for pumps and recreation uses. Another constraint is the demand for protection of development on the floodplain, to reduce or prevent flooding to protect economic investment, even though the location is known to be flood-prone.

As a first step in identifying opportunities to deliver environmental water requirements in the Lower Murray, Ohlmeyer (1991) outlined opportunities to vary release sequences and sources in the operation of storages, particularly Lake Victoria and Menindee Lakes, and to manipulate flows in a limited way at individual weir structures under particular flow conditions.

The Lower Murray Flow Management Working Group has developed these opportunities in more detail, preparing data sheets which indicate the physical constraints of each weir structure, flow thresholds for key floodplain wetlands controlled by operation of each weir, and key social and economic constraints (eg minimum depth for ferry operation, effect on irrigation pumps).

It has been generally agreed by the Working Group that the greatest potential for improving flows to floodplain wetlands lies in raising water levels at weirs, since lowering of levels would have unacceptable social and economic impacts on large sections of the community. These could include stranded ferries and pump offtakes, as well as draining of saline deoxygenated backwaters prior to high flows. However, minor lowering of levels to introduce variations in mainstream levels would be feasible.

The application of variation in storage management has already been demonstrated, with the diversion into Lake Victoria of 12 000 ML/day during the peak of 1993 flow (Figure 2). This action reduced flood levels by 100mm and prevented closure of the key road link between Berri and Loxton. The flood peak was extended from approximately four days to nearly four weeks. While a very small area of outer floodplain was not wetted because of this action, widespread inundation lasting nearly four weeks instead of four days had a very beneficial effects on large areas of the floodplain ecosystem.

Analysis of opportunities for changed flow management indicates a range of flow bands with varying control over flows. These are outlined in Table 1. An area of major debate is whether to enhance or mitigate flood peaks. The social and economic pressure is always to mitigate, and this has been the primary objective of past flow management during floods. In times of normal flow, the primary objectives are security of supply and water quality. Both of these objectives have driven the operating rules for Lake Victoria, with the resulting extended influence of turbid Darling water.

The environmental consequences of mitigating floods have not been fully investigated, although the best judgement for the 1993 mitigation was that the environmental consequences were more positive than negative. Further investigation is required for sound environmental judgements on the consequences of the mitigation scenario.

This debate will require major community involvement, since the issue of how river levels and flows are managed has a very direct impact on all river users and residents. The community consultation phase of the flow management process is seen as the most important activity, requiring time and resources to ensure informed debate and constructive input from all parties.

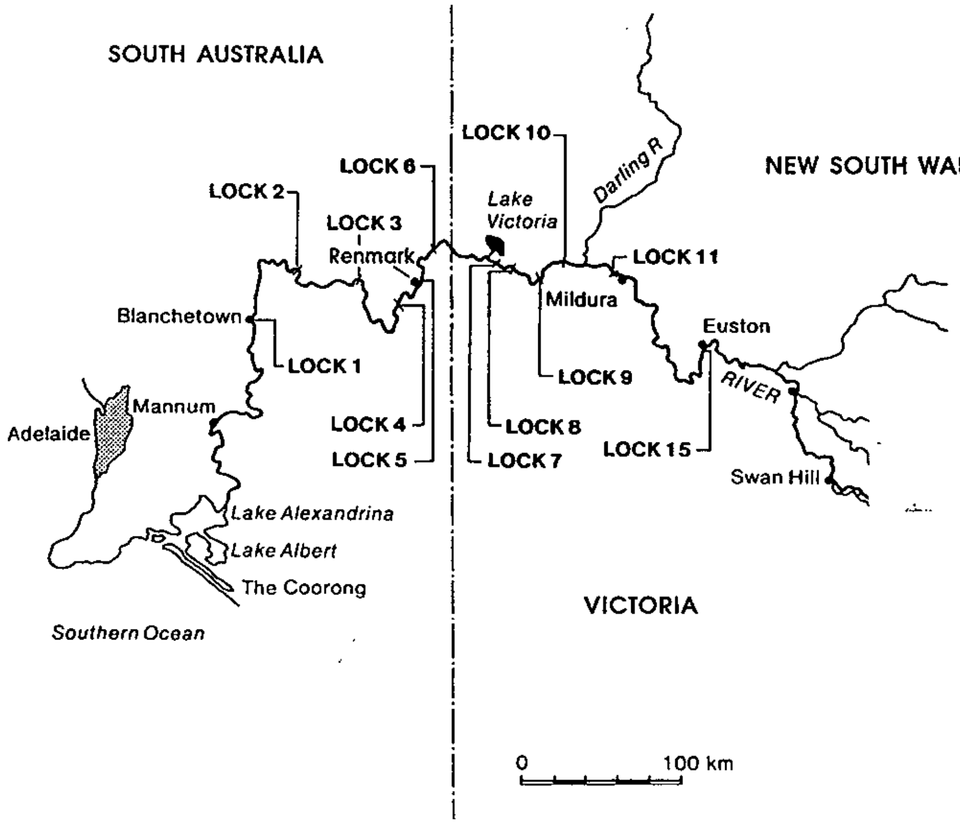

Figure 1: Regulating Structures on the Lower River Murray

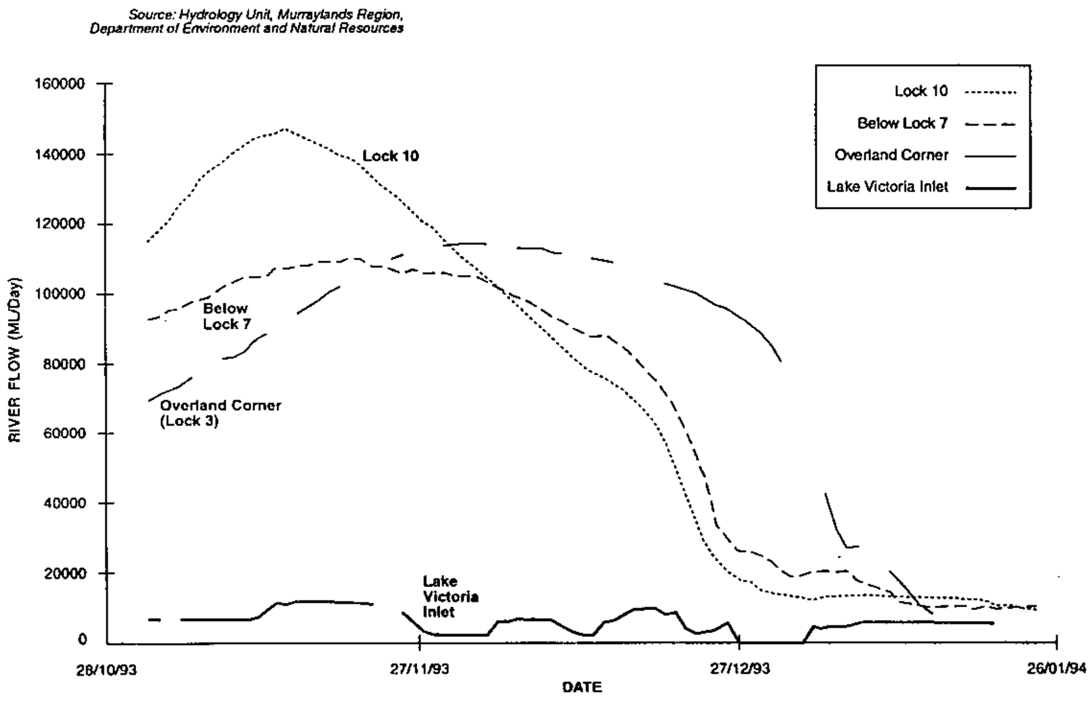

Figure 2: Mitigated River Murray high river flows into South Australia in 1993

Flow band	Potential control
> 35 000 ML/d	local regulators on individual wetlands, manipulation of mainstream levels at weirs
35-50 000 ML/d	manipulation of weir levels to simulate higher flows to achieve selected wetland filling
50-80 000 ML/d	manipulation of weir levels (where structure still in place) plus storage release sequences to achieve selected floodplain inundation
80-100 000 ML/d	social and economic demand to lower flood peak to protect floodplain development

Table 1 Potential for environmental flow management for different flow bands in the Lower River Murray

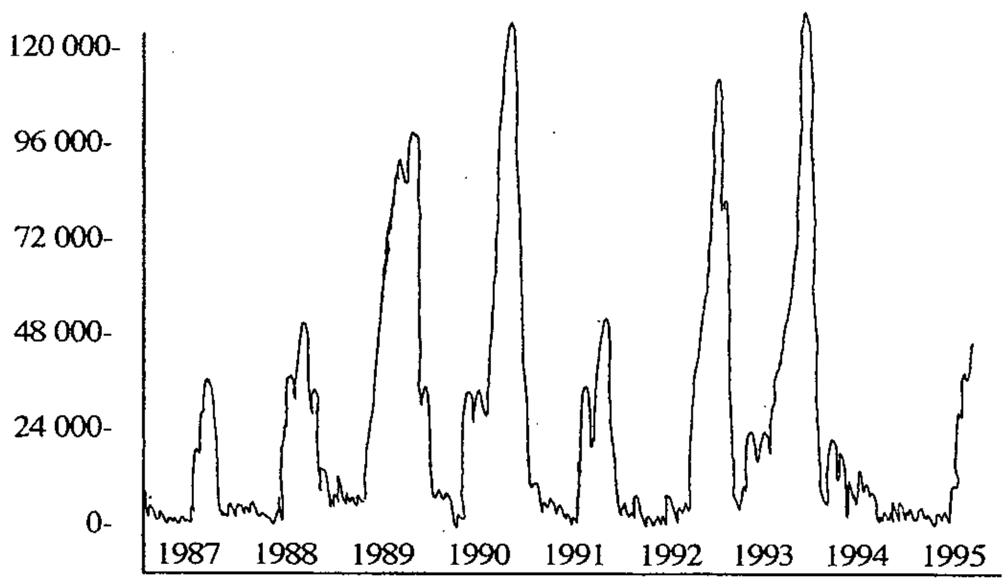

Figure 3 Flow hydrograph for River Murray at Overland Corner, showing peak spring flows (Ml/day) since 1987

3. DISCUSSION

As a first stage in developing a flow management strategy for the Lower Murray, a draft flow management package has been formulated and presented to key policy bodies, including the South Australian Water Resources Council. The package sends the clear signal that the area of greatest potential for improved environmental management is in the band of flows from 15 000 ML/d to 60 000 ML/d. The package is outlined in Table 2.

These flow bands are above the minimum entitlement conditions which govern allocations and normal river operating rules. Flows in this range may be declared 'surplus' by the Minister, allowing unregulated diversion by irrigators (similar to 'off-allocation' water in upstream states). The call for environmental water allocation from this band of flows is thus potentially in conflict with preliminary proposals for 'opportunity' licences which would offer water with reduced security. However, it is anticipated that a compromise could be reached which allows both activities.

The amount of water which could be used for environmental purposes within the minimum entitlement flow of 3-7000 ML/day is only a small component of the environmental needs, since it could only supply individual wetlands. No overbank flows are possible within the entitlement flow range. It is more important to fluctuate levels within the mainstream to increase biodiversity in the littoral zone, and this would not require a water allocation, just a change in operating rules.

An important distinction which must be made in this debate is that flushing flows for algal management and water quality objectives do not benefit the riverine environment. They are generally too small in volume and too short in duration to achieve overbank flows or to fill wetlands. Environmental flows in the Lower Murray must reach the floodplain to have significant environmental benefits.

Discussions of environmental water requirements frequently seek to define these requirements in terms of a share of the annual average flow volume. However, environmental flows must incorporate the natural variability of the hydrological regime, which is not easily expressed in averages. It is suggested that the answer might lie in allocating water from the secure part of the average hydrograph for consumptive uses and allocating the upper variable section of the hydrograph, with its peaks and troughs, to the environment (eg flood peaks above 25 000 ML/day; Figure 3). Thus the consumer has a reliable supply and the environment has a hydrological regime with variation on a natural cycle.

4. CONCLUSIONS

It is the firm conclusion of investigators and managers in the Lower Murray that the reinstatement of key elements of the hydrological regime is the primary objective in rehabilitation of the riverine ecosystem.

The first key element of the hydrological regime defined for environmental water requirements in the Lower Murray is the reinstatement, or simulation, of overbank flows to compensate for the lost small to medium floods with frequencies up to 1 in 7. This altered flow regime has already been achieved for six sites through on-site works.

A flow management strategy is being developed to increase overbank flows for whole reaches along the length of the Lower Murray. This strategy will seek to build in the flexibility required to incorporate the natural variability of the hydrological regime and to make smart use of available opportunities to provide key elements of the hydrological regime. It will incorporate changing operating guidelines for both regulated and flood flows.

Owing to the potentially controversial nature of proposals to alter river levels and flow patterns, a long process of negotiation and community involvement will be required before this strategy can be finalised and implemented.

Flow Band	Flow Management Strategy
< 15 000 ML/d	fluctuate mainstream levels
15-25 000 ML/d	allocate water to individual wetlands
25-60 000 ML/d	manipulate weir levels to create overbank flows
25-80 000 ML/d	enhance flood peaks
80-100 000 ML/d	mitigate flood peaks
> 100 000 ML/d	enhance flood peaks

Table 2 Preliminary Flow Management Package for Lower River Murray

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Urban Creeks—Streams or Drains?—Implications for Management

Louise Ormerod[*]

ABSTRACT: *The perception that urban streams are stormwater drains has long influenced, and indeed limited, management policies for these streams. The hydraulic geometry technique was used on Winding Creek, NSW, indicating that while channel parameters for the whole stream are in equilibrium with a discharge surrogate, smaller reaches are apparently more heterogeneous. These results imply that smaller rather than larger channel reaches may provide a better scale for channel management. This process could involve clearing the stream of anthropogenic debris and revegetation of small reaches, while retaining natural fluvial features, as opposed, or in addition to, large scale management of stormwater. Much of this work is time consuming, but community-based groups, such as urban Landcare or Rivercare, could be involved.*

1. INTRODUCTION

Increases in flood frequencies, peaks and velocities, and altered sediment yields are common consequences of urbanisation (Pickup, 1986) because of the replacement of vegetation with impervious surfaces which reduce infiltration rates and increase runoff (Douglas, 1983). In addition, artificial drainage systems, such as gutters and stormwater drains that are superimposed on the natural drainage system, hasten the flow of water entering the channel system (Park, 1981). Channelisation, which can involve the artificial enlarging, straightening or sealing of a channel for the purpose of flood mitigation markedly increases flood velocities (Brookes, 1987). Sedimentation yields often increase during construction phases, reducing channel capacities, causing increased flooding and channel erosion (Douglas, 1985) but may fall below natural levels following urbanisation. The effect that urbanisation will have on a channel is dependant upon precipitation, soil properties, slope, distance from channel, amount, intensity and age of the urbanisation and riparian vegetation (Hammer, 1972; Ebisemiju, 1989).

In many areas of Australia, and within the Newcastle and Lake Macquarie areas in particular, urban streams have been grossly neglected by management and local residents, with little interaction between groups. Management of urban streams has generally been the responsibility of local government who have historically interpreted this role as being primarily related to flood control (Rolls, 1995). The urban streams in our environment today have little in common with their natural state. Many have undergone a succession of transformations to aid flood control by a variety of methods and over a substantial period of time. Early work on urban streams was carried out in a time when humans attempted to control and dominate their environment. However, it is suggested here that not only does present management have to deal with the reality of past management decisions, but is presently restricted by a continuation of this former philosophical stance.

Hydraulic geometry has been suggested by fluvial geomorphologists as a model for estimating flood discharge and to assist in river management (Wharton, 1995). This model is capable of being both general and site specific in nature. It is the aim of this paper to illustrate the complex nature of urban streams, by the examination of Winding Creek, NSW, using hydraulic geometry, and to point out some implications for present and future management.

2. STUDY AREA

Winding Creek is located near Lake Macquarie, NSW (32° 55'S, 157° 40'E) and drains the eastern portion of Cockle Creek catchment, which subsequently flows into the northern side of Lake Macquarie (Fig 1.) The total catchment area of Winding Creek is 19.6 km^2. Much of the original vegetation of dry sclerophyll forest has been cleared, with residual woodland of 34%. The remainder of the catchment is 16% open area, with approximately 50% urbanised. There are two main business districts included within the catchment: Charlestown at the headwaters, and Cardiff, located in the lowland area. Approximately 30%, or 2.3 km of the trunk stream was channelised between 1930 and the mid 1970s.

3. HYDRAULIC GEOMETRY

Hydraulic geometry has been traditionally used by geomorphologists to describe channel morphology. Channel parameters such as width, depth, channel capacity, velocity, slope and meander wavelength, are explained by their relationship to discharge, or surrogate. These relationships may be quantified by a series of power functions. The exponents of these power functions, which express the ratio of the rates of change for each parameter, vary uniquely for each stream. Hydraulic geometry techniques have been found valuable in the identification of the character and magnitude of human-induced channel change (Ebisemiju, 1991). This is achieved by comparing power functions for natural and urbanised catchments, or downstream reaches along individual streams. The relationships from natural areas

[*]Department of Geography, University of Newcastle, NSW, 2308
Telephone: (049) 21 7439 Fax: (049) 21 5587 Email: gglmo@cc.newcastle.edu.au

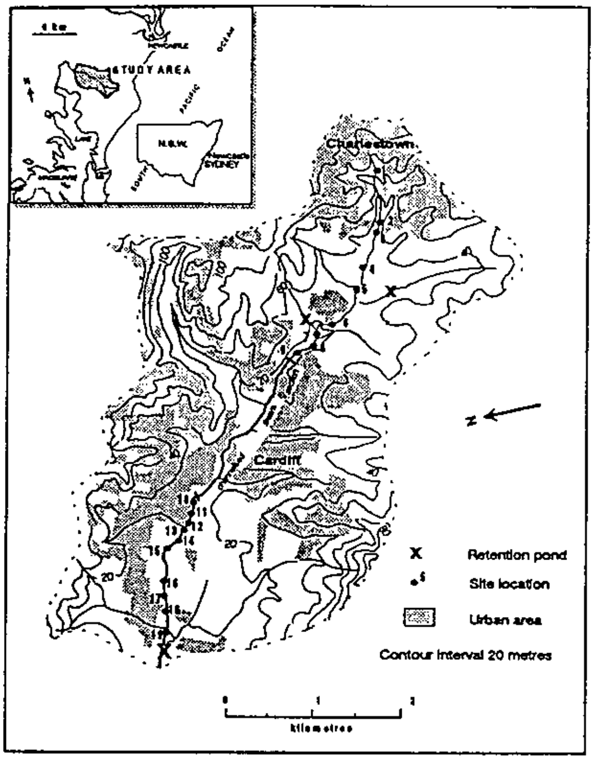

Figure 1: Winding Creek Catchment, N.S.W.

are used as a base from which to quantify changes in the size of channel parameters in areas altered by humans. This technique assumes, however, that the rate of change in any part of a system is a constant fraction of the relative change of the whole system (Ebisemiju, 1991), and may ignore alterations to sedimentation rates associated with urbanisation. Additionally, Wharton (1995) maintains that hydraulic geometry can assist in river management, by estimating flood discharge on ungauged streams where engineering works are being considered, to identify particular reaches that may need increased management, and to monitor stream variation over time.

Oversimplification has often been a major criticism of hydraulic geometry. Phillips (1990, 1991), for example, argues that hydraulic geometry is inherently unstable, and that channel parameters are capable of multiple modes of adjustment, that may take place in both expected and unexpected directions. It is also recognised that there are complex interrelationships operating at a variety of scales at any given point, that will influence the channel morphology (Penning-Rowsell and Townshend, 1978). The complexity of channel responses is further augmented where intricate anthropogenic landuse changes have taken place. Wharton (1995) however, suggests that it is the deviations from expected values, or residuals, that indicate the sensitivity of particular river reaches to changes.

Given that Winding Creek catchment is substantially and unevenly urbanised, and that 30% of its trunk stream is channelised, it was hypothesised that downstream hydraulic geometry relationships would fail to describe the channel morphology. Channel parameters (width, depth and channel capacity) were derived from 19 pairs of cross sections (Fig 1.), surveyed at adjacent pools and riffles (to overcome the problem of inherent morphological and hydraulic differences (Gippel, 1982)). The stream sites are divided into upstream and downstream sites which are separated by the section of channelisation in the middle section of the stream. The upstream sites are likely to have been impacted upon by urbanisation and the downstream sites by both urbanisation and channelisation. A maximum of three sets of channel parameters were defined at each site. These relate to bankfull levels for a low water bench level, a second bench level defined at the height of flood debris and/or a higher morphologic bench, and thirdly at the valley floor. The valley floor is believed to be a terrace, due to stream incision associated with climatic changes (Erskine and Bell, 1982) and urbanisation (Nanson and Young, 1981; Roberts, 1989). Catchment area was used as a surrogate for discharge.

The results of regression analysis significant at the 0.05 level or better are given in Table 1. Pools and riffles are treated separately, firstly for one set covering the length of the stream and secondly as two data sets relating to sites upstream and downstream of the channelisation.

There were a greater number of significant results for the data set covering all sites rather than for the split sets, but the r^2 values are generally lower than for the other sets. As r^2 values decrease from unity, the degree of equilibrium decreases because of destabilising effects of catchment or climatic changes (Ebisemiju, 1989). Bench level 2 appears to have the strongest relationship indicating that it may be associated with the main channel forming discharge.

For the upstream data set, channel width at bench level 3 appears to be in equilibrium with the surrogate discharge with r^2 of 0.99 for both pools and riffles. However, field observations and comparisons with rural data indicate that bench level 3 is a terrace and therefore a reflection of past landuse and climatic regimes. The number of significant results for pools increases downstream, however the strength of these relationships decreases and there are no significant results for riffles, a situation which may well be expected due to the additional destabilising effects of the channelisation, evident by a marked change in the hydraulic geometry relationships downstream of the channelisation, as indicated by the exponent values.

It is clear from these results that the initial hypothesis must be rejected as hydraulic geometry results appear to more adequately describe channel parameters for the whole stream rather than individual reaches. It is obvious that oversimplification has occurred in this particular example, as hydraulic geometry cannot

TABLE 1
Regression Analysis
(*NB*—log values are used)

Data Set	Independent Variables	Dependent Variables	R^2	Coefficient (a)	Exponents (b)	Significance Levels
All Sites						
Pools	Catchment Area	W1	0.59	0.49	0.30	0.003
		D1	0.40	–0.45	0.32	0.0041
		C1	0.56	–0.03	0.67	0.0002
		C2	0.67	0.90	0.40	0.002
		D3	0.42	0.07	0.21	0.0164
		C3	0.37	1.34	0.25	0.0279
Riffles	Catchment Area	W1	0.41	0.42	0.35	0.0001
		D1	0.59	–0.62	0.36	0.0001
		C1	0.61	–0.12	0.66	0.0001
		W2	0.36	1.11	0.11	0.05
		D2	0.81	–0.20	0.31	0.0002
		C2	0.96	0.90	0.46	0.0001
		D3	0.58	0.07	0.21	0.0017
		C3	0.49	1.40	0.22	0.005
Upstream and Downstream Sites						
Upstream Pools	Catchment Area	W3	0.99	0.97	1.02	0.0158
Upstream Riffles	Catchment Area	D1	0.60	–0.61	0.30	0.01
		C1	0.67	–0.12	0.61	0.0074
		C2	0.91	0.90	0.50	0.003
		W3	0.99	0.97	1.03	0.003
Downstream Pools	Catchment Area	W1	0.41	5.25	–3.73	0.0472
		D1	0.62	5.99	–5.11	0.0069
		C1	0.56	11.35	–8.93	0.0130
		W2	0.91	11.15	–8.45	0.0457
		C3	0.40	4.84	–2.73	0.05
Downstream Riffles	Catchment Area			No Regression Results are Significant		

W = width; D = depth; C = capacity; 1 = bench level 1; 2 = bench level 2; 3 = bench level 3

distinguish between an equilibrium state of a fully adjusted channel and a channel undergoing continual adjustments (Richards and Greenhalgh, 1984).

There are several explanations for this unexpected result. Firstly, as the highest percentage of urbanisation occurs in the Charlestown area located at the headwaters, it is likely that the major effect of urbanisation in the form of channel enlargement is effected in the upstream sites (Ebisemiju, 1989). The downstream sites may be enlarged primarily in response to channelisation, thus giving an overall impression of equilibrium. Indeed, comparisons with rural catchments within the region (Ormerod, 1988) implied that channel enlargement, predominantly of channel width, had occurred in upstream sites due to urbanisation. Immediately downstream of the channelisation, the stream displayed until recently, a typical 'bulbous caving re-entrance' (Brookes, 1987), as a result of channel incision and bank erosion. The size and depth of the stream at this point was anomalous, and it was therefore excluded from the sample, thus eliminating the section of the stream that had perhaps undergone the most adjustment. Channel enlargement tended to decrease with distance from the channelised section, as velocities are reduced (Brookes, 1987), and fining of sediment in a downstream direction (Nanson and Young, 1981).

Secondly, as suggested by Phillips (1990, 1991), multiple modes of adjustment are common as channel parameters may be sharing channel responses, thus smoothing out or even negating expected channel responses. These phenomena may manifest as heterogeneous forms that occur along a stream. Some reaches of Winding Creek appeared to be oversize for the upstream catchment area, while others were choked with sediment and debris, thus indicating inadequate channel capacity. Alternating sections of erosion and aggradation, and even combinations of both at the same site, were common along Winding Creek, supporting the concept of multiple modes of adjustment. Downstream pool and riffle parameters responded differently to changed flow conditions (Table 1), which may be partially explained by an unequal distribution of stream power, with more power being expended over riffles than pools (Leopold, 1969). Planform adjustments may have been significant, especially in stream reaches downstream of the channelisation. Here, sinuosity is reduced due to vigorous bank erosion, thus reducing or increasing the apparent changes in other channel parameters. The concept that the direction of change can be opposite to what might be expected is supported by Ormerod (1988) who found for example, that there were generally weak correlations between channel slope and channel parameters, and in some instances the relationships were direct rather than inverse as anticipated.

Thirdly, adjustments are time dependant so that channel changes due to urbanisation are dependant on the age of the urbanisation, which varies throughout the catchment. During construction phases sediment load may increase dramatically (Wolman and Schick,1967), and despite increased discharge, channel parameters may decrease because of increased sediment loads (Neller, 1985). There is often a time lag in channel response to increased sediment if temporary storage occurs prior to entering the stream, thus taking several years for sediment to pass through the system (Douglas, 1985). At some upstream sites stripping of benches is evident, implying that sediment is being moved through these reaches. However, large channel bars were present especially in the downstream section of Winding Creek, indicating reduced competency to transport material. Some of these channel bars have become attached to the channel wall, forming compound cross-sections through, the construction of channel benches or incipient floodplains. Some degree of stability is maintained by a cover of herbaceous and shrub species.

The presence or absence of channel and bank vegetation can have a profound effect on the channel morphology of Winding Creek. Bank vegetation is able to stabilize banks and help prevent bank erosion and thus channel enlargement. In some areas however, the cover of vegetation within the creek is such that it must inhibit or divert flows.

Debris, both natural and anthropogenic, has had some effect on channel morphology especially in the upstream sites. Flood debris at these sites is directly responsible for channel widening by diverting water around the obstruction. Changes to channel slope are also common where debris jams occur.

There are several other possible factors, such as presence of bridges, weirs and gravel extraction, which may have an influence on the channel morphology of Winding Creek, but these are more likely to further destabilise hydraulic relationships rather than contribute to a stable channel.

4. MANAGEMENT STRATEGIES

As stated above, both past, and to a lesser degree, present management of urban streams is based on the premise that their primary function is to contain storm water. Large scale flood control and training works, such as channelisation and retention ponds, (Fig. 1) have been the major management strategy to achieve this goal for Winding Creek. This type of management tends to deal with the stream as a whole, rather than individual reaches, whereas it has been demonstrated above, that streams in general and urban streams in particular, exhibit complex responses to inputs manifested as environmental heterogeneity (Ebisemiju, 1991). As it is one of the goals of geomorphologists, to develop general models of river form and behaviour, and since geomorphologists are increasingly employed in environmental management areas, there are implications for the use of models such as hydraulic geometry.

While hydraulic geometry relationships may fail to describe a stream's variability, it can quantify general trends of change in channel parameters, and residuals can be used to look in more detail at channel response in particular reaches. From a management point of view, smaller reaches may be more applicable than larger ones.

Since this hydraulic geometry study was undertaken, several retention ponds have been put in place along Winding Creek. Two of these are situated in the upstream section, and the third downstream of the last site (Fig. 1). Each have a dual purpose of retaining floodwaters and trapping sediment. These retention ponds, while addressing flooding further downstream, reducing sediment loads and fit in with a new-found desire to recreate wetlands within our environment, are expensive in contrast to some alternatives, and may be ill-placed for the greatest benefit as far as storing excess floodwater and sediment is concerned.

For example, native trees were cut down to make space for the most upstream retention pond, located within a predominantly forested subcatchment and therefore would contain relatively small amounts of sediment and produce significantly less runoff than other sub-catchments. While available space was given as the main reason for the placement of this retention pond, open land is available further downstream, where a series of smaller ponds could have been built on presently unused land. This land was formerly part of a natural wetland that has been infilled to create useable land, but has been left vacant due to flooding. This would have returned some of the retention storage provided by original natural wetlands (Arnold *et al*, 1988).

The retention pond at its present site appears to be an example of this particular reach of the stream being overmanaged, where by comparison the channel reach immediately upstream from this retention pond has been grossly neglected and undermanaged. This section of the creek is choked with sediment, weeds and urban refuse, and is 'illegally' dammed in several places to provide water for gardening purposes. The official standing on this overt neglect was that the sediment, weeds and refuse are able to slow down floodwaters because of additional roughness. However, increased sediments may actually reduce roughness by filling in pools and obliterating riffles (Hall and Ellis, 1985). Also, additional debris within the creek, such as old appliances, car bodies and shopping trollies (all a feature of Winding Creek) may increase bank erosion as water washes around these objects. Surely a well maintained creek that is clear of refuse and excess sediment would provide greater capacity for storm water (Knight, 1989), and with more suitable vegetation, and the retention of meanders, pools and riffles, could also reduce velocities.

By contrast, at sites below the channelisation, sediment in the form of incipient floodplains, channel islands and bars has been removed from the channel, along with anthropogenic debris and weeds, in order to provide greater capacities for flood waters. The bed and banks along this channel reach have been reformed by infilling deeply incised pools, battering banks (which had previously been badly eroded by undercutting and slumping), and revegetating them with kikuyu. Despite chicken wire underlying the grass on parts of the banks, renewed erosion is taking place, with subsequent sedimentation within the channel. Perhaps a more sensible revegetation program and the retention of some of the natural features such as pools and riffles, may have produced longer term results for this expensive work and reduced renewed erosion and sedimentation.

5. DRAIN VERSES STREAM

Whether a creek is treated as a natural feature with potential to retain some linkages with a former landscape, or treated merely as a drain which is managed in order to reduce flooding, depends on the perception of both the public and those responsible for its management. The above examples demonstrate that Winding Creek has been treated as a drain by management, and as an agent for the removal of refuse by the general public.

Surely there is an alternative to inevitable transformation of urban streams into totally controlled, single purpose, 'sterile' feature within our cities? Streams generally are one of nature's great connectors between one area and another. This is one of the main axioms behind Total Catchment Management (TCM) which is looked upon as having great potential in NSW as a management strategy, and in thwarting future land degradation.

Is it possible for our urban drains devoid of any riparian vegetation, save for choking weeds, overburdened with sediment from construction sites, and channel erosion, dumping places to the general public, to become an environmental asset? Imagine a place where water can be heard to flow through green places in our urban environment, where remnant native fauna can still prevail, where channel erosion is kept in check by appropriately vegetated banks and well placed bed controls. The use of vegetation has the added benefit of filtering and utilising anthropogenic pollutants thus reducing their effects further downstream. Urban streams are obvious places to encourage natural vegetation corridors which could link up with other remnant vegetated areas within the catchment.

6. MANAGEMENT SUGGESTIONS

It is my opinion that very little can be done to improve urban streams, as far as amenity and aesthetics is concerned, unless there is a change in attitude of government departments, management agencies and the general public.

How then are urban streams to be rehabilitated in a manageable way? Natural streams are also in a constant state of flux, but they are able to repair unvegetated surfaces and rework sediment. In urban streams this is not always the case. The presence of weeds while being particularly efficient at colonising streams often break off during floods, causing debris jams downstream. In addition, there is no seed stock for specialised native plants such as reeds, that colonise the base of banks and trap sediment.

It is clear that revegetation of urban creeks with native vegetation is a first step to their possible improvement. This may also involve the battering of banks and clearing of some, but not all of the woody debris within the creek. Woody debris is important in creating variety within a channel which may encourage the return of some fauna species. Riparian vegetation is also important to aquatic biota, as it creates variety in stream temperatures due to shading effects and has a crucial role in preventing channel erosion.

Sedimentation within creeks is a symptom of erosion elsewhere within the stream or catchment. Strategies which involve the removal of the sediment from the stream do little in solving the source of the problem (Thoms and Erskine, 1995). Again, revegetation at the source of the erosion is one answer. In recent years councils have been more responsible in trapping sediment from construction sites with meshing. However, there does not appear to be any maintenance of these traps as many become buried or broken over time, allowing sediment to enter nearby creeks.

Over the last few decades there has been greater awareness by the public of environmental problems, but one of the least appreciated problems is that of sedimentation. There has been little public education of the importance of structures, such as sediment traps or even on the consequences of sedimentation within streams. Public education could also decrease the tendency for streams to be used as refuse dumps for garden wastes or worse. The general public need also to become aware of the connection of streams to their catchment areas. Urban Landcare and Rivercare groups are either non existent or grossly underutilised. There appears to be a growing number of people within communities that would be willing to provide labour for environmental rehabilitation, Dunecare groups being a good example. However, these groups take time to develop, and appear at present, to lack direction, policies, guidance and information.

7. CONCLUSION

Urbanisation within Winding Creek catchment NSW has had both direct and indirect effects on the stream. Stream management has been mainly implemented to relieve flooding, especially in the commercial centre of Cardiff. Both community and local government attitudes have meant that the stream has been reduced to a single purpose conduit of stream water, and other amenities and aesthetics of the stream have been ignored. Urban streams could play a role in providing natural vegetation corridors, and could be managed in a way to reduce flooding and sedimentation and still provide habitats for native fauna, providing that there is flexibility in the types of models used. However, the attention of management and the general public needs to turn to smaller reaches in addition to whole stream management practices.

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Channel Change, Bank Stability and Management for North Queensland Coastal Streams

Ross Kapitzke, Scott Smithers** and John Lowry***

ABSTRACT: *The flow regimes and catchment physiographies that characterise north Queensland coastal streams differ from those of other regions in Australia and overseas. The pressures of urban and agricultural development are increasing in this area which has significant natural conservation value. In spite of this, records of basic process data and quantitative information on the condition of the streams are seriously deficient in spatial coverage and historical extent. Little information is presently available on the relative significance of bank instability problems and of the suitability of particular bank stabilisation practices for the region. This paper reviews streambank stability for the region in terms of the 'State of the Environment' pressure-state-response model and outlines research and development activities that are leading to new stream management approaches. The research outcomes are significant for stream management in other humid tropical environments.*

1 INTRODUCTION

The streams of coastal north Queensland drain catchments with markedly varying geomorphologies, geologies and vegetation covers and are subject to diverse climatic and hydrologic regimes. Agricultural and urban development have affected the quality and stability of many of these streams, particularly over the relatively fertile lowland coastal plains. Many of them link two ecosystems of international significance, namely the Wet Tropics Rainforest and the Great Barrier Reef, and so it is critical that appropriate management strategies for the streams be developed and implemented. Recent reviews of Australia's fluvial systems (Tooth and Nanson 1995; Rutherfurd et al, in review) state that there is very little process data and quantitative information available for these streams.

This paper reviews bank stability for north Queensland coastal streams between Mossman, just north of Cairns, and Mackay. We follow the SoE reporting framework and use the OECD's pressure-state-response model. The model assesses the impact of human settlement and activity on rivers (pressure), present stream condition (state), and human responses to these conditions (response) (Rutherfurd et al, in review). The object of this review is to: i) describe the status of the streams; ii) identify the shortage of basic stream process data; and iii) emphasise the need for appropriate stream management practices for the region. We also outline research and development initiatives which respond to Tooth and Nanson's (1995) timely call for studies that take account of local 'hydrological peculiarities', and of relationships between the biological and physical components of fluvial systems.

2 REGIONAL CHARACTERISTICS

The study area encompasses 16 coastal river basins between the Daintree River in the north and the Pioneer River in the south (Figure 1). A great variety of climatic, hydrologic, and geomorphic conditions occur throughout the region, which encompasses three distinct biogeographies: the wet tropics (north from Ingham), the dry tropics (Proserpine to Ingham) and the moist central coast (Proserpine and Mackay).

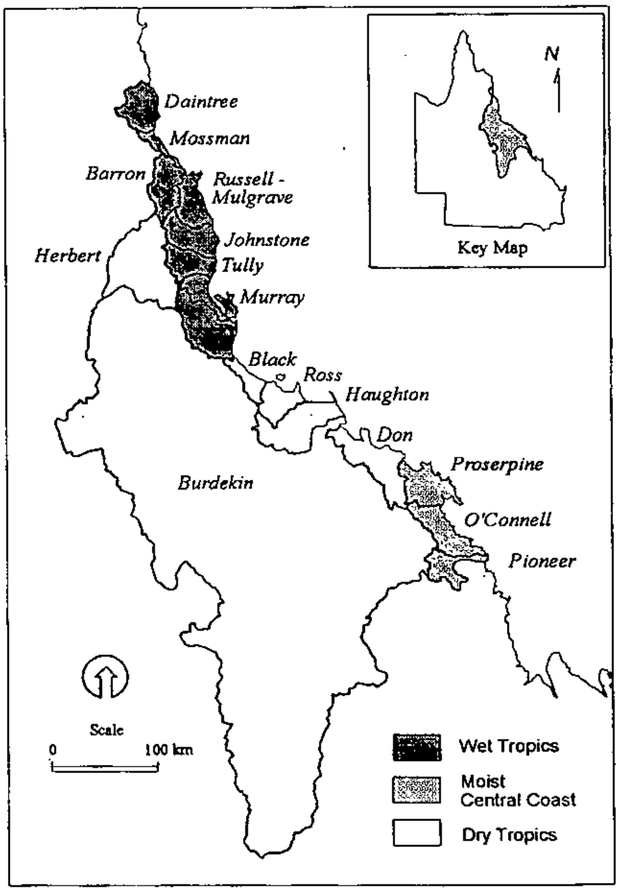

Figure 1 - North Queensland Coastal River Basins

* Department of Civil & Systems Engineering, James Cook University of North Queensland, Townsville, Qld 4811
Telephone: (077) 814 810 Fax: (077) 751 184 Email: Ross.Kapitzke@jcu.edu.au

** Department of Tropical Environment Studies & Geography, James Cook University of North Queensland

2.1 Climate

The region's climate is characterised by hot humid summers (December to April) and mild winters, with temperatures generally in the range 24-33^0 C and 15-30^0 C respectively. Monsoonal troughs commonly affect the region during summer and can develop into tropical depressions that produce high intensity, long duration rainfalls. Occasionally these depressions deepen further to form tropical cyclones with extremely high rainfalls (Bonell 1988). Accordingly, the region experiences high spatial, seasonal and inter-annual variability in rainfall.

The spatial variation in average annual rainfall throughout the study area is shown in Table 1. Average annual totals range from approximately 500 mm in the southern parts of the Burdekin catchment to more than 6000 mm in the Mulgrave-Russell catchment on the Bellenden Kerr Range (Hausler 1990). Inter-annual variability in rainfall is high, particularly in the dry tropics where droughts periodically occur. Rainfall throughout the region is strongly seasonal; even in the wet tropics 63% of the annual total is monsoonal (Bonnell 1983). Daily totals commonly exceed 250 mm, and both short and long duration high intensity falls may occur, alternating with periods of dry weather.

2.2 Hydrology

The coastal drainage basins range in size from 490 km^2 (Mossman River) to 129 000 km^2 (Burdekin River). The Burdekin, Herbert and Barron river basins are bounded to the west by the Great Dividing Range, whilst the remaining basins have their headwaters in the lesser coastal ranges. These configurations, coupled with the regional climatic variations, generate considerable diversity in catchment hydrology.

Spatial, seasonal and inter-annual variability in streamflow largely follows that of rainfall. Table 1 shows the marked variation in annual runoff volumes and rainfall/runoff percentages between streams within the three biogeographic zones. Whilst seasonal variability in streamflow is typical of many Australian streams (Finlayson & McMahon 1988), it is particularly pronounced in the study region. All streams have a distinct summer maximum flow. Streams north of the Herbert are mostly perennial, whereas south of this the flows are typically intermittent (Hausler 1990).

Table 1 - River Basin Hydrology

River Basin (Area - km^2)	Mean Annual Rainfall (mm)	Mean Annual Runoff (1000 ML)	Runoff / Rainfall (%)	Max. Instant. Flow [a] (m^3/s)
Daintree [w] (2125)	2576	3560	65	-
Mossman [w] (490)	2459	687	57	-
Barron [w] (2175)	1447	1153	37	4556
Mulgrave - Russell [w] (2020)	3233	4193	64	-
Johnstone [w] (2330)	3405	4698	59	-
Tully [w] (1685)	2970	3683	74	-
Murray [w] (1140)	2485	1628	57	-
Herbert [w] (10 131)	1331	4991	37	11 919
Black [d] (1075)	1510	509	31	-
Ross [d] (1815)	1071	372	19	-
Haughton [d] (3650)	923	756	22	-
Burdekin [d] (129 860)	640	10 100	12	35 999
Don [d] (3885)	1022	689	17	4983
Proserpine [m] (2485)	1562	1431	37	-
O'Connell [m] (2435)	1705	1668	40	-
Pioneer [m] (1490)	1418	994	47	9842

Notes: a) selected catchments only; w) wet tropics; d) dry tropics; m) moist central coast

(from Hausler 1990)

The nature of flooding in north Queensland is different to other areas in Australia (Fenwick 1982). Floods normally result from cyclonic or monsoonal activity, and the relatively steep stream grades and high rainfall intensities cause rapid flood rises to prominent peaks. A peak flood discharge of approximately 36 000 m^{3}s^{-1} was recorded at Clare on the Burdekin River in 1958. The inter-annual variability in flow is extreme for many streams. The coefficient of variation of the annual flows varies from 0.3 in the wet tropics to 1.2 in the dry tropics. The ratio of maximum to minimum annual flow volumes for the Burdekin River is 218, compared with 5.6 for the North Johnstone River (Hausler 1990).

2.3 Geomorphology

River basin landforms for the region are characterised by a coastal floodplain bordered to the west by ranges and high hills. In the wet tropics and to a lesser extent the moist central coast catchments, the ranges are rugged and are separated from a narrow coastal plain by short upland to lowland stream transition zones. By comparison, the catchments of the dry tropics usually have lower relief, a wider coastal plain, and longer stream transition zones.

A diverse range of morphological forms and processes occur in the study area and broad generalisations on stream and floodplain systems are difficult. However, natural stream levees and backswamps are prominent on the coastal floodplains. Stream channel size and bankfull channel capacity typically decrease in the downstream direction in the lower reaches, and distributary flow channels and elevated natural levees present a threat of channel avulsion during overbank flow conditions.

3 PRESSURES ON THE STREAMS

Human development is placing increasing pressures on the streams in a region that has significant conservation value (eg Wet Tropics and Great Barrier Reef World Heritage Areas). The pressures are discussed here in terms of direct impacts (activities within the stream channels and riparian lands), and indirect impacts (activities within the catchment remote from the streams).

In the wet tropics and moist central coast areas the narrow alluvial plains and hills have been largely cleared of native vegetation and are extensively used for sugar cane production and other intensive cropping. *Eucalyptus* and mixed closed rainforests cover the mountains to the west, while dairying on improved and irrigated pastures is common in elevated areas in the Barron, Johnstone and Pioneer river basins. In the dry tropics, the coastal plains of the Burdekin, Haughton and Don river basins have intensive irrigated sugar cane and horticulture crops, and beef cattle grazing is prevalent in the hinterland areas, where the native vegetation typically includes *Eucalyptus*, *Melaleuca* and *Acacia* woodlands.

Major urban centres and other towns are situated on streams in the coastal lowlands, eg: Cairns (Barron River), Townsville (Ross River) and Mackay (Pioneer River). Tourism is now an important industry throughout the region.

3.1 Direct Impacts

Direct impacts on streams within the study area include flow regulation and water storage; channelisation and river improvement; aggregate extraction and mining; encroachment from agriculture, urbanisation and infrastructure; introduction of exotic fish and plant species; and recreation and boating.

Dams and weirs have been built on several of the major streams for water supply and irrigation (Barron, Ross, Haughton, Burdekin, Proserpine, Pioneer); hydro-power (Barron, Tully); and flood control (Ross, Proserpine). These reservoirs alter seasonal flow distributions and reduce flood frequencies, but may not reduce flood peaks and durations since flood volumes can be in excess of storage capacities. The larger dams affect downstream sediment supply, environmental flows and in-stream vegetation conditions.

'River improvement' activities, characterised by hard engineering techniques such as rock revetment, channel realignment, clearing and desnagging, have historically been carried out in all river basins in the region. Sand and gravel has been extracted from the Barron, Mulgrave, Black and Gregory rivers in particular. Alluvial mining was once practised in the upper areas of the Mulgrave-Russell (gold) and Herbert (tin) catchments, resulting in increased downstream sedimentation in these streams.

Sugar cane farming has severely modified drainage systems on the coastal plain. Many small streams have been relocated or completely filled and land development typically extends to the very edge of the major streams. Land clearing for farm development and inappropriate farm management practices such as spraying and burning have degraded riparian lands. The narrow riparian zone that remains offers little protection to stream banks and is commonly dominated by introduced plant species. It provides only low grade habitat and most often represents a fragmented, rather than continuous, natural corridor.

3.2 Indirect Impacts

Indirect impacts on the streams include modified water and sediment flow regimes from agriculture, forestry and urbanisation; and pollution from organic matter, biocides, heavy metals and nutrients.

Catchment erosion is a problem in the wet tropics and the moist central coast where widespread clearing of the coastal plain and hinterland has occurred from sugar cane and small crop farming. Cattle grazing in upper catchment areas, particularly in the dry tropics, has also accelerated soil erosion. Increased sediment supply, channel aggradation, and increased flood levels are causing concern to river managers.

Rainforest logging once had a significant effect on water quality and stream sedimentation in wet tropic areas (Bonell 1988), but changes in forestry practices and the declaration of the Wet Tropics World Heritage Area have since ameliorated these effects. However, agricultural fertilisers and chemicals and effluent discharges from sewage treatment and sugar mills continue to affect stream water quality. Improved farming and industrial practices have the potential to reduce nutrient export to the river systems, estuaries and the Great Barrier Reef lagoon.

4 STATE OF THE STREAMS

The degree of human impact on the natural system and the effect of natural and accelerated stream processes on human development can be evaluated from the state of the streams. The present physical condition of the streams in the region is described here in terms of the types and rates of channel change and associated bank instabilities.

4.1 Rates of Channel Change

The collection of information on the type and rate of channel change in north Queensland coastal streams enables researchers to predict present-day natural change, to understand the significance of human induced change, and to provide a chronological framework for estimating human effects on the fluvial systems. Information is required on short-term changes that have occurred since European settlement (past 150 years), as well as long-term changes occurring over a geomorphological timescale of thousands of years. A lack of long-term data means that it is difficult to determine whether channel changes in the region are naturally or artificially induced, or are due to episodic or cyclic events.

This review of rates of change data for the region uses two broad time scales: historical (approximately 150 years of European settlement) and mid - to - late Holocene (past 5000 years). The limited published material that does exist for the historical period consists mainly of aerial photographs, maps, field surveys and anecdotal data for the past 50 years. The lack of Holocene data demonstrates the need for an extensive program of stratigraphic sampling, dating and analysis.

Limited studies of historical rates of change have been undertaken in each of the river basins. For example, changes in channel morphology between consecutive photographic and mapping surveys of the Mulgrave River were described by Connell Wagner (1992). Connor (1987) used a series of aerial photographic surveys conducted over 40 years to note changes in the channel position, morphology, and surrounding landuses of the South Johnstone River. Records of historical and anecdotal data on flooding and channel change in the Burdekin River have been compiled by Medley (1993). For these studies, the cumulative changes in bank position over a period of 50 years were sometimes in the order of 10s to 100s of metres, but were commonly much less.

Other studies have been undertaken by Hopley (1970), who described the coastal geomorphology of the Burdekin delta using drill cores, aerial photographs, and ground surveys; and Pringle (1984) who described the evolution and rates of change of the east Burdekin delta coast between 1940 and 1980. Channel movements of several hundred metres have been recorded in the Pioneer River estuary within the comparatively short timespan of 150 years (Gourlay and Hacker 1986). Only the Burdekin (Hopley), the Don (Nolan and Casey 1981) and the Pioneer (Gourlay and Hacker) have been studied over Holocene time scales, using geological interpretation and stratigraphic dating. Even so, the limited extent of the long-term data makes it difficult to assess the significance of the contemporary changes.

4.2 Channel Change and Bank Instabilities

This section provides an overview of the various types of channel change (metamorphosis, accelerated channel migration, avulsion, bed degradation) and associated bank instabilities (fluvial erosion, mass failure, overbank erosion) that are common in the region. Information on the relative significance of the types of change and bank instability problems is scarce.

As far as we are aware, no major channel metamorphosis (complete change in channel morphology) has occurred in the region. Significant sedimentation has been recorded, however, in the lower reaches of many of the rivers, notably the Don River. Growth of instream vegetation has increased following flow regulation in the Barron, Burdekin and Proserpine rivers. Channel migration is most evident on the high sinuosity streams in the wet tropics such as the Russell, Tully and Murray. The Russell, Johnstone, Herbert, Haughton, Burdekin, Don, Proserpine and O'Connell rivers have a potential for channel avulsion. Bed degradation, while not significant in the main streams on the coastal plain, is a problem in the smaller streams and tributaries in the catchment headwaters where stream gradients are steeper.

Bank instabilities are usually associated with one or more of the above morphological processes, but can also result from local channel processes, unrelated to the broader channel changes. Human impacts commonly play a large part in bank instabilities. Fluvial erosion occurs mostly on meandering streams where riparian vegetation is degraded and channel morphology is substantially altered. Such erosion is prevalent in all river basins and is of particular concern in the Daintree, Barron, Mulgrave, Russell, Tully, Haughton and O'Connell rivers. Mass failure is commonly associated with fluvial erosion and piping failure, and is prevalent on larger streams such as the Herbert, Burdekin and Pioneer. Overbank erosion is common on lowland streams with a tendency for channel avulsion, and is most severe where the land slopes significantly away from the streams, eg the Russell, Herbert, Haughton, Burdekin, and Proserpine rivers.

5 RESPONSE

In this section we assess the human response to bank instabilities. We focus on traditional and more recent stream management approaches and bank stabilisation practices, strategic planning studies and institutional arrangements.

5.1 Traditional Stream Management Approaches

Like other areas of Australia, stream management in the north Queensland region has traditionally been characterised by an engineering bias and an emphasis on structural methods without consideration of the full range of issues (cf Strom 1962). The principal objectives have been to mitigate against flooding and to check erosion (Fenwick 1982). A variety of bank protection, alignment training, and channel modification methods have been used, however their success has been affected by a lack of consideration of ecological values and geomorphic setting, by poor integration of physical and biological techniques, and by limited technical and economic suitability for the prevailing conditions.

Rock revetments are the most common physical protection works, and subsurface drainage is installed at some of these sites. Rock protected spillways are sometimes used for flood outflow control. Alignment training works include steel pile and wire mesh embayments and fields of groynes (typically rock). Channel modifications have in some instances involved pilot channel excavations and alignment cutoffs. Vegetative treatments have had limited success because of inappropriate species selection and plant establishment or maintenance techniques. Integrated physical (rockwork) and biological (vegetation) treatments have not been successful, and the introduction of vegetation, although intended as a means of stabilisation, has often merely improved the landscaping effect. Habitat and ecological aspects have traditionally been neglected.

5.2 Recent Developments

River improvement trusts were first established in Queensland in the mid 1940s (Burdekin River) to provide specialist management of flooding, erosion and sedimentation. However increased environmental awareness, altered community perceptions, and pending legislation changes, are changing stream management approaches in the region. The river trusts, constituted within 11 regions from Mackay to Mossman, have recently been engaged in the preparation of stream management strategies addressing key problem areas, appropriate methods and funding arrangements. An integrated catchment management (ICM) approach is being adopted, and five ICM groups have been established. Table 2 summarises the present river trust, ICM and strategic planning arrangements for the individual river basins.

Table 2 - River and Catchment Management

River Basin	River Trust [a]	ICM	Strategic Planning
Daintree - Mossman	√		√
Barron	√		√
Mulgrave - Russell	√	√	√
Johnstone	√	√	√
Tully - Murray	√	√	√
Herbert	√	√	√
Black - Ross			
Haughton	√		
Burdekin	√		√[a]
Don	√		
Proserpine	√		√
O'Connell	√		√
Pioneer	√	√	√

Notes: a) part catchment only

6 THE WAY FORWARD

An understanding of local environmental conditions and characteristic stream processes is necessary to satisfactorily address bank instabilities and degradation in north Queensland coastal streams. Furthermore, the development of appropriate stream management responses for the region depends on the knowledge of pressures on the streams (direct or indirect), the state of the streams (rates of change, bank instabilities, ecological condition), and the interrelation of these factors.

The dearth of fluvial research on north Queensland's coastal streams has historically reflected the remoteness of the region from population centres in south eastern Australia. Unfortunately, the deficiency of process data prohibits the development of rigorous local models for the unique and varied fluvial landscapes of the region. Hence, stream managers lack an appropriate theoretical context to guide their decisions.

This is presently being addressed through a number of research and development projects that are leading to new stream management approaches in the region. These projects involve integrated engineering, geomorphological and ecological studies, which include a review of bank stability problems and stabilisation practices, field monitoring and case study activities and implementation of various trial bank stabilisation techniques (Johnston et al 1994). Researchers, government agencies, industry, landholders and community groups are collaborating in these efforts. Through these research, planning, implementation and extension activities, the emphasis is shifting from traditional approaches to broader stream management values, ecosystem management and stream health.

We believe that these initiatives represent the way forward for stream management in the region. They also go some way towards addressing the shortcomings in fluvial research (Tooth and Nanson 1995) and the lack of stream data identified in the OECD *State of the Environment* reporting.

7 ACKNOWLEDGMENTS

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Management of River and Dyke Protection Red River Delta, Vietnam

Eric J Lesleighter and Tran Xuan Thai***

ABSTRACT: *The paper reveals how the scale of the dyke protection works in the Red River Delta which have been needed has not been matched even closely by the budget available. The Government strategy has been to concentrate on critical areas, with the inevitable result that many needy areas miss out or are covered insufficiently. The suggestion is that embarking on a course of large-scale river training would greatly compound the budgetary constraints faced by the Government and the provinces, and would create a compelling ongoing program of river "control" that would be never-ending. The paper addresses the specific areas of concern, the river management works which economically meet the requirements, and the program of strategic personnel training, in order to optimise the budgetary allocations by sound management of the costs of design, materials and construction.*

1. INTRODUCTION

Flood and storm control, and natural disaster mitigation, are a State strategy for countries where there is intense monsoonal rainfall over a dense river system like that of the Red River in Vietnam. The realities of yearly flooding has been a part of life for the Delta's 17 million inhabitants for centuries. The scale of the problem is reflected in the extensive system of major river levees (dykes), and the measures which are taken to safeguard the integrity of the system.

While not the only method of flood management, systems of levees along river banks have been adopted in many countries as a tangible, and visible, way of protecting riverine lands. The use of such an approach has been criticised. In the major floods in the central USA in 1993, a number of levees were breached, naturally leading to the inundation of large areas of land. Criticism has included the claim that the resultant flooding would have been less if the levees had not been there in the first place; or at least the flooding would have been more "equitable" with "all" being flooded rather than the unlucky ones who happened to have properties beside the breach.

The major flooding in Bangkok in October 1995 was blamed (probably wrongly) on riverside embankments by residents in certain eastern areas of the city. As a result many embankments were demolished in efforts to "let the water out", only to lead to more flooding from the river during subsequent high tides and discharges. So the debate goes on. When the studies, which spauned this paper, were commenced in Hanoi in 1993, some of the local opinion was that the levees along the Red River should be removed.

In reality, no such measures would be technically or socially acceptable, and as in many other cases, highly developed systems are there, and there to stay. Following extreme flooding in 1971, active measures for flood control, dykes management, and bank protection in the Red River Delta have produced appreciable benefits in the development of the Vietnam economy.

2. THE DYKES IN THE RED RIVER DELTA

In the Red River Delta, the system of dykes is the result of the labour of the Vietnamese people for over 1 000 years. In 70 years of this century, a large amount of money has been allocated to increasing the dyke elevation, repair, and generally upgrading the dykes in the Red River system, to keep the top elevation above certain design flood water levels. All of the river bank protection works are initiated and developed in response to changes in the river morphology and socio-economic demand in the Red River delta. Although the river works concentrate on protecting critical areas only, even then the total budget allocated to them each year is significant for a limited economy such as that of Vietnam.

The rivers are bordered by 3 000 km or so of river dykes. The major tributaries of the Red River are the Da, Thao, and Lo Rivers. The three main tributaries have catchment areas (including those outside of Vietnam) of 52 900 km^2, 51 800 km^2, and 39 000 km^2, respectively, in a total Red River catchment (including the delta) of 155 000 km^2. Figure 1 presents a general map of the Delta river system.

Over a large part of its length the Red River is 1 km or more in width, and is characterised by large mid-channel shoals, elongated shoals adjacent to the banks, and occasional islands. The banks of the rivers are alluvial, typically 3 m to 4 m in

* *Eric J Lesleighter, Chief Engineer Water Resources, Snowy Mountains Engineering Corporation Limited, Cooma, NSW, 2630*

** *Tran Xuan Thai, Director, River and Coastal, Vietnam Institute of Water Resources Research, Hanoi, Vietnam*

height (excepting adjacent to the main dykes where they are higher), and erodible. It is when the erosion occurs along banks where the dykes are close to the river's edge that measures are taken to stabilise the banks and avoid direct erosion of the river side of the dykes.

3. MANAGEMENT

In the Red River delta, bank protection works, water intakes and drainage structures along the rivers have been built and managed by the Ministry of Water Resources (MWR) and local water resources services. The MWR comprises a number of key departments. Of particular relevance to river works, dykes, river intakes and associated facilities are the Department of Dyke Management and Flood Control (DDMFC), and the Vietnam Institute of Water Resources Research (VIWRR).

The DDMFC, includes the Dyke and Bank Protection Works section and the Planning Section. Both act on advice from the VIWRR. Together, decisions are made on how the Government's budget for such works is used. While the DDMFC has a vital role in safeguarding the integrity of the dyke system, its functioning comes down to a 'balancing act' between the available budget and the actual needs. The construction of river engineering works is both difficult and expensive.

In the whole Ha Tay Province dyke system (Figure 1) there is a total length of 294 km of main and sub-dykes. Every year new and repair dyke work is necessary. Seepage is a major problem under dykes in a number of places, as is the occurrence of fracturing due to differential settlement.

Figure 2 shows the reach of the Red River from the entry of the Da and Thao Rivers down towards Hanoi. On the right bank of the Da River in the vicinity of the Thao River confluence, bank protection to safeguard dykes have been constructed over a 5 km length. The works generally consist of revetment of riprap and short groynes spaced at about 150 m. For some 5 km or more the dyke in the 'loop' downstream of the Thao River confluence in recent times has been perilously close to the water's edge, and the bank protection works have been an essential part of assuring the integrity of the flood protection system.

The Hoa Binh Dam on the Da River is approximately 100 m high. Its reservoir is used to supply an 1800 MW underground power station, but it is also utilised in a significant flood mitigation role. The Da River makes up 34 % of the Red River catchment. The present operation rules for Hoa Binh reservoir require lowering of the reservoir level during June each year just prior to the flood season. It has been estimated that utilisation of the Hoa Binh reservoir for flood control would lower the Hanoi flood level for a repeat of the 1971 flood by 1.3 m.

While upstream reservoirs are proposed as a flood control device, the Hoa Binh dam was built primarily for power. The reservoir, however, provides flood mitigation in the Red River and its branches, and it is a trap for the large amount of sediment originating in the Da catchment. Consequently, the classical degradation situation prevails in the Da River downstream of the dam.

4. BUDGETS

The scale of the river and dyke works which have been attempted over the years has not been matched even closely by the budget available. Accordingly, the strategy has been to concentrate on critical areas, with the inevitable result that many needy areas are not being attended to, or some group areas are being covered inadequately.

The annual budget for the various provinces has been allocated for

* construction of new bank protection works on severely eroded river bank reaches
* repair of bank protection works which have been attacked and damaged
* repair of dyke reaches which are damaged, and there is the danger of dyke failure by sliding or undermining, and
* maintenance of dykes and bank protection works.

The amount of the budget spent in a certain area depends on the physical length of the dyke under attack, a judgment on how imperative the work is, and the population of the province. Besides the central Government's budget, each province contributes from its own budget for river works and dyke repair, but its budget is usually smaller that the allocation from the Government.

5. DESCRIPTION OF RIVER WORKS

The bank protection works are usually distributed along the river in 'groups'. Due to budget limitations, however, the necessary works in a certain reach are often not completed and the subsequent flood season places great stress on those works which were. In addition to the limited number of groynes which can be funded on a particular reach, resulting in groynes which are spread too far apart, the complex nature of the river geomorphology means that it is difficult to foresee problem areas. In order to illustrate the ongoing challenge, a brief history of events in the Thao-Da area is presented. Figure 3 shows the river features in the area in 1979 and 1985.

The main types of bank protection that have been used in the Red River system are revetments or groynes, or a combination of these. Groynes are almost invariably of an impermeable construction.

The Thao - Da confluence group of work includes bank protection on the right bank, in the Co Do village portion of Ha Tay Province (Figures 2 and 3), and works on the left bank at Le Tinh in Vinh Phu Province. The morphological processes in this area, being at the confluence of the Thao River and the Da River, are particularly complex. The thalweg and formation of mid channel bars are subject to major changes from year to year. Moreover, the construction of the Hoa Binh Dam on the Da River has been found to have a direct effect on this area. This group of works is the most extensive in the Red and Thai Binh River system.

In typical fashion, urgent remedial measures were performed during 1989/1990, consisting of a number of new groynes and upgrading of four groynes by increasing their top level and their length.

In 1979, (Figure 3), a large point bar is present alongside groynes 1 to 8, where previously the flow pattern was such that protection works were necessary. Subsequently, the bar extended to groyne 12, the main stream was directed towards the bank upstream of groyne 13, and groynes 16 and 17 were generally away from the main stream. In 1985, the point bar had extended almost to groyne 13, the main stream was directed towards the groyne 16 and 17 area, the mid-channel bar across from groynes 13 to 16 was enlarged, and the main channel was almost all directed across the river towards the mouth of the Lo River.

In the light of such major morphological changes, a situation which is repeated in other areas of the river system, the engineering of the river aimed at protecting the dykes should emphasise the management of the problem areas rather than wholesale control, which in fact is not possible.

6. IMPROVED RIVER ENGINEERING PRACTICE

6.1. Summary of Present Practice

The works which have been implemented, the unpredictable nature of where the next trouble spot will occur, and the limited budget, has imposed a 'reactionary' situation of responding to evident needs.

The budgetary constraints will not be removed without a sizeable injection of funds from other than normal sources, but the present practices of revetments and impermeable groynes needs to be re-evaluated in an effort to 'stretch' the value of allocated funds.

Over the years, hydraulic model testing has been carried out at the VIWRR to assist in understanding the flow patterns during flooding and to selecting the best locations for groynes. There are a large number of 'trouble spots' which means that the modelling process is faced with a huge task of keeping abreast with the apparent need.

In addition to the evident budget limitations in the face of a huge system of dykes, intakes and river works, the authors proposed a training program for river engineering personnel in the VIWRR as a tangible means of upgrading present practice.

6.2. Summary of Problems with Existing Techniques

Technical measures to train rivers to displace sand bars from the front of water intakes are very costly, and in any case, due to the river's response to other major flow and sediment transport influences remote from the intake locality, such works would not be effective in many cases. Structural measures such as river training to direct water and separate water and sediment flow is very difficult, in fact, infeasible for the wide rivers which make up the Red River system.

The imbalance between a limited budget and a very great demand on that budget to stabilise rivers is very real. The use of impermeable groynes has been accompanied by problems experienced in many other fine-bed rivers due to the 'sudden' impact they have on the flow, causing intense eddies and turbulence, the difficulty in constructing them with sufficient foundation depth to adjust, without significant collapse, to the scour hole which normally forms at the tip of the groyne, and the sheer volume of materials required to construct them. This raises the need for a better technical solution accompanied by economies of construction.

6.3. Alternative Techniques

Permeable groynes have been proposed as a technical solution more suited to the bank protection requirements in the Red River system.

River works have to optimised for cost as well as durability, and thus a flexible approach is desirable. Materials have to be chosen which are appropriate to the area. Given the immense scale of the river system and the protective works required, the management of such a program points up a clear need for training of engineers in river engineering and river management. The first author has experienced the need and the value of training so that new concepts are appreciated and better management is achieved.

6.4. Implementation Plan for Improved Practice

The need is to address the specific areas of concern, and introduce river engineering (management) works which economically meet the requirements and embark on a program of technical upgrading for VIWRR and DDMFC personnel.

Budget enhancement may be considered a priority management measure. However, in this context, the authors suggest that this means more efficient use of funds tied into more durable and effective methods, and organisational streamlining. This is a management objective, even though increased funding may be required to handle critical problem areas in the short term.

Of the yearly budget for dyke and river works in the Red River system, little of this allocation is directed towards field studies and research to enhance the practitioner's appreciation of the problem/solution optimisation process, nor field investigations to provide information on which to base the design of works.

Policy and Planning

The authors' experiences on the Red River and its tributaries suggest scrutiny and possible modification of policy and planning which can be applied with benefit in other major river systems, particularly when funds are limited. The following guidelines are advanced:

- ★ there is no one correct answer to the river engineering problems
- ★ embrace a policy of management of the rivers' problem areas
- ★ recognise the economic disadvantages of completing insufficient works in specific trouble spots, ie, avoid spreading of the works 'too thinly', and resist the temptation to treat more areas than the funds will adequately cover
- ★ maximise the budget and optimise the budgetary allocations by sound management of the costs of design, materials, and construction
- ★ allocate a small proportion of the yearly budget (say 1%) to field measurements, survey, and research into better methods
- ★ recognise that the budget share between provinces needs to take account of the fact that improvements in problem areas in one province may have a significant benefit for a neighbouring province
- ★ ensure that there are clear lines of technical and financial management in one organisation, and that the knowledge gained with new techniques is disseminated and utilised, and
- ★ incorporate a program of training of key personnel.

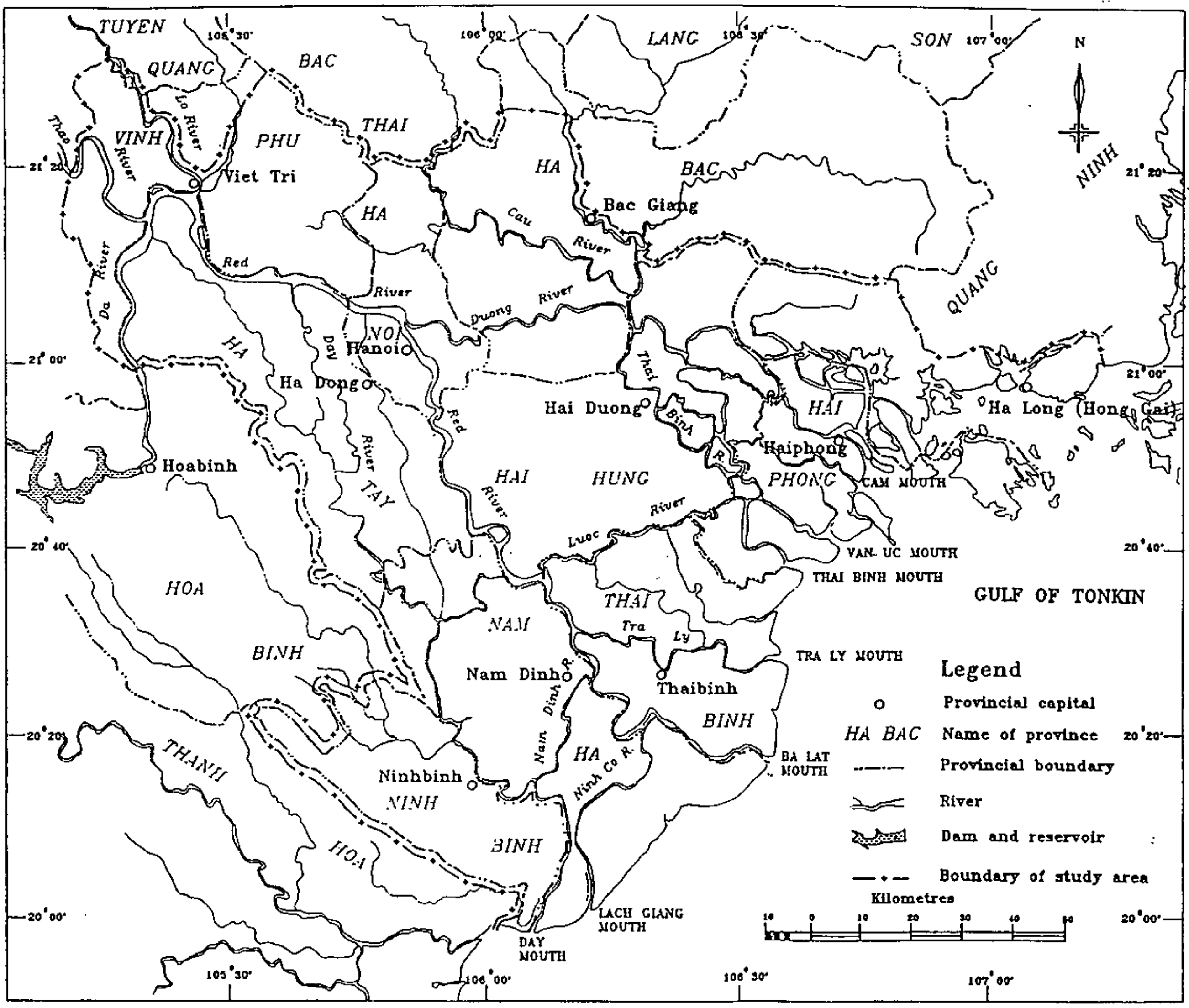

Figure 1 - Area Map Red River Delta, Vietnam

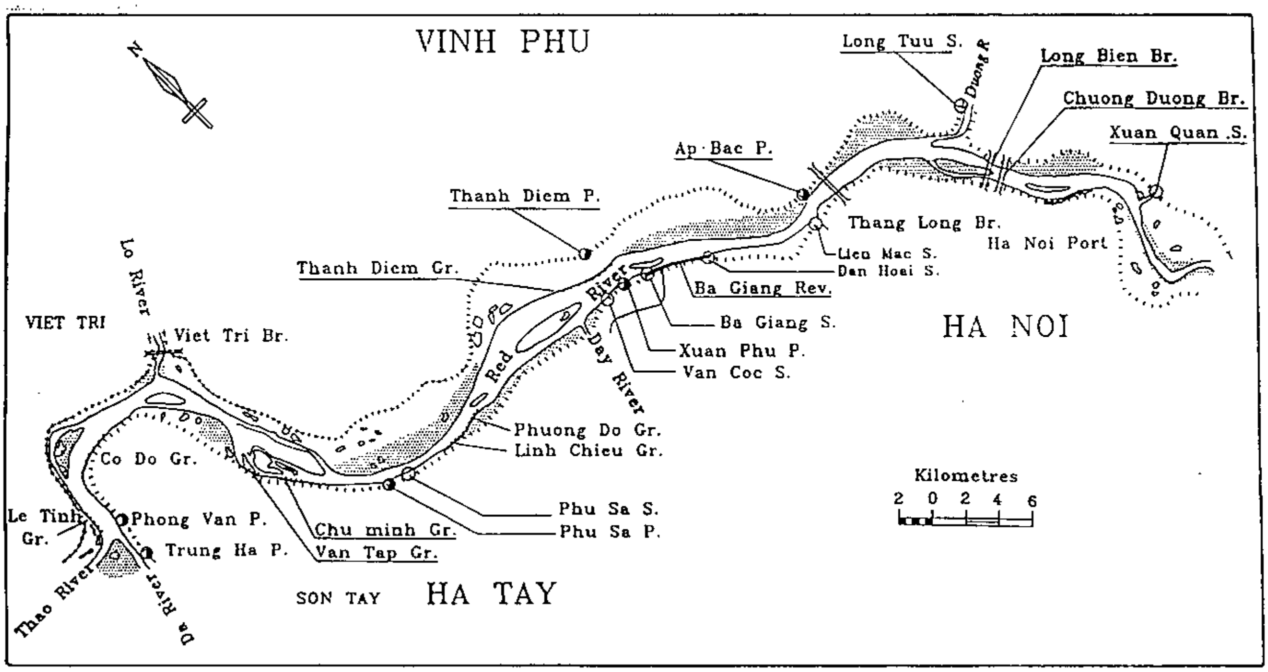

Figure 2 - Red River from Thao-Da Confluence to Hanoi

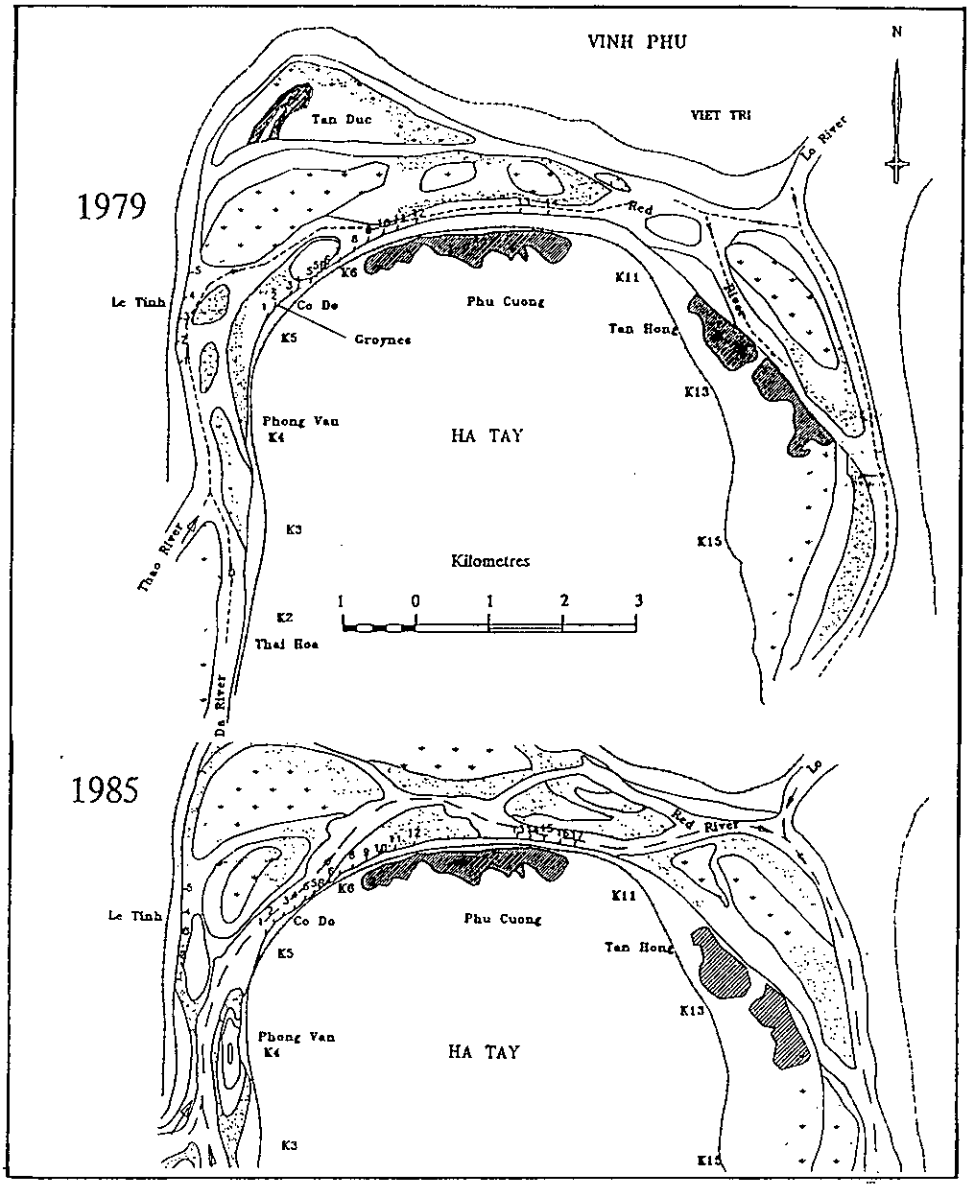

Figure 3 - River Features Thao-Da Confluence 1979 and 1985

A Simple Model to Illustrate the Effects of Riparian Revegetation on Stream Values in Large Catchments

Cathy Wilson[1], Robert Argent[2], Stuart Bunn[3], Peter Davies[4], Roger Grayson[2], Peter Hairsine[5] and Ian Rutherfurd[6]

ABSTRACT: *Catchment managers and scientists involved in the LWRRDC sponsored National Riparian Zone Project gathered in Yungaburra, QLD in November 1994, to carry out a workshop aimed at developing a program of integrated research to meet management needs. The workshop was focussed around the production of a computer model of the North Johnstone River Catchment, which indicates the response of stream values to riparian vegetation management. We used the Adaptive Environmental Assessment and Management (AEAM) approach to define and develop the model. The model includes expert knowledge on how riparian vegetation affects sediment and nutrient filtering, bank erosion and terrestrial and in-stream ecological habitat.*

1. INTRODUCTION

The management of riparian lands has become an important issue in Australia. In response to the concerns of many government agencies and community groups, the Land and Water Resources Research and Development Corporation (LWRRDC) commissioned a national research program on the rehabilitation and management of riparian lands. The program aims to:

- identify and quantify the effects of riparian lands on channel morphology, bank stability, and the ingress of sediment and nutrients to rivers and water bodies;
- identify the key processes by which riparian lands influence in-stream ecosystems and their functioning, and quantify major effects;
- demonstrate practical, cost effective and ecologically sound methods for rehabilitation and management of riparian lands.

It involves researchers from a wide range of disciplines and institutions, as well as managers and practitioners from state agencies and local land care groups. Details of the National Riparian Zone Program (NRZP) are given by Wilson *et. al.* (1995).

The objectives above reflect the fact that riparian vegetation provides numerous functions (Herron, this volume). Most Australian streams have been cleared of all or most riparian vegetation. Great effort is now going into restoring these lands. Many kilometres of streamlines are being fenced and revegetated with little understanding of the impact that will follow. Our hope is that stream banks will stabilise, water quality will improve, fish will spawn, terrestrial fauna will flourish, the land will look good, and the landholder will benefit from his or her efforts.

To ensure these outcomes we need to optimise the design of riparian restoration projects to perform a range of functions. This requires understanding the physical and ecological processes which occur in the zone, and the links between those processes. It also requires an understanding of the needs of, and management constraints experienced by landholders.

2. WORKSHOP OBJECTIVES

In light of these issues, the participants in the NRZP felt that an important first step in a large management oriented research program was to bring together managers, practitioners and researchers in a workshop setting to identify each party's expectations, requirements and expertise. The workshop focussed on formalising our collective understanding of how riparian vegetation works to enhance stream values, within the framework of a computer model.

The workshop was not however, primarily designed to be an exercise in model development. The intention was to use the *process* of developing a systems model to identify and explore our understanding of the physical and ecological responses occurring in riparian zones at time and space scales relevant to management. Our specific objectives were to:

- develop strong links across research disciplines and establish an integrated approach for carrying out field investigations and model development;
- develop a computer model which predicts the likely impact of riparian land management on stream water quality, stream bank stability, and in-stream and terrestrial ecology;
- determine previously unidentified knowledge gaps and research tasks from "holes" in the model and assess how these new tasks fit into the research program;
- identify common data requirements for both the ecology and physical research groups, and determine how can we use existing data sets;
- design field experiments and demonstrationsites which link ecological and physical program objectives with practical management options.

[1] CRC for Catchment Hydrology (CRCCH), CSIRO Division of Water Resources, GPO Box 1666, Canberra ACT 2601
Telephone: (06) 246 5816 Fax: (06) 246 5845 Email: cathy@cbr.dwr.csiro.au
[2] Centre for Environmental Applied Hydrology, University of Melbourne
[3] Centre for Catchment and In-Stream Research, Griffith University
[4] Department of Zoology, University of Western Australia
[5] CRCCH, CSIRO Division of Soils
[6] CRCCH, Department of Civil Engineering, Monash University

3. WORKSHOP METHODS

The style and objectives of the workshop were based on the Adaptive Environment Assessment and Management (AEAM) process developed by Carl Walters and others. It is a technique which facilitates "...the development and exploration of management options for complex systems and is particularly applicable to environmental issues." (Grayson *et. al.*, 1994).

AEAM typically involves a workshop at which participants from diverse interested groups define and build a computer model for a system that requires management. These people may include scientists, planners, resources managers and competing resource users. The process aims to embed the best available technical knowledge in a model that addresses the issues of the group. It can be used to run a range of scenarios which lead to a set of management actions that meet the needs of, or are acceptable to, most of the interested parties.

In our case, the interested parties are the scientists and resource managers (including farmers) involved in the riparian zone program. In particular, we focussed on the development of a computer model to predict the environmental impacts of riparian vegetation management in the North Johnstone River Catchment, Queensland.

This catchment was chosen for several reasons: 1) it is one of the riparian zone program "focus" catchments, 2) relevant ecological research was under way in the catchment; and 3) QDPI had developed a substantial knowledge base for the catchment which included (i) sediment and nutrients production and transport rates on pasture, cane and banana lands; (ii) a GIS containing a wide range of relevant parameters; and (iii) long term groundwater, stream flow and water quality data sets.

In preparation for the workshop, participants were asked to think broadly about the riparian zone in relation to the following questions: 1) What can be managed in the riparian zone (eg. stock access, vegetation composition), 2) what indicators of the system can be used to assess whether the change has had an effect, and 3) what are the relationships between what can be changed and the indicators that measure the impact of the change on the system?

Participants were also asked to bring specific information to the workshop as given here:

Ecological Information:
- Water quality targets (solute and sediment concentrations, temperature, etc.) required to support desired in-stream ecosystem for a given stream type/order.
- In-stream habitat requirements (woody debris, bed material size, undercuts).
- Relationships between riparian vegetation (type, age, height) and habitat suitability (food, shelter, algal growth).

Water Quality and Quantity Data:
- Storm based data of N, P and sediment concentrations at several stations for a range of catchment types (size and land use) and flood size.
- Monthly rainfall, stream flow and turbidity data for a period of 5 years, including wet and dry years.
- Long term trends in surface and subsurface water quality parameters.
- Water quality targets set by the State or other groups.

Source Strengths and Material Pathways:
- Production rates of N, P and sediment from different land use for normal and best practice management conditions.
- Proportions of water, N and P that move through subsurface and overland pathways to streams.

Catchment Management:
- Trends in land use over time.
- Timing of significant land use changes (eg. green cane harvesting widely adopted)
- Information on actual riparian rehabilitation projects in place or planned.
- Air photography and 1:50,000 maps of the catchment.

Physical Processes:
- Statistics on amount of catchment draining through riparian zones on different order streams for grid cells.
- Relationships between riparian zone vegetation type and dominant flow pathways.
- Surface and subsurface sediment and nutrient trapping efficiencies for different vegetation types and widths.
- Relationships between riparian vegetation type, channel geometry, channel migration rates, and gully erosion rates.
- Effect of riparian vegetation on flood hydrographs.

Other:
- Experimental designs
- Several management scenarios.

A subset of this information was available, and a smaller subset was in a form that could be brought to the workshop. This information formed the basis of the algorithms incorporated into the riparian zone model.

The workshop was held at Lake Eacham Hotel in Yungaburra, Queensland on the 9th through the 10th of November 1994. Each of the workshop participants developed and presented data, algorithms (sediment trapping, bank stability, stream order statistics, stream temperature) or other information (farmer behaviour, process descriptions) relevant to how vegetation affects processes in the riparian zone. This information was coded into an existing base model during designated workshop sessions. A series of riparian management scenarios were run using the computer model during the last sessions of the workshop.

4. SUMMARY OF ALGORITHMS

A grid-based digital elevation approach is used to drive the suite of hydrologic, erosion and ecological processes in the model. A 930 km² area of the North Johnstone River Catchment was represented, covering a region which includes gauging stations at Glen Allyn and Tung Oil (Figure 1). Elevation, land use, rainfall isohyets and geology are distributed through the catchment at the resolution of 1 km grid cells. These data were extracted from 1:1,000,000 topographic maps and information presented in the Johnstone River Catchment Atlas (QDPI, 1993).

4.1 Hydrology

The model uses a single bucket approach to calculate the runoff in each cell. The water balance for each cell is calculated on a monthly basis from pan evaporation data and rainfall at Innisfail. Pan data have been modified to give potential evapotranspiration via the monthly relationships of Chiew and MacMahon (1992), and rainfall at Innisfail is distributed across the catchment using annual isohyets. The water balance is calculated as follows:

$$R = \alpha S + X \quad \text{and} \quad S = I - E$$

where R is monthly runoff, a is a seepage factor, S is the monthly store of moisture in the soil, X is overland flow generated when the store is full, I is rainfall

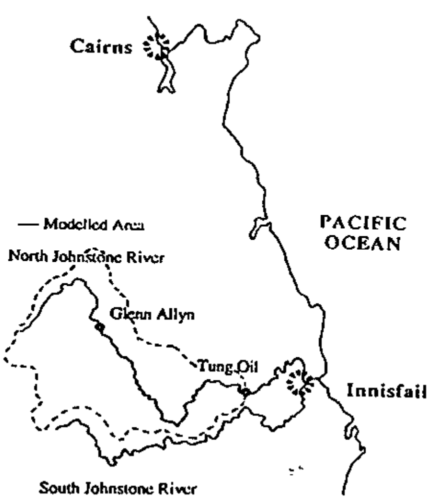

Figure 1. Location map for modeled portion of the North Johnstone River Catchment, QLD.

and E is actual evapotranspiration. Maximum evapotranspiration is allowed to be 75% of the maximum soil water store. Runoff is routed through the catchment along flow paths calculated using the steepest descent method. All runoff that is generated during a given month is assumed to reach the outlet of the catchment by the end of that month.

Adjustment of α and the maximum soil store S, were used to fit modelled runoff to observed streamflow at Glen Allyn and Tung Oil.

4.2 Stream Order Statistics

How well riparian vegetation treats bank stability, provides shade, enhances undercut habitat, or traps sediment and nutrients depends on either the size (width and depth)of the stream being treated or the amount of hillslope runoff flowing over and through the bank of the stream. For instance: shallow rooted shrubs and grasses may work well to stabilise the walls of a small gully, but deep rooted trees may be required to slow down bank erosion in bigger streams

To predict the impact of riparian management with our model, we need to know the characteristics of the streams that flow in and through each grid cell. In particular, if we want to calculate the cost of fencing the streams in part of the catchment, the length of stream running through the grid cells in the treated area is required. If we want to manage different streams in a cell with different types of vegetation (grasses and shrubs on small gullies and trees on big streams) then we need to know the distribution of stream sizes flowing through that cell. Finally, in order to predict how much sediment and nutrient can be trapped in grass filter strips along stream lines, we need to know how much material is delivered to the riparian zone from hillslopes. For this we need the proportion of hillslope runoff that flows into different stream types located in that cell.

In the riparian zone model this was achieved by constructing a set of tables which provide a statistical representation of the stream network within each 1 km grid cell. Stream data was extracted by hand from 1:50,000 topographic maps of the region. The tables uses the concept of stream order as a surrogate for stream size, since it is easy to calculate stream order, but impossible to measure stream geometry, from a 1:50,000 map.

A separate table in the model gives the relationship between stream geometry (width and depth) and stream order. This relationship was based on a quick field trip around the Yungaburra countryside during the workshop. We did not attempt to explicitly represent every stream in the North Johnstone Catchment, because it would require the use of a much smaller grid size and more complex runoff routing algorithm.

4.3 Sediment and Nutrient Generation and the Effect of Riparian Vegetation on Material Trapping
The riparian zone model includes 29 different land use types. Each land use has been assigned sediment and nutrient generation values in units of mg/l. These base level concentrations are used for runoff values less than 10 cm/month. If runoff in a cell exceeds 10 cm/month then concentrations of sediment and phosphorous in runoff increase in a non-linear manner:

$$C = C_{base} R^{\beta} \quad \text{and} \quad S_{gen} = CR$$

where C (mg/l/km²) is the concentration of sediment or phosphorous in the runoff generated in a given cell, C_{base} is the base level concentration, R is runoff, β is the coefficient used to increase sediment and nutrient generation as runoff increases, and S_{gen} (mg/km²) is the amount of sediment generated in a cell during a month.

The model does not aim to accurately predict sediment and nutrient generation rates. Although real sediment concentration data was used to get an approximate value of b where it was available. The concentration equation only attempts to calculate a reasonable amount of material which is delivered to the riparian zone. Trapping algorithms then calculate how different vegetation management scenarios may modify the concentrations of materials that pass through the riparian zone.

Trapping is achieved in the model using a sediment and nutrient delivery ratio approach. The delivery ratio algorithms are derived mainly from a review of grass filter strip literature (see Hairsine, this volume). The main factors affecting delivery ratios which are included in the model are: 1) the type of riparian vegetation, 2) the width of the buffer strip, 3) nutrient enrichment values, 4) the presence or absence of stock in the riparian zone, and 5) and stock access to the stream.

The model calculates the amount of sediment entering the stream, S_{stream} (mg/km²), as follows:

$$S_{stream} = S_{gen}(SDR)$$

SDR is given as:
WDR * [1-(1-(GCF*UCF*CCF)*(1-SIF)*(1-SAF))]

where WDR is the width delivery ratio, GCF, UCF and CCF are the ground, understorey and canopy cover factors respectively, SIF is the stock influence factor and SAF is the stock access factor. Under ideal conditions of a wide dense grass buffer strip, mature rainforest next to the stream, and limited stock presence, SDR can be as low as 0.15. If there is no buffer strip, then all material delivered to the riparian zone goes through it and into the stream and SDR=1.

The amount of nutrient (phosphorus) entering the stream, N_{stream} (mg/km²), uses a nutrient delivery ratio, NDR, and is calculated in a similar manner:

$$N_{stream} = N_{gen} * NDR \quad \text{and} \quad NDR = SDR * ER$$

where N_{gen} (mg/km²) is the nutrient generation rate and ER is a soil dependent enrichment ratio. The sediment delivery ratios for different vegetation types is given in Table 1 below.

4.4 The Effect of Vegetation on Stream Hydraulics and Stream Bank Erosion
Vegetation affects channel morphology by influencing flow and by increasing the strength of the banks. The influence of vegetation on both velocity and bank resistance varies with the scale of the stream. In general, a suite of riparian vegetation is about the same size throughout a stream network, while the forces that are applied to the stream bed and banks tend to increase downstream.

In the model we allocate an index value to represent the influence of vegetation upon bank erosion rates. This bank erosion index (BEI) is a measure of the importance of vegetation. Thus a BEI of 0 means vegetation has no impact on erosion rates, a BEI of 5 means vegetation will dramatically reduce erosion. To account for the scale effect discussed above, the BEI varies with stream order as well as vegetation types.

The BEI is mainly a measure of the strength and resistance effects of vegetation at high flows, as this is when most bank erosion occurs. We also assume in the model that the influence of vegetation on flow velocity is small during high flows, even though it is clear that grasses and macrophytes in particular, greatly reduce low flow velocities in small to medium sized channels. Similarly, we ignore the impact of large woody debris, LWD, on bank erosion. This is because in the wet tropics LWD breaks down very quickly, and any collections of surviving wood are flushed out of the channels during cyclones.

The ratings applied in the model can be summarised as follows: riparian vegetation, including dense ground cover and overstory, considerably reduces channel erosion rates in channels of all sizes. The effect, however, declines with stream size. Groundcover alone has less effect than full rainforest, and understorey is considered to have the least effect on bank stability. The ranking adopted in the model reflect findings in the literature (see Rutherfurd *et. al.*, 1995; Abernathy & Rutherfurd, this volume).

4.5 The Effect of Vegetation on Undercutting as Habitat
Undercutting of the banks provides critical habitat in a stream. Bank vegetation allows undercutting to develop

because the roots hold the bank above the toe. Without vegetation, the bank will collapse as soon as it erodes. Typically banks are undercut where there is well developed riparian vegetation (ie. rainforest species), and observations in the North Johnstone indicate this is particularly evident on third and fourth order streams. There are several explanations for this distribution:

- Grasses do not provide enough root strength to sustain undercutting.
- In small first and second order streams the root zone extends well below the toe of the stream bank so that undercutting is reduced. There may, however, be increased habitat around the roots themselves.
- The toe of the bank is just below the root zone, so the tree provides maximum support.
- In larger streams (>4 order) roots provide some support, but erosion is often below the root zone. Thus, undercutting may occur but vegetation has less influence on it.

As a result, the model is set up to predict maximum undercutting on third and fourth order streams with rainforest riparian vegetation.

4.6 Ecological Values of Riparian - Stream Linkages

Important in-stream ecological processes are both regulated and maintained by riparian vegetation. Ecological processes in forested streams including community metabolism and the structure of the major aquatic food-webs are maintained by the supply of terrestrial detritus from the surrounding catchment. This food-web typically supports a well-defined shredder and collector macroinvertebrate community. Due to low rates of primary production, the algal-scraper food-web is of lesser importance. Other inputs from the catchment including large woody debris (LWD) are an important component of both fish and macroinvertebrate habitat, particularly in sandy rivers.

Australian streams and rivers are characterised by a depauperate algal-grazing community (Bunn & Davies 1992, Davies 1993). Therefore, excessive in-stream primary production may remain largely ungrazed and, as such, not enter aquatic food-webs. Excessive primary production is typically the result of cultural impacts and includes excess macrophyte and filamentous green algal growth and blue-green algal blooms. Riparian vegetation regulates in-stream primary production by shading the channel, reducing both light inputs and water temperature. Riparian vegetation also filters inputs from the catchment, ultimately reducing nutrient levels in streams and rivers.

The importance of riparian vegetation for in-stream ecological processes is therefore based on two basic properties; (1) regulators of primary production and (2) suppliers of both energy for the maintenance of aquatic food-webs and LWD as important components of habitat.

In the model, the important features of riparian vegetation for ecological processes are:

- factors regulating in-stream primary productivity: vegetation height, and vegetation shading ability;
- factors influencing the supply of material from riparian vegetation to the stream: supply of coarse particulate organic matter (CPOM) and supply of large woody debris (LWD); and
- its ability to support terrestrial habitat for birds, other vertebrates and arthropods.

Table 1 below was developed to rank the benefits of different canopy, understory and groundcover vegetation in relation to each ecological factor listed above.

Vegetation	SDR	Height	Shade factor	LWD	CPOM	Birds	Other Vert.	Arthro-pods
Canopy								
Bare	1.0	0	0.0	0	0	0	0	0
Rainf. Short	0.9	10	1.0	4	10	10	9	10
Rainf. Tall	0.7	30	1.0	5	10	10	10	10
Exotic	0.8	20	0.6	2	2	2	0	0
Callist.	0.95	5	1.0	1	4	6	6	4
Understory								
Bare	1.0	0.0	0.0	0	0	0	0	0
Sparse Poor	1.0	3.0	0.4	0	2	2	2	2
Sparse Rich	1.0	3.0	0.4	0	2	4	2	5
Dense Poor	1.0	3.0	1.0	0	4	6	8	4
Dense Rich	0.9	3.0	1.0	0	4	10	10	8
Ground Cover								
Bare	1.0	0.0	0.0	0	0	0	0	0
Sparse Tuss.	0.9	0.5	0.0	0	0	0	0	0
Sparse Unif.	0.8	0.5	0.0	0	0	0	0	0
Dense Tuss.	0.7	0.5	0.0	0	0	1	2	2
Dense Unif.	0.6	0.5	0.0	0	0	1	2	2
Litter	0.9	0.0	0.0	0	1	2	4	10

Table 1. The above table shows the model rankings of different types of Canopy, Understorey, and Groundcover vegetation, for the following functions: sediment delivery, height, shade, LWD production, CPOM production, and habitat for birds, other vertabrates and arthropods.

4.7 Shading and Stream Temperature

To determine the amount of shading on the stream channel associated with different vegetation types, it was necessary to consider the width of the channel, the height of the vegetation, the shading ability of the vegetation (*e.g.* the density of the canopy cover) and the orientation of the stream. Shading ability is a function of height of vegetation, canopy density, stream width, and stream orientation.

Water temperature is also strongly affected by shading. With 100% shading in first and second order streams, water temperature was considered to decrease by 10°C during summer and increase by 2°C during winter (Quinn *et al.* 1993). An estimate of the shading effect on water temperature in a given cell is given by:

$T_{cell} = T_0 - fT_s$ where

$T_0 = 19 + 9\sin 2p(\text{month}+1)/12 - 5(\text{elevation})/700$ and

$T_s = 4 + 6\sin 2p(\text{month}+1)/12.$

These equations predict T_0 to vary between 28°C in summer and 10°C in winter, where T_0 is the unshaded stream temperature in the cell, T_s is the change in stream temperature caused by shading, f is the fraction of stream shaded in the cell, and T_{cell} is the combined shaded and unshaded stream temperature for the cell. This value is flow weighted with incoming stream flow to give the temperature of the outflow at that cell. Stream temperature is treated as a conservative constituent in the system. This is crude, but gives a reasonable indication of the impact of shading on stream temperature throughout the catchment.

4.8 Output

No output from the model is presented in the paper because the AEAM base model structure is designed to inhibit hard output. This is to discourage the use of the model in a predictive mode. Screen based output includes time series garphs and maps which track system response as the model runs (Table 2).

Line Graph Choices	Map Choices
Rainfall	Soil Water Store
Runoff Ml/Month	Landuse
Suspend. Sed. (Mg/L)	Suspended Sed. Load
Phosphorous (Mg/L)	Temperature
Stream Temperature	Phosphorus Load.
Cum. Susp. Sed. (T)	Stream. Erosion
Cum. Phos. (T)	Undercutting
Cum. Sed. In Rip. Zone	Hyd. Resistance
Ecological Index	Ecological Index
Erosion Index	
Undercutting Index	
Velocity Index	

Table 2. Screen output options for the riparian zone model.

5.0 WORKSHOP OUTCOMES

The workshop resulted in the expected outcomes listed here:

- Computer model which illustrates the functions of riparian vegetation in relation to stream water quality and ecological values.
- Definition of knowledge gaps related to predicting the impact of management options on stream values.
- Definition of experimental designs to obtain best data to address management issues.
- Identification of joint experiments between ecology group and physical/chemical group.
- Definition of farm and catchment based riparian management options and indicators of their success.

Two very important, but unexpected, outcomes were:

- Opportunity for Scientists to work through physical and ecological processes in riparian zones with catchment managers, and demonstrate the need for research.
- Support of catchment managers for experimental work in Johnstone River Catchment.

The practical significance of these outcomes is that the planned research will be better targeted to meet the needs of catchment managers. The workshop was the first step in ensuring that scientists understand management questions and capabilities and that managers understand what research should be done to help them achieve better stream values. The process of model development demonstrated to both the scientists and managers the extent and depth of collective knowledge regarding the functions of riparian vegetation. The fact that many basic parameters in this very simple system model could only be assigned values based on 'informed guesses' provided strong motivation for undertaking the proposed program of research.

6.0 CONCLUSIONS

The model itself is not intended to be adopted as a management tool. At this stage it is only a "game". Even so, it serves as a very powerful tool for explaining the functions of the riparian zone and their interactions to individuals from diverse backgrounds. It also acts as a tool for measuring the ongoing success, or otherwise, of the National Riparian Zone Program. We will continue to use it to evaluate whether or not our experimental efforts have provided useful data, and enhanced our understanding enough to enable accurate predictions of system response.

A full description of the tables and parameter values used in the model, and a Users Manual, is provided in the LWRRDC Project CWA16 Final Report.

7.0 ACKNOWLEDGMENTS

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A Review of Water Flow Pathways through the Riparian Zone

*Natasha Herron**

ABSTRACT
The current level of understanding of riparian zone hydrology is reviewed and gaps in our knowledge identified. Since riparian zone hydrological research has largely been focused in temperate, humid areas with near stream areas prone to saturation, the knowledge base may not be relevant to many Australian environments. To date most studies have identified subsurface flow and saturation overland flow as the major hydrological processes occurring in riparian zones. Flow pathways and processes in environments where pollutants are predominantly transported to the riparian zone as overland flow, including in semi-arid and degraded environments, are a major knowledge gap.

1. INTRODUCTION

The term "riparian" has its origins in the Latin term for bank or shore, and refers to land adjacent to a body of water. Although definitions of the riparian zone may vary according to the perspectives of different interest groups, the term is generally used to denote vegetated areas of land which bound stream channels. Riparian zones do not have fixed boundaries but vary in width, shape and character. Problems of declining stream water quality in Australia, have generated considerable interest in the potential of riparian zones to buffer streams from terrestrially-derived sediments and nutrients. Increases in stream turbidity and nutrient loads are often attributed to poor land management practices and the use of fertilisers and pesticides to increase productivity on pasture and crop lands. From a water resources management perspective, the riparian zone is being viewed as a key area for reducing non-point source pollutants to the stream. Underlying this is the recognition that the near stream area is the immediate source of all streamflow outputs from a catchment, including all water-borne pollutants (Lowrance *et al.*, 1985).

Although this paper does not address all the functions of riparian zones in detail, their multi-functionality should be recognised. Not only do riparian zones moderate fluxes of water, sediment and nutrients to streams, they also serve ecological functions: wildlife corridors; sources of organic carbon, detritus and large woody debris; provison of shade and greater habitat structure (Vought *et al.*, 1995; Sweeney, 1992). In addition, riparian vegetation can contribute to stream bank and channel stability (Karl & Schlosser, 1978), and in some locations it creates aesthetic river side areas for recreational purposes. It is the purpose of this paper to review our current knowledge of riparian zone hydrology, as it is generally agreed that not enough is known about the processes driving sediment and nutrient delivery to streams (streambank sources of sediments and nutrients are not considered in this review), including what controls water flow paths and flow rates within, and to, riparian systems (Gilliam, 1994; Bosch *et al.*, 1994; Eshleman *et al.*, 1993; Cooper, 1990; Warwick & Hill, 1988; Rhodes *et al.*, 1985; Hynes, 1983). Characterisation of the various components of the hydrologic cycle, and the sources and sinks of water and pollutants in a catchment is essential to prudent water resources management (Shirmohammadi *et al.*, 1984; 1986). Before reviewing the current level of understanding of near stream hydrology, a brief comment on why riparian zone hydrology warrants special attention is needed.

2. LITERATURE REVIEW

2.1 A Hydrologically-Distinct Unit

Riparian zone hydrology is concerned specifically with the passage of water in the near-stream zone. The same hydrologic processes operating in the catchment generally operate in the riparian zone, but the zone is distinguished here, from the catchment as a whole, for the following reasons:

- The topographic position and the soil and vegetation characteristics are sufficiently distinct from those of the rest of the catchment to constitute a hydrologically distinct system. It is generally agreed that although only a small part of the catchment, the near-stream zone is hydrologically dynamic

*CRC for Catchment Hydrology, Melbourne University
CSIRO Division of Water Resources, GPO Box 1666, Canberra ACT 2601
Telephone: (06) 246 5813 **Fax:** (06) 246 5845 **Email:** natasha@cbr.dwr.csiro.au

and exerts a major control on catchment hydrology (Smith, 1992; Pionke *et al.*, 1988; Dunne and Black, 1970a, b; Hewlett and Hibbert, 1967). Altering riparian land use can have complex, disproportionately large effects on catchment hydrology (Smith, 1992).

- It is the zone which directly links source areas of runoff, sediments and nutrients with the channel network.
- The occurrence of reverse flow, i.e. flow from the stream channel into the banks, can complicate local hydrology.
- Management strategies aimed at influencing hydrological flow paths in the riparian zone are often quite separate from those for agricultural land in the catchment generallly.

Although a distinction is drawn here between hillslope and riparian hydrology, their connectivity is paramount. The riparian zone is important because it is well connected to both terrestrial and aquatic systems. This link is especially close in headwater streams (Karr & Schlosser, 1978; Vought *et al.*, 1994) which, despite draining relatively small catchments, contribute as much as 85% of water in large rivers (Vought *et al.*, 1994; Welsch, 1991). Baseflow in headwater streams is maintained by groundwater flow which may be influenced by passage through the riparian zone. Consequently, low order stream catchments are preferred management target areas as their riparian areas represent the maximum interface between terrestrial and aquatic environments. Most sediment enters the stream network from headwater catchments and the most extensive channelisation has occurred in these areas (Karr & Schlosser, 1978).

2.2 Flow Pathways

The question of whether storm flow is composed primarily of surface or subsurface flow contributions is important because of the different sediment and nutrient transport capabilities of the two pathways. The former pathway allows for very little contact between water and soil, while the latter permits considerable interaction with subsurface materials (Eshleman *et al.*, 1993; Hynes, 1983). Maintaining a riparian zone may mean the difference between a near stream hydrologic regime dominated by subsurface flow and one dominated by overland flow. Their value as hydrologic buffers arises because of their potential to store and retard the flow of water from precipitation and upslope sources. Located in the topographically low area of a watershed, they frequently possess thick alluvial soils, relative to the adjacent hillslopes (Lowrance *et al.*, 1985). The volume of valley floor sediment varies as a function of valley geometry, position within the stream network, and the flood characteristics of the system. The storage capacity of this sediment varies, in turn, as a function of soil texture, porosity, transmissivity and structure. In headwater areas, streams drain small watersheds and often have narrow valley floors. Accordingly, the available volume of soil adjacent to the stream is relatively small per unit length of stream and the potential to store water is limited by this volume and the water-holding characteristics of the soil. However, the total length of these low order streams far exceeds that of the larger streams. As stream order and the catchment area increase, valleys tend to be wider and occupied by low flat floodplains, often terraced. The volume of sediment stored in these floodplains per unit length of stream is many orders of magnitude greater than in headwater catchments and the water storage potential is vast. Consequently, floodplains tend to have an attenuating effect on both lateral contributions from adjacent hillslopes and on routing of high flows in the channel (Beven *et al.*, 1988). Catchment response to rainfall events will tend to reflect the available water storage volume of the near stream area, with headwater streams exhibiting flashier responses than higher order streams.

Although, little research has been directed at riparian zone hydrology *per. se*, there is a considerable body of literature that deals with hydrological processes in the near stream zone. In particular, near stream areas have been identified as important source areas of overland flow because of their propensity to be saturated or at near saturation for significant portions of the year (Dunne and Black, 1970a, b; Hewlett and Hibbert, 1967; Betson, 1964). As a result, available storage is small and the area responds more rapidly than other parts of the watershed to rainfall events. In some situations this rapid response can be explained by a capillary fringe effect and water table mounding (Abdul and Gillham, 1989; Sklash and Farvolden, 1979). Soils characterised by a capillary fringe, the zone above a water table that remains near-saturated under negative pressure, have little or no storage capacity. Where this zone extends to the ground surface, the application of only a small quantity of water can cause a rapid and large water table rise and almost immediate generation of saturation excess runoff. Where this process operates, instead of retarding or preventing the passage of contaminants to the stream, the riparian area becomes an efficient conveyor of sediments and nutrients to the stream, and the possibility for biological nutrient uptake and removal is diminished.

Subsurface flow is also an important source of nutrients to streams and delivery can be very rapid, such as in steep forested environments (Bonell and Gilmour, 1978; Mosley, 1979; McCaig, 1983; Sklash *et al.*, 1986; McDonnell, 1990), but sediment is far less likely to reach streams by this pathway. Because many nutrients are sediment-attached, a near stream hydrologic regime that promotes the deposition of sediment will reduce the nutrient flux to the stream also. This is particularly pertinent to phosphorus which is mostly transported in particulate or sediment-bound forms (Karr and Schlosser, 1978; Cooke, 1988; Lee *et al.*, 1989). Nutrients moving in solution, however, do reach the stream by subsurface flow pathways and rapid transit times will diminish the opportunity for nutrient uptake by plants and limit the denitrification potential. Like surface runoff, subsurface flow contributions to storm flow are also associated with saturated areas, although saturation is not a prerequisite if an extensive piping network exists (McCaig, 1983).

Because riparian zone research has tended to be concentrated in areas subject to waterlogging, shallow subsurface and saturation overland flow pathways appear to dominate near stream storm responses. Generally, infiltration-excess (or Hortonian) runoff is not recognised as a significant component of storm flow from riparian areas. Table 1 contains an overview of various riparian zone studies that have been undertaken. Much of the research has been focussed in the Coastal Plain area of the southeastern United States where streams flow over broad alluvial flats with intact riparian forests. These forest belts have survived clearing because annual rainfall in excess of evapotranspiration, impeded drainage and seepage faces along the valley flanks have resulted in significant areas of agriculturally non-productive wetlands (Gilliam, 1994). Of

Author	Climate	Land use	Topography	Hydrology
Eshleman *et al.* (1993, 1994)	*Not stated* MidAtlantic Coastal Plain, so similar to below	75% forest; 25% agric.	Low relief	Dominated by subsurface discharge; SOF during high intensity storms
Shirmohammadi *et al.* (1984, 1986)	1200 mm/yr summer - convect. early spring - cyclonic. storms - short, high intensity	Agricultural	Relatively flat	Some HOF (summer convective); mostly sub-surface, but SOF in higher order streams
Bosch *et al.* (*in prep.*)	As for Shirmo-hammdi (1984, 1986)	Tilled field	Relatively flat	Winter - subsurf. fluxes towards stream Summer - flux reversal driven by ET demands of riparian forest
Yates and Sheridan (1983)	As for Shirmo-hammdi (1984, 1986)	K: 37% crop, 56% woods Z: crop	Gently sloping uplands	Swampy riparian area. SOF and subsurface drainage
Pionke *et al.* (1988)	1100 mm/yr temperate humid	Crop/forest RZ - grass strip (15m wide)	350 m relief	SOF and subsurface drainage
Hill (1990)	*Not stated* located near Toronto, Canada	60% forest 40% grass	Gentle to steep sloping hummock moraine cut by dry valleys	Shallow subsurface flow from hillslope. saturated RZ
Chappell *et al.* (1990)	2629 mm/yr	Forest	150 m relief; steep slopes	Lateral subsurface flow from hillslope; perched water table
Abdul & Gillham (1989)		Grassed	Low relief	Water table mounding and subsurface flow. SOF

Table 1. An overview of riparian zone hydrological studies (SOF - satuation overland flow, HOF - Hortonian overland flow).

these studies, only one identifies Hortonian overland flow as a source of runoff in the near stream zone (Shirmohammadi *et al.*, 1984; 1986). Rather than conclude that Hortonian overland flow is a relatively insignificant phenomenon in riparian areas, I suggest that this mechanism of runoff generation has been neglected because the location of riparian forests, and our interest in the denitrification potential of wetlands, has dictated experimental site selection. If, as the U.S. examples indicate, riparian forests have largely survived where the underlying soil is waterlogged and agriculturally non-viable, results will show the dominant runoff process to be saturation overland flow. The other factor which biases the outcomes of riparian zone research is the predominance of field sites in temperate, humid areas with land uses dominated by crop production and forestry.

I would suggest that in semi-arid areas, and in areas where pastoral production is the dominant land use, Hortonian overland flow could be an important process. Soil compaction, associated with intensive grazing for example, leads to a reduction in the infiltration capacity of the surface soil and a hydrological shift towards infiltration-excess generated runoff. The efficiency of livestock tracks in conveying water, nutrients and sediments to and across the riparian zone has not been determined, yet the damage done to stream banks by stock trampling and the linking, by livestock tracks, of streams with upslope sources of contaminants suggest that tracks may be significant and rapid conveyors of materials to streams. Further research is needed to ascertain the importance of this form of surface runoff as riparian zone management strategies may differ depending on the nature of the runoff generating process.

2.3 Spatial distribution

As noted above, most studies in the literature deal with near stream areas that are consistently wet. However, soil saturation is not normally uniform along the entire length of a stream. Wetter and drier areas do exist. Downslope water flow tends to be via preferred pathways, therefore, near stream areas will not supply water to a stream uniformly along its length (Anderson and Kneale, 1980; Anderson and Burt, 1978). Cooper (1990) observed markedly non-uniform lateral inputs along a small New Zealand headwater stream during low flow conditions. Several reaches of 50 m or more showed no increase in flow whereas other reaches of 10-20 m showed substantial increases. During conditions of higher flow, lateral inputs of flow tended to be more uniformly distributed, with most reaches exhibiting some longitudinal flow increase. Whether a particular area is a source of or a sink for storm runoff, and the relative proportioning of the flow pathways depends upon topography, soil properties, and 3individual storm characteristics (Dunne and Black, 1970a, b; Engman, 1974; Yates & Sheridan, 1983; Pionke *et al.*, 1988). Although controls have been identified, very little research has been directed at quantifying their relative importance to processes in the riparian zone. An exception, perhaps, is the buffer effectiveness modelling of Phillips (1989) which indicates that the gradient of the riparian zone is a more important control on riparian zone effectiveness than saturated hydraulic conductivity or soil moisture storage capacity. Heede (1990) also suggests that riparian buffer effectiveness will reflect slope gradient.

2.4 Temporal Distribution

Not only is there uncertainty about spatial behaviour of riparian systems, but the hydrology of riparian systems has a temporal dynamism which adds to the overall complexity of their processes and management. Stable isotopes are being used increasingly to investigate the proportions of event water and stored water comprising storm runoff (Pearce *et al.*, 1986; Sklash *et al.*, 1986; McDonnell, 1990; Stewart and McDonnell, 1991). McDonnell (1990) observed differences in the sources of storm flow to be dependent on peak runoff rates. In smaller events, matrix-dominated near-stream water was able to account for storm period streamflow. In larger events (>2mm hr^{-1} peak runoff), however, perched water tables developed and storm flow was attributable to rapid hillslope hollow drainage via a well-connected pipe network. From a study of chemical-hydrologic interactions in the near stream zone, Pionke *et al.* (1988) described the changes in the relative contributions of surface and subsurface flow pathways during the passage of a single storm. Hydrologic sources of streamflow were observed to progress from (1) baseflow dominated to (2) rainfall-diluted baseflow, to (3) surface-runoff dominated flow, to (4) a progressively subsurface-discharge dominated flow, before draining back to (5) normal baseflow, corresponding to the expansion and contraction of seep zones. In temperate, humid areas, such as the area investigated by Pionke *et al.* (1988) and the other experimental catchments on the south-eastern U.S. Coastal Plain, the initiation of surface runoff during a storm depends on the antecedent moisture conditions of the near stream area. However, antecedent moisture is not the only control, nor necessarily the dominant control in all environments. A preliminary investigation of the controls on water fluxes through riparian zones (Herron and Hairsine, *in prep.*) demonstrates that topographic convergence and the infiltration capacity of the soil are also extremely influential. Soils characterised by surface crusting, surface compaction and/or hydrophobicity can be significant source areas of overland flow because their infiltration rates are limiting.

Temporal variations also reflect seasonal climate changes. Using the riparian forest buffer specifications of Welsch (1991) as a starting point (a three-zone structure of minimum 30 m width), Bosch *et al.* (1994), working in the southeastern United States Coastal Plain, investigated the seasonal and spatial patterns in water flow pathways through riparian areas. The influence of season was found to be pronounced. During the wetter winters, soils are close to saturation and shallow subsurface flow is driven by the gravitational component of the hydraulic head in the direction of the stream. In summer, riparian plant water demands are large enough to cause a drop in the local water table elevation and a reversal in the gradient of saturated flow back toward the grass/forest interface. The authors attribute this high water usage to the riparian forests. However, transpiration demands of the grass buffer may also be significant, since grasses will transpire at rates similar to trees where surface soil water is non-limiting (Hodnett *et al.*, 1995). Such a seasonal flow reversal is believed to significantly retard the movement of contaminants travelling via subsurface flow from the hillslopes, at a time when solutes are most likely to be transported from the field to the riparian buffer (Bosch *et al.*, *in prep*). Seasonal reversals in hydraulic gradients within the riparian zone may depend on the nature of the forest zone. A forest comprising species with a high leaf area index will transpire more than those characterised by less foliated species, and rainfall interception will be higher. For evergreen species, such as eucalypts or conifers, water table fluctuations may not be as pronounced as those observed under deciduous trees, but higher transpiration rates and interception during winter should reduce the extent of saturated conditions. Once again, it is in humid, temperate areas that seasonal influences on soil water status will be most important. Where infiltration capacity limits soil water uptake, hydrological flow paths will only reflect seasonal differences in areas where seasons are characterised by different average rainfall intensities, such as monsoonal climatic regimes.

3. KNOWLEDGE GAPS

To summarise, our current understanding of riparian zone hydrology is based on research that has largely been undertaken in humid, temperate areas, characterised by waterlogged soils adjacent to stream channels. Accordingly, the bulk of available information emphasises the role of shallow subsurface flow and saturation overland flow as principal pathways of water to streams. It is suggested that the range of environmental conditions in which riparian zone studies are undertaken needs to be broadened and that the role of Hortonian overland flow be evaluated in semi-arid and degraded areas. The significance of livestock tracks as conveyors of water and contaminants to streams also needs to be determined.

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Comparing grass filter strips and near-natural riparian forests for buffering intense hillslope sediment sources.

Peter Hairsine[1]

ABSTRACT: *In relating hillslope sediment and sorbed pollutant fluxes to in-stream water quality, it is often assumed that vegetation on the lower portions of hillslope can act as a buffer, or sink, by storing sediment and pollutant. Much of the literature on this topic concerns highly-idealised grass filters with a diffuse source. Riparian forests are commonly environments with heterogeneous vegetation and soil, and diffuse, but non-uniform, upslope sources. The study reported here compares the sediment filtering capabilities of grass filters strips with those of near-natural riparian forests. The study sites were in the catchment of the Tarago river in west Gippsland, Victoria.*

Fluxes of water, sediment and sorbed nutrients were measured at the inlet and outlet of the grass filter strips, riparian forests and a combination of both, with a range of sediment fluxes and runoff rates from an intense upslope source-area. Dense grass filter strips were found to have sediment trapping efficiencies of greater than 95% for a relatively high intensity sediment source. Near-natural riparian forest, was found to have trapping efficiencies greater than 90% for a range of sediment-laden inflows. The sediment trapping efficiencies of both buffer types were found to diminish slightly with increasing water inflow, though the results support the overall effectiveness of these buffers as measures to lessen the downstream impact of intensive land use.

1. INTRODUCTION

It is now widely recognised that grass filter strips and riparian forests have a significant role in reducing the movement of sediment and sediment-attached pollutants to streams. Grass filter strips and riparian forests are both a subset of buffer strips, a term used to describe any zone of vegetation between the hillslope and the stream. The role of buffer strips in the management of waterway pollution may be divided into the protection of stream banks and the reduction of pollutant fluxes from adjacent hillslopes. In a recent review of research concerning buffer strips, Barling and Moore (1992) found that there are two general approaches to the design of buffer strips: stream protection based on transport distances through the buffer strip, and stream protection based on the protection of runoff generating areas. In this paper the first of these approaches is examined for contrasting buffer types.

Grass buffer strips are purpose planted, or reserved, areas of pasture with the single purpose of reducing the movement of pollutant from an intense upslope land use. Riparian forests are multiple objective zones of remnant or planted near-natural vegetation adjacent to stream channels. It is the objective of this paper to compare the effectiveness of these two types of zones in reducing sediment movement for the same upslope source. This comparison is made in the environment where the input of water, sediment and nutrient is delivered as an intense localised input to the buffers. The effectiveness of the zones is examined for three different magnitudes of runoff from upslope.

The difference in behaviour of these two types of buffers is expected to be understandable in terms of the difference in the hydraulic roughness provided by the different plant material. Overland flow through grass filter strips is expected to be nearer uniform flow conditions than is overland flow through riparian forests where there will be more discharge through preferred flow paths (Mackenzie and Hairsine, this volume).

2. METHODS

Experiments were conducted in the catchment of the Tarago Reservoir in West Gippsland, Victoria. The hillslope was planar with a mean slope of 16 percent, and has been in pasture for many years. An intact riparian forest forms the lower boundary of this pasture.

The general lay out of the experiments is shown in figure 1. Overland flow was generated on the hillslope prepared as for the planting of potatoes using local practice. The slope was tilled and rotary hoed four weeks prior to the experiments. A ridge and furrow system was formed with the ridges orientated along the natural fall line. Furrows were at a spacing of 0.85 m. Inflow was provided to the

[1] CSIRO Division of Soils and the Co-operative Research Centre for Catchment Hydrology,
PO Box 639, CANBERRA, 2601, AUSTRALIA.
Telephone: 06 246 5924 Fax: 06 246 5965 Email: peterh@cbr.soils.csiro.au

upslope end of each of two furrows to generate a water and sediment flux at the top of each buffer strip. The water inflow rates provided to buffer strips are given in table 1. The three inflow rates are equivalent to 5, 10 and 20 mm hr^{-1} runoff rate for a 50 metre slope length above the buffer strip.

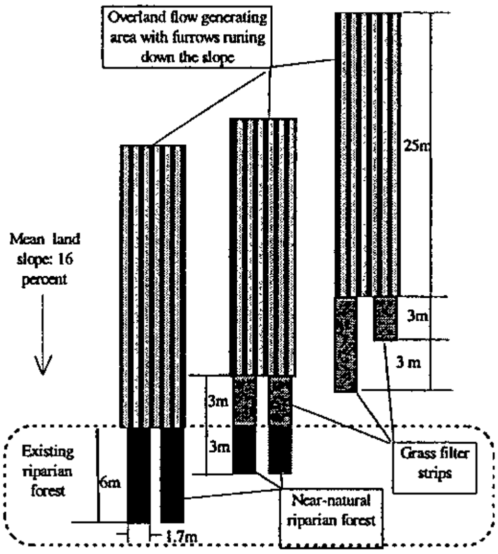

Figure 1. General layout for field experiments.

Inflow Level	Water Discharge per unit width ($m^3s^{-1}m^{-1}$)
Low	0.069×10^{-3}
Medium	0.138×10^{-3}
High	0.278×10^{-3}

Table 1. Nominal water discharges entering buffer strips for the three levels of inflow.

Six buffer strips, as described in table 2, were tested. The three and six metre wide grass filter strips were unreplicated. The combined grass buffer / riparian forest and 6 metre wide riparian forest had two replicates.

Soils are sandy loams overlying sandy clay subsoil and are derived from Upper Devonian Granites (Soil Conservation Authority, 1973). Sediment was transported predominantly in an aggregated form. Analysis for soil classification and aggregate size distribution are in progress.

Layout of buffer	Vegetation
3 m wide grass buffer strip (GFS)	dense near-uniform pasture dominated by Dactylis glomerata (cocksfoot) and Agrostis capillaris (brown top bent grass)
6m wide grass buffer strip (GFS)	dense near-uniform pasture (as above)
3 m wide grass buffer strip (GFS) + 3m wide riparian forest (RF)	medium density grass (as above), some patchiness and complete cover of litter including leaf mat, sparse woody debris and understorey shrubs dominantly Kunzea ericoides, Olearia stellulata (daisy bush) and Cassinia longifolia (common cassinia)
6 m wide riparian forest (RZ)	complete cover of litter including leaf mat, sparse woody debris and understorey shrubs (as described above)

Table 2. Description of buffer strips investigated.

Rainfall was provide on the buffer strip area using the CSIRO Division of Soils portable rainfall simulator. Rainfall having a mean drop size of 1.5 mm and terminal velocity was provided to the full area of the buffer. Rainfall intensity was fixed at 60 mm hr^{-1} for all runs. Having rainfall present was considered essential as the action of raindrop impact will influence sediment transport within the buffer strip.

Each buffer strip was subjected to the three inflows in order of increasing magnitude, each of duration 30 minutes with no delay between. Outflow discharge was measured continuously using a calibrated runoff collection tower. Runoff samples were collected at both the inlet and outlet of the buffer strips at three minute interval. These samples were analysed for total sediment concentration, sediment by aggregate size class, total nitrogen (TKN), total phosphorous (TKP), nitrate/nitrite (NO_x-N) and ammonia (NH_4-N), ortho-phosphate (PO_4-P) and for selected samples for TKN, TKP, NO_x-N, NH_4, PO_4-P for each of seven aggregate size classes. Only the total sediment concentration data are reported here. Analysis concerning nutrient transport, size sorting of sediment and the influence of the roughness configuration of the buffer material is in progress.

Additional measurements include the sediment fan dimensions with time, and measurements of the vegetation in terms of projected cover, contact cover and above ground biomass.

3. RESULTS

Figure 2 shows the sediment concentration leaving the range of buffer strips. All buffers acted to trap greater than 90 percent of the sediment entering the buffer strip. This is encouraging in view of the high sediment concentrations entering the buffers shown in table 3. The combination of 3 metre wide grass filter strip and 3 metre riparian forest was less effective in removing sediment than the 3 m wide grass filter strip. This reflects the reduced density and uniformity of the grass at the fringe of the riparian forest. As expected, the riparian forest was less effective in trapping total sediment, though the percentage passing is still very low.

Inflow level	Mean sediment concentration entering buffer ($kg\ m^{-3}$)
Low	10.2
Medium	14.1
High	23.7

Table 3. Mean sediment concentrations entering the buffer strips for the range of inflows.

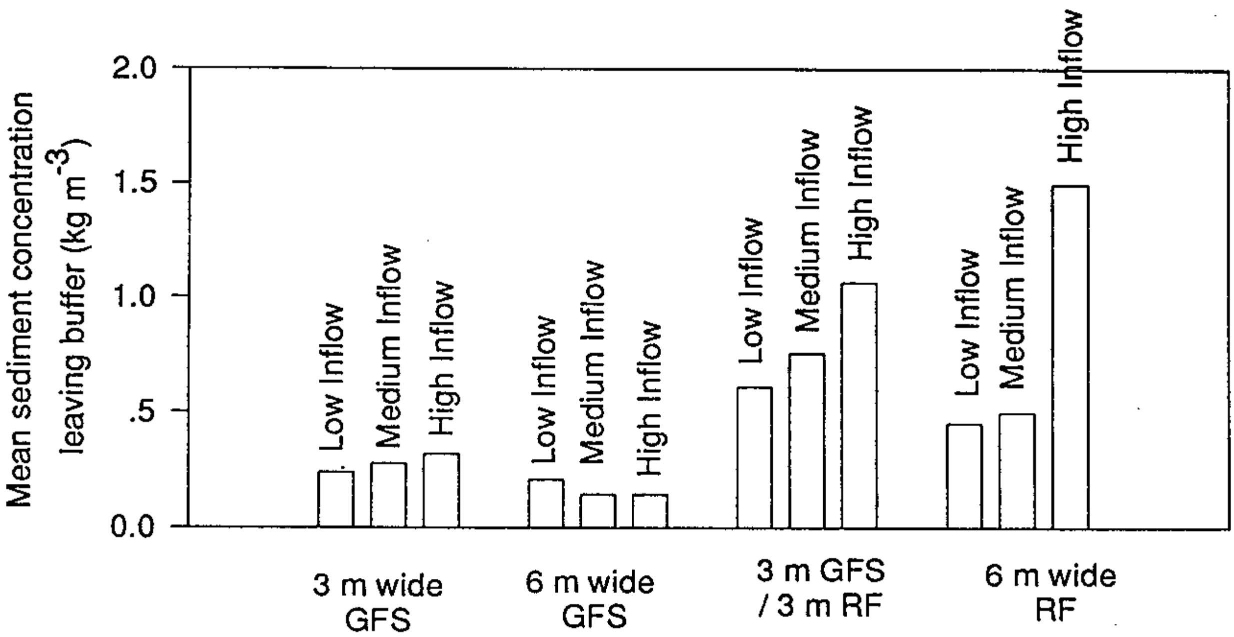

Figure 2. The mean sediment concentration leaving the range of buffer strips (grass filter strips, GFS and riparian forest, RF) for the three inflows.

As shown in figure 2 the mean sediment concentration of outflow from the 6 metre wide near-natural riparian forest is higher than that of the 6 metre wide grass filter strip. Also, the trend to higher sediment concentration with increasing inflow is most marked for the riparian forest. It should be noted that the sediment concentrations leaving the strips are still high relative to typical instream sediment concentrations.

While the total sediment trapping efficiencies reported here are high, it is expected that the size analysis of the sediment leaving the buffers will find it to be predominantly fine sediment. This sediment is likely to be enriched in sorbed nutrients relative to the sediment trapped in the buffer strip. Also this sediment is likely to be of increased importance in terms of stream turbidity.

4. DISCUSSION

Grass filter strips have been reported to have reduced sediment fluxes by 20 to 97 percent in field and rainfall simulator experiments (Wilson, 1967, Magette et al., 1989, Flanagan et al., 1989). This wide range of behaviour is likely to result from a range of factors including the intensity of the sediment source, the degree of channelisation, width of the strip, the land slope and the nature of the filtering material. It should be noted that the high trap efficiencies obtained in this study were obtained under conditions of relatively high sediment input, relatively high slope and relatively concentrated flow at the entry to the buffer strip. It appears the high density of the surface roughness, produced by vegetation and litter, resulted in these high trap efficiencies.

There has been comparatively little research done on the sediment trapping ability of near-natural riparian forest. The results presented here demonstrate the considerable potential of both grass filter strip and riparian forest to reduce the movement of sediment from an intense hillslope sediment source. This is particularly encouraging for natural riparian forests given the additional physical and ecological roles these systems have. The results also show that the effectiveness of both buffers can be maintained across a range of inflow rates. The high trapping efficiencies obtained for the high inflow rate are particularly encouraging as it is widely recognised that infrequent high intensity rainstorms are responsible for the majority of sediment entering streams from hillslope sources.

Interpretation of the above results must recognise the short term nature of these experiments. No conclusions can be drawn about the remobilisation of the deposited sediment in subsequent events. Also, conclusions regarding the relative trapping efficiencies for fine sediment and nutrient analysis.

5. CONCLUSIONS

Dense grass filter strips were found to have sediment trapping efficiencies of greater than 95% for a relatively high intensity sediment source. These results were relatively high compared with other studies. This was attributed to the high input load and the dense and near-uniform nature of the grass in the strip.

Near-natural riparian forest, predominantly litter with sparse understorey shrubs and woody debris, was found to have trapping efficiencies greater than 90% for a range of sediment-laden inflows. The sediment trapping efficiencies of both buffer types were found to diminish slightly with increasing water inflow, though the results support the overall effectiveness of these buffers as measures to lessen the downstream impact of intensive land use.

6. ACKNOWLEDGEMENTS

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The hydraulics of shallow overland flow: a comparison between a grass filter strip and a near-natural riparian forest

D.H.Mackenzie[1] and P.B. Hairsine[2]

ABSTRACT: *The hydraulic resistance to overland flow presented by buffer strips can reduce flow velocities and hence the ingress of sediments and associated nutrients to streams. The spatial variability of overland flow is a key factor affecting the effectiveness of the buffer. Grass filter strips and near-natural riparian forests are compared in terms of the spatial distribution of flow and flow velocities. Spatial variability of these two quantities was measured for a range of sediment-free inflows in the field. Flow velocities in a near-natural riparian forest were relatively higher and more variable than those in a grassed filter strip. This is consistent with lower sediment and sorbed-nutrient trapping efficiencies of near-natural riparian forests (Hairsine, 1996).*

1. INTRODUCTION

The riparian zone is the strip of land flanking a stream where overland flow from general catchment runoff enters the stream channel. It is subjuect to shallow overland flow from hillslope runoff, hence rills and small gullies may form normal to the contour. It may also be subject to overbank flow and to streambank erosion from channel discharge.

The zone is frequently specially managed to minimise streambank erosion and also to provide a buffer zone to overland flow which may contain sediment and sorbed nutrients from upslope origins (Barling and Moore, 1993; Woodfull, *et al*, 1993). In this paper we concentrate on the role of riparian vegetation in slowing overland flow to induce sediment deposition and thus the removal of a significant proportion of sediment and sorbed nutrients which would otherwise enter the stream.

This paper describes an investigation of the hydraulics of overland flow through two types of buffer zones, a grassed buffer strip and a near-natural riparian forest. It examines the velocity distributions of flow of sediment-free water across these two landscape types and is complementary to another investigation at the same site which measures the generation and entrapment of sediment (Hairsine, 1996). These two studies are linked to a larger project which investigates the role of the riparian zone in the management of Australian waterways (Wilson *et al*, 1995).

Flow through natural vegetation is heterogeneous (Kadlec, 1987; Abrahams *et al*, 1994). However, much of the study of shallow flow has been on artificial surfaces, often with regularly spaced artificial resistance elements introduced. The common descriptors of hydraulic roughness (Manning's n; Darcy-Weisbach's friction factor, f; Chezy's coefficient, C) have been derived from such studies and cater adequately for the uniform conditions of those studies. The difficulty of obtaining some appropriate measure to describe roughness elements (microtopography, stones, vegetation) has invariably led researchers to attempt the application of these same descriptors to variable natural surfaces.

Here we measure rates of shallow flow over differently vegetated surfaces, describe the spatial distribution of the resulting velocities and discuss the implications for sediment transport.

2. SITE DESCRIPTION

The study area is in the 116 km^2 catchment of the Tarago Reservoir (Victoria, Australia), constructed to supply water to the Mornington Peninsula. The reservoir is fed by the Tarago River: approximately 70% of the catchment is forested and drained by the West Branch and the remainder, drained by the East Branch, is given to mixed farming, predominantly dairying and seed potato growing. The reservoir was out of service at the time of the experiments partly because of recurring water quality problems thought to be related to sediment and nutrient accessions, particularly from the agricultural segment of the catchment.

The study site was located on a planar hillslope in the catchment of a small stream which enters the reservoir downstream of where the Tarago River enters the reservoir (lat 37° 59' 45"; long 145° 54' 30"). The soils are sandy loams overlying sandy clay subsoil and are derived from Upper Devonian Granites (Soil Conservation Authority, 1973). The riparian zone of the stream, comprising forest vegetation, was 2-300 m wide on the study side of the stream. A cleared area sown to pasture adjoined it on the upslope side. An experimental site was chosen from each vegetation type.

2.1. Grassed Filter Strip

The Grassed Filter Strip site (GFS) had a mean slope of 16.2% and was on semi-improved pasture, ungrazed for some years, but topped (slashed) intermittently to reduce fire hazard. The pasture was 30-50 cm high and comprised mostly introduced grasses of generally low grazing value which reflected a relatively low soil nutrient level, as did the presence of sundry non-grass

[1] CRC for Catchment Hydrology, CSIRO Division of Water Resources, GPO Box 1666, Canberra, ACT 2601 Australia
Telephone: +6 (06) 246 5750 Fax: +6 (06) 246 5845 Email: dhm@cbr.dwr.csiro.au

[2] CRC for Catchment Hydrology, CSIRO Division of Soils

weed species. There was little or no legume component. Nevertheless, there was a dense mat of dead aboveground roots which apparently had developed in the moist near-ground environment during wetter periods. This layer varied from 0 to about 15 mm thick. A dense network of grass stems arose from this root mat. There was little or no bare soil in the experimental area.

2.2. Forested Riparian Zone

The Forested Riparian Zone site (FRZ) had a mean slope of 20.8%. Although the vegetation may have been disturbed many years previously, it was regarded as being in a near natural state. It was classified as open mid-high mixed *Eucalyptus* forest (Walker and Hopkins, 1990). There was a sparse, mixed species understorey comprising mostly leggy shrubs with stem diameters up to 2.0 cm. Very little vegetation grew at the soil surface which was covered by a litter of dead and decaying leaves up to 5 cm thick. From the surface of the litter down to the soil surface there was a gradation from loose dry leaves to decayed leaves almost completely incorporated into the solum. The surface was strewn with occasional fallen twigs and small wood in varying stages of decay up to 3 cm diameter.

3. METHODOLOGY

At both sites, water was supplied to a 3 m x 10 m flume constructed on the undisturbed field surface (Figure 1). The flume consisted of 3 mm galvanised steel walls driven vertically into soil slots cut normal to the contour. The walls were sealed into the soil with paraffin wax, melted for pouring and allowed to set.

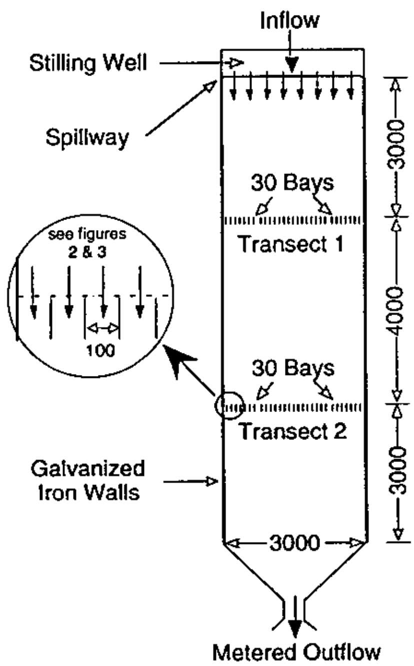

Figure 1. Field layout of experimental flume for shallow overland flow studies. (Dimensions in mm.)

Inflow was metered through a portable 90° V-notch sharp crested (or Thomson) weir (Bos, 1989) into a stilling well and delivered as a constant depth line source over a level spillway. At the lower end of the flume, outflow was metered through a portable long throated (RBC) flume (Bos *et al*, 1991). Outflow stage was sensed with a capacitance water depth probe and logged at 1 minute intervals.

Flow rates for the experiment were calculated to correspond with runoff levels of 5, 10 and 20 mm h^{-1} from a 200 m contributing hillslope length. The corresponding outflow rates were respectively 0.833, 1.667 and 3.333 l s^{-1}, subsequently referred to respectively as the low, medium and high rates.

Two sampling transects normal to the flume walls were located at 3.5 m and 7 m downstream from the inlet spillway (Figure 1). Along each 3 m transect, 29 vertical baffle plates of galvanised steel (22 cm high x 35 cm long and 0.7 mm thick) were inserted into the soil, normal to the contour and to a depth of about 2.5 cm. These created 30 mini-flumes each 10 cm wide (subsequently referred to as bays) (Figure 1). The downstream end of a bay was made into a 3-sided metal sluice box by covering the ground surface between the baffles with a 10 cm square horizontal sill plate (0.7 mm thick) and sealing it to the baffles on either side with silicon rubber (Figure 2). A 25 mm vertical downturn on the upstream edge of the sill plate was driven into the ground to deter flow under the sill.

These devices partitioned the total flow into segments of equal width. They allowed measurements of the depth of undisturbed flow over an undisturbed surface at the upstream end of a bay. At the lower end of a bay water flowed through the sluice box from which it could be extracted for flow rate measurements. The baffles offered minimum resistance to the flow and reduced

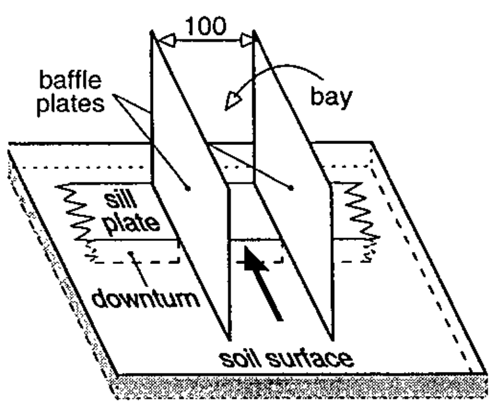

Figure 2. Detail of a bay showing baffle and sill plates forming a three-sided sluice at exit. (Dimensions in mm.)

the total width of the flume by only 0.68%. The 30 bays effectively provided the opportunity to sample the variability in flow across the flume along a 3 m long transect. This approach is similar to the partial section technique of Abrahams *et al* (1986) and the sampling technique of Parsons and Abrahams (1989) and Parsons *et al* (1990).

Discharge in any one bay was measured by suction sampling. A close fitting suction head attached to a flexible hose was inserted into the metal lined sluice box at the downstream end of a bay. Flow in a bay was intercepted and removed by vacuum (provided by an industrial vacuum cleaner) over a timed interval. The sample was collected in a cyclone, decanted and weighed. Total discharge was calculated for each bay.

A 3 m long level tool bar (constructed from 3 mm aluminium as a box section, 150 x 50 mm) was fastened above the entrance to the bays. Water level was measured at the mid-point of the entrance to each bay using a digital reading depth gauge suspended from the tool bar (Figure 3). Surface profile elevation along the line of the entrances was measured with a recording profilemeter (pin spacing 15 mm) suspended from the tool bar. Profiles were measured at the conclusion of the experimental flows and vegetation was clipped to allow pin contact with the exposed soil surface.

Velocity of flow in a bay (V_{bay}) was calculated using the relationship

$$V_{bay} = q_{bay} . A_{bay} \quad (1)$$

where q_{bay} is the discharge from a bay and A_{bay} is the area bounded by the baffle plates, the water surface and the soil surface, calculated using the trapezoidal rule.

4. RESULTS AND DISCUSSION

There was no marked difference in data trends between transects at either site. Consequently, we report results from Transect 1 only where local slopes were 15.8% (GFS) and 21.7% (FRZ).

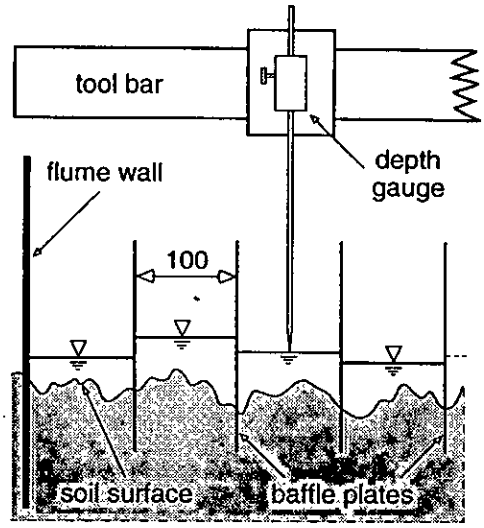

Figure 3. Components of field equipment: level aluminium tool bar and depth gauge suspended above entrance to bays. (Dimensions in mm.)

Soil surface profiles are presented in Figure 4. Total relief was 45 mm (GFS) and 73 mm (FRZ). Apart from this difference, variations in microtopography were markedly greater at the forested site. Localised channelling of overland flow would have resulted at each site, but the potential for this would have been greater at the forested site.

The distribution of discharge from individual bays has been expressed as cumulative percentage of total flow less than a specified value of discharge (Figure 5). These data reflect the effect on discharge of resistance to flow and micro-topography over the distance from the inlet to the transect. Heterogeneity of roughness results in channelling of flow with consequent variations in discharge across the transect. At each site the different distributions reflect the different outflow rates. If the flow had been evenly distributed there would have been mean discharges per bay of 27, 56 and 111 ml s^{-1}. The grassed site maximum discharges were between two and three times the mean discharges per bay. However,

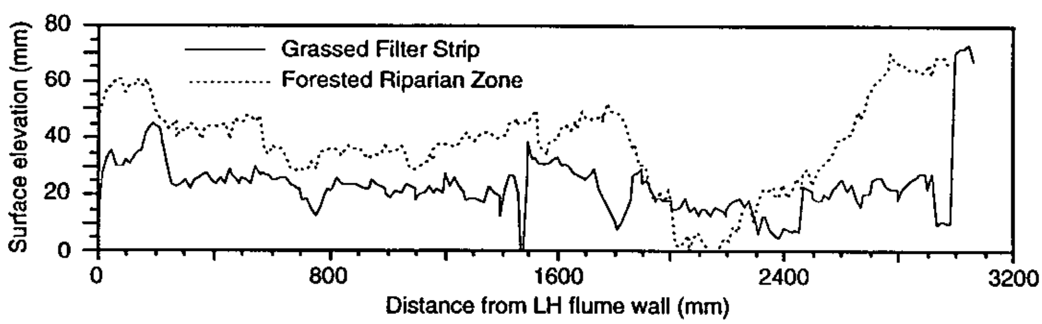

Figure 4. Soil surface elevation (mm) profiles for the Grassed Filter Strip and Forested Riparian Zone sites. **Note:** verical exaggeration x 10.

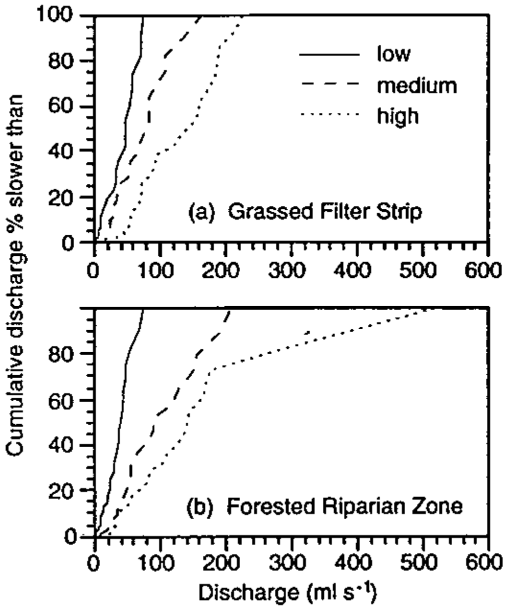

Figure 5. Distribution of discharge (ml s^{-1}) of shallow overland flow through 30 bays along a 3 m wide transect for each of 3 rates of flow. Data expressed as cumulative percentage of total flow less than specified value of discharge. (a) Grassed Filter Strip; (b) Forested Riparian Zone.

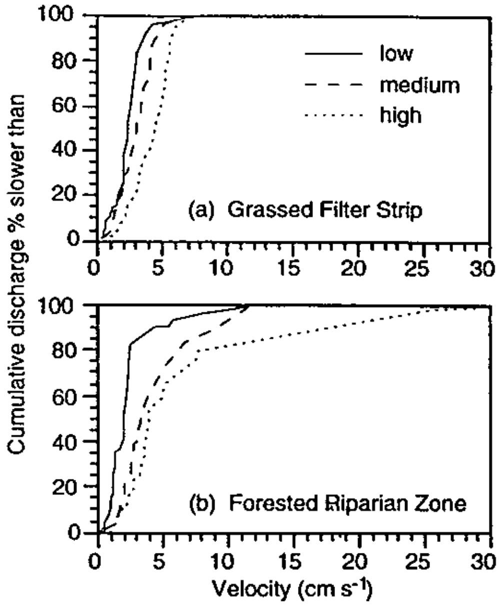

Figure 6. Velocity distribution of discharge (cm s-1) of shallow overland flow through 30 bays (miniflumes) along a 3 m wide transect for each of 3 rates of flow. Data expressed as cumulative percentage of total less than specified value of velocity. (a) Grassed Filter Strip; (b) Forested Riparian Zone.

the forested site maxima were three, four and finally, five times the mean dicharges.

The ranges of discharge levels in the bays differ markedly between sites. Note that at the forested site (Figure 5b), the maximum discharge for the medium flow exceeded the highest discharge of all recorded in the grassed plot (Figure 5a). For the high outflow rate, considerably higher (133%) discharges were recorded at the forested site than at the grassed site. From these data we infer that, over the lengths of the flow paths, there is a greater variability in total roughness of the forested site than of the grassed site.

In Figure 6 we present flow velocities in the bays expressed as cumulative percentage of discharge less than a specified value of velocity. The steeper slopes of the forested sited would have resulted in higher velocities independant of roughness effects. For purposes of comparing velocities between the two vegetation types we have scaled the forested site velocities according to Equation (2), on the assumption that $V \propto S^{1/2}$, where V is velocity and S is slope.

Thus, $$V_{frz(corrected)} = V_{frz(measured)} \cdot S_{gfs}^{1/2} \cdot S_{frz}^{-1/2} \quad \text{.......... (2)}$$

As with the discharge distributions (Figure 5), at each site the different distributions of velocity reflect the different outflow rates. Again there is similarity with the discharge distributions in that the range of maxima is much less at the grassed site than at the forested site. This indicates a relatively higher, more uniform roughness at the grassed site. At the forested site (Figure 6b), the high outflow rate resulted in velocities that exceeded the maximum at the grassed site by nearly threefold. This trend is in accord with the development of channelling observed during the high flow treatment at the forested site. No such phenomenon was observed at the grassed site. However, at the grassed site maximum velocities (Figure 6a), in marked comparison to maximum discharges (Figure 5a), cover a much narrower range: maximum velocities are all similar while the maximum discharge at the high flow rate is nearly twice that of the low flow rate.

The wider distributions of discharge and the higher velocities observed in the forested site are considered the result of larger roughness elements there (calculated mean flow depths ranged from 1-36 mm). The leaf litter appeared to present a reasonably heterogeneous resistance to flow as evidenced by the relatively even distribution of discharge at the lower flow rates. However, the material was sufficiently mobile that during high flow there was some redistribution observed as channelling developed and rills formed. Also, the relatively narrower distributions of discharge and the lower velocities at the grassed site can be attributed to the apparently greater resistance presented to flow by the dense network of above ground roots and stems (mean flow depths ranged from 3-45 mm). At the flow rates imposed there was sufficient energy to remove portions of the organic protective layer on the forest floor but not at the grassed site

For maximum sediment trapping efficiency, discharges ideally should be evenly distributed and velocities should be minimised. These conditions are more readily met in the grassed site than at the forested site, trends which are in accord with the findings reported in this volume by Hairsine (1996). While it is not possible to partition roughness effects between vegetation, microtopography and slope at this stage, the usefulness of the comparison between total roughness at the two sites is evident.

5. CONCLUSIONS

A grass filter strip has been shown to result in slower, more uniform overland flow in comparison with a surface formed under a riparian native forest. The difference between the two vegetation types was found to be greater for increasing total overland flow input. The trend in the results is consistent with lower sediment and sorbed-nutrient trapping efficiencies of near-natural riparian forests (Hairsine, 1996).

6. ACKNOWLEDGEMENTS

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Vegetation and Bank Stability in Relation to Changing Channel Scale

Bruce Abernethy*[*] *and Ian D. Rutherfurd

ABSTRACT: *Many unsubstantiated claims are made about the effectiveness of vegetation in controlling stream bank erosion. As a result of these claims, and other perceived benefits, riparian vegetation is increasingly being used as a first-line technique for river bank stabilisation. This paper argues that the influence of native vegetation on erosion rates and stream hydraulics varies as the size and shape of the river, the erosion processes, and the suite of vegetation species, change through the stream network. The interaction of vegetation and erosion is demonstrated using a scale analysis of the Latrobe River in Gippsland, Victoria. A scale analysis matches the stream erosion processes to the vegetation characteristics.*

Two main erosion processes are identified: bank slumping and corrasion. Slump blocks are larger than average-wattle rootballs in the lower floodplain tract and, in these reaches, slumping dominates the erosion process. Our analysis shows that the surcharge weight of wattles is unlikely to have major implications for bank stability. Moreover, although trees transpire at a greater rate than does pasture, saturated hydraulic conductivities of bank materials are such that bank drainage rates, following draw-down in the channel, are unlikely to be influenced to any substantial degree by riparian cover-type. Increased bank shear strength due to root reinforcement is probably the major effect exerted on bank stability by trees along the Latrobe river with respect to mass stability.

By reducing the velocity of near bank flow, riparian vegetation can have a profound effect on rates of corrasion. In the upper 20% of the catchment area, vegetation occupies a large proportion of the channel and provides a relatively large hydraulic resistance. Finally, the period of inundation of riparian vegetation varies dramatically along the river and this is shown to have management implications. Considering all of these variables we define the river reaches in which vegetation will be most effective for erosion control.

1. INTRODUCTION

Sedimentary deposits older than about 400 million years old (the Silurian) contain only records of braided streams. Coincident with the evolution of plants with roots and rhizomes in the Silurian was the appearance of single thread, meandering channels (Mosselman, 1992). Vegetation both reduced sediment yields and floods from the catchment, and provided bank stability (Pannekoek & van Straaten, 1984). The importance of vegetation in stream stability would come as no surprise to most stream managers, who are increasingly seeing native vegetation as a prerequisite for a healthy, stable stream system.

Native species are now being used to augment or, in some cases, replace traditional structural engineering solutions to stream erosion problems. Indeed, some $10 million per annum is directly spent on riparian re-vegetation schemes in Australia at present (Rutherfurd *et al.*, subm.). But how does a stream manager decide whether a particular vegetation type will work or not? Moreover, in what parts of the river system will replanting programmes produce the best results?

General statements describing the role of vegetation in bank stability abound in the literature; both in terms of perceived benefits and liabilities. Many authors have suggested that tree roots enhance bank shear strength and reduce the occurrence of slumping (e.g. Thorne, 1990; Gray & Leiser, 1982; Stryczen & Morgan, 1995). In addition to this, a root permeated soil is markedly more resistant to direct erosion by corrasion. Experiments by Smith (1976) suggested that bank sediments reinforced by roots were some 20,000 times more resistant to corrasion than non-reinforced sediments. Is this a typical or an extraordinary number? Zimmerman *et al.* (1967) found that the width of small streams in Vermont (USA) were overwhelmingly controlled by riparian vegetation. Forested streams narrowed significantly where they emerged from the trees and flowed in banks lined with rushes and sedges.

This paper presents an approach that we are developing that aims to help stream managers decide where, in a stream network, specific types of vegetation will most effectively assist in bank stabilisation. We call this approach *scale analysis* (after Rutherfurd *et al.*, 1995). The basis of scale analysis is that the influence of vegetation on bank erosion rates varies through the stream network. For instance, it is little use planting a species whose root zone extends to one metre if the main erosion

[*] CRC for Catchment Hydrology, Department of Civil Engineering, Monash University, Clayton VIC 3168
Telephone: (03) 9905 5581 Fax: (03) 9905 5033 Email: bruce.abernethy@eng.monash.edu.au

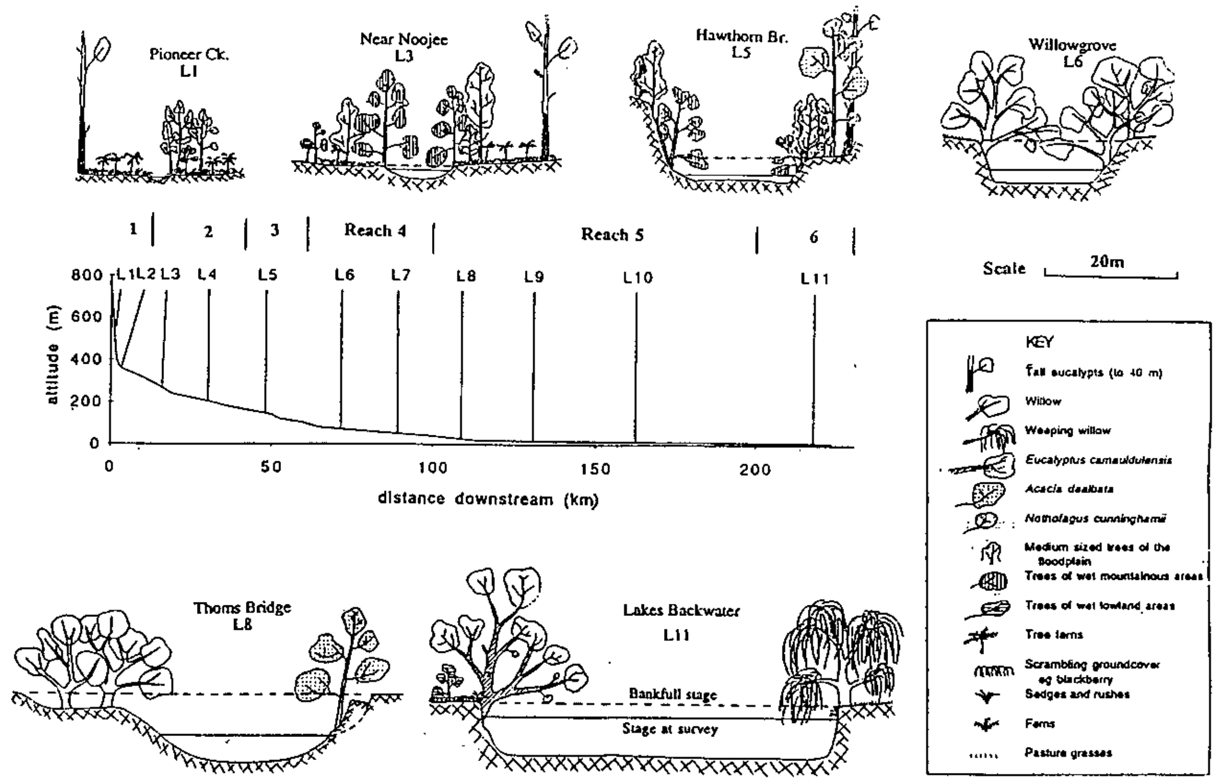

Figure 1: Long profile of Latrobe river with reaches, cross-section locations, and typical vegetation.

process occurs at the toe of a bank two metres high.

The study reported here extends the recent work of Rutherfurd *et al.* (1995) on the Latrobe River. Following a description of the erosion processes and vegetation characteristics of the Latrobe, we present an analysis of the various mechanisms by which vegetation is purported to influence erosion. Our study was undertaken as part of the national riparian zone research project which aims, eventually, to define the role of vegetation in bank stability and other processes.

2. LATROBE RIVER

The Latrobe River, in Gippsland, Victoria, is 242 km long and drains a catchment of 5,200 km^2. The river is almost entirely alluvial, with few bedrock reaches. Lower reaches are characterised by a meandering single thread channel, about 35 m wide and 5-6 m deep; typically with silt-clay banks and a sand bed. Backwater from Lake Wellington influences the final 30 km. The headwaters largely remain forested, whilst the floodplain is cleared for cattle grazing. Rainfall in the catchment ranges from 600 mm to 1600 mm.

Rutherfurd *et al.* (1995) surveyed eleven sites along the length of the river, describing boundary sediments and dominant erosion processes; six of the sites are located at stream gauges. For their purposes, Rutherfurd *et al.* considered vegetation on the edge of the floodplain, on the bank face, and in the channel. Vegetation in the headwaters is wet, closed canopy *Eucalyptus regnans* forest, whilst the downstream floodplain vegetation was originally open forest: wattles (*Acacia dealbata*) and red gum (*E. camaldulensis*). Today, riparian vegetation of the lower channel is dominated by basket willows (*Salix rubens*), and wattles.

The changing role of riparian vegetation in channel erosion processes can be best understood by dividing the river into six reaches, with each having a characteristic relationship between riparian vegetation and erosion process (Figure 1 & Table 1). Vegetation has a profound effect on erosion processes in Reach 1. Fallen trees, or large woody debris (LWD), span and choke the channel and the bank is undercut, by up to 0.5 m, below the 0.3-0.5 m root-zone. The floodplain is narrow and permanently saturated. It is only in this reach that riparian vegetation can buffer hillslope runoff. Downstream, the floodplain widens and the channel is progressively isolated from the hillslopes.

The channel banks of Reach 2 are vertical and too low to sustain trees on the bank face. Undercutting below the root-zone remains the dominant erosion process.

Table 1: Latrobe reach characteristics.

Reach No.	1	2	3	4	5	6
Distance From Divide (km)	<10	10-40	40-60	60-100	100-200	200-230
Channel Width (m)	4-6	6-16	17-18	20-40	40-50	50
Bank Height (m)	<1	1.5-2	3-4	3.5-4	4-8	2-3
Riparian Vegetation	Ferns & Sedges	Paper Barks	Paper Barks	Wattles & Red Gums	Wattles & Red Gums	Wattles & Red Gums
Vegetation Height (m)	~1	~10	~8	10-20	10-20	10-20
Dominant Erosion Process	Corrasion	Corrasion	Corrasion	Slumping	Slumping & Corrasion	Corrasion
Effect of Vegetation	Flow Resistance	Flow Resistance	Flow Resistance	Bank Strength	Bank Strength	Bank Strength

Major changes occur in Reach 3 as the river flows out of the confined floodplain reaches into the broad alluvial floodplain. Trees grow on the bank face and their roots often extend below the water line. The channel is broader than trees are tall. LWD tends to be swept against the bank at an angle of about 30° and does not divert flow onto the banks. Meandering commences in this reach so that undercutting is concentrated on the outer bank of bends.

Levees develop in Reach 4, and the floodplain slopes away from the channel; riparian vegetation has little or no role in buffering runoff. The dominant erosion process is bank slumping. Slump blocks are smaller than the average size of wattle rootballs and tree roots extend through potential shear planes, increasing bank shear strength.

The river attains its largest dimensions in Reach 5, being up to 50 m wide and 7 m deep. Erosion is most pronounced on vertical concave banks where slumping occurs. On these bank sections, roots of bank-top trees do not extend to the mean water level; outer banks with trees are often undercut by up to two metres. Slump blocks in this reach are over twice as large as those in reach four and are often larger than the typical wattle rootball.

Reach 6 is located in the backwater of Lake Wellington. Here, the channel widens, banks are vertical and the stage varies by only 0.5 m. Water logged sediments limit root depth to about 1 m deep and, as in reaches one to three erosion is by undercutting below the root-zone. There is little slumping.

The Latrobe reach descriptions indicate that we may simplify bank erosion as the product of two major processes. Banks erode by either the removal of individual grains, termed corrasion, or mass failure under gravity, where the shear forces acting on a bank section overcome its shear resistance. Both processes act throughout the length of the river but one process dominates over the other, depending on the scale of the river in a given reach. The same suite of vegetation - groundcover, understorey, trees - may exert a more or less significant role in the erosion process at different river scales.

3. VEGETATION AND BANK STABILITY

In considering changing channel scale down the length of the river it becomes clear that the degree and type of vegetative effects vary in different reaches. Bank instability leading to erosion by slumping is only a major process on Reaches 4 and 5. The process is most prominent in Reach 5 around the Thoms Bridge gauge where the banks attain their maximum height. What would be the effect of revegetating this reach with wattles and river red gums? Many locals argue that wattles contribute to slumping by surcharging the banks, while the literature suggests that soil moisture modification, slope buttressing and soil arching, and root reinforcement are important considerations in the bank stability problem.

3.1 Surcharging

Depending on the slope angle and the position of a tree on the bank, surcharge due to the weight of a tree may be beneficial or detrimental to bank stability (Gray & Leiser, 1982). On gently sloping banks, the slope normal contribution of surcharge is much greater than the downslope component. Consequently, the net effect of surcharging is to increase stability through increasing frictional resistance to shearing (Thorne, 1990). On steep banks surcharging decreases stability because additional weight tends to produce a shear force and turning moment that may aid in toppling failure mechanisms. The effect is exaggerated when trees lean over the channel due to wind loading or asymmetrical growth patterns. In this regard a wide stand of trees is preferable to a single line of trees on the bank top (Thorne, 1990).

Wattles growing on the banks of the Latrobe River probably have little surcharging effect. This is shown by considering typical slump blocks in Reaches 4 and 5. The dimensions of slump blocks are shown in Table 2. Wattles tend to grow at about 2m spacings, so that only one tree can be accommodated on a slump block in Reach 4 and five trees on a slump in Reach 5. The weight of an average wattle was estimated in the field to be about 235 kg.

Table 2: Slump block dimensions.

	Reach 4	Reach 5
Size of slump blocks (m^3)	4	48
Bulk density (kg/m^3)[†]	1,320	1,320
O.D. slump block weight (kg)	5,160	63,380
Sat. slump block weight (kg)[‡]	7,115	87,470
Weight of trees (kg)	326	1,175

[†] Mean oven dried bulk density of bank materials.
[‡] The total porosity of a soil estimated from:

$$\text{Porosity}\,\% = \left(1 - \frac{BD}{SG}\right) \times 100$$
$$= 50.2\%$$

where *BD* is the bulk density of oven dried slump material and *SG* is the specific gravity of the soil particles (assumed here to be 2.65 after Craze & Hamilton, 1991).

In Reach 5, the surcharge weight of five wattles represents only about 1.8% of the weight of a dry, and 1.3% of a saturated slump block. This weight is probably trivial in terms of initiating a slump failure, particularly when it is compared with bank saturation. Surcharging due to bank saturation increases the slump block weight by some 40%.

In Reach 4 the effect of surcharge is somewhat more pronounced as slump blocks tend to be smaller. Here the weight of a tree represents about 4.4% of dry slump block weight, falling to about 3.2% as the block saturates. Again much of this weight aids in bank stability and we consider that surcharging is unlikely to contribute to failure initiation. In this reach however, the additional surcharge effect may aid in moving slumps down the banks after initial failure. Additional forces produced by wind loading lead to only marginal increases in bank loading and for the scale of the processes we are discussing here remain largely insignificant.

3.2 Soil Moisture Modification

Vegetated slopes are more stable, with respect to mass failure, because they are drier and better drained than their unvegetated counterparts (Gray & Leiser, 1982). Vegetation reduces the bulk unit weight of soil due to the proliferation of macropores and other soil structure modifications, and increases the effective and apparent cohesion (Thorne, 1990).

Stream banks are most likely to fail following rapid drawdown of the stream (Twidale, 1964). Can trees remove water from the banks of the Latrobe River at a fast enough rate to affect bank slumping? That is, if slumping occurs following drawdown, can vegetation, by evapotranspiration, reduce the time that the banks are saturated?

Trees use more water than does pasture. Eastham *et al.* (1990) showed that a greater proportion of soil water was extracted from deeper down the soil profile under trees than under pasture, owing to lower soil water contents in upper horizons and the deeper and denser rooting patterns of trees compared to pasture. Greenwood *et al.* (1985) found that evaporation from *Eucalyptus* plantations (4.3-7.4 mm/day) can be up to seven times that from surrounding grazed pasture (1.1 mm/day). Evapotranspiration rates of red gums growing on river banks are in the order of 3 mm/day (Jim Morris, DCNR; pers. comm.).

Draw down rates in the Latrobe River vary from reach to reach (Fig. 2). At the Noojee gauge, for example (Reach 2), the draw down rate is on average 45 cm/day during the first 24 hours after bankfull flow, whilst at Thoms Bridge (Reach 5) drawdown is 105 cm/day and at Rosedale it is only 20 cm/day.

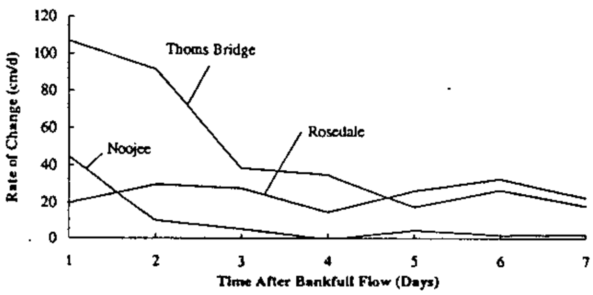

Figure 2: Mean rate of change of stage at Latrobe R. Gauges.

Field tests of hydraulic conductivity show that replacing pasture with trees is unlikely to reduce the effect of drawdown in Reach 5. Field tests of bank materials under pasture and wattles at Glengarry Bridge yield saturated hydraulic conductivities (k_{sat}) ranging from 16 to 117 cm/day depending on the bank materials. In reach five the average time for the stage to fall from bankfull (5.5 m) to normal flow levels (2.0 m) is about 7 days, and this rate is consistent between hydrographs. At this rate of drawdown it is likely that water will be able to drain from the bank back into the channel at a rate that can pace the falling stage in the channel, and is many times faster than the evapotranspiration rate of the trees.

3.3 Root Reinforcement

The most obvious way that vegetation stabilises river banks is by root reinforcement. The intermingled, lateral roots of plants tend to bind the soil together in a monolithic mass. According to Gray & Leiser (1982), a root-reinforced soil behaves as a composite material in which elastic roots of relatively high tensile strength are embedded in a matrix of relatively plastic soil. Additional strength is mobilised within the composite material by the development of tractive forces between the roots and the surrounding soil. Shear stresses in the soil mobilise tensile resistance in the roots, which in turn imparts greater strength to the soil (Thorne, 1990).

In Reaches 1, 2 and 6, slumping is rare because the banks are low (less than 1.5 metres high), and the roots of trees pass through potential slump-failure planes. Similarly in Reach 4, where slump-blocks tend to be smaller than the root balls of wattles, the roots pass through both the back and base of the failure plane and restrict the incidence of large scale slumping. As the banks get higher and the size of potential slump blocks increase in Reach 5, fewer roots pass through the base of the block. Nevertheless, observations in Reaches 4 and 5 show that bank sections under only pasture and isolated trees are more prone to slumping than those sections of bank with trees in greater density. Our future research will examine the influence of vegetation roots in more detail, as it is probably the critical role of trees in slumping.

3.4 Slope Buttressing and Soil Arching

Well rooted and closely spaced trees along the toe of a river bank can provide an effective buttressing effect which retains the slope and loads the toe against shear failure (Thorne, 1990; Gray & Leiser, 1982). Examples of buttressing can be found in Reach 5 where slumps have occurred, only to be held at the toe of the bank by a row of wattles. Where there is no buttressing, slump blocks reach the toe of the bank, where it is subsequently removed by corrasion.

4. VEGETATION AND CORRASION

Bank vegetation increases flow resistance, thus reducing the forces of drag and lift acting on the bank surface. As the boundary shear stress is proportional to the square of near bank velocity, a reduction in this velocity produces a great reduction in the forces responsible for corrasion (Ikeda *et al.*, 1981).

Richards (1982) shows that detachment and entrainment of boundary materials usually occur under turbulent eddies, where velocities may, for short durations, attain values in excess of the time-averaged mean. Vegetation reduces the magnitude of instantaneous velocity and shear stress peaks by suppressing meso- and macro-scale eddies thus reducing the erosive attack on the banks (Thorne, 1990).

The rate of bank migration in a meandering stream is proportional to the strength of the secondary circulation cells in a bend, which are proportional to the velocity gradient between the near bank velocity and the mean cross-section velocity (Ikeda *et al.*, 1981). The role of vegetation in reducing this velocity gradient is a product of scale, for two reasons. As we shall show, vegetation has a relatively greater role in small streams, but there is also the issue of flow duration.

4.1 Flow duration

In terms of flow resistance and direct protection of the banks from scour, vegetation can only have an influence if it is in contact with the flow. The period of time that bank vegetation will be in contact with the flow varies dramatically along the Latrobe because of the changing shape of the cross-section.

When stage duration is plotted relative to bankfull depth (Fig. 3) it is clear that the shape and hydrology of different reaches means that different portions of the bank are underwater for different amounts of time. For example, planting vegetation on the upper-half of the bank at Hawthorn Bridge (Reach 3), where flow occupies the top three fifths of the bank for less than 2% of the time, would be less effective than at Noojee, where flows occupy the top three fifths for 97% of the time. Similarly, revegetating the top metre of the bank at Rosedale would provide direct protection for more than 10% of the time, but less than 1% of the time at Willowgrove or Thoms Bridge.

4.2 Effects on channel hydraulics

Flow velocity is affected by live vegetation projecting into the channel area, and also by dead vegetation (LWD) in the channel bed. The hydraulic effects of vegetation in flow are complex (Kouwen, 1988), so we assume here that the hydraulic effect is proportional to the area that the vegetation projects into the bankfull flow (the blockage ratio). This area

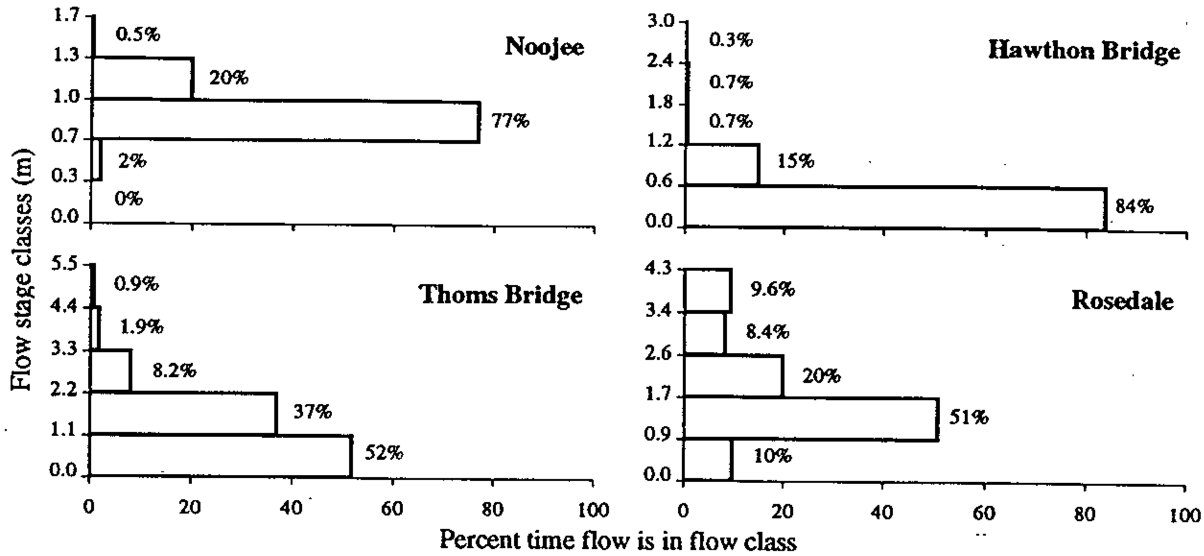

Figure 3: Bankfull depth at four gauges on the Latrobe R. Is divided into 5 stage classes. The graphs show the percentage of time that the flow stage lies within each class.

is estimated for the natural suite of vegetation that would have lined the banks prior to clearing.

Below Willowgrove, LWD has been artificially removed up to four times, so natural LWD projected area is estimated from measurements made by Gippel *et al.* (1992) in the nearby lower Thomson River that has not been snagged. The median LWD projected area on the lower Thomson (similar size to the Latrobe at about Thoms Bridge) is about 1 m^2/m. Figure 4 shows that more of the channel is blocked by LWD than by live vegetation, and that both live vegetation and LWD occupy a progressively smaller proportion of the channel downstream.

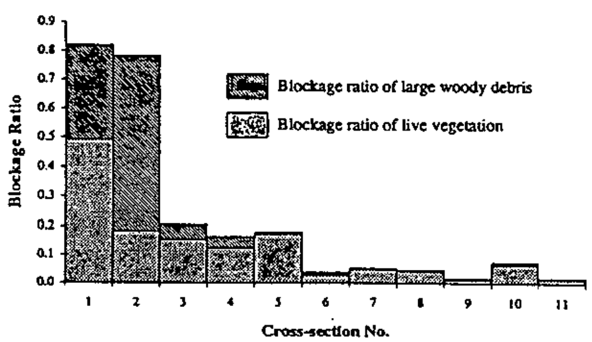

Figure 4: Proportion of cross-section (blockage ratio) occupied by vegetation.

Gippel *et al.* (1992) suggest that LWD will have little influence on velocity below a blockage ratio of 10%. In the upper reaches, the vegetation and LWD occupy up to 80% of the cross-section, having a large impact on flow resistance. The combined blockage ratio falls rapidly to 20% Reach 2, and to only 2% at the mouth of the river. Thus, for over 80% of the river's length, vegetation probably has little influence on mean flow velocity, although it may still influence the near-bank velocity.

5. CONCLUSIONS

The influence of vegetation on bank erosion rates varies through a stream network. This is because, along the stream network, the size and shape of the river, the erosion processes, hydrology, and the suite of vegetation, all change. A scale analysis matches the stream erosion processes to the vegetation characteristics so that managers can plant vegetation in the reaches of the river where it will be most effective. In this case study of the Latrobe River, we have attempted to give a brief overview of the changing hydromechanical effect of riparian vegetation on river bank stability in relation to channel scale. We draw the following conclusions for the role of vegetation in bank stability on the Latrobe River.

- Slumping is an important erosion process in the floodplain reaches of the Latrobe. Replacing pasture with trees (i.e. wattles) will not lead to increased slumping because of surcharge. The weight of the trees is trivial in comparison to the weight of the slump blocks.

- The role of vegetation in drying out stream banks following drawdown of the river is also negligible on the Latrobe because the water-table probably drains at the same rate as even the fastest drawdown in Reach 5. This means that the influence of roots on bank strength is probably the most important role of vegetation in the Latrobe, and this is most important in Reach 4 where the roots cross both the back and base of the failure blocks.

- Vegetation also influences corrasion rates by reducing flow velocities. The effect of live and dead vegetation on mean velocity is dramatic in the top 20% of the stream length, but this becomes negligible through most of the channel length. Furthermore, because of changes in the shape of the cross-section, vegetation planted on the banks will be in contact with flow for very different lengths of time.

- Overall, replacing pasture with trees will have the most pronounced effect on bank erosion rates in the upper end of the lower floodplain reach (Reach 4) where slump blocks are small in relation to the size of rootballs. Revegetation with wattles is unlikely to increase the frequency of bank slump failures because of surcharge, this is particularly true where trees grow on a sloping bank.

This paper has presented a rational method for deciding where vegetation may, or may not, be preferable to more expensive bank stabilising options. Moreover, in pursuing this technique we expect that the theory required for locating these zones will strengthen our understanding of the mechanisms of river bank failure.

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Ecological Investigations into Streambank Stabilisation Practices in North Queensland

Stephen Skull*, Paul Clayton* and George Lukacs*

ABSTRACT: *Tropical streambank stabilisation initiatives have not previously been investigated with a view to improving the ecological sustainability of streambanks. Maintaining the physical integrity of streambanks has been the focus of traditional engineering works. Field survey data from representative stream sites has enabled comment on the ecological effects of different types of stabilisation works. Qualitative vegetation and semi-quantitative aquatic fauna surveys are recommended as useful means of investigating the ecological effects of stabilisation works. It is concluded that unless works designs maximise every opportunity to restore riparian vegetation habitat, stabilisation techniques will remain ecologically unsustainable.*

1. INTRODUCTION

In April 1993, a national workshop was conducted on the research and management needs of riparian zones in Australia (Bunn *et al.* 1993). The following list of the ecological roles of riparian vegetation represents a synthesis of the many varied papers presented at the workshop, coupled with roles and values proposed by the authors of this document. These roles include:

- provision habitat for a high diversity of terrestrial and aquatic faunal species;
- importance as drought refugia for many faunal species;
- acting as a filter for sediment, nutrients and agricultural chemicals when present in catchment runoff;
- protect streambanks from erosion;
- acting as a source of organic matter (including snag formation) for the creek they inhabit;
- provision of shade, thus reducing temperature fluctuations and keeping the growth of plant and algal populations in check;
- functioning as wildlife corridors for terrestrial wildlife;
- exerting an influence on downstream "receiving" systems;
- possessing an intrinsic aesthetic value; and
- possessing an intrinsic conservation value in terms on the unique plant species and communities that grow in these areas.

The widespread clearing of vegetation for agriculture and urbanisation has resulted in the riparian ecosystems of most northern Queensland lowland streams becoming severely impacted. In many cases, the clearing of vegetation to the water's edge has resulted in a disjointed riparian system with consequent disruption to riparian wildlife corridors, reduction in stream inputs and modification of aquatic bank habitat. The extensive clearing of vegetation in catchments has probably resulted in increased run-off rates. This increase, coupled with the tropical climate (i.e. short, high intensity rainfall periods) has altered and hastened natural riverbank erosion processes. The streambank vegetation within the lowland sections of tropical catchments is often the only vegetation remaining and may be the major mechanism controlling this erosion. Further impact on this vegetation may only exacerbate erosion problems.

In collaboration with the Department of Civil and Systems Engineering, James Cook University, the Australian Centre for Tropical Freshwater Research (ACTFR) began research into the ecological aspects of streambank stabilisation in July 1993. The ecological sub-program has the following objectives:

- to compare the environment created by traditional stabilisation practices with intact, remnant riparian ecosystems;
- to assess riparian and instream habitat changes caused by the instability of banks and stabilisation works; and
- to discuss the ecological impacts of different types of stabilisation works and evaluate potential alternatives.

* Australian Centre for Tropical Freshwater Research (ACTFR), James Cook University, Townsville, QLD, 4811.
Telephone (077) 81 4262 Fax (077) 81 5589

To date the LWRRDC funded project has had the following outcomes:

- a review of bank stabilisation practices for north Queensland streams; and
- a review of the methods of environmental assessment of streambank stabilisation.

Future outcomes will include the production of a streambank stabilisation guidelines handbook for use by all groups involved in tropical river management.

2. METHODS

2.1 Vegetation

Study sites have been established along five coastal lowland rivers from Mackay to Cairns (Table 1). At each location, the vegetation assemblage at the different stabilisation works sites was compared with a relatively undisturbed riparian vegetation community (control sites). Habit, likely depths of root systems and percentage cover were recorded for the dominant species within a defined area (50 x 30 m) at each location.

Table 1 Sites (listed from south to north)and the types of stabilisation works assessed

Site	Stabilisation Works
Pioneer River	Wire embayment
Burdekin River	Rock revetment
Haughton River	Rock revetment and groyne
Herbert River	Rock revetment with berm
Mulgrave River	Rock revetment and groyne with re-vegetation at top of bank

To assess a variety of stabilisation options, a case study site has been established on the Herbert River and the following stabilisation treatments have been applied to a highly eroded section of streambank dominated by exotic species:

- rock placed at toe of bank with sub-surface drainage;
- rock placed at toe of bank with no sub-surface drainage;
- remnant riparian trees left on toe of bank with replanting on remainder of bank; and
- tree planting only.

The results of this work are still to be determined and will not be considered further in this paper.

2.2 Aquatic Fauna

The quantitative aquatic ecological program has been conducted at three of the five vegetation study sites (Mulgrave, Herbert and Burdekin Rivers). A pilot sampling program showed that dip-netting was the most useful technique for the collection of benthic macroinvertebrates from the instream under-bank habitat. Fish and crustacean traps baited with light (i.e. Cyalume sticks) that were placed close to the bank were successful in providing information on small fish and crustaceans.

Artificial substrates were introduced for the main sampling program; the use of artificial substrates to quantitatively sample deep rivers, or habitats that are difficult to access, has been successful in other investigations (ACTFR 1994). Artificial substrates were the best solution to the instream sampling problems encountered during the pilot program, providing comparable, quantitative macroinvertebrate information (composition and abundance) at both rock revetment and control sites.

Five dip-net samples were collected from the bank habitat at random locations in control and rock areas at each site (10 samples per site) to quantify instream population differences between rock revetment and natural bank. Substrate installation and exposure periods varied between study sites according to the predetermined protocols. Observation and detailed habitat description were used to provide a broad assessment of the aquatic ecology at each study site

2.3 Terrestrial Fauna

Pilot study sampling was undertaken at the Herbert and Burdekin River. At the Herbert River study site two areas were sampled, namely the works area and a control site approximately 500 m upstream. The same survey method was employed at each area, consisting of four lines of 12 small mammal traps placed parallel to the river bank (i.e. a total of 48 traps per area) and fixed-time bird observations.

At the Burdekin River study site three areas were sampled; namely new rockwork, old rockwork 500 m upstream, and a control site a further 350 m upstream. The same survey method was employed at each sub-site. The mammal trapping technique was different from that employed at the Herbert River in that traps were placed in clusters of six; eight clusters in each area gave a total of 48 traps per area. The traps were pre-baited on the first and second nights (i.e. trap doors were not opened) and opened for the third and fourth nights. Fixed-time bird surveys were conducted early in the morning during the time of peak activity.

3. RESULTS

3.1 Vegetation

A summary of the vegetation results for the different study sites is provided in Table 2. Works sites are dominated by shallow rooted exotic species and have much reduced vegetative cover when compared with remnant riparian communities. From an ecological viewpoint, the most important result is shown by the figures for the Mulgrave River. Where an attempt was made to incorporate vegetation into stabilisation works, the predominance of exotics was reduced and cover increased.

Table 2 Summary of vegetation results at the different study sites. The first figure listed for each parameter is the works site value, followed by the remnant riparian community value. Figures include both terrestrial and aquatic plant species.

Site	Dominance of exotic species (%)	Predominance of shallow root systems (%)	Cover (%)
Pioneer	78/6	100/50	10/85
Burdekin	50/19	80/30	15/75
Haughton	31/12	100/43	10/90
Herbert	75/18	70/50	15/80
Mulgrave	15/7	40/25	35*/90

* Figure increasing as tree species in planting program mature.

3.2 Aquatic Fauna

Results from the dip-net and artificial substrate samples are still being determined in the laboratory. Quantitative assessments of the instream macroinvertebrate communities will be made after the completion of specimen sorting and identification.

3.3 Terrestrial Fauna

The results of the small mammal trapping at the Herbert River site are presented in Table 3. A similar abundance of two main rodent species was detected at both the control and works areas, with a single individual of a third species detected at the control area; however, there was a great difference in the total numbers of mammals detected by trapping at each area - two species at the works and six species at the control. Three of the additional species at the control area were species typically found in denser vegetation types such as riparian forests. The water rat usually occurs in a range of habitats including grassy banks such as that at the works.

The abundance of *Melomys cervinipes* at the works area was not anticipated as this is typically a closed forest species. However, the pattern of the trapping returns for this species suggests that many of these individuals may have been drawn by the scent of the baited traps from the adjoining, more densely vegetated bank area. The attraction of small mammals to baited traps outside their usual home range area can cause problems in small areas such as the rockworks where it is impossible to provide a large buffer area between the habitat being studied and the adjoining habitat. This can lead to spurious results when attempting to describe the fauna of a small area.

The number of bird species detected during observations at each of the areas were similar. Eleven bird species were detected at the works area and thirteen at the control. There was a clear difference in the types of species encountered. Six of the species from the works area were ground-dwelling species commonly found in shrubby or grassy areas; however, none of these species were detected at the control area where the bird fauna was dominated by forest birds.

Table 3 Small mammal trapping results at the Herbert River study site

Site	Species	Abundance
Works	*Melomys cervinipes*	25
	Rattus sordidus	11
Control	*Melomys cervinipes*	28
	Rattus sordidus	14
	Rattus fuscipes	1
	Uromys	2
	Hydromys	2
	Perameles nasuta	3

The results of the small mammal trapping at the Burdekin River site are presented in Table 4. Mammals were not abundant at any of the Burdekin River sites. The old rock work area had the highest capture success with 5 individuals from two species, one being the introduced House Mouse (*Mus musculus*). Only two individuals were trapped in the control area which, although selected as the comparison area for the works, was highly disturbed by exotic weed invasion and subsequent canopy mortality. Furthermore, the remnant riparian community along this reach of the Burdekin River is disjointed and this may have an effect on mammal populations. Greater numbers of animals were expected for this area although previous survey work in the Burdekin River delta area has shown that small mammals generally occur in low densities even in riparian communities.

Table 4 Small mammal trapping results at the Burdekin River study site

Site	Species	Abundance
New Works	*Melomys burtoni*	1
Old Works	*Melomys cervinipes*	4
	Mus musculus	1
Control	*Melomys cervinipes*	2

A total of four hours of bird observations were undertaken at each site. The new works and control area had the highest diversity of species with 17 and 16 respectively, while only seven species were detected at the old works area. A similar suite of species were seen at both the new works and control sites and consisted predominantly of canopy species. At the new works, most birds were observed to be briefly visiting the two clumps of fig trees remaining within the rocks and very few individuals were observed to utilise the remaining area. These observations highlight the ecological importance of leaving established vegetation wherever possible amid rockwork. Since the work has only recently been finished there is little substantial vegetation in the area so that even ground-dwelling birds do not appear to be utilising the area.

The total number of birds detected at the new works site may reflect the ease of bird observation at the site as compared to the vine thicket community of the control site where a number of birds were unable to be identified as a result of the dense vegetation.

4. DISCUSSION

4.1 Vegetation

A few ubiquitous traits of artificial stabilisation practices in northern Queensland appear evident. Where there has been streambank stabilisation work conducted on the riverbank, the vegetation community is distinct from the intact riparian vegetation. Native species do not establish easily in the stabilisation work and often it is mostly colonised with exotics. There appears to be little regeneration of the stabilisation gaps by the adjacent native vegetation, although this may occur with time. Establishing weeds also act as seed sources for further invasion of any relatively intact remnant riparian vegetation communities. Traditional works thus provide a mechanism for an increase in the distribution of exotic species throughout a given catchment. Increases in exotic species abundances and distributions recorded during this study include declared plants (e.g. *Riccinus communis*), the management of which is governed by the Rural Lands Protection Act (1985-1990). Aquatic weeds also appear to be concentrated in the still backwaters of many of the stabilisation works.

The works have also resulted in the fragmentation of otherwise continuous riparian wildlife corridors. The importance of corridors in the maintenance of riparian and catchment integrity are widely accepted (Bennett 1990). Environmentally based stabilisation techniques such as tree planting can reduce the fragmentation effect of works programs (e.g. Mulgrave River), but the reduction will remain minimal if rock work is extensive or the main focus of a particular project (e.g. Burdekin River site). Streambank modification also results in the loss of bank habitat structures and morphology for the aquatic and terrestrial fauna.

Although current attempts at tree planting (e.g. at the top of rock dominated works) will partially re-establish a riparian corridor, they do not satisfactorily replace the original stream habitat. It is also unlikely that this landscaping approach to planting will provide long-term solutions to local bank stability problems. Further, unless specific design components (e.g. berms) are integrated with tree planting schemes, they are of little or no ecological benefit.

Traditional works also allow for the encroachment of exotic species into adjoining remnant riparian vegetation communities, which leads to further long-term degradation of stream and river ecosystems. Exotic species are usually shallow rooted when compared with native species. It follows that vegetation communities either side of the works will, over time, become more susceptible to stability problems as the exotic species invade. For stabilisation practices to fit within an ecologically sustainable framework, rock work should be minimised (e.g. restricted to the toe of the bank only) or completely absent in work designs.

The remnant riparian communities documented during this survey are highly diverse both floristically and structurally. Unfortunately, it is usually well beyond the resources of most vegetation schemes to re-establish this level of diversity. Once the replanting scheme has been in place for sufficient time for trees to approach maturity (flowering, fruiting and canopy cover becoming continuous), this recorded diversity could be utilised as a baseline to monitor the longer-term success of a planting program.

Another ecologically unsustainable impact of the use of rock in stabilisation works is the removal of the material from elsewhere in the catchment (usually granitic hills and mountains). This indirectly compounds the ecological impacts associated with the placement of this material in the streams and rivers of a particular region.

4.2 Aquatic Ecology

Though sorting and analysis of the macroinvertebrate samples is incomplete, some general observations can be made. Macroinvertebrates were present at both control and stabilisation works sites. At the stabilisation works sites, the community is generally diverse, but has a different structure than at control sites, particularly due to an absence of shredders (e.g. Trichoptera). It is likely that construction of revetments and other forms of stabilisation works has catastrophic, short-term consequences to invertebrate communities; however, recovery is probably rapid. The newly established macroinvertebrate community is diverse and abundant but appears to show structural and species compositional differences compared with undisturbed communities in nearby control sites. Stabilised streambanks, particularly rock armouring, provide complex habitat for instream invertebrate colonisation but attract species from less common hard and muddy substrate areas.

In large streams and rivers, small lengths of bank stabilisation are unlikely to force significant changes to instream macroinvertebrate communities; however, long sections of stabilised bank (hundreds or thousands of metres) such as those on the banks of the Burdekin River pose concerns for the integrity of stream systems. Following a full analysis of the results further conclusions may be drawn including an adjustment to those outlined above.

4.3 Terrestrial Fauna

The results have confirmed the expected species composition and patterns of distribution for birds and mammals. The impact of bank slumping and subsequent rock revetment on riparian vertebrate ecology is plain since the riparian corridor is disrupted and, most often, native vegetation species are not replaced or are replaced by exotics. Essentially, the vertebrate fauna reflects the riparian habitat quality. Continued investigations of the riparian zone were, therefore, not deemed necessary and subsequent description of the riparian zone was based on vegetation and habitat quality.

An intact riparian zone is clearly important to the riparian fauna. Loss of vegetation resulted in a reduction in species abundance and a restriction to faunal movement. An altered species composition was observed for the birds as ground dwelling, grassland species (e.g. finches and quail) replaced forest dwelling (e.g. doves and orioles) species at the works sites.

Aquatic vertebrate species of birds and mammals seemed little affected by the stabilisation works because these species are known to move greater distances and range over large areas and, normally, the scale of the river bank impact caused by streambank instability and revetment is small. However, it is important to note that at sites such as the Burdekin River, the length of continuous river bank under rock work has already reached an alarming scale which may be detrimentally affecting aquatic birds and mammals (particularly with regard to nesting and roosting sites).

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Preliminary Investigation into the Management of Riparian Rainforests in South-east Queensland

Simon ODonnell*

Abstract

The project "Cost-effective Riparian Zone Revegetation Management" funded by the Queensland Department of Primary Industries (QDPI) and the National Landcare Program (NLP) drew attention to the need for careful management of remnant riparian vegetation in Queensland and the difficulties associated with attempts at re-establishment and rehabilitation. Experimental planting sites have demonstrated the differences between fast-growing dry sclerophyll species and mixed rainforest plantings as far as establishment techniques and post-establishment management are concerned. Monitored remnant strips are providing information on the different structural types of the vegetation, seedling regeneration and damage by floods. Vegetation surveys have been used to establish occurrence of species throughout the region..

1. INTRODUCTION

The Mary River catchment, 200 kilometres north of Brisbane, has been the site of preliminary investigations to prepare guidelines for the management and rehabilitation of riparian vegetation in Queensland.

In high-velocity flow areas where river-banks are steep and frosts are severe, the establishment of indigenous native rainforest tree species is time-consuming and costly. Limitations such as flooding, poor nutrition, active erosion, siltation, weeds and frosts render the re-establishment of vegetation extremely difficult. Special management techniques are required to grow plants in these areas. On the other hand, in more sheltered sites native species can be relatively easily established.

Surviving remnant strips in these situations do not escape these problems. Simply fencing out domestic stock results in woody weed and tropical grass infestations which inhibit the regeneration of native plants. Seedlings suffer badly from physical damage by flood debris, insect attack, dehydration, siltation and by being competed out by invading ground flora weeds.

2. METHODOLOGY

The project took a three-pronged approach. This involved surveying remnant strips of riparian forest to determine which species occurred on the river banks, and structural classification. Experimental sites were then planted to evaluate the potential of as many of these species as possible.

2.1 Vegetation Survey

Riparian vegetation surveys established the existing species distribution throughout the Mary River catchment and provided data on possible local native species for planting.

Aerial photographs and random selection were used to identify sites for species surveys on the Mary River mainstream and its tributaries. Species lists from local amateur botanists were also reviewed. Twenty-five-metre-wide terrain surveys were carried out to establish the nature of the different plant communities. Where possible species at each site were rated as "very common", "common", "in scattered groups of a few trees", or "rare". Fifty-four sites were surveyed.

2.2 Structural Classification

Three 0.4-hectare permanent sites are being monitored to identify structural characteristics of riparian forests, and to permit observations on natural regeneration and plant populations. Seedlings within these plots are permanently marked, and information on their survival and growth is being collected.

Details of height, the number of each species, and, if relevant, damage either by flood or cattle are recorded.

2.3 Planting Sites

Three planting demonstration sites representing the three most common plant communities were selected, at Conondale, Gympie and Maryborough. Seven thousand plants of 110 species were planted between October 1993 and June 1995. Records on growth, ease of management, costs and species configurations are being kept. Standard forestry techniques are used to maintain the plants.

* Senior Extension Officer Forests, Resource Management Business Group, Queensland Department of Primary Industries, Gympie, Queensland.
Tel: (074)821522 Fax: (074)821529 Email:ODonneS@DPI.QLD.GOV.au.

3. VEGETATION SURVEY RESULTS

One hundred and ninety-seven species were recorded, excluding grasses and sedges. Twenty-nine of these were woody or vine-type weeds. A small number of common species dominated most sites (Table 1).

TABLE 1
The most common species of the Mary River mainstream.

Aquatic species	**(upper stratum cont.)**
Cyperus spp.	Castanospermum australe
other sedges	
Avicennia marina	Casuarina cunninghamiana
Aegiceras corniculatum	
Excoecaria agallocha	Eucalyptus tereticornis
	Melaleuca linariifolia
Ground layer	Syzygium australe
Adiantum sp.	Syzygium francisii
Commelina cyanea	Waterhousea floribunda
Doodia sp.	
Lomandra hystrix	**Vines (native)**
Lomandra longifolia	Geitonoplesium cymosum
Oplismenus aemulus	Malaisia scandens
Pseuderanthemum variabile	
	Vines (introduced)*
Shrub stratum	Asparagus plumosus*
Cleistanthus cunninghamii	Cardiospermum halicacabum*
Lower tree stratum	Macfadyena unguis-cati*
Acacia aulacocarpa	
Aphananthe philippinensis	Passiflora subpeltata*
Casuarina glauca	
Cryptocarya triplinervis	**Weeds***
Ficus coronata	Duranta erecta*
Ficus opposita	Eugenia uniflora*
Hibiscus tiliaceus	Lantana camara*
Mallotus claoxyloides	Leucaena leucocephala*
Mallotus philippensis	Maclura cochinchinensis*
Streblus brunonianus	Psidium guajava*
Upper tree stratum	Ricinus communis*
Argyrodendron trifoliolatum	Schinus terebinthifolia*
	Solanum mauritianum*
Callistemon viminalis	Solanum torvum*

* (naturalised since European settlement.)

On the mainstream, species associations varied from the headwaters south of Conondale to the reaches near the town of Maryborough in the north.

Vegetation structure types along the tributaries to the north-west of the catchment were predominantly classifiable as dry sclerophyll river forests of *Eucalyptus, Callistemon, Melaleuca* and *Casuarina*. Those on the tributaries to the south and east and on the mainstream were predominantly subtropical rainforest associations. Species varied significantly from the toe of the river bank to the top of the bank. The greatest species diversity occurred along the face of the bank. Natural regeneration of dry sclerophyll forest species occurred on degraded rainforest areas. Some rainforest species had established themselves on, and stabilised several severe slips near Maryborough.

An interesting feature was the seed dispersal characteristics of the plants, many of which are dispersed by birds. This is seen as an important factor in the stability of some forests (Catterall & Kingston, 1993). Only a few of the plant species are water-dispersed, with *Waterhousea floribunda* (weeping lilly pilly) being the most common species. Sun-intolerant species such as *Cryptocarya triplinervis* (three-veined cryptocarya) and *Neolitsea dealbata* (white bolly gum) were common in dense healthy remnants. Few of these species occurred close to the margins of the remnants, which are open to sunlight and wind, and adjoin cleared areas.

It was evident that a loss of species from significant associations affected bank stability at the toe, defined by Anon. (1993) as from the water mark to the lower bank, and that this had an adverse effect on the entire riparian vegetation ecosystem (Arthington *et al.*, 1992). The most diverse remnants had up to 60 species whereas degraded remnants had as few as 15 species. Few remnants are not grazed but floodplain remnants still had up to 90 native species (Smith, 1987).

Genetic diversity and species survival is threatened when remnants are devoid of species. Regeneration and planting projects are also made more difficult due to loss of the seed bank.

4. STRUCTURAL CLASSIFICATION

4.1 Flood and Cattle Damage

Investigations indicated that cattle damage such as plant stripping, grazed leaves, broken branches and trampled plants was very common. The species diversity of the vegetation was in fact seriously diminished in many places due to the effects of grazing. The damage from cattle was particularly severe in the case of the ground flora, but tree seedlings and the shrubby component were also severely depleted.

Signs of flood damage such as injuries to trees from logs, dumping of litter and silt over plants, and lodging of plants were recorded. In addition, once a remnant was opened up, the impact of flood damage became increasingly severe and hastened the decline of the remnant as rushing waters gouged out terraces once protected by shrubs, ferns, creepers and stooled plants like *Lomandra spp.*

One species, *Cleistanthus cunninghamii* (cleistanthus), occurred only in a band a few metres wide along the toe banks and in places which are inaccessible to cattle. Cleistanthus is a significant species in that it occurs in mallee-like form and in populations in excess of 5 000 trees per hectare.

An interim condition assessment was established using the attributes identified in the species surveys and in the measurements from the remnant plots. Comparisons between degraded remnants and healthy remnants were made and information from ungrazed remnants was used to establish criteria for a presumed "healthy stable state".

4.2 Degraded Remnants

Some of the characteristic features of degraded remnants are:

- The loss of many species and a great number of plants, particularly shrubs and seedlings, from cattle damage and the multiplication of robust species that are rough-leaved and presumably less palatable.
- Greater flood damage; flood damage becomes greater than cattle damage as the remnants are opened up or long stretches of the bank are denuded of vegetation.
- The loss of key species, e.g. *Cleistanthus cunninghamii*, *Lomandra hystrix*, that stabilise the toe.
- An increase in vine weeds and woody weeds.
- An increase in ground weeds and herbs which inhibit regeneration and compete with native seedlings.
- The deposition of massive logs and litter.
- An increase in some dry-forest species which may dominate if the area regenerates.

4.3 Healthy Remnants

The characteristic features of healthy remnants are:

- that the structural integrity of the forest remains in order (see 4.4.1 below),
- that there are no gaps in the vegetation,
- that there is no erosion,
- that the plants in the remnant grow vigorously with an abundance of new growth at appropriate times of the year,
- that there is a high density of plants - *c.*10 000 trees of all ages per hectare - and a species diversity of greater than 60 species,
- that there are reasonable populations of large rainforest trees to provide seed, food and habitat, especially for animals which disseminate seed,
- that the rainforest community should be dense and difficult to walk through,
- that there are few exotics.

4.4 Condition Assessment of the Riparian Forest

Healthy and sound riparian rainforests contributes to the stability of river banks. These forests are layered and each layer plays a role in maintaining ecological stability, by ameliorating floods, filtering pollution, catching silt by reducing stream velocity and by preventing the erosion of river banks,.(Arthington *et al.*, 1992).

In an endeavour to understand the dynamics of change in remnants I have identified five phases of condition of rainforest remnants in south-east Queensland as shown in Figure 1. These phases are dynamic and their definition is open to discussion, but they are designed to stimulate ideas.

4.4.1 Healthy Phase

Complete structural integrity with plant populations in excess of 5 000 and possibly more than 10 000 trees per hectare.

- Upper tree stratum: tall and very tall trees, providing deep-rooted trees for bank stability and shelter for the understorey, and which have emergent trees that overshadow the canopy. Included here are several species of vines.
- Lower tree stratum: tall shrubs and small trees, contributing to water filtering and subsoil stability and providing a high degree of cover.
- Shrub stratum: small shrubs and large seedlings, provide ground cover, stability. and filtering.
- Ground layer: ferns, herbs, grasses and seedlings, all of which protect the floor of the forest from sheet erosion caused by water runoff.

4.4.2 Surface Erosion Phase

- Cattle damage trees and graze out the shrub stratum, seedlings of lower and upper stratum species and ground covers.
- Greater sheet erosion occurs on the forest floor after depletion of ground cover, caused by local water runoff from the steeper parts of the forest or from floodplain torrents.
- Greater light and wind penetration then occurs from the top of the bank.
- There is a loss of organic matter and a reduction in collection of silt which once provided seed-beds for germination, especially for *Cryptocarya* and *Cleistanthus* species.
- Gradual infiltration of creepers, vines, herbs and woody weeds.
- A reduction in plant numbers to 2 000-5 000 plants per hectare, patchy in occurrence.

4.4.3 Flood Erosion Phase

The loss of canopy creates gaps which allow higher velocity flows of floodwater, creating a vicious circle of increasing degradation.

- There is an increase in sunlight and wind, limiting some species and dehydrating seedlings.
- There is a reduction in plant density to fewer than 2 000 trees and shrubs per hectare, very patchy in occurrence.
- Terraces develop as a result of soil loss, slipping or slumping.
- There is an increase in exotic tropical pasture grasses.
- The end result is the creation of a plant community composed of large- or rough leaved plants and vigorous growers in inaccessible positions and an increased infestation of weeds

4.4.4 Bank Failure Phase

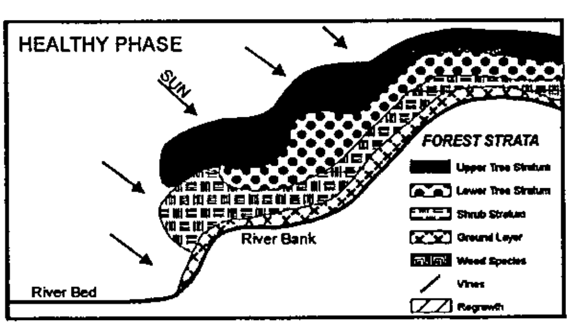
- There is a weakening of the toe of the bank.
- The occasional tree remains on the bank, sometimes causing erosion from scouring at the roots.
- Weeds are now dominant and pasture grasses severely inhibit the regeneration of native riparian species.
- Mass bank failure occurs.

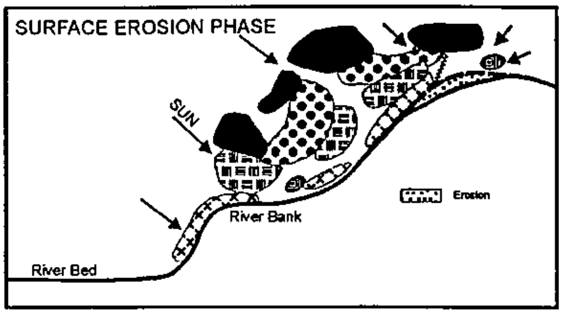
4.4.5 Return Phase

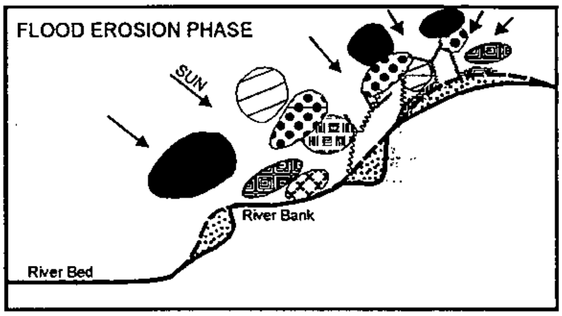
This can occur at any of the bank phases 4.4.2 to 4.4.4 above by natural regeneration if conditions permit.

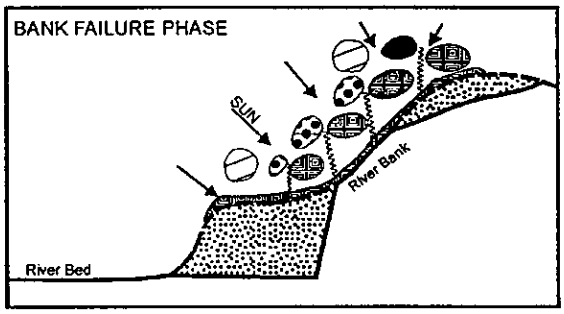
- The establishment of fast-growing natives not necessarily indigenous to the site occurs, for example *Eucalyptus tereticornis*, *Callistemon viminalis* and *Casuarina cunninghamiana*. There is a lack of species diversity and the construction of a completely new ecosystem, for example *Casuarina* forest.
- Woody weeds, vine weeds and tropical pasture weeds can become completely dominant.

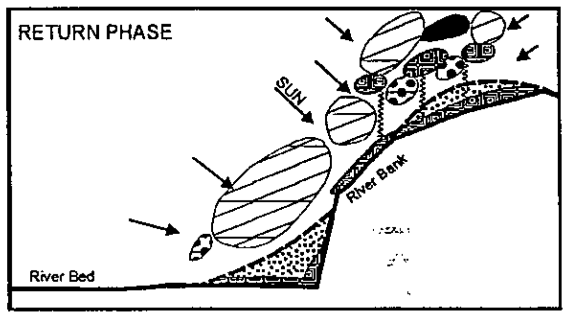
Figure 1: Condition assessment of riparian rainforest.











5. PLANTING SITES

To be able to establish plants on riparian zones an understanding of the limitations to plant growth in this demanding habitat is required. Good growth performance is dependent on the manager being able to overcome these limitations.

5.1 Frost Damage

Frost is a significant limitation that rainforest trees have to contend with. In the first two winters of this project severe frosts defoliated most plants at the Conondale and Gympie sites. Damage by frost was found to be dependent on three main factors: position on the bank, severity of frost, and time of planting.

5.1.1 Position on Bank

On steep banks frost damage varies throughout the site, with plants at the toe suffering less damage than those on top of the exposed bank and those in open situations.

5.1.2 Severity of Frost

Most plants were completely defoliated by severe frosts. Species responses varied greatly to lighter frosts.

5.1.3 Time of Planting

Young seedlings suffer more and die from frost damage if planted close to winter before they have become properly established. Time of planting seemed to significantly affect survival, especially for rainforest plants. Plantings made just prior to winter suffered severe mortalities from frost, especially of *Ficus coronata* (creek sandpaper fig), *Elaeocarpus grandis* (blue quandong) and *Streblus brunonianus* (whalebone tree).

5.1.4 Shelter

Frost proved to be less of a problem in protected areas such as cliff faces with overhanging vegetation and where large trees sheltered seedlings. Pioneer plantings of plants with a good frost recovery potential may need to be established on severe frost sites before planting climax rainforest species, although pioneer plantings may affect the growth and vigour of underplantings.

5.2 Recovery from Frost

Recovery from frost was influenced by the health and growing conditions of the plant.

5.2.1 Health

Recovery from frost was satisfactory for plants that were in good condition at the time of planting, but was also dependent on the plants being healthy when the frost struck. Healthy plants have the vigour to reshoot regularly after defoliation. Nevertheless a loss of growth does occur, this loss varying considerably between species. Plants such as *Mallotus claoxyloides* (green kamala), *Mallotus philippensis* (red kamala), *Grevillea robusta* (silky oak), *Pararchidendron pruinosum* (snow wood), all recovered after 100 per cent defoliation from frost. Some plants such as *Ficus racemosa* (cluster fig) were reshooting as soon as two weeks after frost.

5.2.2 Growing Conditions

Few rainforest plants were completely unaffected by frost but established plants of most species, if given reasonable growing conditions, soon recovered. Good growing conditions - warmth and adequate moisture - influence the recovery of plants by permitting vigorous growth. Should drought occur after frost, the mortality rates in certain more sensitive species are likely to be higher, or alternatively growth is severely reduced. Irrigation through dry periods may aid recovery after frosts.

5.3 Species Tolerance

Species selection is critical for successful plantings. Frost reduced vigour of some species such as *Syzygium francisii* (giant water gum). *Elaeocarpus grandis* (blue quandong) suffered severely from frost with 100 per cent mortality. *Melia azedarach* (white cedar) fared very well under frost conditions and this may be a consequence of the deciduous nature of this species. *Syzygium australe* (brush cherry) showed the best tolerance of all the rainforest plant species studied.

The non-rainforest species such as *Casuarina cunninghamiana* (river she oak), *Melaleuca linariifolia* (snow in summer), *Melaleuca bracteata* (black tea tree), and *Callistemon viminalis* (weeping bottlebrush) showed good tolerance to frost. We are investigating the use of these species as pioneer plants for establishing rainforest plantings. The fast-growing plants naturally also provide faster rehabilitation.

5.4 Other Limitations to Plant Growth

Nutrition and Flooding impact on the growth of plants.

5.4.1 Nutrition

Nutrition of river banks is generally poor and severe deficiencies do occur. Elements such as nitrogen, sulphur, phosphorus, potassium and zinc were recorded in low to very low levels. NPK fertilisers were used along with some special mixes containing other elements such as zinc and boron. Up to 550 grams of fertilisers were applied in split applications. Research on nutritional requirements will certainly provide information that will help to improve the performance of trees.

5.4.2 Flooding

Like frost, flooding severely affects plants. However, little is known of the impact of flooding on different species of plants. Several factors need to be considered with flooding:

- Submersion of foliage. Prolonged submersion can cause rotting leaves or dieback of leaves. This was found to be particularly so with the creek sandpaper fig, *Ficus coronata*, and the white cedar *Melia azedarach*, which defoliated severely after inundation. Tolerant plants, especially the hard-, smooth-leaved plants such as *Waterhousea floribunda* (weeping lilly pilly) and *Syzygium australe* (brush cherry), seemed to suffer little initial flood damage.

- Siltation. Plants are covered or partially buried in silt, inhibiting photosynthesis, reducing plant vigour and perhaps eventually causing death; for example *Diploglottis australis* (native tamarind) tended to die after a prolonged period covered in silt.
- Lodging. Small plants with shrubby habit, e.g. *Melaleuca linariifolia* (snow in summer), lodged less than tall thin trees such as *Cupaniopsis parvifolia* (small-leaved tuckeroo). Some species such as *Melia azedarach* (white cedar) completely bent over. *Glochidion sumatranum* (umbrella cheese tree) reshot very quickly at the roots after being lodged and having its roots exposed by floods. Another impact of lodging may be from the subsequent erosion from turbulence around the exposed roots and the plant being washed away. Lodged trees are also much more difficult to maintain.

5.5 Erosion Hazard

Active erosion needs to be addressed prior to planting by means of engineering works as well as cover cropping. Strategic application of cover crops proved to be a useful tool in the protection of small erosion-prone areas on site. The young trees were planted in the cover crop in patches previously sprayed with herbicide, the dead cover crop plants serving as an erosion-control measure. Months later, when the dead plant material had rotted, more ground cover seed was sown around the base of the plants. After a further three weeks the new crops of young cover plants were sprayed in their turn with herbicide to renew the dead mat of erosion-control mulch at the base of each tree.

5.6 Topography, Geography and Site Condition

There were significant differences in performance of similar species on the different sites. Extreme differences also occurred on steep banks of the same site. Growth was much better for species at the lower bank positions even with the impact of the floods. In summer the tops of the banks and the floodplain were exposed to wind and heat, and we had considerable trouble establishing some species in these situations. Windbreaks may have to be provided on these sites well before the establishment of the riparian species.

6. OVERCOMING LIMITATIONS

In overcoming the limitations to growing plants on riparian sites close consideration must be given to the level of inputs required for success. On sites of high soil erosion potential, with banks that are unstable from active inundation and high-velocity floods, inputs from management will obviously need to be higher than for, say, a bank in a sheltered area that would not suffer the same severe climatic and hydrological perturbations. The selection of species would also vary depending on the site conditions. Obviously fast-growing plants are needed for severely degraded sites for fast stabilisation. In this context species selection is not only a factor of the growth potential of the plant but also the type of site.

The growth of the plants also influences costs. Fast-growing plants need a shorter period of management for establishment than the slower growing plants.

7. CONCLUSION

Plants at the demonstration project sites are proving successful in stabilising severely eroded banks with minimal delay and under severe climatic growing conditions. It is probable that landowners with eroding banks will not have the resources for engineering works and will need to rely on planting as the most cost-effective method for rehabilitation.

Reafforestation programmes on sheltered un-degraded sites will achieve greater survival rates, plants are generally most successful when planted in moist sites in good growing conditions, after frosts and with good weed control and fertilising practices. Floods will impact greatly on plants and erosion-control methods are required to reduce loss of plants by floods.

Standard forest management techniques allow the establishment of riparian plantings through good site and plant maintenance.

On remnants close attention needs to be paid to the control of woody weeds. Windbreaks could be used to protect remnants as well as plantings from severe environmental conditions, especially from direct sunlight and wind caused by clearing at the top side of the banks. Timber plots could be used for this purpose. In plantings a canopy of plants may need to be planted two years in advance before sun-sensitive plants are brought to the site.

Where limitations are severe the choices of species is critical. On severely limited sites few rainforest species are available to stabilise the site quickly. If the site can be made stable using strategic engineering works and cover crops the chances of survival of rainforest plants is greatly improved. These severely limited sites may need to be established with the faster-growing forest riparian species, perhaps mixed with some of the more hardy rainforest species (whose fruit may encourage birds in due course). Plantings of rainforest plants can be commenced at a later date when the situation becomes stable.

On stable protected sites species selection is relatively unlimited with choices between slow growing plants and fast growing plants possible. On sites like this greater attention can be made to creating the original riparian rainforest habitat.

8. ACKNOWLEDGEMENTS

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Assessment of River Channel Stability

Robert Millar[1] *and Michael Quick*[2]

ABSTRACT: *An optimization model is used to assess the effect of bank stability on the equilibrium hydraulic geometry of alluvial rivers. The bank-stability constraint is formulated for channels with either cohesive or noncohesive bank sediment.*

The model is tested on published data for rivers with varying types and density of bank vegetation. The results show that the bank vegetation can exert a large influence on the stability of the banks, and hence the hydraulic geometry of the channel.

The bank-stability parameters can be "calibrated" using the observed channel geometry. This permits the effect of the bank vegetation on the stability of the banks and the hydraulic geometry to be indirectly quantified.

1. INTRODUCTION

Currently throughout Australia, River Improvement Trusts and other organisations are involved in the development of riparian zone management plans. One of the common goals of these management plans is to promote stability of the river channels, and to minimise river bank erosion.

In order to better manage rivers it is essential that the influence that the bank stability exerts on the channel be recognised, and that the hydraulic and geotechnical processes which determine the stability of the banks be more fully understood. In the companion paper (Millar and Quick, 1996a) the optimisation model developed by the authors is presented. In this paper the model is used to investigate the influence of bank stability and bank vegetation on river channel geometry.

2. BANK-STABILITY CONSTRAINT

The bank-stability constraint requires that the reach averaged condition of the banks be stable. The bank-stability constraint can be formulated for banks with cohesive sediment or noncohesive sediment.

Note that stability here applies to the reach-averaged condition of the banks. Locally, such as along the outer bend of a meander, the banks may not be stable. However the reach-average condition of the banks must be one of stability, otherwise there would be a net change in the hydraulic geometry over time, and the channel could not be considered to be in equilibrium.

2.1 Erosion Processes

In channels with cohesive banks there are essentially two fundamental processes of bank erosion (Thorne, 1982; Grissinger, 1982):

- mass failure, and
- fluvial entrainment of discrete grains or aggregates.

Mass failure of a river bank occurs when the driving force due to the weight of the failed soil mass, exceeds the resisting force which is produced by the cohesion and internal friction of the soil. The critical height of a bank H_{crit} which fails along a surface passing through the toe can be expressed by the following equation:

$$H_{crit} = N_s \frac{c'}{\gamma_t} \qquad (1)$$

where γ_t = total unit weight of the soil, c' = the effective soil cohesion, and N_s = the stability number.

N_s is a function of the effective friction angle ϕ', and the bank angle θ. The value of N_s can be obtained from computed limiting stability curves. Stability curves can be determined from a geotechnical slope-stability analysis of the bank sediment using the method of slices, or similar techniques. Examples are shown in Figure 1.

Fluvial entrainment is the process whereby individual grains or aggregates on the surface of the bank are removed and entrained by the flow. The driving force is the shearing action of the fluid on the bank sediment. The resisting interparticle force for cohesive sediment is the net result of several forces of attraction and repulsion. These forces result from complex electro-chemical processes which include the clay mineralogy and content, and

[1] Manager, Environmental Studies, Water Studies Pty. Ltd., PO Box 80, Red Hill Qld 4059. **Telephone:** (07) 3369 6499 **Fax:** (07) 3368 1466

[2] University of British Columbia, Vancouver Canada.

the temperature and chemistry of the pore and eroding fluids (Grissinger, 1982).

For noncohesive sediment, fluid forces exerted on the grains, as well as the down-slope gravity component must be resisted by the frictional forces for a grain to remain stable.

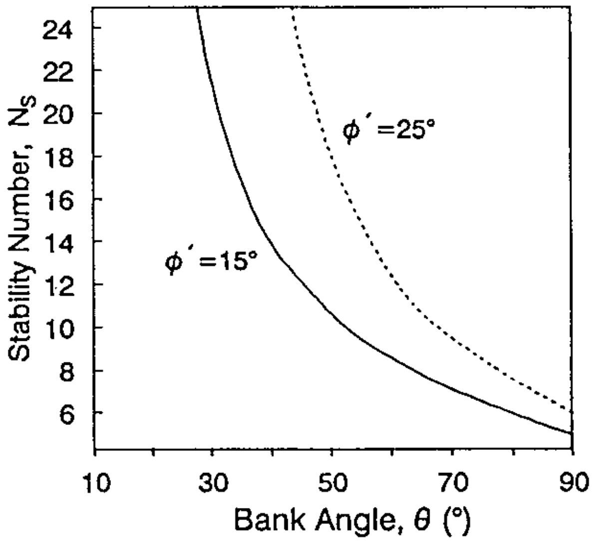

Figure 1. Limiting Stability Curves.

2.2 Mathematical Formulation

2.2.1 Cohesive Bank Sediment

For banks composed of cohesive sediment there are two separate components to the bank-stability constraint, one corresponding to the mass stability of the bank material, and the second corresponding to the stability of the bank sediment to resist fluvial entrainment. In order for a bank to be stable both constraints must be satisfied.

The bank-height constraint requires that the bank height H, be less than or equal to the critical bank height H_{crit}:

$$H \leq H_{crit} \tag{2}$$

The value for H_{crit} is calculated by Equation (1), and N_s is obtained from the limiting stability curves (see Figure 1).

The bank-shear constraint requires that the bank shear stress be less than the critical value required for fluvial entrainment of the bank sediment:

$$\tau_{bank} \leq \tau_{crit} \tag{3}$$

The value τ_{crit} is considered to be an independent variable. The mean bank shear stress, τ_{bank}, is a dependent variable that is calculated by the model.

2.2.2 Noncohesive Bank Sediment

The bank-stability constraint for noncohesive bank sediment is a modified form of the well-known USBR relation (Lane, 1955). The original form of the relation was modified allowing the effects of bank vegetation, and packing and imbrication of the bank sediment to be included.

For noncohesive sediment, the maximum bank angle that can remain stable is equal to the angle of repose, ϕ. Loose, noncohesive sediment has a maximum value of ϕ of about 40°. River banks composed of noncohesive sand and gravel with little or no cohesive material often appear much steeper than the maximum value of ϕ. The effects of packing and imbrication, binding of the sediment by root systems, and small amounts of fine cohesive material can produce noncohesive banks that remain stable when bank angles exceed 40° or so.

The *in situ* friction angle, ϕ_{is}, is introduced to account for these additional effects. ϕ_{is} can take a value up to 90°.

The modified form of the USBR equation was developed in Millar and Quick (1993):

$$\frac{\tau_{bank}}{\gamma(s-1)\,D_{50bank}} \leq k\tan\phi_{is}\sqrt{1-\frac{\sin^2\theta}{\sin^2\phi_{is}}} \tag{4}$$

where τ_{bank} = mean bank shear stress, γ = unit weight of water, s = specific gravity of the sediment, $D_{50_{bank}}$ = median bank grain diameter which is assumed to be representative of the bank sediment, k = empirical constant, and θ = bank angle.

3. BANK-FULL DISCHARGE

The bankfull discharge, Q_{bf}, is defined as the flow that just fills the channel to the tops of the banks. Q_{bf} is significant in terms of bank stability.

The value of τ_{bank} generally increases with increasing discharge up to Q_{bf}. Therefore, if the banks are stable with respect to fluvial erosion at Q_{bf}, then they will be stable for all lower discharges.

When the discharge exceeds Q_{bf} and overbank flow occurs, the additional flow is usually spread across a wide floodplain. Therefore, despite the larger discharge, the depth of flow in the main channel, and therefore τ_{bank}, may not be significantly greater that their respective values at Q_{bf}.

Furthermore research has shown that in cases where the depth of the overbank flow is significant, complex momentum transfer effects between the main channel and the slower floodplain flow result. When this occurs the velocity of the main channel flow, sediment transport rates, and the value of τ_{bank} can actually decrease for discharges that exceed Q_{bf} (eg Sellin, 1964; Barishnikov, 1967).

Therefore for modelling purposes the bank stability (with respect to fluvial erosion) is only assessed at Q_{bf}. If the banks are found to be stable at Q_{bf}, then they are assumed to be stable for all other discharges.

Q_{bf} is also relevant for bank stability with respect to mass failure. Q_{bf} defines the 'size' of the channel. The bank height H, is by definition equal to the flow depth at Q_{bf}.

4. RESULTS

Results obtained using the optimisation model for channels with both cohesive and noncohesive banks will now be presented. These results have been published previously in Millar and Quick (1993, 1994), and are discussed fully in Millar (1994).

4.1 Noncohesive Banks

The model was tested on the published gravel river data collected by Andrews (1984) and Hey and Thorne (1986). The published data was used as input to the model, and the output geometry compared to the observed geometry.

The banks are characterised in terms of their vegetation density. Andrews (1983) subdivided his data set into those channels with thin and thick vegetation. Similarly, Hey and Thorne (1986) subdivided their data into four bank Vegetation Types ranging from Vegetation Type I (grass with no trees or bushes) to Vegetation Type IV (> 50% trees and bushes).

Figure 2 shows the agreement between the modelled and observed dimensions for the rivers described as having the lowest densities of bank vegetation. The value of ϕ_{is} was not available, and therefore $\phi_{is} = 40°$ was assumed. The constant k in Equation (4) was adjusted to provide the best agreement between modelled and observed.

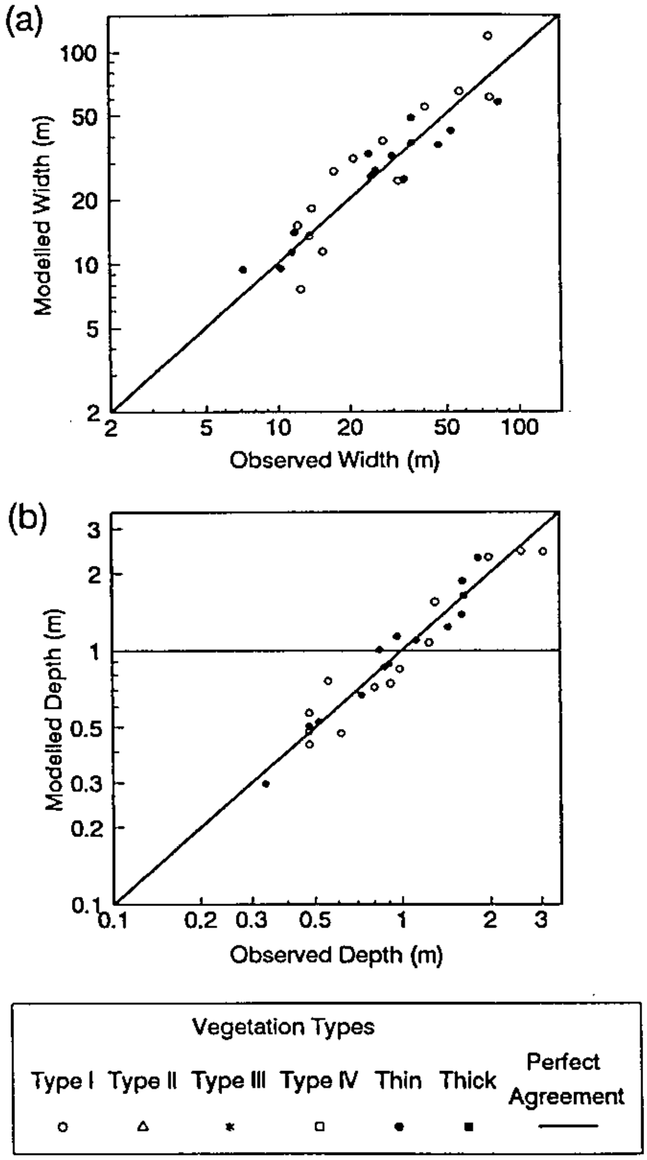

Figure 2. Analysis of channels with noncohesive bank sediment and low densities of bank vegetation. (a) Channel Width. (b) Channel Depth.

The model was then run using the full data set. The results are shown in Figure 3. A large degree of scatter is evident. Note that the scatter is asymmetric about the line of perfect agreement. The modelled channels are wider and shallower than their observed counterparts. A more detailed analysis revealed that the discrepancy between modelled and observed increased systematically with the reported bank vegetation density (Millar and Quick, 1993).

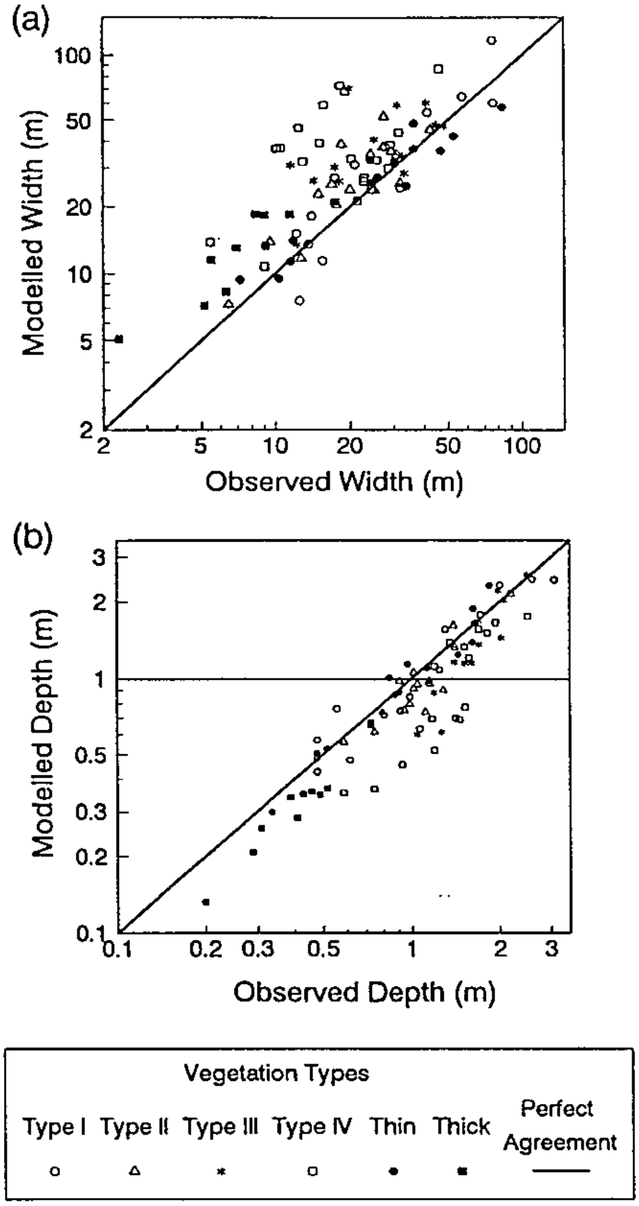

Figure 3. Analysis of channels with noncohesive bank sediment and various densities of bank vegetation. (a) Channel Width. (b) Channel Depth.

It was surmised that the bank vegetation was influencing the value of ϕ_{is}. The assumption of ϕ_{is} = 40° was valid only for the channels with the lowest densities of bank vegetation. Therefore the modelled channel dimensions in Figure 3 should correspond to the unvegetated condition. The actual channels had a range of densities of bank vegetation, and the effect of this the bank vegetation was to increase the stability of the channel banks. This resulted in observed dimensions that were narrower and deeper than the modelled, "unvegetated" channels.

This analysis indicated that the widths and depths of the most heavily vegetated channels were in the order of 0.6 and 1.4 times their respective unvegetated dimension.

The modelled channels could be brought into agreement with their observed counterparts by adjusting the value of ϕ_{is}. The "calibrated" values of ϕ_{is} were shown to increase systematically with the density of the bank vegetation from a mean of 42° for the lowest densities, to 60° for channels with the densest bank vegetation (Millar and Quick, 1993).

4. 2 Cohesive Banks

The 14 rivers from the Charlton *et al.*(1978) data set are used to test the formulation for cohesive banks. The data included sufficient information to permit a good estimate of the bank-height constraint parameters (c', ϕ', γ_t).

The values for τ_{crit} were not given by Charlton *et al.* (1978), and it is not possible to directly estimate the values for τ_{crit}. The model was initially run using a value of τ_{crit} = 1000 N/m^2. This value is unrealistically high and forces the bank-shear constraint to be degenerate.

The term *degenerate* in optimisation terminology means that the constraint is not actively affecting the solution. For example if τ_{bank} is equal to say 15 N/m^2 for the optimal solution, and τ_{crit} = 25 N/m^2, then the bank-shear constraint would be degenerate because $\tau_{bank} < \tau_{crit}$ (or $\tau_{bank} / \tau_{crit} < 1.0$). Similarly if $H < H_{crit}$ (or $H / H_{crit} < 1.0$) then the bank-height constraint would be degenerate.

If either of the constraints were active, then the value of the ratio $\tau_{bank} / \tau_{crit}$ or H / H_{crit} would be equal to 1.0 for the active constraint.

At least one of the bank-stability constraints must be active in natural rivers. For an alluvial river to adjust its boundary bank erosion must occur. Therefore changes to the reach-average geometry can only occur when the bank-stability constraint is not satisfied. As soon as it is satisfied, that is when the values of the ratios of H / H_{crit} and $\tau_{bank} / \tau_{crit}$ are both less than or equal to 1.0, net bank erosion will cease.

A comparison between the modelled and observed channel dimensions is shown in Figure 4. The channels are subdivided into bank-height and bank-shear constrained on the basis of the active constraint.

The modelled dimensions of the two channels denoted as bank-height constrained agree closely with the observed geometry. For these two channels the values of H / H_{crit} are both equal to 1.0, and the values of the ratio $\tau_{bank} / \tau_{crit}$ are both less than 1.0.

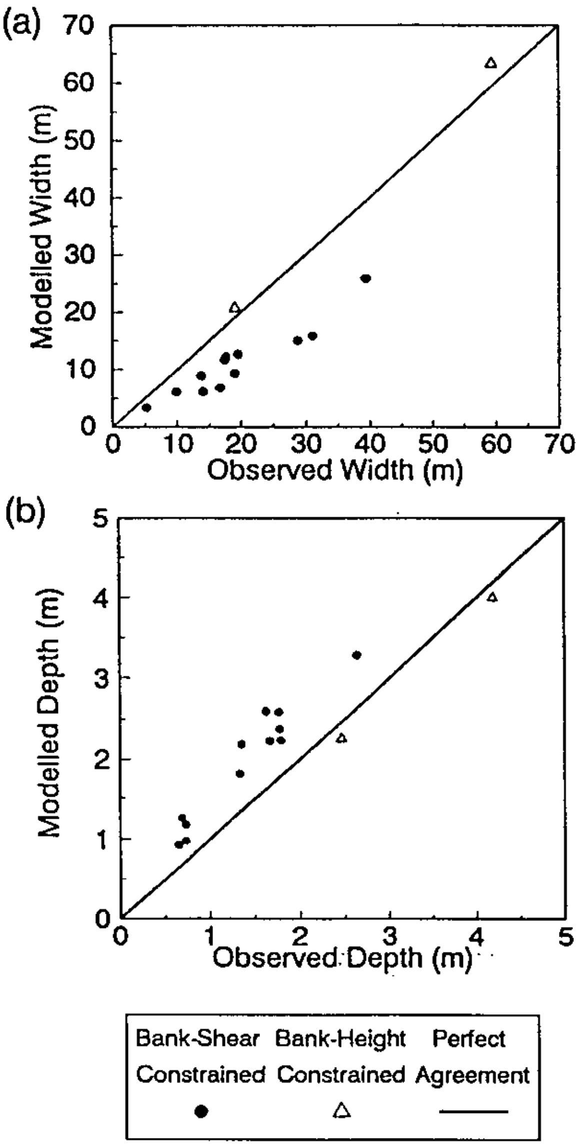

Figure 4. Analysis of channels with cohesive bank sediment. (a) Channel Width. (b) Channel Depth.

The remaining channels, which are denoted as bank-shear constrained, are narrower and deeper than their observed counterparts. For these channels the values of H / H_{crit} and $\tau_{bank} / \tau_{crit}$ are all less than 1.0 when the value $\tau_{crit} = 1000\text{N/m}^2$ is used.

The bank-shear constrained channels can be brought into agreement with their observed geometry by reducing the value of τ_{crit}. As τ_{crit} is reduced the modelled channels become wider and shallower. This reflects the reduction in the stability of the channel banks.

The value of τ_{crit} for each channel was reduced until there was agreement between the modelled and observed channel widths. At agreement, the values of $\tau_{bank} / \tau_{crit}$ are all equal to 1.0, indicating that the channels are bank-shear constrained. The values of H / H_{crit} are all less than 1.0, indicating that the bank-height constraint is degenerate.

The "calibrated" value of τ_{crit} that results in agreement between the modelled and observed geometry provides an indirect estimate of the actual value. This is similar to the method used to estimate ϕ_{is} for noncohesive channels discussed in Section 4.1.

4.2.1 Effect of Bank Vegetation.
Charlton *et al.* (1978) categorised their data set on the basis of bank vegetation into channels with grassed or treed banks. The values of τ_{crit} obtained from the previous analysis show a strong influence from the bank vegetation. The mean and standard deviation of τ_{crit} for channels described as having grassed banks (n=6) are 10.4 and 2.3 N/m^2 respectively, compared to 29.8 and 12.7 N/m^2 for the treed banks (n=6). The calibrated values of τ_{crit} for channels with grassed banks are significantly lower compared to the channels with treed banks.

This result suggests that the effect of the bank vegetation is to increase the value of τ_{crit} either by binding the sediment by the root masses, or conversely by affording protection of the bank and effectively reducing the value of τ_{bank} acting on the bank sediment.

Furthermore the bank vegetation may bind the bank sediment so as to increase the stability of the banks with respect to mass failure. In this way the roots act as internal reinforcement, and have the effect of increasing the effective values of c' and ϕ' above the values obtained from the analysis of small samples of the bank material.

5. CONCLUSIONS

The optimisation model presented in the companion paper (Millar and Quick, 1996a) has been used to assess the effect of bank stability on the equilibrium geometry of alluvial rivers. Despite deficiencies in the data sets available to test the model, it was demonstrated that the bank vegetation can exert a large influence on the stability of the banks, and hence the geometry of the channel.

The bank-stability constraints presented in this paper are simple models of relatively complex processes. The bank stability parameters, such as ϕ_{is} and τ_{crit}, represent lumped parameters that incorporate several effects.

The calibration procedure described in this paper for estimating the values of ϕ_{is} for noncohesive banks, and τ_{crit} for cohesive banks represents an indirect method for quantifying the effect of the bank vegetation on the stability of the banks, and the channel geometry.

For channels with cohesive banks it has been demonstrated that, based upon the active bank-stability constraint, two distinct channel types are identified. It is essential that in an assessment of bank and channel stability, that the active constraint be identified. Failure to do so can lead to erroneous conclusions regarding bank stability, and the influence of the bank vegetation.

The model is seen as an important adjunct to field-based investigations investigating the influence of bank vegetation on the stability of alluvial creeks and rivers. It can provide a theoretical framework for the design of field programs, and is a tool that permits the effect of bank stability to be isolated and assessed independently of other variables such as discharge and sediment load.

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A Model For Funding Watercourse Fencing On Farms

*Basil Schur**

Abstract: *There is an Australia-wide need for innovative schemes for funding watercourse fencing on farms. The paper outlines a model for catchment based watercourse fencing programs involving local government, community landcare groups, land holders and other agencies. The model is based on the Wilson Inlet catchment rehabilitation program on the south coast of WA. Between 1989 and 1995 $52,600 of fencing subsidy grants at $400/km have been allocated to farmers. This has supported 135 km of fencing on 77 watercourse fencing projects on 45 farms. The program demonstrates a model with wide application in rural Australia.*

1. Introduction- The Challenge

Australia has major land care problems arising from the loss of remnant vegetation along watercourses. The cost of fencing is one of the biggest obstacles preventing the protection of watercourses on farms. With public funds for landcare already stretched to the maximum, it is vital that simple but innovative schemes for funding landcare fencing be developed as a matter of urgency. The paper presents a model for catchment based watercourse fencing and regeneration programs based on a cooperative venture between local government, community landcare groups and other Government agencies. The model is based on the experience of the Wilson Inlet catchment rehabilitation program since 1989.

2. The Wilson Inlet Experience

The Wilson Inlet, on the south coast of Western Australia and adjacent to the township of Denmark, is a regionally significant estuary. It is threatened by eutrophication, due mainly to excessive nutrient input from agricultural areas in the catchment. The catchment area of the Inlet covers 2363 square kilometres mainly comprising farmland and public (Crown) land. The Denmark and Hay Rivers are the two major tributaries of Wilson Inlet. (Hodgkin and Clark,1988)

Large quantities of nutrients and sediment that discharge into Wilson Inlet each year come principally from the Sleeman, Hay and Denmark Rivers, and the Cuppup Drain. These nutrients have the potential to cause algal growth which smothers the *Ruppia* seagrass meadows of the inlet. Research has highlighted the importance of streamline fringing vegetation in attenuating nutrient and sediment loss from farms into waterways (Apace Green Skills and Pen,1995).

There is an increasing concern in the local rural community that rivers and other watercourses of the catchment should be fenced. This would protect these large natural biofilters and prevent erosion of the riverbanks, which occurs when the supportive and protective fringing vegetation is lost through livestock grazing and trampling.

2.1 The Fencing Subsidy Program

In 1989, the Denmark Environment Centre, a local community group, began coordinating a watercourse fencing and regeneration program in the Denmark Catchment. From 1990, it offered subsidies of $400/km for land holders who wished to fence off watercourses. The distances fenced off have progressively increased (see Table 1 below).

The early stages of the catchment based program were set up as a pilot project so that problems could be identified and efficient administrative and liaison arrangements developed.

The program received a boost from 1992, when the Shire of Denmark began to allocate $6000 a year towards the Denmark Environment Centre's program, and again in 1995, when the then newly formed Wilson Inlet Management Authority (WIMA), a statutory body serviced by the WA Waterways Commission, commenced allocating annual amounts towards fencing off watercourses on farms.

Participating organisations implementing the Wilson Inlet program have included local landcare groups, Apace Green Skills, the Australian Conservation Foundation South Coast Branch and WIMA. Smaller amounts of funding or material support have come from Greening Australia's One Billion Tree Program, the Federal Government's Save The Bush scheme, the WA Water Authority, the Department of Conservation and Land Management and local businesses. More recently the Wilson Inlet Management Authority, a statutory body serviced by the WA Waterways Commission, has provided substantial financial resources towards watercourse fencing in the catchment. The land holders have also contributed over half the cost of fencing and labour to the program.

* APACE Green Skills and Wilson Inlet Management Authority
C/-P.O. Box 577 Denmark WA 6333
Telephone 098 481 019 Fax 098 482 061

2.2 Revegetation and Environmental Training

Since 1989 landcare groups in the Wilson Inlet catchment have coordinated a revegetation program in association with the watercourse fencing projects. In some instances, there is sufficient native vegetation left along the watercourses for regeneration to occur. In other cases tree plantings have been carried out.

Table 2 provides information on the number of trees planted along stream and river banks fenced under the Wilson Inlet Catchment fencing program.
27700 local tree and shrub species and 134000 non WA species (mainly eucalypts with potential wood production value) were planted in fenced off watercourse areas between 1989 and 1995. The Denmark Environment Centre coordinated most of these plantings working with the land holders, other community groups and State agencies (ie the Department of Conservation and Land Management) to implement them. Most of the local species of trees and shrubs were provided under Greening Western Australia's Plants For Conservation Program.

2.3 Examples of Projects

Fencing and revegetation projects have been carried out on the Denmark Agricultural College farm, within 2km of Denmark. High profile projects now established on the College farm include revegetation along the Denmark river and associated wetlands.

Other projects have been carried out on farms in the Upper Denmark catchment from whole farm plans have been designed by research officers from the Department of Agriculture. These projects are also being used for demonstration and education purposes in this section of the catchment, which has been given a high priority by the WA State Government for rehabilitation for water resource purposes.

Fencing and revegetation work has also been carried out along the lower reaches of the Sleeman river, a significant contributor of nutrients into the inlet. Some of this revegetation work is readily visible from a major highway, serving as a demonstration site.

There has been significant input into implementing many of the fencing and revegetation projects from community groups. Trainees from Apace Green Skills programs for longer term unemployed have carried out many projects while training on the job.

These have included 3 Commonwealth funded LEAP (Landcare Environment Action Program) courses for 15 unemployed youth, 1 NWO (New Work Opportunities) program for 11 unemployed adults and several other labour market programs. Thus the Wilson Inlet fencing program has tied in with other activities that assist with social and landcare development.

2.4 River Foreshore Surveys

To assist with rehabilitation of the watercourses in the catchment the Wilson Inlet Management Authority commissioned a botanical inventory of sites along the Denmark and Hay Rivers by B.G. Janicke in 1994 and a survey by Green Skills to assess the condition of the foreshores of the two rivers. The survey ran from April 1995 to June 1995. The resulting reports (Janicke, 1994; APACE Green Skills and Pen, 1995) aim to assist government agencies and community landcare groups to cooperate with land holders to assist in protecting the health of a much valued south coast estuary and its associated waterways. These surveys provided the next step in enhancing the effectiveness of the fencing subsidy program for the Wilson Inlet, as they provided the data base for more effective targeting and evaluation of watercourse fencing grants to land holders.

This work graded the condition of sections of foreshore of each river bank into three categories: (A) pristine to slightly disturbed, (B) degraded, (C) erosion prone to eroded and (D) eroding ditch or weed infested drain; on the basis of weed infestation, soil exposure and erosion. This classification system is being widely adopted in South West WA and is based on the work of Luke Pen (Pen, 1994;Pen and Scott ,1995). The extent of riverbank fencing and revegetation, river valley form, and the general quality of the fringing vegetation were also assessed.

Foreshore condition and fencing status were assessed in detail and results for specific sections and subsections are reported, along with fencing and rehabilitation needs and other information.

The 80 km of the Denmark River was surveyed, having a farm river length of 37km and 39km along the left and right banks, respectively. Of the total 76km of farm river length, about 49% was already fenced. Of the total river length about 62% of the riparian zone was A grade, about 25% B grade and 13% C grade. About 49ha of river valley embankment and foreshore requires revegetation to stabilise the embankments, maintain the ecological corridor and protect river pools.

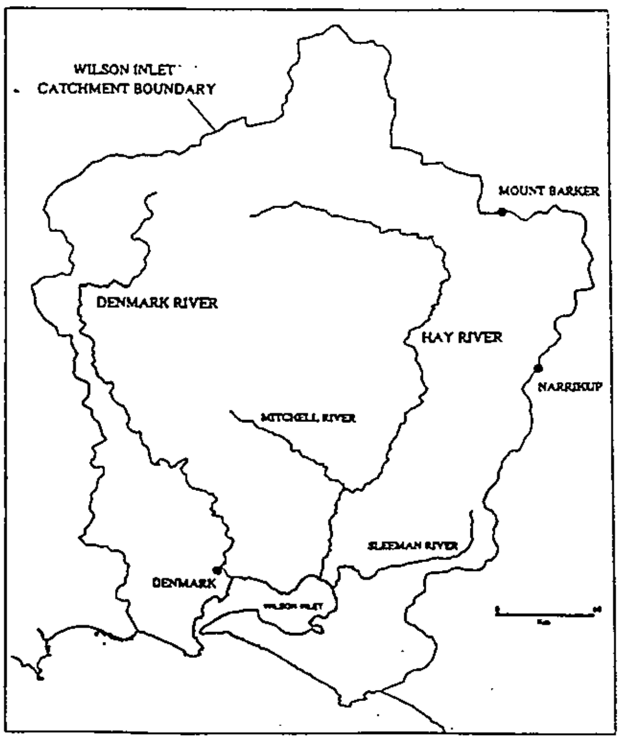
The 77 km of the Hay River was surveyed, having a farm river length of 65.6km and

Table 1. Funds Allocated Under the Wilson Inlet Catchment Fencing and Regeneration Program 1989 - 1995.

Year	Monies Allocated $	Distance Fenced km	No. of Watercourse Fencing Projects	Number of Different Farms Involved (Cumulative)
1989	900	0.8	1	1
1990	500	1.2	1	1
1991	2250	6.2	4	4
1992	13100	32.7	17	16
1993	11850	30.3	19	28
1994	10400	31.0	15	35
1995	13600	32.8	20	45
Totals	$52600	135km	77	45

Table 2. Tree and Shrub Plantings along watercourses carried out within the Wilson Inlet Catchment Fencing and Regeneration Program 1989 - 1995.

Year	Local Native Tree and Shrub Species planted	Non-WA species (mainly Eucalypt) plantings (No.)	Total number of plants
1989	3000	35000	38000
1990	600	3000	3600
1991	2600	5000	7600
1992	3200	31000	34200
1993	7700	15000	22700
1994	5100	45000	50100
1995	5500	-	5500
Totals	27700	134000	161700



Map 1 - The Wilson Inlet Catchment and the Denmark and Hay River systems.

72.8km along the left and right banks, respectively. Of the total 138 km of farm river length, about 39% was already fenced. Of the total river length, about 42% of the riparian zone was A grade, 22% B grade, about 36% C grade and a small section (0.5%) was D grade. About 173ha of river valley embankment and foreshore requires revegetation.

The findings and recommendations of the survey were designed to provide advice and encouragement to land holders and managers to carry out measures which protect and restore river foreshore condition. The survey reports are being actively used to allocate fencing subsidies for the 1995/1996 financial year, and to plan revegetation work along the two rivers for the 1996 planting season.

Following on from the surveys of the two rivers, the Shire of Denmark's Revegetation Nursery is propagating 20,000 local endemic trees and shrubs for stream and river bank revegetation in the 1996 planting season, with the prospect of greatly increased production of plants for subsequent years.

3. The Model

Based on the Wilson Inlet experience, it is possible to recommend a model for how water course fencing can be implemented in other catchments around Australia.

The model involves Local Government Agencies (LGAs) allocating annual funds towards catchment based watercourse fencing programs. Under the model these funds are matched where possible from Federal and State Government Agencies. The funds are distributed by a local landcare organisation which advertises the availability of the watercourse fencing grants at a rate of around $400 per km for projects judged to be of high priority in terms of catchment rehabilitation. (The figure of $400/km represents about half the material cost of conventional fencing. Providing any less may represent insufficient subsidy for most landholders.) Land holders participating in the scheme are required to construct the fence within six months of receiving the grant. The primary aim of the fencing is to keep grazing stock our of the riverine bush so permitting it to regenerate.

3.1 Administration of the Program

Forms outlining the program are mailed to each land holder in the catchment. These forms invite participation and seek basic information on the length and location of proposed fencing. The form is returned by post. The landcare group then prioritise the fencing projects according to criteria that are developed to meet local requirements. This process normally involves site visits and inspection of catchment resource maps. In the case of the Wilson Inlet catchment, the WA Department of Agriculture has produced catchment maps showing areas prone to salinisation and nutrient loss. Criteria used to prioritise project sites include the quality and area of riverine forest to be protected, eutrophication and or salinisation risk of that sub-catchment, the rate of vegetation decline in that locality, and the suitability of the site for demonstration/promotional purposes.

3.2 Benefits

Some of the environmental benefits of watercourse fencing include:

- reduction of erosion and siltation
- provision of wildlife corridors
- provision of a bio-filter reducing nutrient run-off (Howard-Williams and Downes, 1984.)
- protection of riverine bio-diversity (Hussey and Wallace, 1993)
- rehabilitation of saline valley areas

Community Benefits include;

- Shelter belts for adjacent farmland
- protection of scenic landscapes along waterways
- rehabilitation of polluted estuaries (see Prout and Weaver,1992 or Weaver,Pen and Reed, 1994)
- water quality improvement

3.3 Sources of Additional Support

The model can work with Local Government Agency support alone. However financial contributions from State and Federal agencies, as well as corporate sponsors can make limited fencing funds go much further. State and Federal Governments could make a major contribution to implementing the proposed model on a regional or national scale by offering to provide matching funds to any local shire that commits fencing funds as outlined in this program. This would have a major effect in expanding watercourse fencing and regeneration programs in Australia.

3.4 Performance Indicators

The model allows community groups and shires to set clear goals and to precisely monitor progress towards these goals over a set time period. Precise performance indicators can be specified and monitored. The capacity to set quantifiable goals can provide a motivating incentive to all concerned, because they know the scale of the problem, and how to realistically address it.

Progress of individual catchment based shire programs can be judged from obtaining such quantifiable data as:

- Number of participating landcare groups

- Number of participating land holders
- Length of watercourses protected
- Area of remnant vegetation protected
- Distance of watercourse fencing completed each year
- Number of trees planted in fenced off area
- Water quality sampling

3.5 Monitoring and Evaluation

Monitoring of fenced off riverbanks can be carried out by the participating land holders and landcare groups. This should be done to assess regeneration success, for improving the targeting and administration of the program. Photographic documentation of monitoring sites provides useful information. Individual farms can be revisited to assess the ongoing status of areas. Priorities for allocation of fencing grants can be reviewed and refined.

3.6 Community Education

Community education activities can be closely integrated with each step of the program. Educational information can be included in promotional material advertising the availability of grants. Field-days can be held and media releases and articles can promote the scheme. Signs can be put up on road reserves adjacent to prominent sites providing information and inviting participation from other land holders.

4. Conclusion

This paper presents a proposal for a simple, but effective mechanism for funding watercourse fencing for important river catchments. It involves cooperative funding arrangements between LGAs, landcare groups and custodians and any number of contributing agencies. The scheme requires a low level of administration and can be readily modified to suit local needs.

The model does not place onerous administrative burdens on land holders yet ensures public funds are spent directly on projects of lasting community benefit. The program lends itself well to evaluation and associated community education programs. The program has additional advantages in that watercourse fencing on farms has multiple environmental and social benefits, representing a cost-effective way for achieving multi-objective landcare goals.

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6. About the Author

Basil Schur was born and raised on a cattle ranch in Zimbabwe, Africa and has lived in Australia since 1981.He holds degrees in biological science and education and in 1992 completed a Master of Arts from Murdoch University, focussing on landcare policy in Western Australia. He is Assistant Coordinator of Apace Green Skills, a non-profit environmental training provider, based in Denmark on WA's south coast. He is also a community representative on the Wilson Inlet Management Authority. Basil has coordinated catchment landcare work for the past 7 years.

WATERCOURSE REVEGETATION - JUST A WALK IN THE PARK!

Jim Burston[1] *and Wayne Brown*[2]

ABSTRACT:
The art of revegetation is generally poorly understood by river managers. All too often, revegetation is done using the outdated, expensive, labour intensive technique of tubestock planting. If we are to revegetate the vast lengths of watercourse across Australia, then a new approach is needed. The answer is direct seeding. The technique was first used more than 100 years ago. It is now the primary method of broad-acre revegetation in South Australia. Its application to watercourses is limited only by the conservative approach of river managers.

1.0 INTRODUCTION

Ask river engineers or river managers about grade control and other erosion control structures, and they are more than likely to tell you that the main function of such structures is to provide an opportunity for vegetation to re-establish (Ian Drummond and Associates 1993). It is generally accepted among most river managers that vegetation is the best long term approach for erosion control. For smaller watercourses, erosion problems can be addressed directly through revegetation and natural regeneration, without the use of any structural works. In South Australia, this refers to watercourses of magnitude 5th order or lower (as defined by the Strahler method, from 1:50,000 map sheets, see Good & Burston, this volume).

Unfortunately, the method by which most people revegetate watercourses is decidedly primitive. Since the mid 1980s there have been great advances made in broad-acre revegetation. They appear to have passed by most of our river managers, who are well versed in the geomorphological and engineering aspects of the business, yet in a time warp when it comes to revegetation. We all hear talk of the great benefits of riparian revegetation, but in south-eastern Australia, little appears to be happening "on the ground". This is surprising, given how easy it is to revegetate watercourses.

It is disappointing to find that the use of willows (*Salix* spp) is still being promoted, both in Australia (Ian Drummond and Associates 1993, p. 57-58) and in New Zealand (Collier *et al.* 1995). This is despite the fact that the willows have created major management problems for some river managers in south-eastern Australia. Some authors have made the suggestion that once willows have stabilised the site, the landholder can then remove them (eg. Standing Committee on Rivers and Waterways VIC., 1991). Such a suggestion demonstrates a failure to understand the character of landholders. Furthermore, we believe that it reflects a lack of knowledge of the growth potential of native plants and the efficacy of direct seeding and natural regeneration.

Where revegetation is occurring, it is usually done using an outdated technique - tubestock (Ian Drummond and Associates 1993). This expensive, labour intensive form of revegetation is arguably one of the major factors constraining the rate of watercourse revegetation. Ian Drummond and Associates (1993, p58) quote a figure of $11,200 per km of watercourse (figure includes materials, labour and planting - for both banks). This has surely to be a printing error!! Any funding application to the National Landcare Program, quoting such a figure for revegetation, would be rejected in an instant. If we are to seriously address the issue of revegetating our watercourses, then there will have to be a quantum leap in the rate and extent of revegetation. The solution (developed more than 100 years ago - R. Jamieson pers comm) has been used for broad-acre revegetation for nearly a decade. The solution is direct seeding.

2.0 DIRECT SEEDING IN SOUTH AUSTRALIA

South Australia undoubtedly leads the nation in broad-acre revegetation of agricultural lands. This is due, in part, to the extension programs run by the Department of Environment and Natural Resources (then Department of Environment and Planning - see Prescott and Bishop 1990), Primary Industries (SA) (the then Department of Agriculture), Trees for Life and Greening Australia (SA Inc.). As a result there has been a major shift in the attitudes of landholders toward broad-acre revegetation.

[1] Mount Lofty Ranges Catchment Program,
Department of Environment and Natural Resources (Water Resources Group),
2/85 Mt. Barker Rd, STIRLING S.A. 5152 Phone: (08) 339 7111 Fax: (08) 339 7112
[2] Mount Lofty Ranges Catchment Program
Primary Industries (SA)
5c Cameron Road, Mt Barker SA 5152 Phone: (08) 391 7500 Fax: (08) 391 7524

Revegetation is now taken for granted as a major component within Primary Industries (SA) Property Management Planning programs. The success of direct seeding in South Australia is due to the fact that it is farmer-driven. The basic direct seeding machinery has changed little since the mid 1980s, but it was not until 1989 that Primary Industries (SA) and Greening Australia (SA Inc.) adopted an extension programme to take direct seeding to landholders. In 1995, more than 200 linear kilometres of direct seeding (equivalent to 50 km of watercourse - both banks) was undertaken in the Mount Lofty Ranges alone.

A comparison with revegetation activities in other states is intriguing. It is ironic that community groups in NSW and Qld can apply for tree planting grants under the One Billion Trees program, yet at the same time, large tracts of native scrub are still being cleared. In South Australia, broad-acre clearance of native vegetation has been effectively prohibited since 1985 with the introduction of the Native Vegetation Management Act Because broad-acre clearing is still permitted in these states, landholders (and peak farming bodies) in these states have not seriously entertained the notion of broad-acre revegetation and therefore direct seeding. Watercourse revegetation will not take off until there is a fundamental shift in the attitudes of both landholders and government agencies.

3.0 DIRECT SEEDING: THE BASIC STEPS.

The factors for success in direct seeding are:

- site preparation,
- time of sowing,
- seed viability / species selection, and
- maintenance of the site.

The broad principles of direct seeding have been the topic of a number of books (Dalton 1993, Venning 1988), a national conference (Greening Australia Ltd 1990) and other extension material

3.1 Site Preparation

Undoubtedly the most important factor in a successful revegetation program is weed control (both herbaceous and woody). The vast majority of revegetation projects fail due to poor weed control. Good weed control starts with understanding the weed spectrum at your revegetation site. Depending upon the weed spectrum (eg. couch, kikuyu, phalaris, cocksfoot, gorse, blackberry) weed control may need to be initiated up to 24 months prior to sowing. This is particularly important if the weed spectrum includes aggressive summer growing plants. Good weed control means a complete kill of all weeds. Weed control ensures adequate soil moisture for plants to grow through the summer months. The experience from hundreds of revegetation sites across South Australia is that unless weed control is excellent, direct seeding will fail. In fact, if you don't control your weeds, don't bother with direct seeding.

Control of most herbaceous weeds is generally achieved through the application of a knockdown herbicide (eg. glyphosate 360g/L, @ 1-2 L per Ha). For best results, two applications should be used: the first application at one - two months prior to sowing, followed by a second application one week prior to sowing. Some broadleaf weeds (eg. strawberry clover, prickly lettuce, wire-weed), can be controlled with herbicides such as MCPA®, DiCamba®, Ally®. Extreme care should be taken to ensure that no herbicide enters the water body.

Some practitioners (R. Bird, pers comm) have encouraged the use of residual herbicides to achieve satisfactory weed control. However, unless the soils to which these herbicides are applied have a high clay content, there is a risk of herbicide leaching into the zone where the seeds have been laid.

For best growth, it is desirable to remove weed competition for a distance of 1.5m from the seedlings. This will ensure the seedlings have access to sufficient soil moisture and nutrients. Good weed control will render fertiliser application unnecessary.

Weed control with herbicides generally takes the form of blanket, strip or spot spraying. When revegetating watercourses, it is desirable to allow weeds to grow to a height of approximately 150 mm prior to spraying. As the weeds die, they will form a mulch and protect the soil from erosion (but not necessarily flood events). Sowing in Spring will also lessen the chance of the site being damaged by a major flood event (ie risk management). On steeper slopes, or where access may be difficult, strip or spot spraying are appropriate.

There are two other methods of weed control - grading and cultivation. Both techniques have serious pitfalls - they physically remove the seed bank that is stored in the top few centimetres of the soil profile, exposing the site to erosion in heavy rainfall events, and may change the weed spectrum. Many hard-coated seeds can survive in the soil for many years (eg seeds of *Acacia* spp - up to 120 years). Any potential for natural regeneration from the seed bank to compliment the direct seeding is lost if site preparation involves grading or cultivation.

3.2 Seed Treatment / Seed Viability / Seeding Rates

Many individuals tend to be obsessed with seeding rates and have devised all sorts of formulae to determine the "correct" seeding rate. It is the view that much of this concern is unwarranted. The most important factor is to ensure that there is an adequate floristic (ie wattles, banksias, bottle-brushes, gum trees, tea-trees, etc) and structural diversity (ie. trees, shrubs, grasses) within the seed mix. The approach to revegetation in South Australia has been to encourage and develop the seed collecting skills of landholders. Germination tests are unnecessary if emphasis is placed on collecting fertile seed - which is an easy task. You don't need a Ph.D to collect native seed.

Most hard-coated seeds (eg. *Acacia* spp) will require some form of treatment (ie. scarification) prior to sowing. The easiest method is to place the seeds in very hot water for a short length of time, for further details see Bonney (no date). This can be done a few days prior to sowing.

3.2 Sow At The Right Time

Sowing should be timed to coincide with optimal soil moisture and soil temperature. In southern Australia, where sites receive rainfall of >450 mm pa., the optimal time is Spring (ie. August - October, depending upon average annual rainfall). In fact, direct seeding is arguably more successful in years of slightly below average annual rainfall - due to less opportunity for weed growth.

3.3 Methods of Direct Seeding

The depth to which seeds are sown will have a major bearing on the success of direct seeding. It is important that seed has good contact with the soil. Ideal burial depth can vary according to the amount of light required by the seed. A general rule of thumb is to sow seed at a depth that is twice its diameter (Dalton 1993).

Most direct seeding is done using machines that resemble up-market "1080" rabbit bait layers. But this is central to the widespread adoption of direct seeding in South Australia - a simple, "farmer friendly" technology.

All direct seeding machinery currently used in South Australia perform the following tasks:

- removal of soil and trash (ie generally the top 1-2 cm of the soil profile),
- preparation of a level seedbed for sowing with standard (or modified) agricultural seedling implements,
- ensuring that germination takes place in mineral soil,
- pressing the seed into the soil in order to minimise predation by ants (Dalton 1993).

Where access is limited, machines can be attached to 4WD motorbikes. Where access can only be achieved on foot, hand direct seeding is the answer. The procedures for hand direct seeding are outlined in Figure 1 below.

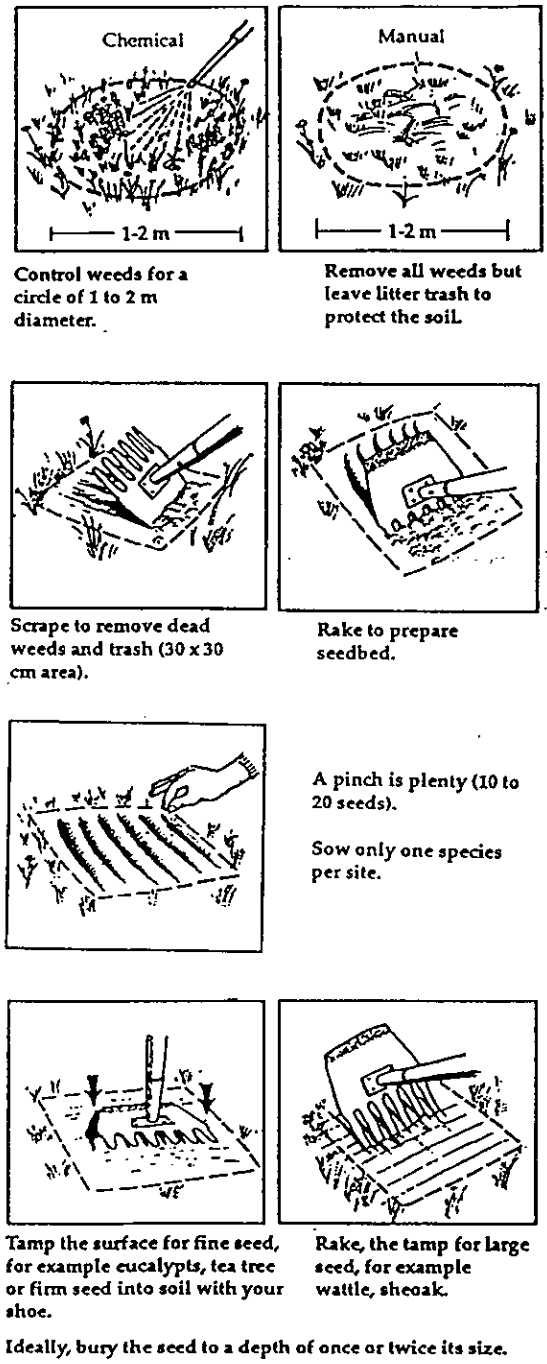

Figure 1. Hand direct seeding of native plants (source: Primary Industries (SA) Fact Sheet 7/95)

In the agricultural regions of South Australia, there are only two soil types which present problems for direct seeding:

- alkaline black cracking clays (these sites were originally native grasslands), and
- deep non-wetting sands in low rainfall areas (ie. less than 350 mm pa.).

In the last two years, the success rate of direct seeding onto non-wetting sands has been dramatically improved with the use of wetting agents at the time of sowing, seed treatment prior to sowing and advances in seeding machinery. Successful germination on cracking clay has been achieved, but most seedlings die as the soil cracks upon drying.

3.4 Use Of Local Species

For the last decade there has been a concerted effort in the field of revegetation toward the planting of indigenous species. The reasons are many, including:

- maintaining landscape character,
- conserving biodiversity,
- avoiding genetic pollution of remnant vegetation, and
- longevity of local species.

South Australia is littered with sites that have been planted with "exotic" native species (ie Australian species that are not indigenous to that area). Unsurprisingly, most of these sites have failed in the longer term (ie 15-20 years) and now require a second revegetation effort. Species selection can vary within a few hundred metres, owing to a change in aspect, soil type, geology or any number of other factors. Thus, species lists have to be very site specific.

In South Australia, several landholders (including one of the authors) have planted river oak (*Casuarina cunninghamiana*) along their watercourses. We do not recommend this species because it appears to have a habit similar to willows - roots protruding into the channel, thereby reducing its capacity. This is of particular concern on the smaller watercourses (ie. < 4^{th} order).

3.5 Maintenance

Young seedlings are vulnerable to defoliation from insects such as red-legged-earth-mite and lucerne flea. In some circumstances, it may be necessary to add an insecticide (eg. Le Mat ®) to the herbicide solution. It is essential that extreme caution be used in the use of insecticides near watercourses, regardless of the concentration.

It is highly desirable to provide young plants the opportunity to grow through a second summer in a weed-free environment. This can be achieved by spraying the site with a knockdown herbicide, at a reduced rate (ie. glyphosate 360g/L @ 0.5 L per Ha), during late winter (ie. late July - early August). This approach may cause minor tip burning to some species, but it is quite safe. At this time, the young native plants are relatively dormant as compared to introduced grasses and broadleaf weeds. Most native plants will be physically shielded from the herbicide by the growth of herbaceous weeds.

Some individuals are concerned that direct seeding can create a situation of "too many seedlings", and express a desire to "thin-out" the site. Over time, Nature will ensure self-thinning, leaving only the strongest individuals.

4.0 WHAT ARE THE ADVANTAGES OF DIRECT SEEDING?

- Plant density: an average germination, using a seed mix of 1 kg per Ha, will deliver approximately 4,000 - 6,000 seedlings per Ha (Dalton 1994, M Campbell pers comm). Compare this to tubestock, using a 3m x 3m spacing, which produces less than 1,000 seedlings per Ha.
- Cost: Site preparation and fencing costs are the same for either technique. However, direct seeding will require approximately 1 kg of seed mix (approximate price of $170 per kg), whereas tube stock at 50c per seedling (@ 1,000 per Ha) will cost $500.
- Species diversity: Most sites in South Australia are sowing, on average 20-25 species and at some sites the range is 35-45. Such plant species diversity is just not feasible using tubestock plantings.
- Randomness: most tubestock planting tends to be done on a rigid adherence to a 3m x 3m format. This leads to the appearance of a geometric pattern, like a pine (*Pinus* spp) plantation, at odds with the ebb and flow of the natural landscape. Direct seeding allows a more random pattern.
- Growth rates: Many first-time direct seeders are disappointed with the early results as compared to tubestock planting. Although direct seeded seedlings "appear" to grow slower, experience in South Australia indicates that by Year 2, the height of these seedlings surpasses that of tubestock. In the ensuing years the difference in performance widens. Refer to Plates 1 & 2.
- Time: for the average site, one hectare (= 3 linear km of sowing) of direct seeding will take

approximately 20 minutes. How long would it take you to plant 1000 trees?

5.0 CONCLUSION

River engineers build erosion control structures mindful of the fact that vegetation is a vital tool in attaining a stable watercourse. However, the revegetation component is the weak link in the chain. Most revegetation is undertaken using an out-dated technology - tubestock planting. There has been nearly a decade of using direct seeding for broad-acre revegetation. The technique is dependant upon good weed control, sowing at the right time and using viable seed. Most importantly, the method is cheap and farmer friendly.

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Plate 1: Revegetation of 3rd order watercourse, September 1990.


Plate 2: The same site as in Plate 1, five years later, October 1995.

Environmental Impacts of Tidal Dredging on the Brisbane River, Queensland

*Wayne D. Erskine**

ABSTRACT: *Over 173.2 million m³ of material has been dredged from the Brisbane River estuary since the 1860s for navigational purposes, construction materials and flood mitigation. The detrimental environmental impacts of such large scale dredging have included substantial increases in water depths throughout the estuary; loss of pool-riffle sequences; channel widening; bank erosion; increased turbidity; changed tidal hydraulics, particularly an increase in tidal range, peak tidal discharge and peak tidal velocity; and increased tidal salinities. These physical impacts have also produced a number of largely unquantified biological impacts. It is recommended that a range of best management practices need to be implemented to improve management of tidal dredging.*

1. INTRODUCTION

Large scale tidal dredging has been carried out in the Brisbane River estuary for the construction and maintenance of navigation channels and ship berths, for the supply of sand and gravel to the building industry and for flood mitigation purposes over the last 130 years. While dredging has generated much controversy (see chapters in Davie *et al.*, 1990), no major review of the environmental impacts of dredging activities has been completed to date (Erskine, 1990; O'Faircheallaigh, 1995). The purpose of this paper is to briefly outline the history of tidal dredging in the Brisbane River, to review the major environmental impacts of such activities and to propose additional best management practices for the reduction of the identified environmental impacts.

2. STUDY AREA

The Brisbane River is a large drainage basin (13560 km²) in south east Queensland with a major sea port and state capital city located on its estuary. For the purpose of this paper, the tidal section of the Brisbane River will be taken as the 84 km length between Mt Crosby Weir and the mouth at Fisherman Island (Figure 1). The major tributaries of the Brisbane River estuary are the Bremer River (1866 km²), Oxley Creek (260 km²) and Bulimba Creek (110 km²). Mean annual rainfall over the entire basin is about 942 mm, of which 11% is converted to runoff, allowing for the effects of water abstractions (Davie *et al.*, 1990). The Brisbane River is significantly regulated by a series of dams and weirs above the estuary.

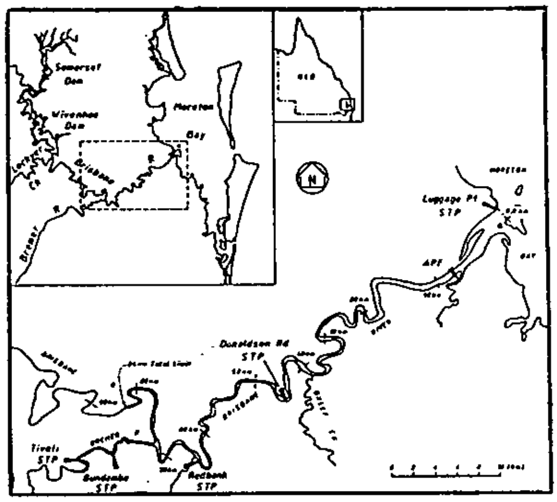

Figure 1 The Brisbane River estuary

3. TIDAL DREDGING

Dobson (in Davie *et al.*, 1990) reported that 140 million m³ of material were dredged from the Brisbane River estuary over the last 130 years for navigation purposes alone. Furthermore, another 33.2 million m³ were extracted between 1900 and 1990/91 for construction materials. No volumes are available for material dredged for flood migration purposes. Current dredging rates are about 1.2 million m³/a for navigation purposes and 650,000 m ³/a for construction materials (Davie *et al.*, 1990; O'Flynn, 1992). There are presently 9 dredging permits held by 5 companies for the removal of sand and gravel for construction materials from the estuary. Of the 9 permit holders, 8 are members of the Brisbane Sand and Gravel Producers' Association and two companies, Pioneer Concrete and Boral Resources, dominate production. Extraction is largely self-regulated by the Brisbane Sand and Gravel Producers' Association although the Department of Environment and Heritage has regulatory control. Extraction is restricted to the estuarine reach between Norris Point (New Farm) and Venus Pool (Karana Downs) and is controlled by permits which specify conditions, such as hours of operation, dredge areas, buffer zones, subaqueous batters, dredge depths, etc. The extraction reach is

* School of Geography, University of New South Wales, Sydney, NSW 2052
Telephone: (02) 385 4386 Fax: (02) 313 7878 Email: W.Erskine@UNSW.edu.au

divided into 190 by 333 m long dredge zones which can only be worked for a maximum of 5 hours every two days (O'Faircheallaigh, 1995). Dredging is prohibited in some areas where previous bank failures have occurred or where there are important structures.

Dredging for navigation purposes has been concentrated in the reach downstream of the CBD although many navigation hazards have also been removed by dredging from the estuary upstream of the CBD (Davie *et al.*, 1990). The Port of Brisbane Corporation conducts navigation dredging within the port area to maintain channels and berthing areas. Suction dredgers and grab dredgers have been used and the material is usually pumped ashore for reclamation purposes although bottom dumping and side casting have occurred (Dobson, 1990; Connor and Copper, 1990). Measured sedimentation rates in selected berths are rapid at between 10 and 300 mm/month and are largely caused by nearby dredging activities (Connor and Cooper, 1990). Future navigation and berth dredging rates are likely to be approximately 1 million m^3/a (Connor and Cooper, 1990). Significant dredging of the Brisbane River estuary was also conducted for the reclamation of Brisbane airport (at a cost of $80.2 million according to Crabb, 1986).

While rates of construction material extraction have declined from their maximum values in the 1970s, all types of current dredging activities are producing environmental impacts which are still interacting with those of earlier dredging activities to have a significant effect on the estuary.

4. ENVIRONMENTAL IMPACTS OF TIDAL DREDGING

There has been little detailed scientific work conducted on the environmental impacts of tidal dredging on the Brisbane River (Erskine, 1990; Anon., 1991; O'Faircheallaigh, 1995). The purpose of this section is to identify the most significant detrimental environmental impacts from a detailed literature review. As all types of dredging activities have often occurred simultaneously but on different reaches of the estuary, their impacts are cumulative and interactive. No attempt has been made to partition either the cause or effect between the various types of dredging. The most significant detrimental impacts are briefly discussed in the following subsections.

4.1 Increased Water Depths

Wallace (1987) compared river bed levels for 1860 and 1974 surveys of the lower 25 km of the estuary and found that the average increase in depth below approximate low tide level was about 6m with a maximum of 15m. Dobson (in Davie *et al.*, 1990) documented the progressive increase in water depth at the river entrance by dredging from only 1.2 m at low water datum at the Outer Bar in 1860, to 3.1 m by 1867, to 4.5 m in 1886, to 6.0 m by 1900, to 7.1 m in 1912, to 11.6 m in 1965, to 13.0 in 1990. Furthermore, the navigation channel upstream of the entrance was progressively increased to a depth of 9.1 m. Oxley, the explorer, had to haul his whaleboat over rapids in the upper estuary where navigation occurs at all tidal stages today.

Increased water depths are produced by a combination of the passive removal of essentially immobile bed material and by extraction - induced degradation actively eroding and redistributing the bed material. Extraction-induced degradation is caused by the creation of 3 sediment transport discontinuities which result in bed erosion both upstream and downstream of the dredge hole as well as deposition within the dredge hole (Erskine, 1990). Degradation and increased water deposits in estuaries result from the extraction of bed material at rates in excess of the replenishment rate. (Erskine *et al.*, 1985). The gravel in the bed of the Brisbane River estuary is most likely a fossilised Pleistocene deposit which is not being replenished today. Sand replenishment, however, is also low because bedload transport is only active during large floods (such as 1974) (Sargent, 1978), post-flood modification of the resultant bedforms is by upstream-directed flood tides (Holmes, 1980), dredge holes remain unfilled voids (Holmes, 1980; Wallace, 1987) and Wivenhoe Dam and Mt Crosby Weir on the Brisbane River and Berrys Lagoon Weir on the Bremer River act as sediment traps, substantially reducing downstream bedload transport. Therefore, dredging is currently a non-sustainable industry on the Brisbane River estuary. If ecologically sustainable development is an aim of river and catchment management, then dredging for sand and gravel should be prohibited. Furthermore, gravel is needed to produce an armour layer or surface coat. Armouring is a natural self-sustaining process of rivers and estuaries (Lagasse *et al.*, 1980; Erskine *et al.*, 1985). Continued dredging destabilises the bed by removing the armour material. Therefore, either all gravel should be screened and returned to the bed (as is the present case for Monarch Sands) or armoured deposits should be identified and all extraction prohibited from these areas.

4.2 Loss of Pool-Riffle Sequence

The macro bedforms of the Brisbane River estuary consist of rhythmically-spaced, alternating pools and riffles. These are clearly shown on the 1974 bathymetric charts with relatively deep pools on bends, and much shallower sections at cross-overs between bends, which also display megaripples (Sargent, 1978). The height difference between a pool and a riffle is up to 6m. Bed sediments in the late 1970s fined downstream within each pool-riffle sequence (Holmes, 1980).

Dredge operators prefer to extract from the upstream coarser riffle sediments which causes the downstream lengthening of pools (Holmes, 1980). This results in the loss of habitat and substrate diversity as well as a general deepening of the estuary by the preferential loss of riffles. The photic zone does not extend to the bed because of bed deepening and high turbidity, and so bed-attached macrophytes and emergents do *not* grow throughout the estuary (Moss, 1987).

4.3 Channel Widening

Four points (Gardens, Kangaroo, Kinellan and Bulimba) plus parts of Parker Island have been extracted to improve boat manoeuvring around these very tight bends (Dobson in Davie *et al.*, 1990). These excavations were carried out between 1901 and 1920, except for Kinellan Point which was excavated in 1941. Some 22 ha of land and more than 4 million tonnes were extracted.

4.4 Bank Erosion

Bank erosion is a significant issue on the Brisbane River estuary with 46.9% of riverside residents experiencing moderate to severe erosion and 69% of the same residents using some form of erosion control (Davie *et al.*, 1990). Dredging and boat-generated waves were perceived as important causes of bank erosion (Davie *et al.*, 1990).

Coffey and Partners (1975) identified 6 types of slumps in the Brisbane River estuary following the 1974 flood. They carried out stability analysis using the modified Bishop method for large scale rotational failures (3 of the 6 types) identified for "idealised bank profiles" and "assumed soil strength parameters". Factors of safety were calculated for both normal flow conditions and for rapid drawdown following a flood for 3 types of bank sediments and for various bank heights. For rapid drawdown conditions following a flood, existing bank heights already exceed the initial bank height for stability. Dredging has been responsible for increasing the initial bank heights. However, other types of bank erosion such as the entrainment of bank material by tidal and flood flows, bank failure by topples, slides and flows, piping and erosion by boat-generated waves have not been investigated. As a result, the impact of dredging on these other erosional processes has not been determined.

While dredging was prohibited in 10 areas following the Coffey and Partners' (1975) report, all but one of these were subsequently reopened because Coffey and Partners (1982) found that the bank materials in the prohibited areas were more resistant than assumed in the 1975 report. To reduce bank erosion by dredging, excavated side batters are not supposed to exceed 1 vertical to 4 horizontal and dredging is not supposed to be conducted within 20 to 60 m of the bank (depending on bank materials).

Despite the importance of bank erosion to riverside residents and to the management of dredging, little meaningful work has been completed to date. Slip circle failure analyses suggest that dredging has predisposed river banks to slumping by excessively increasing bank heights. However, other slope stability models need to be applied and soil strength parameters must be measured. Furthermore, other forms of bank erosion are important and their role in determining long term bank stability needs urgent investigation. Boat-generated waves, in particular, are likely to be a significant cause of bank erosion.

4.5 Increased Turbidity

Moss (1987) used Secchi depth (strictly a measure of light penetration) as a surrogate for turbidity and found that the turbidity maximum in the estuary is usually located just upstream of the saltwater/freshwater interface (Figure 2). However, there is also an extensive (between 30 and 70 km upstream of the mouth), highly turbid mid-reach of the estuary with Secchi depths ≤ 0.2 m (Figure 2). Other data sources show identical trends (Davie *et al.*, 1990). Information collected by the Australian Littoral Society and summarised in Davie *et al.*, (1990) conclusively demonstrates that the estuary was often clear and did *not* exhibit a *permanent* highly turbid mid-estuary earlier this century.

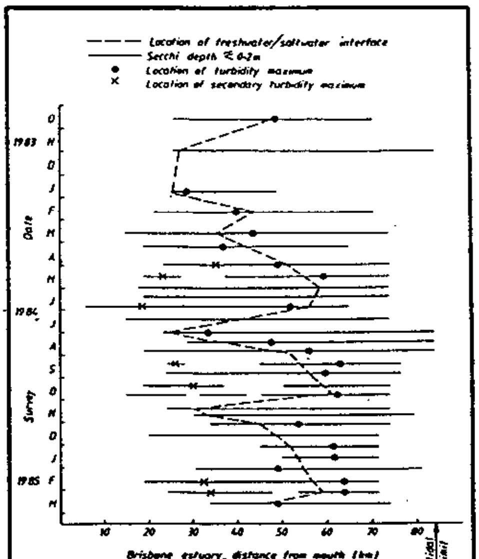

Figure 2. Temporal variations in turbidity of the Brisbane River estuary (After Moss, 1987).

Bristow (1986) found that clam dredges, by disturbing the bottom sediments, increased turbidity by at least 100% over that measured in immediately adjacent non-impacted sections of the Brisbane River estuary. The maximum turbidity of dredging-induced plumes can exceed background values by between 10 and 4,000% (Mayer, 1976; Erskine, 1990; Bell, 1991). However rapid settling of the coarser suspended sediment produces an exponential decline in suspended sediment concentration with increasing distance from the dredge (Erskine, 1990). Bell (1991) also found that peak tidal velocities in the lower Brisbane River estuary are sufficient to entrain bottom sediments and that harbour traffic has a significant effect on turbidity by also entraining these sediments. The discharge of bilge water and bin drainage water from dredging barges further increases turbidity (Bristow, 1986). Processing plants return minimally treated effluent directly to the estuary, further contributing to high turbidity. Extraction of sand and gravel bar and bed deposits and the flocculation of suspended clays has changed the bottom sediment composition of the Brisbane River estuary from relatively clean sand and gravel to much muddier sediments ((Davie *et al.*, 1990; O'Flynn, 1992). Flood flows are often capable of reworking these mud deposits.

The zone system of allocating dredge positions was implemented by the Brisbane Sand and Gravel Producers' Association to minimise complaints about extraction by maximising the length of estuary impacted. It maximises turbidity by permanently dispersing dredging over a greater length of estuary. Concentration of dredging activities would permit the use of silt screens and cutter suction dredges which would discharge the dredged slurry to a processing plant on the bank, thus enabling proper treatment of the effluent to accepted standards before being returned to the estuary.

4.6 Changed Tidal Hydraulics

Tidal hydraulics are important hydrodynamic processes in estuaries which control sediment transport, sediment deposition, nutrient mixing, plant and animal distributions, etc. Incomplete historical records show that by 1904, mean tidal range had increased by 0.25 m (Dobson, in Davie *et al.*, 1990). Mean high water readings did not change between 1860 and 1900 but mean low water dropped by 0.25m. This increased tidal range was caused by dredging of the navigation channel between the Bar Cutting and the Victoria Bridge to a rated depth of about 6 m. Increased tidal range would have also increased the tidal prism, peak tidal discharge and peak tidal velocity. Further changes may have also occurred but have not been recorded (Dobson, in Davie *et al.*, 1990).

The limit of tidal influence has also extended landwards. Navigation was relatively easy to Seventeen Mile Rocks in the early part of last century. Further upstream, various shoals and banks caused much difficulty for boats ((Davie *et al.*, 1990) and would have restricted tidal penetration. Today, the limit of tidal influence is located at Venus Pool (Karana Downs).

4.7 Changed Estuarine Salinity

Any changes in tidal hydraulics will also impact on salt intrusion. The Brisbane River is a salt-stratified estuary with a salt wedge at depth overlain by lower salinity water. At the time of European settlement, mangroves only extended upstream to Hamilton. Today, one species of mangrove, *Aegiceras corniculatum* has dispersed a further *48* km upstream (Davie *et al.*, 1990).

Acid sulphate soils contain pyritic sediments, the formation of which is a bacterial reduction process by which sulphate in seawater is reduced to pyrite (FeS_2). Pyrite is usually formed in vegetated tidal environments, such as mangrove flats. The recent colonisation of a large part of the Brisbane River estuary by mangroves may have resulted in the formation of sedimentary pyrite. Under reducing conditions, pyrite is stable but, once exposed to air, it oxidises, producing sulphuric acid. Stockpiling pyritic sands or muds will oxidise the pyrite as outlined by Lin *et al.* (1995) and Sammut *et al.* (1995). Dredge areas must not contain pyrite because the sulphuric acid produced can react further with other minerals to increase the soluble concentrations of pH-dependent elements to levels which are toxic to most biota. Aluminium, iron manganese and other trace elements increase with increasing acidity (Lin *et al.*,) 1995). When acid products are delivered to estuaries, pH can drop to 1.8 and fish kills and outbreaks of epizootic ulcerative syndrome frequently occur (Sammut *et al.*, 1995).

4.8 Biological Impacts

Erskine (1995) emphasised that dredging produces a multitude of physical impacts which, in turn, cause a range of indirect and direct biological/ecological impacts. In particular, increased water depths, increased turbidity and bank erosion cause loss of macrophytes and riparian vegetation, loss of aquatic habitat, reduced plant uptake of nutrients, water quality barriers to fish migration, reduced light penetration, reduced diversity of aquatic habitats and reduced productivity. While little information exists on these biological impacts for the Brisbane River, it is certain that they have occurred.

5. RECOMMENDED BEST MANAGEMENT PRACTICES

To improve the management and to reduce the environmental impacts of tidal dredging in the Brisbane River estuary, a range of additional best management practices need to be implemented. In particular, state policies which establish major objectives and principles of management should be formulated for estuaries and sand and gravel extraction in Queensland to provide general guidance on the sustainable management of estuaries. To achieve sustainable management of estuaries, it is necessary to:

i) slow, halt or reverse the overall rate of degradation;
ii) ensure long-term sustainability of essential biophysical functions; and
iii) maintain beneficial uses of resources.

On an individual site or regional level, each dredging proposal should be carried out under an extraction plan, operation plan *and* a site rehabilitation plan which should specify the final productive use of the area. Tidal dredging has the potential for causing such large scale environmental impacts that *every* operation above an agreed threshold (say, of annual production rat or total area disturbed) should prepare an environmental impact assessment report. The threshold would need to be set in collaboration with the industry. Standards need to be set for environmental assessment reports to ensure that the predicted environmental impacts are accurate and that appropriate environmental management plans are framed.

On a day-to-day basis, changes to the present permit conditions are essential to reduce the current environmental impacts and to ensure that the activities conform to best management practices elsewhere. Lastly, further investigations are required to establish the environmental impacts of past tidal dredging activities so as to frame more appropriate permit conditions.

6. ACKNOWLEDGEMENTS

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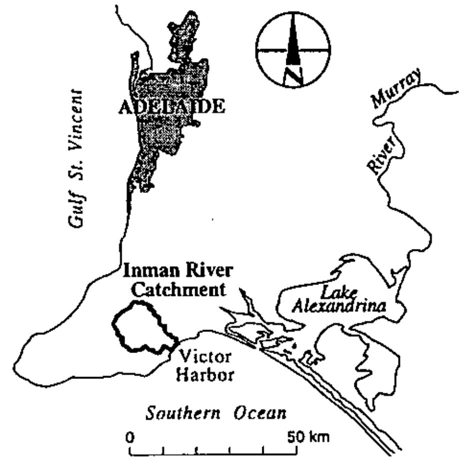
THE IMPACT OF EUROPEAN SETTLEMENT ON EROSION AND SEDIMENTATION IN THE INMAN RIVER CATCHMENT, SOUTH AUSTRALIA

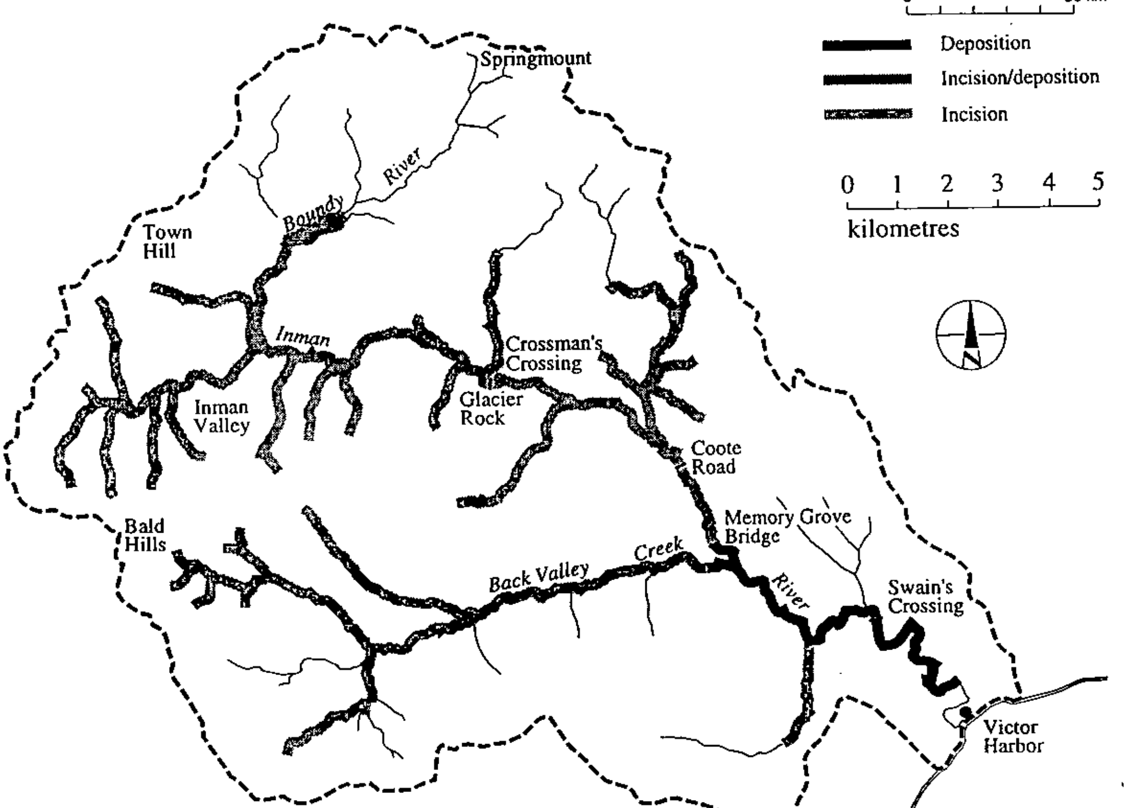
Jim Burston and Michael Good**

ABSTRACT: *The onset of European settlement of the Inman River catchment, breached a geomorphic threshold, unleashing a dramatic cycle of erosion. Evidence of severe stream erosion can be traced back to 1854. This paper analyses the impacts of channelization, swamp drainage, vegetation clearance, sand extraction and unrestricted stock access. Approximately 13.4 million m³ of sediment has been liberated since European settlement. Rates of migration of nick points of 2,100 metres pa. and 82 metres pa. have been recorded. Rates of erosion have declined during the last 40 years. Given the intermittent nature of the majority of watercourses in the catchment, comprehensive revegetation of watercourses is the best long term management option. The approach taken to erosion control is that of "minimalist" intervention, with "hard" engineered structures considered as last resort.*

1.0 INTRODUCTION

The Inman River catchment is located approximately 70 kilometres south of Adelaide (refer to Map 1, below) and has an area of 195.3 km^2. Rainfall varies from less than 520 mm at Victor Harbor to in excess of 900 mm at Spring Mount (the highest point in the catchment).





Map 1. Location of the Inman River Catchment.

* Mt Lofty Ranges Catchment Program
Department of Environment and Natural Resources (Water Resources Group)
2/85 Mt. Barker Rd. STIRLING S.A. 5152 Phone: (08) 339 7111 Fax: (08) 339 7112

The major watercourses of the catchment are believed to follow an ancient valley or basin, cut into the underlying Precambrian basement rocks, prior to the Permian glaciation. Permian glaciation deepened these ancient valleys, but left in its wake considerable depths (up to 300 m) of glacial and fluvio-glacial deposits (Bourman 1969). The following 200 million years was a period of erosion, reducing the region to an area of low relief. Tectonic uplift in the Tertiary period rejuvenated the watercourses (Bourman 1969), re-opening this ancient valley. This has resulted in an undulating to rolling landscape in the valley floor, quite distinctive from the steeper and higher hills of the surrounding hard rock landscapes that enclose the catchment.

The majority of the soils of the valley floor (Quaternary alluvium) are derived from the Permian glacial sediments. The undulating rises and low hills are formed on soft unconsolidated clay or sandy clay. The clays are sodic (ie contain a high level of sodium, thus are highly dispersive), therefore the region is prone to landslip and erosion.

Like many of the watercourses of eastern Australia at the time of European settlement, most of the watercourses of the Inman River catchment were marshy wetlands, with no defined channel, or formed small chain-of-ponds (Bird 1980 & 1982, Eyles 1977, Lush 1971, Starr 1989). These sites were believed to be dominated by dense stands of woolly tea-tree (*Leptospermum lanigerum*) and prickly tea-tree (*L. continentale*) (G. Ellers pers comm).

The Inman valley was settled by Europeans in 1837. As was the case elsewhere in Australia (Recher *et al* 1993), initial settlement and clearance of the catchment focussed on the river flats and open woodlands / grasslands. Governor Gawler, when visiting the region in 1839, described the valley as "...a lovely valley, varying from two to six miles in width, well watered and a rich soil for agriculture and herbage for pasture", (Lush 1971, p19). Since European settlement livestock grazing and dairying have been the mainstay of the valley.

2.0 STREAM EROSION

The erosion that followed European settlement has been primarily nick point migration, followed by lateral migration and bank collapse. There have been eras of rapid, episodic incision, rather than gradual, progressive erosion.

The initiation and development of stream bed erosion was generally associated with intense rainfall events, particularly during the summer months. In January 1941, the area known as Back Valley (refer to Map 1) received 205 mm of rain in less than 48 hours. The ensuing floodwaters destroyed the Back Valley bridge and Keen's Road bridge (L. Keen pers comm).

The rates of erosion have declined since the late 1950s. This coincides with the eradication of rabbits, the sowing of "improved" pastures and the use of superphosphate. Most of the watercourses of the catchment have passed through the phase of maximum instability as they adjust to the hydrological changes and channel disturbances brought about by European settlement.

2.1 "It Was Once All Swamp"

According to long time residents Adrian Lush and Eric Ashby, stories passed down by family members, stated that, at the time of European settlement, the river had no clearly defined course. Rather, it spread out over the river flats. The grandmother of Eric Ashby clearly remembered the Inman River (downstream of the junction of the Boundy River - a distance of approximately 16 km) as being "all swamp and marsh". At the Inman Valley township (refer to Map 1), it was once possible to leap from one bank to the other (Lush 1971). Today, the river has incised to a depth of more than 5m and widened to approximately 20 m (Burston & Good 1995).

In 1844, the Boundy River (refer to Map 1), upstream from the confluence of the Boundy and Inman Rivers, was described as having no defined channel. It was possible for a bullock team to cross at any point (Lush 1971). Today, this reach of the Boundy River, where it joins with the Inman River, has incised over 5m and widened to approximately 50-60 m (Burston & Good 1995).

In 1850, a writer employed by the South Australian Register described areas of the catchment, near "Glacier Rock" (refer to Map 1), as marshy and undrained (Lush 1971).Yet in 1854, Professor Selwyn drew attention to the glacial grooves and polishing in the Kanmantoo bed rock now exposed in the channel of the Inman River (Selwyn 1859). Thus, in less than 4 years, the level of the stream bed had dropped by approximately 4 metres. Either a catastrophic erosion event occurred *in situ* or a large knick point travelled up-stream and "uncovered" Glacier Rock. The trigger that initiated this bed deepening event is unknown.

2.2 Gullying

The development of commercial grain farming in the district in the 1840s (Lush 1971) resulted in spectacular landform changes. The fields were cultivated by single furrow ploughs, drawn by bullocks. A particular practice of ploughing, known as the "lands" (ie. patterns of ridge and furrow), was done by ploughing up and down the slope of the land (Twidale *et al.* 1971). The technique was a disaster in the highly erodible, sodic soils of the catchment, initiating severe gully erosion.

Gullying has been most severe in the headwaters (ie. 1st and 2nd Order streams - as determined from 1:50000 map sheet, following Strahler 1964) of the Inman River in the region of Bald Hills (refer to Map 1). The initiation and development of these gullies were associated with intense rainfall events falling on the ploughed "lands". One gully, Welch's Washout, measuring 100 m long and 1-2 m wide, developed in a single downpour in 1906 (Bourman 1974).

With the abandonment of cereal cropping at the turn of the century, the growth rate of the erosion gullies slowed. The introduction of pasture improvement and the elimination of rabbits in the late 1950's, accelerated the process of gully stabilisation. Since then, the majority of the gullies have battered back, although some are still actively eroding. Much of the sediment mobilised by this process has not entered the river. Rather, it has been stored on alluvial fans or flood-outs, at the break of slope at the bottom of the gully.

2.3 Bed Deepening

It has been estimated that approximately 13.4 million m^3 of sediment has been eroded from watercourses of the catchment (of magnitude 3rd Order or greater) since European settlement (Burston and Good, 1995). The location and size of all knick points on all watercourses of magnitude 3rd Order or greater have also been identified (Burston and Good 1995). For some reaches, the process of bed deepening is occurring as a series of clusters of minor knick points, rather than as one large event. The implication of this habit is not fully understood. Channels have become deeply incised, to the point where more than 60% of watercourses surveyed have now incised to a depth of more than 2 metres (Burston and Good 1995).

Owing to its glacial history, very few natural control points (ie. rock reefs) are present within the catchment. Thus, nick points have the potential to travel long distances. Many of the small bridges and culverts built on the roads that traverse the catchment are acting as *quasi* control points. At several locations, erosion heads have worked up to these structures, where they have been "locked up", in the form of a concrete drop structure on the downstream side of the bridge or culvert.

2.3.1 Swamp Drainage

Swamp drainage is a familiar trademark in the history of land clearance in Australia (Erskine 1994, Recher *et al* 1993, Bird 1980 & 1982). European settlers perceived wetlands as unproductive wastelands that could be converted to agriculture via drainage. Undoubtedly, the drainage of wetlands triggered many episodes of stream bed deepening across the catchment. As the main channel became more incised, so too did its tributaries. The practice of draining "unproductive" wetland continues to this day. In 1994, a 400m drain was cut (to a depth of 1.2 m) through a waterlogged paddock in order to improve drainage. Given the sandy-loam soil type, within a couple of months, bank collapse and bed deepening were severe. The security of a large farm dam is now threatened.

Drains were also cut in order to alleviate problems of sedimentation that were associated with gully erosion. Large volumes of sediment, transported by tributary streams, were being deposited on the flood plain of the Inman River. In one particular case, in the 1940's, a farmer, frustrated by the repeated flooding and sedimentation, cut a small drain from the bottom of the gully to the Inman River, a distance of approximately 250m. In a matter of 3-4 years, the whole channel had incised to depth of 3 m and a width of 8 m (D. Lush pers comm). The banks have now, of their own accord, battered back and revegetated.

2.3.3 Channelization

The main area of channelization in the catchment has been along Back Valley Creek, up-stream from its confluence with the Inman River. It was done by the District Council of Victor Harbor during the 1940's (R. Brown, pers comm) to "protect" two bridges from being outflanked by a meander. The old watercourse channel is still evident, lying approximately 2 m above the present bed of the watercourse.

2.4 Sand Extraction

In recent years, the most severe degradation in the catchment has occurred as a result of sand extraction in the reach of river known as Memory Grove - Swains Crossing (refer to Map 1). Extraction of "concrete sand" occurred for only one year, 1985, during which 6,700 m^3 of sand was mined from the river. As a result, there has been catastrophic erosion upstream and severe aggradation downstream of the mine site. In less than 2 years, a 2 m knick point had migrated 4.2 km upstream (a mean rate of migration of 2.1 km per year), and currently threatens the integrity of the Memory Grove Bridge. Although no photographs were taken at the time, landholders vividly recollect the "6 foot waterfall" that travelled rapidly upstream (C. Liston & R. Liston, pers comm).Burston and Good (1995) estimated that the resultant bed deepening released some 101,000 m^3 of sediment. Currently, the river is undergoing a very active phase of lateral migration, as it strives to attain a new balance. Thus, many more thousands of cubic metres of sediment are being released from the ensuing bank collapse. The affect on channel dimension is graphically illustrated in Figure 1, below.

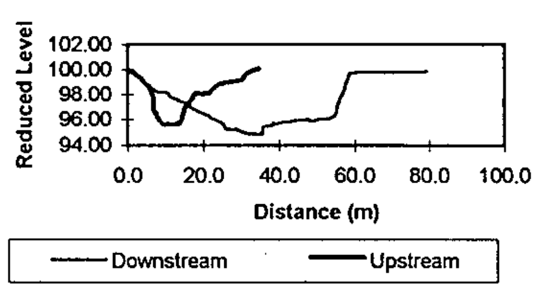


Figure 1. Impact of sand extraction on channel dimension at Memory Grove bridge (cross-sections are taken at the first inflection point upstream and downstream of the bridge).

At a site below Swains' Crossing culvert, approximately 5,300 m^3 of "concrete sand" was removed from the site. As this site currently enjoys a high level of aggradation, there is no visible impact from the extraction.

Although the extent of commercial extraction has been limited (but with devastating impact), extraction by landholders for domestic uses has been widespread, often with grave consequences. In 1976, at a site 1.4 km downstream from Glacier Rock, a small volume (quantity unknown) of sand was extracted from the river (for building purposes and to create a water hole for domestic uses). By 1993, a 1.2 m knick point had travelled 1.4 km upstream (at a mean rate of 82 m per year), mobilising approximately 24,000m^3 of sediment (Burston and Good 1995).

2.5 Rabbits

Rabbit numbers built up rapidly in the catchment as the glacial and alluvial soils of the catchment afforded easy digging. In the 1940's there were "literally thousands, if not millions" (G & P. Stephens, E. Ashby, pers comm). The burrowing activity of rabbits initiated many erosion gullies and exacerbated bank erosion.

The release of the myxomatosis virus did not make a significant in-road to the rabbit population. In 1959, the Inman Valley Rabbit Eradication committee was established to facilitate a community control program. The strategy of poisoning (using 1080) and warren ripping was very successful. Landholders involved in the program recall the stench of dead rabbits (P. Stephens, E. Ashby, pers comm).

Local residents believe that the control of rabbits, followed by pasture "improvement" and the use of superphosphate, was the most important factor in reducing the rate of both catchment erosion and bank erosion along watercourses of the catchment. With rabbits all but eliminated, vegetation, including native plants, began to re-establish along the banks of the Inman River and its tributaries.

2.6 Bank Erosion

The rapid incision of the main channel of the Inman River had a profound impact on bank stability. Adjusting to the "recent" incision and new hydrological regime, the watercourses began (and continue to this day) a process of lateral migration. The unconsolidated alluvial and glacial sediments offer little resistance to this process.

In the 1930's it was considered unwise to purchase property with river frontage, owing to the high rates of bank erosion. Many properties were abandoned or sold to neighbours as their owners feared the river would "sweep all the soil into the sea" (Bourman pers comm). Long time residents attest, that during years of above average rainfall, the sound of banks slumping into the river was a common occurrence, particularly on still nights (Bourman 1969). Poor bank stability (as defined by Ian Drummond & Assoc 1985) currently affects nearly 25% of all banks in the catchment. However, approximately 46% are in good-excellent condition (Burston and Good 1995).

3.0 AGGRADATION

One hundred and fifty years of erosion has released vast amounts of sediment into watercourses of the catchment. The majority of the sediment appears to be sourced from erosion of the channel, rather than from the catchment. The high rates of channel erosion released vast quantities of sediment, much of which has been deposited across the floodplain, as **"Post-European Settlement Alluvium"** (PESA). At points below Memory Grove bridge, PESA attains a depth of more than 1.5m. However, many streams are now incised to a depth where over-bank flow is no longer possible. Consequently, the mobilised sediment is confined to the channel trench. The majority of watercourses show some degree of aggradation. Over 28% of the total stream length are affected by moderate to high levels of aggradation (Burston and Good 1995).

The most pronounced sand slug occurs downstream of Memory Grove bridge. Comparison of early photographic records and aerial photographs from 1949 and 1993 indicate that the sand slug formed between 1922 and 1949. Downstream from Swain's Crossing culvert, for a distance of 1.5 km, the river is severely aggraded, consisting of a tangle of channels of varying width and depth. In the 1920's this reach was still navigable by small craft (Bourman 1969). Refer to Figure 2, below.

Bourman (1969,1974) provided evidence of fence posts, trees and ferry cables being buried by 4 metres of sediment. Furthermore, there are accounts of a house and flax mill being buried under the sediment (Lingard 1987). Near the site of the old Victor Harbor rubbish dump, two buried fences would indicate a rate of sedimentation in this area of approximately 1m per 25 years between the period c.1920-1969. A third fence has been built on top of the two buried fences (Bourman 1969).

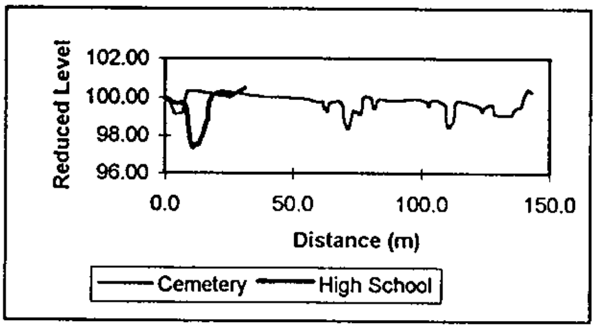


Figure 2. Impact of aggradation on channel cross-section between cemetery and High School.

Sedimentation is still occurring in this reach. Many young river red gums (ie estimated age < 30 years) are encased in sand. The rate of sedimentation is likely to be maintained in light of the large volume of sediment currently being released due to catastrophic erosion occurring in the reach Memory Grove bridge to Swain's Crossing culvert.

During the period 1949-1979, in the reach between Glacier Rock and Stephens Rock (a distance of 2.2 km) the stream bed was raised by approximately 1.2 m.(which has since undergone renewed incision - see Sn 2.4) This was as a result of the deposition of sediment from upstream sources and bank collapse *in situ*. During this time, the banks battered back to a point where vegetation could again grow.

4.0 REHABILITATION

In their study of the Inman River catchment, Burston and Good (1995) identified 185 watercourse management issues, across the catchment, that need redress. Implementation of improved management practices is likely to reduce erosion and sediment supply, with the potential to trigger renewed incision along some reaches.

It is important to recognise that the majority of landholders have inherited problems that were initiated many years ago. Improvements will not occur overnight, but they are certainly achievable within the medium term (ie. 5-10 years). The lack of resources (ie. time and money) and knowledge among landholders will be the most important constraint upon the full implementation of the on-ground works.

The control of erosion (bed and bank) is a fundamental pre-requisite to achieving improvements to the water quality and ecological health of watercourses in the catchment. In the vast majority of cases identified in the catchment, the erosion can be arrested by using the revegetation technique. That is, fence the watercourse to exclude stock access and then revegetate the site with indigenous plant species. At other sites in the Mount Lofty Ranges, direct seeding of local native plant species has shown the efficacy and cost effectiveness of this approach. Revegetation will do much to increase the roughness of the channel and provide physical protection to the bed and banks.

Given the intermittent nature of the majority of watercourses in the Inman River catchment, plus the excellent growing environment, the revegetation approach has a high probability of success. Unlike the large watercourses of the eastern states, the intermittent nature and relatively small discharge of watercourses in the catchment, favour the revegetation approach. However, in catastrophic events, the technique will be overwhelmed. The approach is based on risk management - the trade-off between the risk of an infrequent event and the cost of works.. Furthermore, all in-stream disturbances should be avoided at all costs.

At sites where stock access has been restricted, the growth of reeds and rushes has been prolific. Reed, rushes and sedges will quickly re-establish from their rhizomatic root base (and from seed) and will generally stabilise the site within a couple of years. The most effective plants for this purpose are the common reed (*Phragmites australis*) and the bulrush (*Thypha domingensis*).

Given the highly erodible nature of the glacial and alluvial sediments, the reed beds appear to be playing a vital role in reducing the rate of movement of the knick points. In fact, many erosion heads identified by Burston and Good (1995) are presently located in macrophyte beds, which have dramatically slowed their progress Common reed and bulrush also play an important role in trapping and storing sediment. In following the revegetation approach, however, knick points will continue to migrate upstream, but at a rate much slower than at present. The approach has significant cost advantages over a more interventionist approach based on engineered works.

For smaller watercourses (such as 2nd, 3rd and 4th Order), where knick points are likely to beyond the scope of the revegetation approach, there are a range of "farmer friendly" grade control structures that can be installed to neutralise a knick point (Carter and Collingham 1995). Some of these structures are cheap and can be constructed by the landholder using materials readily available on the farm. For landholders to construct these structures, they must be cheap, "low tech", easy to construct, and use farm materials and equipment.

Fences should be placed at a suitable distance back from the edge of the bank in order to accommodate the gradual batter of the bank. The distance will be dependent on bank height, the nature of the bank material and one's position on the meander. For streams that appear to have a stable morphology, a rule of thumb is for the distances between the fences to be at least 10 times the low flow channel width (Rutherford pers comm). In reality, however, the fence will be placed back by whatever distance the landholder deems appropriate.

5.0 CONCLUSION

The dramatic cycle of erosion encountered in the Inman River catchment during the past 150 years can be added to the litany of similar studies of sever watercourse erosion that accompanied European settlement. The glacial history of the catchment, creating an environment of sodic, highly erodible soils, in which few natural control points exist, exacerbated the impact of European settlement. Since the late 1950's, the rate and extent of erosion has gradually declined. Factors attributed to this include natural stabilisation, the control of rabbits and the establishment of improved pasture base (ie vegetative cover). Fortunately, due to the intermittent nature of the watercourses, the solution to most erosion issues is very simple. Fence the watercourse to exclude stock access and revegetate with indigenous plant species.

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The advent of post European Erosion in a Valley Swamp

Dr. David Fisher[1]

ABSTRACT: *Incision of Scrubby Creek was initiated when human intervention exposed subsoils with an erosive cocktail of high sodium (Na^+) concentrations, alkaline pH and humic material associated with buried swamp deposits to streamflow. Such conditions coupled with clay cracking generated by wetting and drying cycles within the drain itself were critical for subsequent rapid erosion, rather than catchment wide changes. Although subsoils were potentially dispersive, actual losses from the cliffs were governed by the imposed hydrological setting, with the greatest erosion evident during the period of greatest change shortly after the original swamp was drained.*

1. INTRODUCTION

Since the arrival of European settlement, Scrubby Creek has transported some 175,000 m^3 of sediment. Consequently, the original valley swamp 40 km north of Melbourne, fed by a 2,500 ha catchment, has degraded into a 10 m deep incised watercourse. This paper outlines research into the development of gullies along drains originally cut in 1903 and mechanisms contributing to the ongoing instability (Fisher, 1993). Although an emphasis is placed on quantifying the erosion processes within a small study area, a thorough understanding of the important mechanisms potentially has broader applications including rehabilitation strategies for the 17,000 km of degraded streams in Victoria (Mitchell, 1990)

2. THE ADVENT OF INCISION

The arrival of European settlement within the Scrubby Creek valley heralded major changes for the watercourse. The creek flats were cleared to make way for horticultural crops such as apples; and drains were installed to alleviate the waterlogging identified by the original government inspectors. The intensive settlement between 1893 and 1910 laid the framework for subsequent gully formation along the cleared and burnt drainage lines.

Incision along the newly created drains was rapid, especially through Mr. Gilchrist's swampy flats (Lots 12 and 13: Figure 1). The stream erosion progressively destroyed bridge crossings and eventually threatened the safety of pupils at the Humevale Primary School. The magnitude of this erosion is depicted in Figure 2. Erosion along the lower reaches was less severe with no incision evident beneath an aqueduct bridge constructed in 1886.

The period of down cutting between 1900 and 1940 was not linked to unseasonally wet years or widespread catchment clearing. Rainfall and flood records fail to indicate any significant changes in rainfall intensity and flooding frequency during this period. Indeed the largest recorded floods within the catchment occurred in 1878 and 1974, outside the period of greatest stream instability. Similarly, an increase in total discharge during the same period is unlikely as much of the catchment remained forested, initially set aside as a possible water catchment for Melbourne.

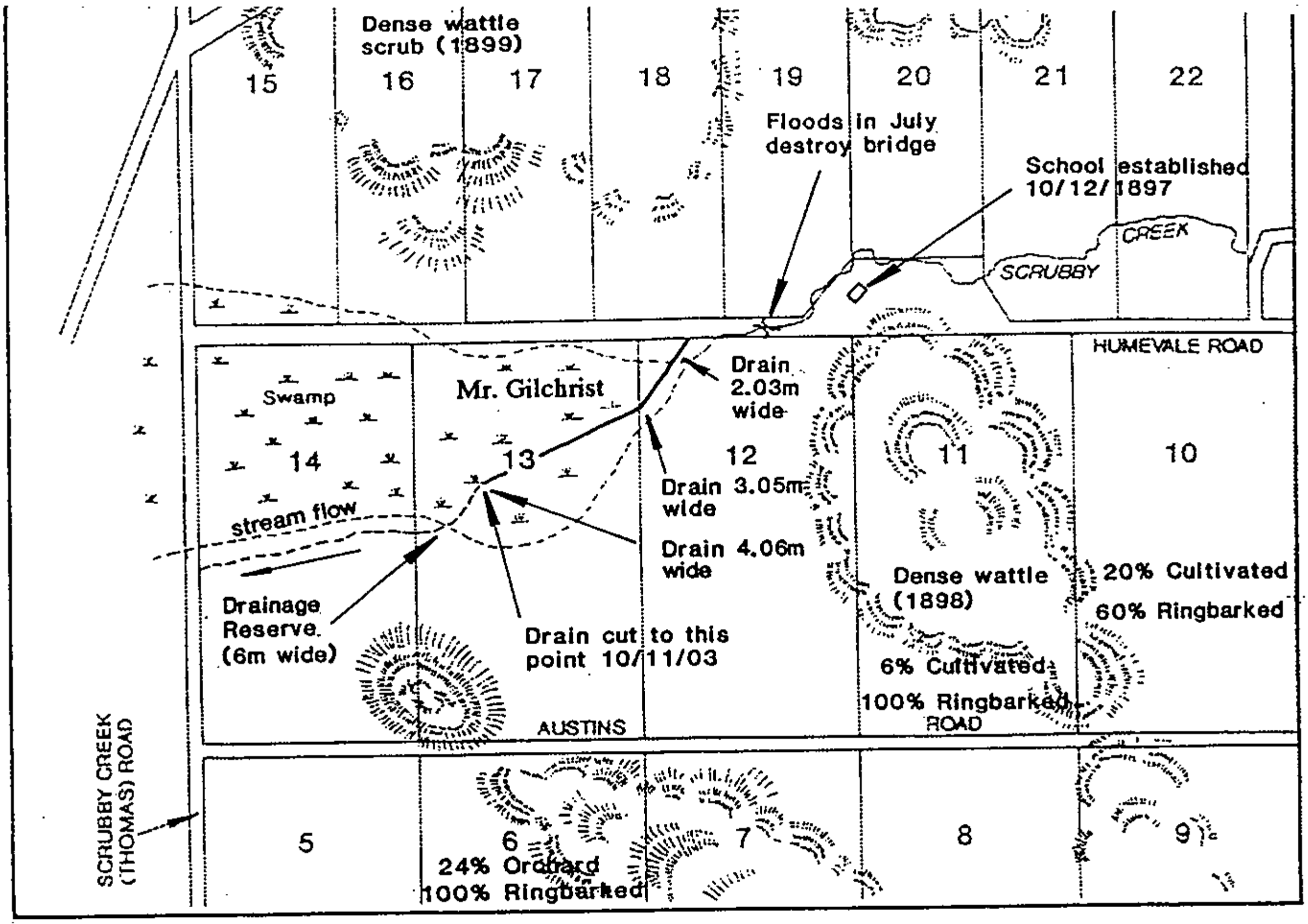
3. THE ROLE OF DISPERSION

The soils adjoining Scrubby Creek developed on an alluvial fan produced by hill wash deposits from the weathering of lower Devonian sedimentary rocks. Successive swamps were buried by erosion cycles, incorporating grey organic sands, muds and humic material within the soil profiles. Finely ground muscovite and illite were the dominant clay minerals.

Weathering produced sodic yellow duplex soils with typically alkaline or neutral subsoils (Northcote and Skene, 1972). These subsoils were highly dispersive when immersed in natural creek water, a process aided by the mechanical energy supplied by running water. In contrast, subsoils saturated with natural groundwater failed to disperse when inundated by creek flows.

Buried humics associated with previous swamp deposits also aided the dispersion process. Organic coatings on the clay particles increased the pH range over which the clays were potentially dispersive. However, difficulties in accurately isolating the organic groups precluded the establishment of any unequivocal relationships between buried humic material and subsequent erosion.

[1] Melbourne Water. P.O. Box 4342,
MELBOURNE, 3001
Telephone: (03) 9615 4068 Fax: (03) 9615 4064



Above: 1904, Drainage works initiated

(Source: field notes, closer settlement files)

Below: 1920, Orchards and Vineyards

0 100 200m

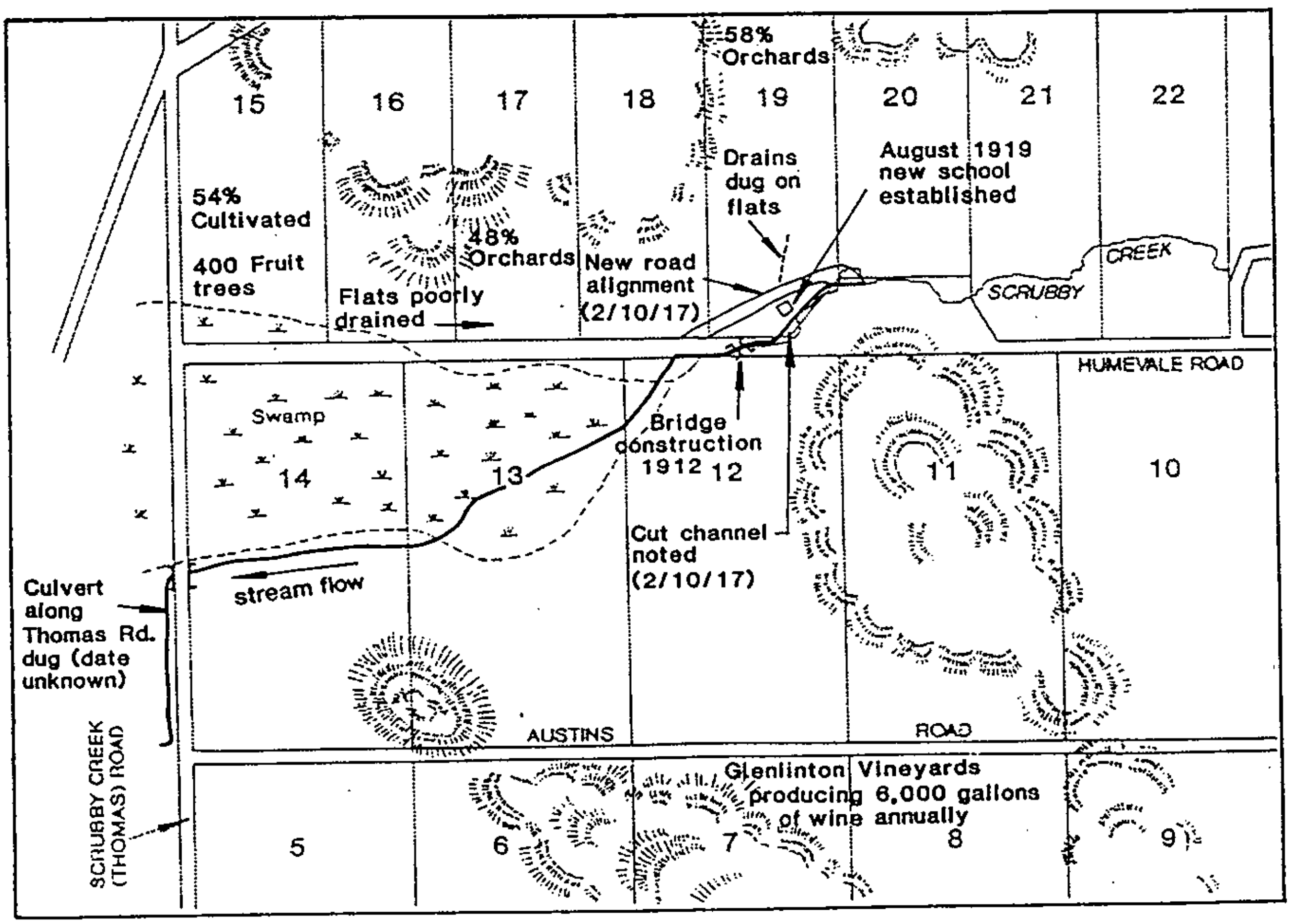


Figure 1. Initial Development of Incision

Above: Primary School site in 1906 looking North. Limited incision is already evident and vegetation has been removed. Note, stock access track.

Right: The same site in 1991 looking west. Note the creek now follows the road alignment depicted above. The fence provides a common reference point. Concrete footings from the school toilet block cling to the edge.

Figure 2. Comparison of the Humevale Primary School Site in 1906 and 1991

4. CONTEMPORARY EROSION LOSSES

Although potentially dispersive in a test tube, the response of subsoils to the imposed hydrological setting must be assessed in the field. The very act of preparing soils for examination in a laboratory radically changes any natural resistance to erosion.

Erosion losses from the Scrubby Creek gully were directly assessed using terrestrial photogrammetry. This technique was adopted as hazardous site access and complex surface shapes precluded traditional tacheometry. Continuous monitoring of sediment discharge was also precluded by sampling difficulties especially fluctuations in sediment generated even within a particular storm (Olive and Rieger, 1986).

Monitoring over two years identified significant differences in erosion rates both down a given cliff profile and between sites along the creek. The greatest erosion on individual cliffs was evident where moisture fluctuation produced cracking. This typically occurred in a zone between maximum and minimum groundwater levels or where banks were regularly inundated. The bulk of the cliff profile which remained either dry or saturated by saline groundwater throughout the season failed to exhibit any significant losses. Significant erosion was confined to a small number of actively eroding sites, less than 11% of the total channel length.

The sodic nature of cracked subsoils aided subsequent fluvial removal. The high Na^+ concentrations ensured that both the clays within the cracked material readily dispersed in running water, and binding vegetation failed to establish in an otherwise suitable seedbed.

Once the cracked material was removed the underlying fresh subsoil was largely impermeable to streamflow, due to the dense structure produced by a combination of overburden pressure and sodic groundwater conditions (Shainberg and Letey, 1984). Consequently, frequent sediment exhaustion was noted as the potentially erodible material became progressively more difficult to detach as the season or individual storms progressed.

The timing of streamflow rather than discharges or length of inundation *per se* was critical for subsequent erosion. Erosion was greatest when drying and wetting cycles occurred in quick succession with frequent flows to remove loose material. Consequently, small Autumn flows removed greater quantities of material than prolonged inundation of already wet profiles such as occurred in July 1990.

Preferential erosion in the zone of moisture fluctuation at the base of the cliff produced a characteristic undercut (Figure 2). Greater undercuts were evident where drying cycles and subsequent fluvial removal were most severe, such as outside meander bends devoid of stabilising vegetation. Undercuts eventually caused the overlying material to collapse either as small fretting failures or as cantilever collapses where the rate of removal was greatest. The former process where small blocks or slabs 'flaked' from the surface and were subsequently removed was the dominant erosion process.

Although visually dramatic, the cantilever failure of large slabs was a minor contributor to overall sediment loads. Such cantilever failures only occurred when the undercuts exceeded approximately 0.60 m or up to 2.0 m when the banks were reinforced with tree roots. Groundwater levels or structurally weak soil horizons did not directly contribute to such failure.

Although trees increased the interval between cliff collapses and reduced subsoil moisture variation, treed banks were eventually undercut by fluvial processes.

Failed slabs also protected the cliff base from subsequent fluvial action for at least six months. The predominately dry material deposited within the channel was not readily removed by fluvial action until subjected to a number of cycles of wetting and drying.

5 . LESSONS FROM THE PAST

Erosion rates during the period of active incision were significantly higher than the 7 $m^3 km^{-2} y^{-1}$ rates currently evident within the incised channel. The Scrubby Creek gully would require approximately 3,000 years to form based on such losses.

Rapid lowering of the groundwater table and headwards erosion within the channel itself doubtlessly accelerated the initial losses. Poor vegetation re-establishment associated with dry, salty subsoils, fluctuating moisture conditions and over grazing, further aided rapid incision.

The role of subsoil cracking in the erosion process was particularly important during the initial incision process. Draining rapidly lowered the water-tables beneath the original swamps introducing major fluctuations in subsoil moisture regimes. In contrast, moisture fluctuations today are linked to seasonal variations in groundwater levels associated with catchment rainfall. Consequently, desiccation cracking was deeper and more extensive immediately after the drains were cut, despite similar rainfall patterns during the 1900-1940 and 1940-1992 periods. A feedback mechanism exists whereby drain incision lowers the water-table which subsequently controls the depth to which the drain can erode (Bird, 1987).

The vulnerability of the cut drain to subsequent erosion was critical for incision within the Scrubby Creek valley rather than either catchment wide landuse change or a significant increase in channel grade. Similarly, the upstream migration of nick points generated by changes in the lower catchment was not implicated in the development of incision. Falling water-tables and the removal of dense suckering swamp vegetation from the drain environs were major factors in subsequent erosion.

Once mobilised by streamflow, less than 0.1% of transported sediment was retained within the gully system. This once again reflects the dispersive characteristics of exposed, dry and cracked subsoils. An additional contributing factor in minimal sediment retention was the overgrazed and denuded floodplain evident during the period of active stream incision.

Draining also potentially altered the anaerobic (reducing), alkaline and sodic conditions under the original swamp and hence the dominant chemistry at the clay surface. Drying and oxidation changed the nature of the humics and potentially increased humic adsorption onto the clay surface (Greenland, 1971). Such adsorption would increase the vulnerability of exposed subsoils to disturbance (cf. section 3, above).

6. CONCLUSION

Although the incised watercourse generated by Scrubby Creek is visually dramatic, the 10 m cliffs have largely stabilised with ongoing collapses expected from less than 11% of the total channel length. Within such actively eroding profiles, losses were often further confined to the zone between maximum and minimum groundwater levels or where banks were regularly inundated. Such moisture fluctuations produced cracked material which is readily removed by subsequent streamflow. Further drying is required before the freshly exposed subsoils are readily entrained. Consequently a focus on the variations in moisture regimes, rather than increases in total discharge is pertinent for erosion studies within comparable watercourses.

Despite contemporary erosion rates being less than intuitively expected and rehabilitation difficult to justify economically, initial incision within the valley was rapid and significantly degraded downstream water quality. Consequently, it is along watercourses starting to incise, or within undeveloped valleys with similar yellow duplex soils, illitic clays, buried humics and high Na^+ concentrations that the preceeding findings have the greatest potential application. Any predictive model for stream incision on similar soil types must consider subsoil chemical charcteristics and focus on disturbances within the channel, especially changes in the hydrological setting. A watercourse best remembered as 'Gilchrist's Gully' has important implications for proponents of major landuse change, especially 'improvements' to natural drainage lines.

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Response of the King and Queen Rivers, Tasmania, to Dramatic Changes in Flow and Sediment Load

*Helen Locher**

ABSTRACT

The King River in Tasmania has been subject to 80 years of mining sediment disposal up until 1994, plus flow regulation for hydro-electric power generation commencing in 1992. About 10% of the mine wastes have remained stored within the river system, with the majority within a delta at the river mouth. The power station has caused a strongly pulsating pattern of sediment transport in the river, particularly major flushes of suspended sediments when the power station comes on line. Suspended sediment concentrations have decreased dramatically since mine closure. Erosion of the river sediment storages is projected take decades to centuries.

1. INTRODUCTION

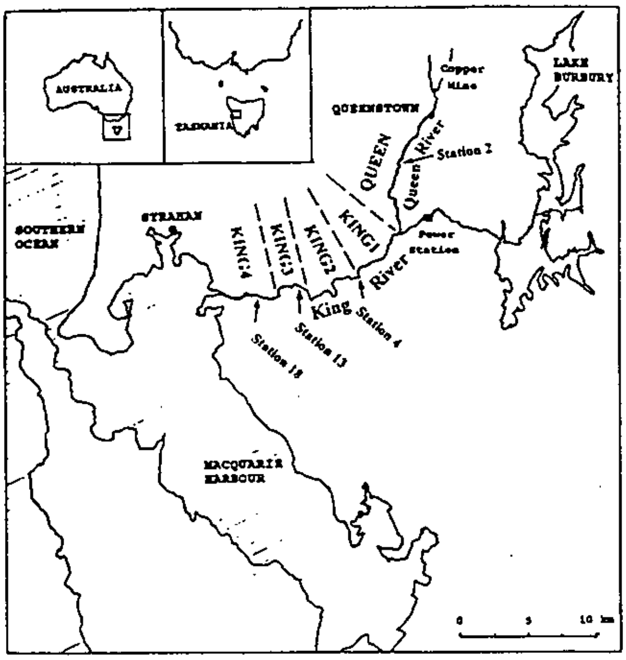
This study aims to determine the physical impacts of mining and hydro-power on the King River system on Tasmania's west coast. This involves identifying the river response to 80 years of tailings discharge, monitoring river response to the cessation of tailings discharge as of December 1994, determining how the regulation of flow which commenced in February 1992 influences river response, and developing future management recommendations for the river system.

This paper presents knowledge gained to date on the storage of mining wastes, the influence of the power station, changes with the cessation of tailings discharge, and future projections for the river system. For detailed methodology and data summaries refer to Locher (1995).

2. SEDIMENT STORAGE

2.1 Sediment Budget

The King River system can be divided into five reaches based on river characteristics, as illustrated in Map 1. Sediment storage within each reach is summarised in Table 1, and can largely be correlated with river gradient. There are little to no storages in the Queen and King1 reaches due to the steep channel gradients. The majority of mining-derived sediments within the river system are stored within reaches King3 and King4. The river storages, totalling 9.4 million tonnes of mining-derived sediments, represent only a fraction of the total sediment discharge from the Mount Lyell Copper Mine in Queenstown, estimated to be 97 million tonnes of tailings and 1.4 million tonnes of smelter slag.



MAP 1 - KING RIVER LOCATION MAP

2.2 Sediment Bank Storages

The extent of sediment bank storage of mining wastes was determined via an extensive augering survey, supplemented by the excavation of a trench perpendicular to the river flow. Identification of sediments as mining-derived was supported by analyses of Caesium-137 and copper concentrations. The majority of bank sediments are stored in reach King3, where banks are up to 7 metres above mean water level. Reach King4 is tidally influenced and the sediment banks are much flatter, only 1-2 metres above mean water level.

Deposition of mining wastes is conspicuous due to devegetation of the sediment banks. Sediment banks

* Co-operative Research Centre for Catchment Hydrology, Department of Civil Engineering, Monash University, Wellington Road, Melbourne VIC 3168

consist almost entirely of tailings, a fine silt to fine-sand sized material, lain down on top of natural levee banks during successive flood events during which the levees were overtopped.

Sediments in Storage (Tonnes)					
		BANKS		BOTTOM	
REACH	Average Gradient	Approx. Amount	% of Total in Banks	Approx. Amount	% of Total in Bottom
Queen	0.012	< 1,000	-	< 1,000	-
King1	0.014	< 1,000	-	< 1,000	-
King2	0.0008	180,800	5.18	< 1,000	-
King3	0.0004	2,624,000	75.19	376,000	6.3
King4	0.0003	684,800	19.62	5,558,400	93.7
TOTAL		3,489,600	100	5,934,400	100

TABLE 1 - King River Sediment Storage

Comparison of river planform with an 1898 railway survey shows there have been no major changes in river course, and all presently observed sediment banks are underlain by the original levee banks.

2.3 River Bottom Storages

The extent of river bottom storages was determined by drill coring. Mine wastes have infilled the river bottom by as much as 6 metres within the last several kilometres of the King River. Bottom sediments consist predominantly of smelter slag, a black coarse granular material about 1 mm in diameter, mixed with lesser amounts of tailings and natural river gravels.

2.4 Delta

The vast majority of tailings are stored in the delta at the river mouth, estimated to contain 80-90 million tonnes of tailings. This volume estimate is based on comparison of a 1993 bathymetric survey with a 1930 British Admiralty Chart. Progressive outward growth of the delta can clearly be traced on aerial photographs. Composition of the deltaic material as tailings is based on drill core collection.

3. INFLUENCE OF POWER STATION

3.1 Changes in Sediment Deposition

The power station came on line in February 1992. It has significantly changed the flow regime, most notably by reducing the peak flows to 30% of their previous levels. The reduced flows have stopped the growth of the sediment banks, by eliminating the flood events during which they were overtopped. The power station has also caused increased bottom deposition of tailings at the mouth of the river immediately upstream of the delta, based on comparative cross-section surveys, due to the inability of the reduced river flow to completely flush out the tailings being delivered by the mine. Observational evidence suggests that outward growth of the delta has ceased since the power station came on line, and that deposition is occurring behind the delta with some erosion of the delta face.

3.2 Changes in Sediment Transport

The operation of the power station has resulted in a pulsating pattern of sediment transport as illustrated by a suspended sediment sampling exercise conducted while the mine was still discharging tailings. Suspended sediment concentrations are shown in Figure 1, and station locations are shown in Map 1. Suspended sediment concentrations increased as much as two orders of magnitude following initial start-up of the power station, from several hundred to 10,000 mg/L, although this rise in concentration was not sustained during the period the power station was on due to sediment exhaustion effects. Propogation of the sediment flush and attenuation of the peak is clearly evident at the progressively downstream stations.

The dynamics at the confluence of the King and Queen Rivers have a major influence on the occurrence of the sediment flushes seen in Figure 1. When the power station is on, the flow in the King River restricts transport of the tailings out of the Queen River. Tailings are able to come out of the Queen River into the King once the power station goes off line, but flow in the King River is insufficient to transport the tailings further downstream and so they settle out of suspension. When the power station comes back on line the temporarily deposited sediments are lifted into suspension and transported downstream, and have been associated with major tailings plumes out into the receiving body of water, Macquarie Harbour.

4. CHANGES POST-MINE CLOSURE

4.1 Influence of Power Station

Figure 2 shows a comparative suspended sediment sampling exercise conducted during 1995, after the mine had closed. Suspended sediment concentrations are dramatically lower, averaging 20-40 mg/L and peaking at 160 mg/L. The same flushing effect of the power station is still evident. Interestingly, the highest sediment concentrations are seen at Station 18 rather than Station 4. Suspended sediments collected during the 1995 exercise were reddish and appear to be iron hydroxide flocs precipitating out of solution, a product of the changed water chemistry post-mine closure. The higher concentrations seen at Station 18 may be a

FIGURE 1
Influence of Power Station on Suspended Sediment Transport
Pre-Mine Closure - June 1994

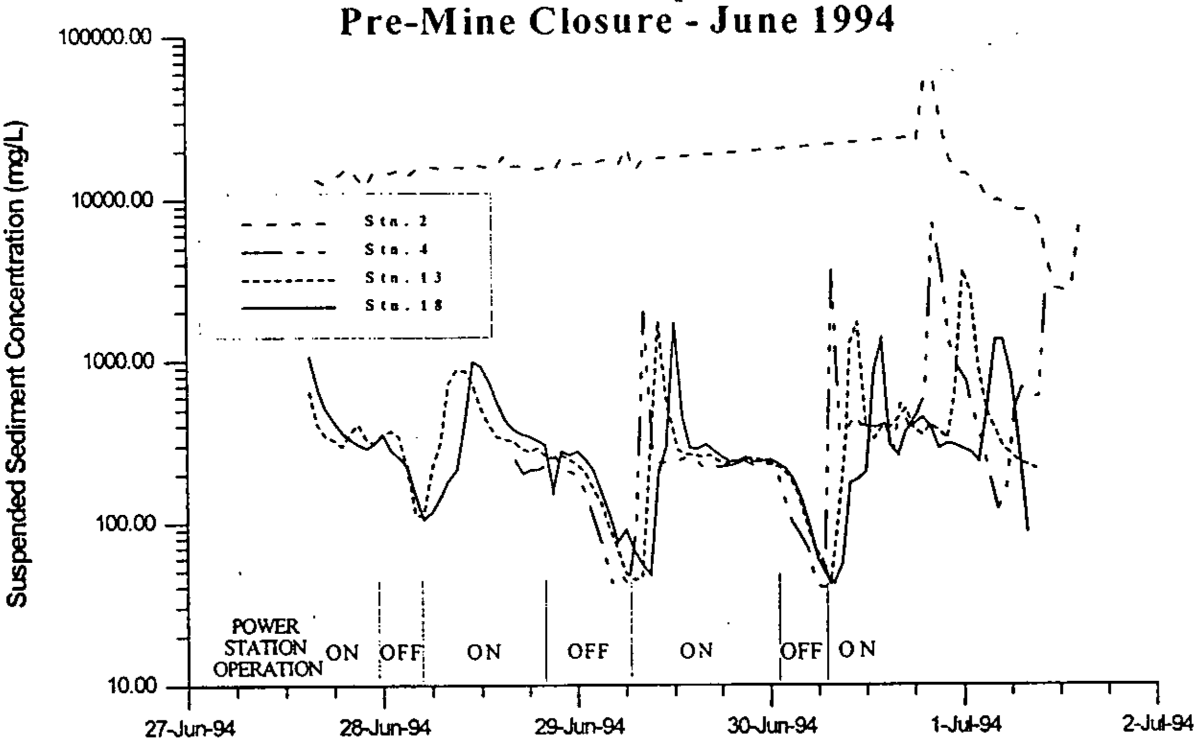
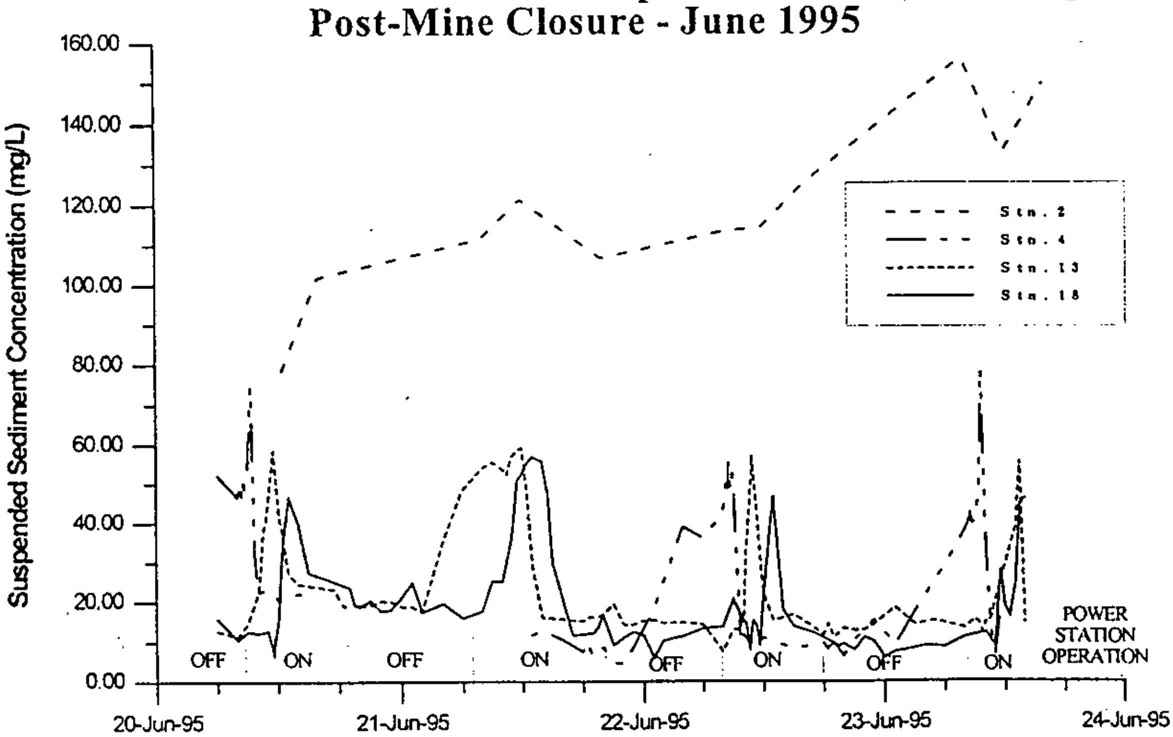


FIGURE 2
Influence of Power Station on Suspended Sediment Transport
Post-Mine Closure - June 1995



result of increased chemical precipitation with distance downstream, or due to the relatively higher availability of sediments within this reach King4. Detailed analyses of the suspended sediment samples and on-going monitoring are required as it is unlikely that the river system has settled into an equilibrium state since the mine has ceased to discharge its tailings.

4.2 Sediment Transport Rates

Table 2 shows a summary of measured sediment transport rates before and after the mine closed. The dramatic decrease in suspended sediment transport rates is clearly evident. There are no significant changes to bed load transport, except for in the Queen River in which the pre-mine closure bed load transport was entirely mine tailings. These transport rates were measured under fairly ordinary conditions of power station operation, with flow ranging from 6 to 110 cumecs, and so they take no consideration of sediment transport during major storm events. Bed load transport rates shown are the maximum measured during normal power station operation.

Sediment Transport Rate (Tonnes/Day)					
		Pre-Mine Closure		Post-Mine Closure	
Station	Reach	Suspended Load	Bed Load	Suspended Load	Bed Load
2	Queen	4,000	189	45	0.01
4	King2	2,000	?	55	0.64
13	King3	2,000	15	73	83
18	King4	2,000	61	90	100
20	King4	?	188	?	37

TABLE 2 - King River Measured Sediment Transport Rates

5. FUTURE PROJECTIONS

Based on the sediment storage locations shown in Table 1, and the measured sediment transport rates summarised in Table 2, a projection of erosion time scales is presented in Table 3. Table 3 ignores the Queen and King1 reaches where there are no significant sediment storages due to the steep gradients. It is assumed that bank sediments, which are mostly fine tailings, will move as suspended load, and bottom sediments which are mostly slag and gravels will move as bed load.

Time scales to erode the sediment storages are seen to depend on the size of the storage; decades for storages in the order of several hundred thousand tonnes, and centuries for storages of several million tonnes. Time scales are deliberately general as erosion will not proceed at the constant sediment transport rates used for this evaluation.

Much of the sediment bank erosion and collapse visible on the King River has been an immediate response to the cessation of tailings discharge. While the mine was still discharging tailings, the older orange-coloured oxidised tailings banks had their river 'faces' regularly coated with the cohesive fresh grey unoxidised silt. Since mine closure this grey silt has dried out and slumped, pulling out sections of the older bank with it.

There are three reasons why bank retreat is unlikely to continue extensively:

1. There is a hardpan coating of iron oxides which forms some stability to the banks faces;

Maximum Erosion Rates					
REACH	Storage Location	Sediment Stored (tonnes)	Probable Transport Mode	Approximate Transport Rate (tonnes/day)	Time Scale for Erosion
KING2	Banks	180,800	Suspended	55	decades
	Bottom	-	-		
KING3	Banks	2,624,000	Suspended	73	centuries
	Bottom	376,000	Bed Load	83	decades
KING4	Banks	384,800	Suspended	90	decades
	Bottom	5,558,400	Bed Load	100	centuries

TABLE 3 - Projected Time Scales for Erosion of Sediment Storages

2. As bank retreat makes the stream widen, stream power will diminish and lessen the energy available for erosion; and
3. The original levee banks should form some sort of natural barrier to erosion.

A realistic maximum distance of bank retreat might be 5m back from the present waters edge. This represents a loss of just over 200,000 tonnes of sediment, or only two months of Mount Lyell's former discharge of tailings.

6. SUMMARY AND FURTHER WORK

The principal findings of this work to date are as follows:

6.1 Sediment Storage

Only a small percentage of tailings remain in the river, the vast majority are in the delta; all slag discharged by the mine remains in the river bottom; and there have been no planform changes to the river system.

6.2 Power Station Influence

The power station has significantly reduced peak flows; it has stopped growth of the sediment banks but caused a short-term increase in bottom deposition at the river mouth upstream of the delta; and it has caused a strongly pulsating pattern of sediment transport.

6.3 Cessation of Tailings Disposal

The suspended sediment load of the river has decreased by orders of magnitude since the mine stopped disposal of tailings, but there is significant chemical precipitation processes occurring and it does not appear to have reached an equilibrium state.

6.4 Future Projections

Erosion of the sediment storages will require time scales in the order of decades and centuries, but it is very unlikely that these storages will ever completely erode at all.

6.5 Further Work

Further work will involve the utilistion of flow and sediment transport models. Mike-11, a one-dimensional unsteady flow modelling package developed by the Danish Hydraulics Institute, has been set up and calibrated for flows in the King River. Sediment transport equations available in the literature are being tested against field measurements of sediment transport. Modelling will be used to answer questions related to river remediation options - for example, what happens to the sediment transport and projected erosion rates if you dredge out the channel or collapse a sediment bank? - and also to project sediment transport rates during major flood events.

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Historical River Metamorphosis of the Cann River, East Gippsland, Victoria

*Wayne D Erskine** *and L.J. White***

ABSTRACT: *At least a 48 km long section of the Cann River has had its channel morphology completely transformed by large scale erosion since 1919. Massive channel erosion was initiated in a large capacity reach near Weeragua by a large flood following clearing of the riparian vegetation. Subsequent river management works in a small capacity reach immediately downstream of the initiation point caused a substantial increase in bankfull stream power which exceeded the stability threshold of 35 W/m². The original sinuous, small capacity, well vegetated stream was converted into a straight, large capacity, eroding river. River management works have now successfully stabilised this channel and are attempting to improve its habitat value.*

1. INTRODUCTION

Many rivers throughout Australia have changed dramatically since European settlement. Schumm (1969) coined the term, *river metamorphosis*, for the complete transformation of river morphology over time. This entomological analogy was made to emphasise that some channel changes are truly catastrophic (Erskine, 1986).

Human impacts on catchments and rivers have been recognised as significant causes of channel changes for a long period of time. Thompson (1938:p28) emphasised that clearing of vegetation from rivers and catchments combined with burning off increased runoff and soil loss rates. As a result, the severity of floods and stream sediment loads also increased. Topsoils were completely eroded in some places exposing subsoils. Timber was often felled directly into rivers causing debris dams and reduced channel capacity. Bare river banks started to erode creating a serious problem. Nevertheless, it does not necessarily follow that all channel changes are human-induced (Erskine, 1986; Brizga and Finlayson, 1990).

River management works should be undertaken following a detailed understanding of historical channel changes. Rivers can substantially alter their cross-sectional size and shape, longitudinal profile, pattern, bedforms and drainage network over short periods of time (Erskine, 1994). To understand the evolutionary stages through which channels develop, it is essential to reconstruct as long a record of channel changes as the available evidence permits. As noted by Wasson and Clark (1985), the past is the key to the present *and* the future. The past can be used to provide analogues of both present and future conditions. A detailed understanding of river channel changes can be used for the practical purposes of explaining present day conditions as well as predicting future trends. This must result in the selection and design of more cost-effective and environmentally sensitive river management works.

The purpose of this paper is to reconstruct historical channel changes on the Cann River, deduce the main causes of these changes and propose suitable strategies for the long term management of the river by the East Gippsland River Management Board. Before addressing these issues, the geomorphology of the study area and the previous approaches to river management on the Cann River will be briefly outlined.

2. CANN RIVER

The Cann River drains a largely forested area of over 700 km^2 in East Gippsland, Victoria (Figure 1). The section of the Cann River investigated here covers the 58 km from the junction of the East and West Branches at Weeragua to Bass Strait (Figure 1). The study area has been divided into 7 reaches which are now described in downstream sequence. The *Weeragua straight reach* is 14km long and extends from Weeragua to Neilson Creek near Noorinbee. A north - south oriented fault strongly controls both valley and channel alignment. Bedrock vertically and laterally confines the channel which has a large capacity with a pool-riffle sequence. The *Cann floodplain reach* is 17km long and extends to about 5km below Cann River township. This reach is characterised by a smaller capacity, active sand bed and a wide floodplain, both of which have substantially changed since European settlement. The *falls reach* is 4km long and is characterised by a series of steep, high granite falls. The *Tonghi straight reach* is 4km long and is a largely alluvial reach sandwiched between 2 bedrock sections. The *Reedy*

* School of Geography, University of New South Wales, Sydney, NSW 2052.
Telephone: (02) 385 4603 Fax: (02) 313 7878 Email: W.Erskine@unsw.edu.au

** I.D. & A. Pty Ltd., PO Box 1372, Sale, Vic 3850.

"To recognise the balance of community values in achieving a compromise between the following aims:
* alleviate or prevent stream related damage to public and private lands, lakes and assets; and
* retain and enhance the amenity of stream systems for the benefit of the general community " (Ian Drummond and Associates, 1988).

The Board is actively trying to create a healthy river by such works as the eradication of willows and wattles growing within the channel, construction of stock exclusion fencing along the top of the banks and revegetation with native species.

4. HISTORICAL RIVER METAMORPHOSIS

The information used in this section includes vertical air photographs (1941, 1961, 1973, 1974, 1979, 1986, 1990), river planform surveys (1876, 1886, 1935, 1970, 1979), channel cross section surveys (1935, 1963, 1971, 1973, 1974, 1983, 1984, 1986, 1993, 1995), hydrological information at 3 river gauging stations, ground photographs (Rural Water Corporation, East Gippsland River Management Board, local landowners and Anderson (1985)), personal interviews with long-term residents, field and aerial inspections, and stratigraphy and palynology of sediment cores from the Cann River estuary and Tamboon Inlet. Channel changes were not initiated until 1919 and have been closely associated with the occurrence of large floods, the clearing of riparian vegetation and the removal of large woody debris from the channel. The following subsections will outline the flood history of the Cann River, the pre-1919 channel and floodplain conditions and the post-1919 channel changes.

4.1 Flood History

Table 1 lists the major floods which have been recorded on the Cann River since 1893. It was compiled from historical sources, rainfall records and river gauging records. While the floods of February 1919 and February 1971 are the largest events this century, the rainfall records suggest otherwise. The reason for this discrepancy is that there are only a few rainfall stations with relatively short records in the catchment and, as a result, they were rarely located at the centre of individual storm cells.

Rivers exhibiting a large range of flood peak discharge are sensitive to flood - induced channel changes (Baker, 1977; Erskine, 1993; 1994). Flood variability is usually measured by the standard deviation of the $\log_{10}$ of the annual maximum flood series. The values for the 3 stations on the Cann River range between 0.542 and 0.671, and average 0.580. These values are similar to those for NSW rivers but are higher than those for most Victorian rivers and indicate that the Cann River has a high potential for large floods. The 1971 flood had a peak discharge at Weeragua which was 12.96 times greater than the mean annual flood. This is close to that for the 1971 flood on the Genoa River (Erskine, 1993) and indicates that flood stream power would have greatly exceeded the usual range experienced by the channel. Therefore, catastrophic erosion should have been expected during this event (Erskine, 1993).

4.2 Channel and Floodplain Conditions Before 1919

The focus of early agriculture was in the valley upstream of Noorinbee. The channel in the Weeragua straight reach before 1919 was certainly a sand-bed stream with a clear bed but well vegetated banks. Channel width was much narrower than it is today. No bedrock was present at the Cann Valley Highway bridge (the Double Bridges) where extensive outcrops are now exposed. The channel in the Cann floodplain reach was sinuous (P=1.60) and exceptionally well vegetated with much coarse woody debris in the bed. We believe that *Tristaniopsis laurina* and *Callistemon palludosus* were very common bankside shrubs.

The floodplain in both reaches was well vegetated in the nineteenth century. Eucalypt forest dominated on the better drained sections with Leptospermum and Melaleucas common in the poorly drained areas. Ringbarking was used extensively to kill the trees (Anderson, 1985).

4.3 Post-1919 Channel Changes

Accelerated bank erosion and channel widening started during the February 1919 flood in the Weeragua straight reach. Further erosion occurred during the August 1919 flood. It has not been possible to identify a specific location as the initiation point, rather erosion seems to have started simultaneously at a number of spatially disjunct sites. Photographs of the Weeragua straight reach taken in the 1920s, 1930s, 1940s and 1950s (Ian Drummond and Associates, 1985; Anderson, 1985, Rural Water Corporation collection), which will be shown at the conference, depict a very wide, active, sand- bed stream with high, bare, eroding banks. The initial isolated erosion sites rapidly expanded and coalesced. The sand generated by the massive widening of the channel on the Weeragua straight reach, produced a sand slug or bed load wave (Erskine, 1994) which propagated progressively downstream through the Cann floodplain reach. The slug produced rapid *granite reach* extends for 4km upstream of the Reedy Creek junction where the channel is laterally and

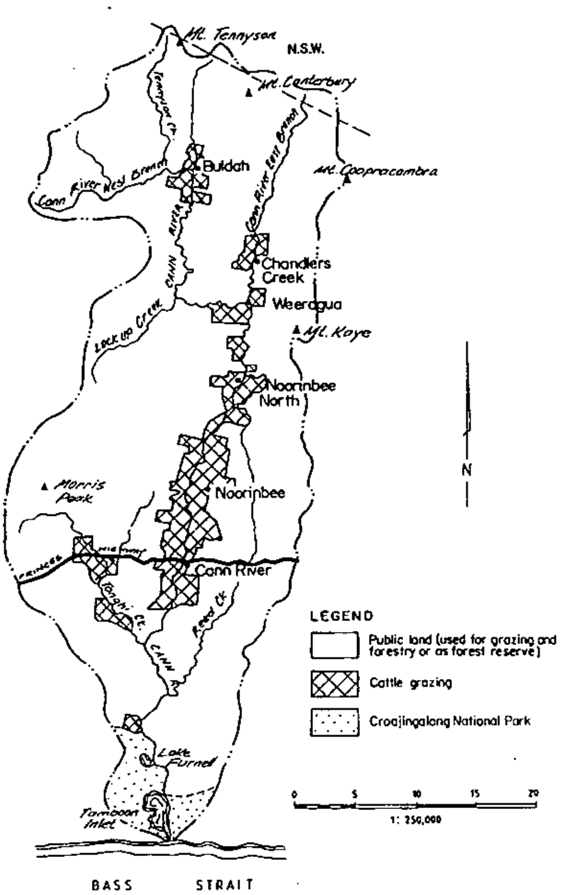

Figure 1 Cann River catchment.

vertically confined by bedrock. Deep pools are present where the channel is laterally confined and divided channel sections are common where the river is vertically confined. The *O'Meara's estuarine reach* extends for 12km from Tamboon Inlet to Reedy Creek and is characterised by deep pools on bends and sandy shallows on cross-overs between bends. Today, the limit of tidal influence only extends to O'Mearas whereas it reached Reedy Creek before 1971. Lake Furnell is a shallow mud basin connected to the Cann River estuary. A well-developed fluvial delta has formed where the Cann River debouches into Tamboon Inlet. The *Tamboon lagoonal reach* is about 3km long and is a coastal lagoon cut along the contact between granite to the east and sand dunes to the west. Harford (1973) has discussed the geomorphology of Tamboon Inlet which is an important recreational resource.

3. RIVER MANAGEMENT

River management of the Cann River has progressed through 3 stages characterised by minimal structural works (before 1963), large scale structural works (1963 to 1989) and riparian zone management (1989 to present).

3.1 Before 1963

Early settlers were preoccupied with clearing vegetation on the floodplain and the river banks, and channel erosion did not become a problem until the flood of February 1919. Between 1919 and 1963 significant erosion problems developed in the Weeragua straight reach and at the upstream end of the Cann floodplain reach near Noorinbee. A total of 13 Rivers and Streams Grants were made by the State Rivers and Water Supply Commission for desnagging, obstruction removal, groyne construction, willow planting and cutting , and channel excavation between 1940 and 1962. These works were largely undertaken by private land holders and generally consisted of desnagging. However many artificial cutoffs were also effected (Ian Drummond and Associates, 1985). The move for the formation of a River Improvement Trust commenced in 1950.

3.2 1963 - 1989

The Cann River Improvement Trust was formed in September 1963 to:

1) clear the channel and Blue Nose Creek (a floodplain drainage line near Cann River) downstream of Noorinbee;
2) protect the natural levees from erosion and prevent an avulsion into Blue Nose Creek ; and
3) protect eroding banks (Ian Drummond and Associates, 1985).

The trust district was a riparian corridor from just upstream of Weeragua to the Tonghi Creek junction (Figure 1). To 1985, $2.162 million were spent on river works. The Trust carried out a lot of desnagging in its first 3 years and then started river training works (including artificial cutoffs), similar to those described by Erskine (1990; 1992) in the Hunter Valley. An artificial levee was built for 5 km upstream of the Princes Highway to prevent the avulsion of the Cann River into Blue Nose Creek. Restoration works of $1 million were completed after the 1978 flood and the Country Roads Board funded $140000 of alignment works near the Princes Highway. Retard fields and rock breaching were built after 1978.

3.3 1989 - present

The Cann River Improvement Trust was replaced by the East Gippsland River 'Management Board in 1989. The new Board was whole - of - catchment based and had much broader objectives, namely:

aggradation and directly caused channel straightening by natural cutoffs. However, at least 16 artificial cutoffs were also constructed .

The downstream progression of the sand slug is shown on the aerial photographs by the conversion of a well vegetated, sinuous channel into a straighter,

Flood Month	Flood Year	Peak Instantaneous Discharge (ML/d)	Maximum Monthly Rainfall (mm)
Dec	1893	N/A	451 [1]
Feb	1919	N/A	311 [2]
Aug	1919	N/A	337 [2]
Mar	1938	N/A	530 [1]
June	1952	N/A	263 [3]
May	1956	N/A	310 [3]
Jan	1971	24 600 [5]	324 [4]
Feb	1971	53 800 [5]	261 [4]
June	1978	23 600 [5]	470 [4]

1- Noorinbee (084026) gauge
2- Tonghi Creek 1 (084066) gauge
3- Cann River Forestry (084027) gauge
4- Tonghi Creek PO (084072) gauge
5- Cann River (West Branch) at Weeragua gauge (2212018)

Table 1. Major floods on the Cann River

wider stream with well developed sandy point bars and side bars. Downstream propagation rates were relatively slow before the 1971 floods. In 50 years, the sand slug moved 10 km (200 m/a) but during the 1971 floods the whole channel between the Cann Valley Highway bridge and the start of the falls reach was substantially widened and infilled with sand . Further erosion was continued by the June 1978 flood. The 1979 air photographs depict a very wide sand-bed stream with a bar braided pattern. Sand oversupply produced bed aggrdation which, in turn, caused the development of small but numerous longitudinal bars. By 1986, the extent of the longitudinal bars had been reduced and transverse and side bars had started to replace them as rapid bed degradation occurred. This is still continuing today.

Between 1886 and 1935, the sinuosity of the channel in the Cann floodplain reach varied slightly between 1.57 and 1.60. By 1970, sinuosity had declined to 1.23, a trend which has continued to the present day (P=1.10). In 1935, the mean bankfull cross-sectional area in the Cann floodplain reach was 42.3 m^2, width was 19.5 m and mean depth was 2.13 m. By 1970, the mean bankfull channel geometry had increased to an area of 102.0 m^2 (141% increase), a width of 49.3 m (153% increase) and a mean depth of 2.02 m (5% decrease). By 1995, there had been further channel enlargement with the mean bankfull channel geometry having a cross-sectional area of

Reach	Channel Erosion (t/km^2/yr) 1935-1970	1970-1995	1935-1995
Weergold straight reach	N/A	N/A	27.7
Cann floodplain reach	69.8	203.5	128.0

1- data only exists for the section between the Cann Valley highway bridge and Neilson Creek (6.5 km).

Table 2 Sediment yields produced by channel erosion on the Cann River

249.2 m^2 (144% increase since 1970), a width of 82.9 m (68% increase since 1970) and a mean depth of 2.97 m (47% increase since 1970). The change in mean bankfull channel geometry between 1935 and 1995 was a 489% increase in cross-sectional area, a 325% increase in width and a 39% increase in mean depth. While the increase in width has been progressive, depth first decreased, due to the passage of the sand slug, and then increased by degradation following the passage of the sand slug. Ian Drummond established 5 cross sections in the Cann floodplain reach in 1983 to determine bed level dynamics. These sections were resurveyed in 1984, 1986, 1987, 1993 and 1995 and demonstrate that there has been up to 1m of bed degradation since 1983, although the trend is not continuous and progressive.

The volume of sediment eroded by recent channel enlargement can be estimated by comparing the channel network volume at various time periods (Table 2). The volume of sediment eroded between each survey was equated to the increase in channel network volume. This volume was converted to mass by assuming a bulk density of 1.6 t/m^3. Specific sediment yields were calculated for a catchment area of 670 km^2 which corresponds to that at the downstream end of the Cann floodplain reach. Given that the bulk of the 1970 to 1995 erosion occurred during the 1971 floods, the 1970-1995 and 1935-1995 yields should be viewed as minimum rates only.

Nevertheless, those yields greater than 100 t/km^2/yr are comparable to the highest yields recorded in temperate south-eastern Australia from agriculturally disturbed catchments (Olive and Rieger, 1986) and further demonstrate that channel erosion alone can produce all of the sediment yield from a catchment for short time periods (Erskine 1994). In keeping with the results of Erskine (1993;1994), a catastrophic flood has again produced massive channel enlargement.

The 1971 flood and the large volumes of sand generated by upstream channel erosion completely destroyed the pre-1971 channel in the falls, Tonghi straight, Reedy granite and O'Meara's estuarine reaches. Essentially all of the pools evident on the 1941 and 1961 air photographs were completely infilled with sand. Furthermore, the limit of tidal influence was displaced at least 4 km downstream by bed aggradation. Below the tidal limit, there has also been substantial aggradation at cross-overs between bends. Estuarine sedimentation represents deposition of the coarse bed load sediments. In an effort to assess the affects of historical river metamorphosis on mud deposition, sediment cores were collected from Tamboon Inlet, the fluvial delta and Lake Furnell. The first presence of such introduced pollen taxa as *Pinus* and *Plantago lanceolata* was taken as the time of European settlement. Up to 0.45m of post-European sediment has been found and this depth far exceeds that recorded in neighbouring lakes and lagoons. It is assumed that most of this sediment was deposited during the 1971 floods.

5. CAUSES OF CHANNEL CHANGES

River metamorphosis was caused by the interaction of the following 4 factors. Firstly, erosion was initiated by a large flood in February 1919 and was continued by subsequent large events in 1938, 1952, 1956, 1971 and 1978. Undoubtedly, the 1919, 1971 and 1978 floods were the most significant. The high flood variability of the Cann River means that large events occur relatively frequently and predispose the channel to erosion by the high stream powers generated by these large events (Erskine, 1994).

Secondly, riparian and particularly bankside vegetation in the Weeragua straight reach was cleared for access to water and river crossings, and by stock, exposing the underlying sandy sediments. The channel was stable until bank resistance was reduced by vegetation removal in the early part of this century.

Thirdly, there are marked spatial changes in bankfull stream power between the Weeragua straight reach and the Cann floodplain reach. In 1935, bankfull unit stream power in the Weeragua straight reach was 72 W/m^2 but in the stable section of the Cann floodplain reach, it was only 27 W/m^2. Brookes (1988) found that channels with low unit stream power do not have sufficient energy to modify their boundary. He proposed that a critical value of 35 W/m^2 discriminated between stable and unstable rivers. Once stream power exceeds 35 W/m^2, channel erosion and/or alignment instabilities usually develop. The Weeragua straight reach was more sensitive to disturbance than the Cann floodplain reach because of its higher channel capacity and hence stream power.

Fourthly, the extensive desnagging and channel straightening carried out by the Cann River Improvement Trust between 1963 and 1970 increased stream power in the Cann floodplain reach to such an extent that it exceeded the threshold of 35 W/m^2. The 1970 data yield a mean bankfull unit stream power of 70 W/m^2 and the 1995 data, a mean of 74 W/m^2. River management works directly contributed to the channel erosion effected by the 1971 floods.

6. RIVER MANAGEMENT STRATEGIES

The existing bankfull unit stream power in both the Weeragua straight and Cann floodplain reaches exceeds 35 W/m^2. Therefore, both reaches are potentially capable of reworking their channel boundaries. Bank erosion is currently not occurring because of the extensive bank protection works (rock beaching, groynes, training fences, etc.) and the dense riparian vegetation, particularly willows. However, bed degradation is still active in the Cann floodplain reach, except where 3 rock chutes have been constructed. Bed armouring and bedrock bars have successfully stabilised the bed in the Weeragua straight reach and armouring is developing by selective winnowing of the finer bed material at the upstream end of the Cann floodplain reach. Nevertheless, degradation will continue to progress downstream until a static armour layer forms, or until relatively non-erodible sediment is exposed or until slope is reduced to a value below that required for bed-material transport. We predict that the channel is now actively recovering from the metamorphosis of 1919 to 1978. This recovery phase is thought to progress through a series of intermediate steps from the large capacity, straight, bare channel to a small capacity, sinuous, well vegetated stream. This prognosis is supported by the presence of at least 5 abandoned channels on the floodplain in the Cann floodplain reach. These abandoned channels are very similar in morphology to the pre-1919 channel and were abandoned by avulsions. The new channels next to the abandoned ones had evolved to the stage where they mimicked the parent stream before the recent metamorphosis.

Riparian landowners do not want to recreate the pre-1919 channel because of poor floodplain drainage. Similarly, they do not want to maintain the 1978 channel because of the rapid erosion. To maintain the present channel in a stable state requires the maintenance of dense bankside vegetation but the removal of vegetation, particularly willows, from the bed and bars. Willow replacement by native riparian vegetation should be progressively implemented and habitat creation for fish should be attempted. Stream monitoring must be carried out to detect changes in morphologic state. Gravel seeding for the creation of rhythmically-spaced, artificial riffles is suggested to assist in the formation of a pool-riffle sequence.

7. CONCLUSIONS

Historical data show that the Cann River at the township of Cann River has metamorphosed from a small capacity, sinuous, well vegetated snag-filled channel to a large capacity, straight, bare, eroding stream since 1919. Erosion was initiated upstream in a sensitive reach of higher stream power due to the interaction of riparian vegetation clearing and the episodic occurrence of large floods. This erosion progressed downstream and was accompanied by the passage of a sand slug. Since 1978, the channel has been stabilised by river management works. Riparian landowners do not want the recreation of the original channel nor the maintenance of the 1978 stream. River management is expected to short circuit the natural channel evolution by maintaining a large capacity, straight, well vegetated stream. Willows will be selectively replaced by natives and instream habitat will be recreated.

8. ACKNOWLEDGMENTS

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Palynology techniques: A useful tool for Integrated Catchment Management.

by *Christine Kenyon, **Elizabeth Anthony, and ***Ivars Reinfelds.

ABSTRACT: *Stratigraphic and pollen studies can extend and complete contemporary environmental information required for Integrated Catchment Management. In Australia, post-European sediments are easily identified by the presence of introduced pollen. Yarra River pollen data verify stratigraphic analyses that indicate the lower reaches of the river act as a sediment sink. The Latrobe River and Lake Wellington pollen studies give data on floodplain and lake sediment deposition, storage and pollution transport. Historical vegetation responses to land-use change are also apparent and management implications are discussed.*

1. INTRODUCTION

Integrated Catchment Management utilises data from many sources to consider sediment mitigation, nutrient transport and pollution problems within catchment systems. Prediction is a major component of these management strategies that often incorporate a "return to natural systems" component. These natural systems operate over time scales beyond those generally considered by land managers. Effective Integrated Catchment Management needs a long term historical component to augment contemporary monitoring programs (Grayson et al., 1994 and Clark and Wasson, 1988).

Instrumental data is broadly based and only of general use for current specific catchment management problems. The introduction of European grazing, agriculture, industry and urbanisation had a rapid and extensive impact on the Australian landscape disrupting Aboriginal land-use practices and altering established fire regimes. Many of these changes were not recorded and as a result historical accounts of the impact of settlement are sparse, incomplete, short and Eurocentric. To resolve modern environmental resource issues concerning vegetation, soil and land-use interactions with increased accuracy, additional techniques such as fossil pollen and stratigraphic analysis techniques are required to augment the contemporary historical and instrumental record (Clark, 1986; Gell et al., 1994).

In Australia, the presence in the stratigraphic record of pollen from introduced plants such as *Pinus, Salix, Plantago* and *Rumex* indicates the beginning of European settlement. This boundary enables comparisons to be made between the pre-settlement landscape and the effects of European land-use. Recent pollen studies have begun to consider the environmental issues of sedimentation, erosion, hydrologic and vegetation changes related to European impact (Clark, 1986; Reid, 1989; Gell et al., 1993; Rutherfurd and Kenyon, in prep.).

This paper shows that fossil pollen analysis is a powerful tool that can be incorporated into Integrated Catchment Management studies. The specific objectives of this paper are to demonstrate: 1) the presence of pollen from introduced plant taxa provides a chrono-stratigraphic marker that delineates pre- and post- European sediments and vegetation thus providing a precise relative dating tool for sediments; 2) pollen assemblages within sediments give information on the patterns and extent of sedimentation and sediment source areas within the catchment and 3) pollen analysis provides a complete extended historical record of vegetation changes and responses to land-use and urban development.

Two examples are used to illustrate these assertions. The first is a combined study from the lower Yarra River and its delta, in the Melbourne urban area. The second is a combined study of sediments from the Latrobe River and Lake Wellington, Victoria. These studies give preliminary results of work-in-progress.

2. SITE DESCRIPTIONS

The lower Yarra River study area extends from Dights Falls to the city of Melbourne. Downstream of the city the river is bordered by a delta that extends into Hobson's Bay (Fig. 1). For the lower reaches of the river few surveys are available (Brizga et al., 1995). Historical and modern vegetation data for the delta and Melbourne area are incomplete and contain little specific local information (Anthony, 1994). Since European settlement extensive alterations to the river channel, floodplain, and the natural habitat of the delta have been numerous. These include draining and infilling of wetlands, dredging, widening and changing the course of the river and levelling hills and costal sand dunes (Anthony, 1994; Brizga et al., 1995).

The Latrobe River in Gippsland, Victoria, drains a catchment of approximately 5,200 km^2 before emptying into Lake Wellington (Fig. 2). The lower reaches of the Latrobe River are highly disturbed, having been subjected to extensive channelisation strategies that included clearing of riparian vegetation, river de-snagging, artificial meander cut-offs and more recently, reinstatement of meander cut-offs (Reinfelds et al., 1995). Overburden from brown coal mining has in the past, been sluiced into the river and historical accounts attest to the

*Department of Geography and Envrionmental Studies, University of Melbourne, Parkville, Victoria, 3052. **48 Outlook Rd, Mount Waverley, Victoria, 3149. ***Department of Geography and Environmental Science, Monash University, Clayton, Victoria, 3168.

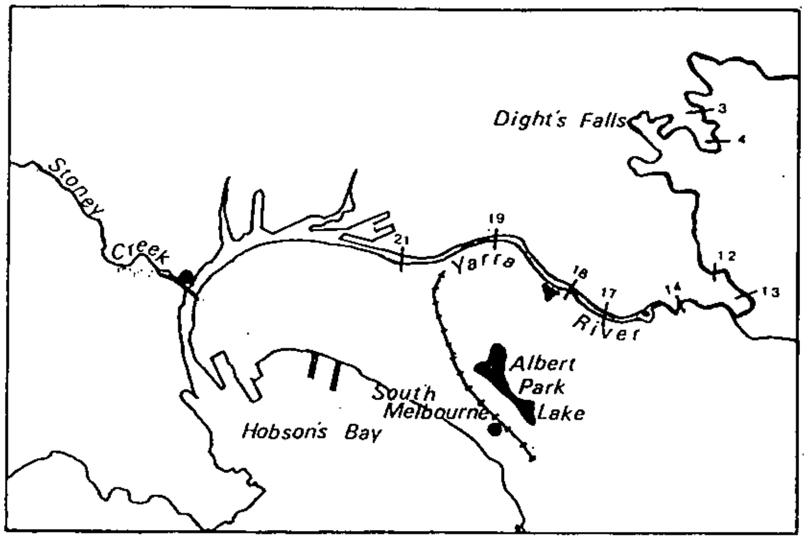

Figure 1. Map of the lower reaches of the Yarra River, Stoney Creek and South Melbourne. Numbers indicate river reaches from which cores were obtained for pollen analysis.

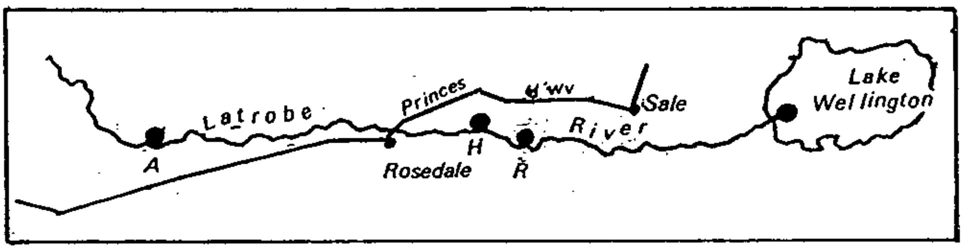

Figure 2. Map of the lower Latrobe River and Lake Wellington showing river and lake core sites. Core sites are A - Archibald's cutoff; H - Holey Plains and R - Robertson's cutoff.

accumulation of coal in the river bed (Erskine et al., 1990; Reinfelds et al., 1995).

3. METHODS

Several sites along the lower Yarra River and its delta were probed to determine sediment depths and locate suitable coring sites (Fig. 1). The Stony Creek Backwash core was taken using a D-section corer (Anthony, 1994). Cores at all other sites were obtained by hammering a 50 mm PVC tube into the sediments (Gippel et al., 1994; Brizga et al., 1995). All cores were sealed, labelled and sampled in the laboratory for pollen after core stratigraphies were recorded.

Samples chosen for pollen analysis were based on the occurrence of major stratigraphic changes and the absence of European artefacts in the sediments. The two delta cores were sampled at more frequent intervals (fine resolution) to provide a continuous chronological record of local vegetation change. The surface of each core was clean and 1 cm thick slices were cut at selected depths. From these slices 1-3 cm^3 samples were taken and prepared for pollen according to the methods of Faegri and Iversen (1975). Pollen preparations were stored in a known volume of silicon oil. Aliquots were placed on microscope slides, covered and sealed. Wherever possible, a pollen sum of 100 dryland pollen grains were counted for each sample at x400 magnification using a binocular microscope. Relative percentages of the pollen sum were then calculated for each taxon.

Pollen types identified were grouped into the following vegetation communities indicative of important environmental conditions: Exotic taxa; wet sclerophyll taxa that also include riparian vegetation elements; tree ferns; coastal taxa and pollen from Tertiary age brown coal deposits.

4. SEDIMENTS

4.1 Lower Yarra River

The objectives of these two studies were to:
1) describe the location and age of sediment deposits in the river channel, identify likely sediment sources, and to examine the implications of sediment processes for waterway management (Brizga et al., 1995); and 2) identify the vegetation communities and provide a history of environmental change relevant to park management and revegetation programs (Anthony, 1994).

For detailed descriptions of all cores see Anthony (1994) and Brizga et al (1995). Pollen data from nine riverbed cores shows that brown fluvial deposits in the Yarra River cores are modern while mottled clays and grey estuarine sediments are pre-European (Table 1). The grey clays at South Melbourne are similar to the grey Yarra River clays.

However, pre-European brown fluvial sediments were identified at Stony Creek (Anthony, 1994). Sediment colour and texture are therefore not definitive indicators for identifying pre- and post-European deposits. Deterimation of the time of deposition can be verified using pollen analysis techniques. Sediment depth increases in the downstream reaches where channel modifications and dredging have occurred in the estuary.

Sample Site	Sample Depth	Sediment	Exotic Pollen
Stony Creek	70 cm	silt & sand	PRESENT
Stony Creek	150 cm	clay & silt	ABSENT
South Melbourne	7 cm	grey clay	PRESENT
South Melbourne	16 cm	organic clay	ABSENT
21	285 cm	fine silt	PRESENT
19	95 cm	sandy clay	PRESENT
19	101 cm	grey clay	ABSENT
18	130 cm	fluvial silt	PRESENT
18	140 cm	estuarine clay	ABSENT
17	#115 cm	mud & sand	ABSENT
14	140 cm	sandy clay	ABSENT
13	50 cm	sand & clay	PRESENT
13	#60 cm	mottled clay	ABSENT
12	80 cm	fluvial clay	PRESENT
12	#115 cm	mottled clay	ABSENT
4	62 cm	silt & sand	PRESENT
3	30 cm	silt & sand	PRESENT

Table 1. Shows the presence or absence of introduced pollen grains and sediment type in selected Yarra River samples . # denote samples with no or very little pollen present.

4.2 Lower Latrobe River

Cores from three floodplain billabong sites along the lower Latrobe River were obtained to investigate whether the infilling sediments provide a record of coal pollution in the river as suggested by the historical accounts, and to identify changes in the character of flood-load sediments resulting from European settlement (Reinfelds, in prep.). The management authority responsible for the Latrobe River and Lake Wellington (Gippsland Water) were concerned that sedimentation rates in Lake Wellington had increased sixfold as a result of the extensive European impacts on the Latrobe River catchment and channel (Craigie et al., 1991). This second study aimed to provide data from the Latrobe River delta to determine the importance of bedload sediment delivery and change in sedimentation rates for Lake Wellington to help improve water quality management targets (Grayson et al., (1994).

At Archibald's cutoff in the upper reaches of the study area a change from silt-clay to sand dominated sediments is associated with the appearance of pollen from introduced and Tertiary age taxa at a depth of 106 cm in the core (Table 2). Although substantial erosion in the river was documented from historical data (Reinfelds et al., 1995), pollen analyses enabled the onset of European settlement to be associated with the switch from silt-clay to sand dominated flood-load sediments. Pollen analyses downstream at Robertson's cutoff reveal that black coloured sediment strata are indeed contaminated with coal as they contain a large proportion of Tertiary age pollen (Table 2) which can only originate from the Latrobe Valley brown coal deposits. Sediments from other strata in Robertson's cutoff contain no Tertiary pollen (Table 2). Although pollen analysis has proved extremely useful to determine the nature of the contaminants causing the black staining of sediment strata, further research is necessary to investigate whether the coal can be attributed to sluicing of mining overburden into the river or, whether it is a 'natural' phenomenon associated with channel incision into riverbed coal seams resulting from the emplacement of artificial meander cut-offs (Reinfelds et al., 1995; Reinfelds in review).

ROBERTSON'S CUT-OFF	Depth (cm)	**96**	**160**	**270**	**274**
	Eucalyptus	14	17	37	17
	Wet forests	14	27	19	18
	Exotics	4	3	4	1
	Grasses	4	0	6	14
	Tertiary	17	17	0	0
HOLEY PLAINS	Depth (cm)	**206**	**211**	**279**	
	Eucalyptus	29	34	30	
	Wet forests	11	7	20	
	Exotics	4	0	0	
	Grasses	26	15	11	
	Tertiary	5	9	1	
ARCHIBALD'S CUTOFF	Depth (cm)	**43**	**82**	**106**	**213**
	Eucalyptus	15	22	38	53
	Wet forests	6	5	37	13
	Exotics	2	6	1	0
	Grasses	34	7	1	1
	Tertiary	12	8	3	0

Table: 2. Latrobe River Billabong sites. Pollen assemblages expressed as percentages of the pollen sum at selected depths from three sites along the Latrobe River.

Pollen analyses of samples from seven cores located in the Lake Wellington Latrobe River delta indicate the sediment deposition rate has increased only twofold to 1 mm/year since European settlement (Grayson et al., 1994), and not sixfold as had been originally suggested. Post-European sediments entering Lake Wellington contain more fine sand and silt than pre-European sediments and these are sufficiently fine to carry large nutrient loads into Lake Wellington, with phosphorus loads increasing fourfold since European settlement (Grayson et al., 1994). The increase in Tertiary age pollen in the modern lake sediments is another indicator that pollution is being transported in fine sediments by the river and deposited in Lake Wellington.

5. VEGETATION

As well as illustrating the usefulness of pollen in determining modern sedimentation deposition patterns, pollen data also show major changes between the pre- and post- European vegetation along both the Yarra and Latrobe Rivers despite the coarse sampling strategy. The finer sampling regime used at South Melbourne shows progressive changes over time in more detail. Post- European pollen spectra provide an indication of land-use changes within both catchments.

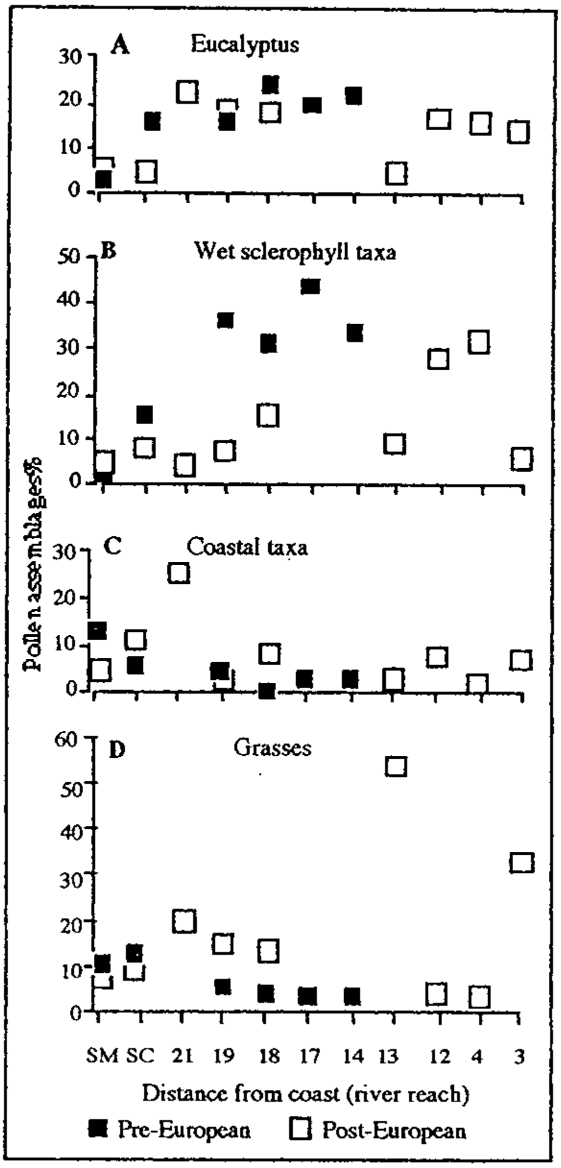

Figure 3. Vegetation communities identifed in the pollen assemblages from Yarra River and delta cores (Fig 1) showing major vegetation changes along the river since European settlement. SM - South Melbourne; SC - Stony Creek Backwash.

Early vegetation records for Melbourne describe coastal grassy shrublands and wetlands with open *Eucalyptus* woodlands along the floodplain. These environments are reflected in the pre-European pollen data (Fig. 3). Since European settlement the pollen data mirror vegetation changes associated with urban development in the Melbourne region and Yarra catchment (Kenyon, 1995). All Yarra river sites (Fig. 3) generally record increases in grasses, but *Eucalyptus* increases only near the delta. The high grass values in reaches 3 and 12 reflect in-river stands of the common reed, *Phragmites*. The increased wet sclerophyll component include tree ferns and Myrtle Beech (*Nothofagus cunninghamii*) (Kenyon, unpubl. data) indicating increased sediment transport and its deposition at these sites from the upper catchment region, possibly a result of land-use changes. Riparian vegetation also includes wet sclerophyll components and the decline, downstream may reflect local riverbank clearance. *Allocasuarina* is commonly used in revegetation programs. This is seen in the record as an increase in the coastal elements of which *Allocasuarina* is a component.

The fine resolution study at South Melbourne (Fig.4) gives a continuous record of change. Pollen from pre-European sediments (Aboriginal phase) showed an open grass and shrub community dominated by Lamiaceae (*Westringia*) and *Pomaderris* consistent with the early historical records (Hannaford, 1856). The pollen representation changed significantly during Early European settlement. Used extensively for grazing, the local coastal open woodland became a closed shrubland of *Pomaderris*. With urbanisation and massive vegetation clearance an open simple community of weeds, grasses and herbs developed. A decline in exotic pollen and an increase in native species due to garden plantings and revegetation of parklands is indicative of the current Revegetation Phase. At Stony Creek Anthony (1994) has described an increase in *Allocasuarina* pollen and a decline in exotic pollen in the upper section of the core reflecting revegetation programs begun in the 1980's. High *Allocasuarina* values were not seen in the pre-European sediments at Stony Creek.

The lower floodplain of the Latrobe River was initially settled because of its fine grazing qualities. A more detailed study of the pollen record from Lake Wellington (Fig. 5) shows decreases in *Eucalyptus* and increases in grasses associated with the development of grazing pasture. These changes have been progressive since settlement began in the region. Increases in Tertiary age pollen from brown coal pollution is also evident. *Ruppia*, a salt tolerant species, was present in the lake pollen spectra (Kenyon, unpubl.data). Its presence can probably be associated with the artificial opening of the Gippsland Lakes to the sea.

6. MANAGEMENT IMPLICATIONS

The two case studies presented here illustrate that pollen analysis is an extremely useful technique for Integrated Catchment Management that can supplement historical data and contemporary

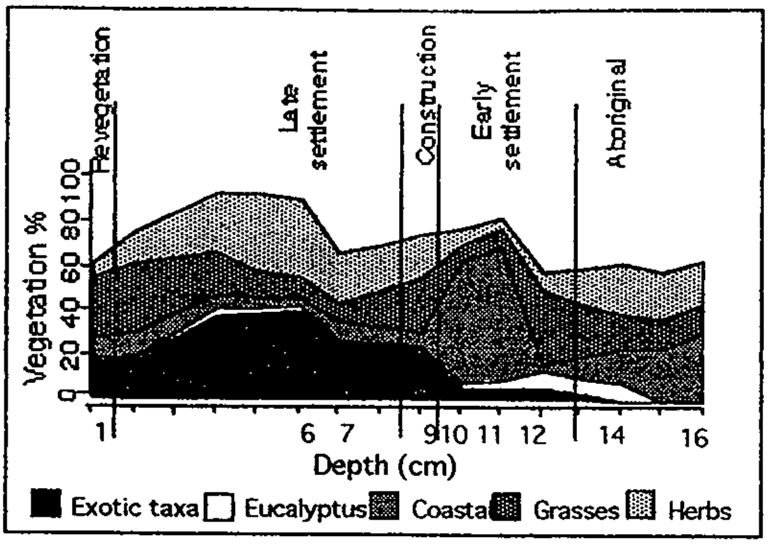

Figure 4. Pollen diagram from South Melbourne illustrating changes in vegetation communities through time in response to land-use changes.

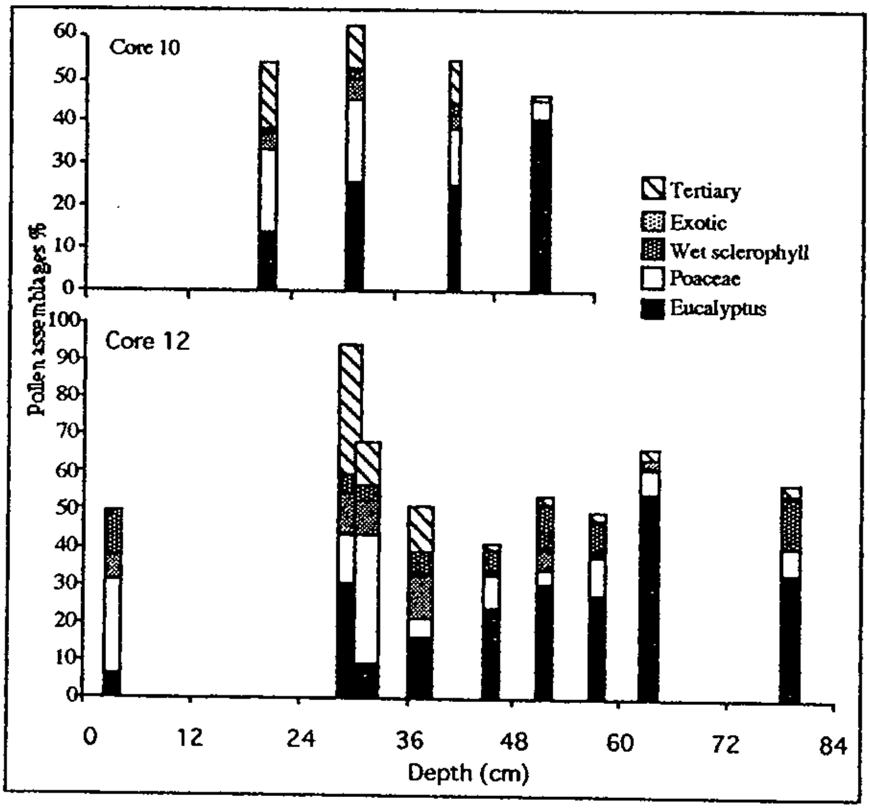

Figure 5. Histograms of 2 cores from the Latrobe River delta, Lake Wellington illustrating the general trends over time in selected pollen assemblages.

monitoring programs. It also provides a relative dating tool marking the post-European contact in the stratigraphic record enabling identification of historical changes in catchment and riparian vegetation responses to land-use. Comparison of the pre-European and post-European stratigraphic record provides baseline data with which to assess sedimentological and hydrological changes in rivers following European settlement.

The Yarra catchment pollen study was integrated into a multi-disciplinary study incorporating geomorphological, hydrological and historical data. The pollen record has helped provide a better understanding of the processes affecting sediment transport and deposition processes within the river channel from which a management plan for the lower reaches of the Yarra River is currently being developed. Vegetation changes over time provide important insights into local historical and ecological processes in the area that can be used as a guide for better resource allocation for catchment and riparian managers when planning revegetation projects.

From the lower Latrobe River it has been determined that the coarse sediments eroded from the river channel are being deposited in the Latrobe River floodplain. The deposition of fine sediments in Lake Wellington is not as great as previously believed and need not be a management priority (Grayson et al., 1994). The fine sediments entering the lake however, carry large nutrient loads and coal pollution. The presence of Tertiary pollen in the sediments has been used to identify coal pollution and transport since European settlement. With regard to the Lake Wellington management study, pollen analysis in conjunction with stratigraphic analysis was instrumental in shifting the management focus from sediment mitigation to nutrient mitigation (Grayson et al., 1994).

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The Role of Non-Structural Options in the Management of Laterally Unstable Streams in North-Eastern Queensland

S.O. Brizga[1], M.F. Carden[2] and N.M. Craigie[3]

ABSTRACT: *Many rivers in north-eastern Queensland are naturally prone to lateral instability due to meander migration, cutoffs, avulsion, and fluctuations in channel width. Conflicts between these processes, and assets which are fixed in location have led to management problems. Traditionally meander migration has been addressed by works aimed at arresting stream movement. It is argued that a non-structural approach may be more appropriate in some situations for economic and/or environmental reasons. A preferred management strategy would include structural and non-structural approaches.*

1. INTRODUCTION

Lateral instability is a significant management issue on the rivers and streams which flow across the coastal plain of north-eastern Queensland. Channel changes apparent over the period of European settlement include shifts in position resulting from meander migration, cutoffs and avulsion; as well as fluctuations in channel width in response to temporal variations in streamflows and flooding.

Climatic, hydrologic and physiographic factors pre-dispose these rivers and streams to channel instability. The area is subject to tropical cyclones, which are often associated with major flooding. Interannual streamflow and flood variability is high, especially in the less humid areas (Finlayson and McMahon, 1988); and phases of above- and below-average streamflows and flooding have been observed (Gourlay and Hacker, 1986), similar to those reported in south-eastern Australia (e.g., by Erskine and Warner; 1988; Brizga et al, 1993). The major coastal streams rise in mountainous terrain of the Great Dividing Range, and then plummet steeply down to the coastal plain. High relief and steep slopes set the scene for mass movements such as landsliding, which lead to episodic influxes of sediment into the waterways.

Many of the major streams of north-eastern Queensland are also large by overall Australian standards, for example, the Burdekin River at Home Hill has a catchment of 130,000 km^2 and a channel 750 m wide. Minor alterations in channel planform can thus result in considerable bank retreat, as viewed from a human perspective.

The expectations of the early settlers were influenced by their experience of the relatively stable or tamed streams of Britain and Europe. Community attitudes to waterway management have long been underlain by the expectation that river channels should be laterally stable, an expectation not met by the natural behaviour of many of the streams of north-eastern Queensland. Problems have arisen because of the conflict between dynamic natural channel and floodplain processes, and assets which are fixed in location (e.g., cane fields, roads, tramways, bridges, remnant vegetation). River management in north-eastern Queensland, as in the rest of Australia, has historically had a focus on structural measures as a means of dealing with bank erosion and other forms of channel instability.

The desirability of total stabilisation of rivers has been questioned in recent years. European studies have revealed ecological problems resulting from channel stabilisation, such as ecological simplification favouring later successional stages of ecosystems which under natural conditions would have been "reset" by reworking of the stream bed and floodplain (Roux et al, 1989). In the Netherlands, works are being carried out to provide for some limited channel instability to maintain or restore ecological diversity (Nieuwenhuijzen et al, 1993).

Waterway managers are today faced with a broad objective: to maintain or restore waterways to a condition which can sustain viable utilitarian uses and protect significant remnant aquatic and riparian habitat, whilst taking all opportunities to enhance overall environmental quality.

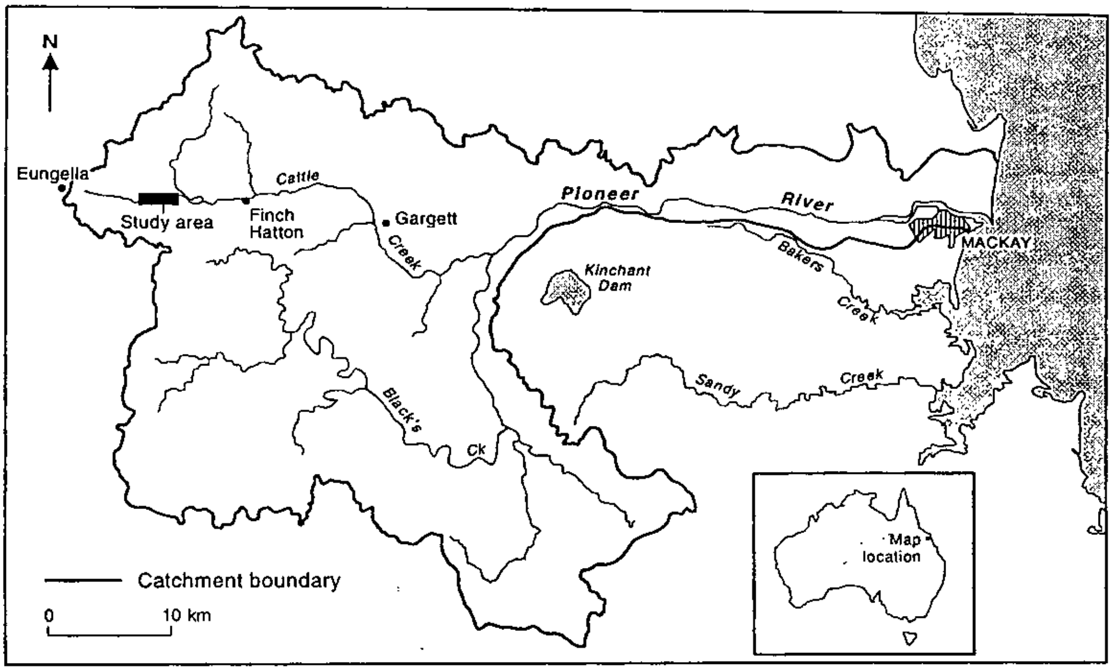
This paper examines the management of meander migration on rural streams, using a reach of Cattle Creek as a case study. A structural approach is outlined and evaluated using benefit-cost analysis, non-structural alternatives are considered and then a preferred management strategy is briefly described. The management of other forms of lateral instability is beyond the scope of the present paper, although it is recognised as an important issue.

2. THE STUDY AREA

Cattle Creek is a major tributary of the Pioneer River, which flows through the city of Mackay in north-eastern Queensland (Figure 1). Cattle Creek rises at Eungella at an elevation of more than 700 m, and to the north, south and west the catchment is bounded by mountainous terrain. Extensive deposits of Quaternary sediments are found within the valleys of Cattle Creek and its major tributaries, although outcrops of older basement rocks such as the Carboniferous-Mesozoic rocks of the Urannah Igneous Complex are exposed in the stream beds in some areas.

[1] S. Brizga & Associates, P.O. Box 68, Clifton Hill Vic. 3068. Telephone/fax: (03) 9482 6885.
[2] Department of Geography and Environmental Studies, University of Melbourne.
[3] N.M. Craigie & Associates

Figure 1: Location of Cattle Creek, North Queensland.



The steep headwater areas of the catchment retain their forest cover, and much of this is protected in the Eungella National Park. The lower hills and floodplains and terraces are used for cane growing and grazing.

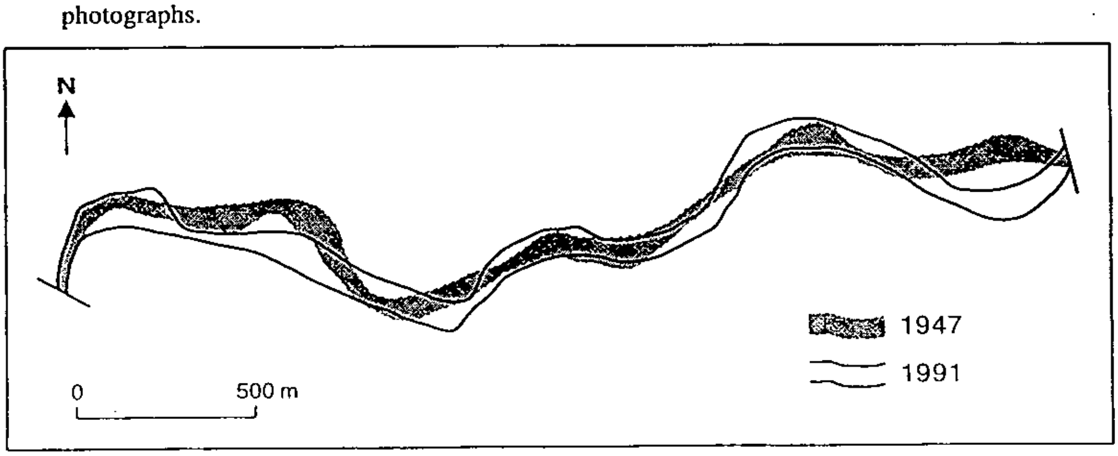
2.1. Geomorphological Processes

Cattle Creek has a history of being troublesome to waterway managers and adjacent landholders. A review of historical data including comparisons of recent and historical aerial photographs carried out by the senior author (reported in GHD, 1995) revealed changes in channel position resulting from meander migration and avulsion. Expansion and contraction of channel width associated with temporal variations in flood activity was also observed. Influxes of landslide debris have led to catastrophic changes, especially at the upstream end of the valley where steep tributaries fall directly into Cattle Creek. Bed degradation has generally not been a problem in Cattle Creek because of the control exerted by bedrock outcrops.

A reach of Cattle Creek between Morugo and Boongana was chosen as a case study (see Figure 1 for location). Differences in channel position between 1947 and 1991 are documented in Figure 2. Changes in bank position over this time period are generally associated with downstream meander migration. Fluctuations in channel width have also occurred, although over shorter timescales. The total area of land affected by stream processes over the period 1947-1991 was 17 hectares.

Downstream meander migration is an inevitable natural process along sinuous high energy alluvial channels. Cattle Creek and its valley are steep, and the floodplain is generally narrow and confined, thus stream power per unit area is high during floods. The bank sediments are in many places unconsolidated sands and gravels similar to those sediments being carried by Cattle Creek. Such materials have little resistance to erosion.

Figure 2: The high flow channel of Cattle Creek between Morugo and Boongana in 1947 and 1991, based on aerial photographs.



3. STRUCTURAL MANAGEMENT OPTIONS

3.1. Management Techniques

Structural techniques used in the management of bank erosion on rural streams in north-eastern Queensland include bank protection and alignment training works. Bank protection works include techniques which artificially increase the resistance of banks to erosion (e.g., rock riprap lining) and techniques which divert or deflect flows from eroding banks (e.g., groynes, retards and embayment works). Alignment training works are aimed at modifying the channel to create a supposedly stable meander pattern by selectively altering hydraulic resistance. Detailed discussions of these and other structural techniques can be found elsewhere (e.g, Working Group on Waterway Management, 1991).

Structural techniques which have been employed on Cattle Creek include realignment and stream clearing for the purposes of alignment training, and various forms of bank protection works including embayment works, groynes, and rock riprap lining. These works have met with varying degrees of success.

Rock riprap lining has several variants ranging from toe protection to full lining of the bank height. This technique is generally found to be effective in all its various forms on Cattle Creek and other nearby streams. It has also been recommended as the preferred technique on other streams in north-eastern Queensland, such as the O'Connell River (Oates, no date). Rock riprap lining has not been the only successful technique, for example, both impermeable and permeable groynes have been successfully used to stabilise eroding banks at sites along Cattle Creek. However, groynes can be relatively expensive in this environment because of the extent of ancillary works required.

3.2 Management Scenario

To assess the likely benefit of major structural works intervention, the rock riprap lining option was applied to the 3.3 km long reach of Cattle Creek between Morugo and Boongana. The premise is that if such lining was carried out in 1947, then the observed movement of the creek thereafter to 1991 could have been avoided, with the benefits realised as avoidance of loss of land and production on the areas known to have been affected by meander processes over the period.

In reality it is debatable whether total stability could indeed be sustained over a protracted time period on such a dynamic stream as Cattle Creek, in particular whether arresting meander migration in this way would lead to other forms of channel instability such as splay development or avulsion in the reach in question, and whether there would be adverse impacts downstream.

Based on aerial photograph measurements, approximately 2.85 lineal km of riprap lining of outer banks on bends would have been required to stabilise the channel, at an average cost of $120 per lineal m. This would provide for rock lining up to a maximum of two thirds of bank height. The areas of land "saved" from meander processes totalled 17 hectares for the period 1947-1991. The ongoing maintenance costs for such work could be expected to average no more than 5% per annum ($6 per lineal m of lining), including repair of flood damages.

3.3. Economic Evaluation

In theory the net worth of any project is determined by assessing and comparing all social, economic and environmental issues and values. Techniques such as Benefit-Cost Analysis (BCA) are commonly used, but application is often hindered by the fact that whilst implementation costs are readily measurable, many of the benefits and indirect costs are often difficult to quantify in monetary terms.

It is not the intent of this paper to enter into debates regarding quantification/valuation criteria for social and environmental issues, nor to distinguish between public and private investment, but instead to keep the focus on the direct valued monetary costs (build and maintain) and benefits (land production value). For projects which aim to protect only commercial productive assets like small amounts of farm land the benefits gained are equivalent to the net value of production.

Table 1 summarises the costs and general data associated with stabilising Cattle Creek in the study reach between Morugo and Boongana. Table 2 displays: 1) the total Net Present Value (NPV) for stabilisation works given three different discount rates; 2) average annual discount cost over fifty years; and 3) the average annual per hectare cost over fifty years. For the purposes of this paper it is assumed that the only threat posed by erosion is to farmland. As a result, other social and environmental values are not considered here.

Table 1: Summary of key data for rock riprap stabilization works in Cattle Creek between Morugo and Boongana.

Length of reach:	3.3 km.
Length of works: bank	2.85 lineal km of
Unit cost of works:	$120 per m
Total cost of works:	$342 000
Annual maintenance provision (%):	5% of capital cost
Annual maintenance Provision ($):	$17 100
Total area protected:	17 ha.

The net value of the land to be protected is dependent on two factors: 1) the price of sugar; and 2) the costs of production. The price of sugar is dependent on a range

Table 2: Cost of rock riprap stabilization works in the Cattle Creek study reach.

Discount Rate	3%	6%	10%
NPV of works	$778 078	$610 599	$511 398
Average Annual Cost	$10 703	$10 019	$9 359
Average Annual Cost per ha of Land Protected	$630	$590	$551

of variables such as: 1) currency exchange rates; 2) the international price of raw sugar; and 3) the quality of the cane grown. This study will consider three sugar price scenarios: 1) the peak price in 1980, A$630/T (current dollars); 2) the average sugar price from 1980-1992, A$403/T; and 3) the average expected international price of raw sugar, A$300/T, assuming an average A$/US$ exchange rate of US 75c (Hafi et al, 1993).

Table 3 contains the NPV of the benefits of protecting the 17 ha of cane land in the study reach given these three scenarios and the range of discount rates in Table 2. The values in Table 3 are based upon published data and a number of assumptions. First, the cost of milling sugar (including interest and depreciation) was assumed to account for about 80% of the gross value to the mill sector. Second, the usual distribution of the gross value of sugar was taken, 66% to the growers and 34% to millers (in 1980 the exact distribution for that year was used: 63.1% to the growers and 36.9% to millers). Third, it was assumed that 7.2 tons of cane yields one ton of raw sugar (Powell and McGovern, 1987), and at Cattle Creek each hectare produces 117 tons of cane (Sutton and Cairns, 1986). Finally, the average farm size at Cattle Creek was taken to be around 225 ha and that therefore the cost of growing one tonne of cane is roughly $22, including interest and depreciation (Industry Commission, 1992).

By comparing the benefits with the cost of protection it is possible to determine on economic grounds when and if riprap lining is justified in this example. The respective Benefit-Cost ratios are displayed in Table 4. These ratios indicate that if sugar prices were to remain at the high values that predominated before the slump in the 1980s then protection would be warranted. In Scenario 2 the situation is less clear, indicating that at these prices the use of structural stabilisation is of marginal value. Consequently, in such a situation cost competitive alternatives should be considered. In Scenario 3, the Benefit-Cost ratios are well below one, indicating that creek stabilisation using rock riprap lining would not be a judicious use of funds if productive value were the sole consideration.

Table 4: The Benefit-Cost Ratios of protecting 17 ha of cane land at Cattle Creek under three sugar price and discount regimes.

	3%	6%	10%
Scenario 1	4.18	3.36	2.62
Scenario 2	1.28	1.02	0.80
Scenario 3	0.56	0.45	0.35

Table 3: NPV of protecting 17 hectares of cane land along Cattle Creek, the average annual benefit, and the average annual per hectare benefit, for three discount rates.

Scenario 1: Sugar Price = $630/T			
Discount Rate	3%	6%	10%
NPV of benefits	$3 252 840	$2 050 704	$1 338 650
Average Annual Benefit	$65 057	$41 014	$26 773
Average Annual Benefit/ha.	$3 827	$2 413	$1 575
Scenario 2: Sugar Price = $403/T			
Discount Rate	3%	6%	10%
NPV of benefits	$992 222	$625 532	$408 332
Average Annual Benefit	$19 844	$12 511	$8 167
Average Annual Benefit/ha.	$1 167	$736	$480
Scenario 3: Sugar Price = $300/T			
Discount Rate	3%	6%	10%
NPV benefits	$437 516	$275 825	$180 052
Average Annual Benefit	$8 750	$5 517	$3 601
Average Annual Benefit/ha.	$515	$325	$212

The Benefit-Cost Ratios reported here are only applicable to the channel migration rates and scale of works outlined for this example, and could be expected to vary in other situations.

Other factors which would need to be taken into account in any specific decision include:

- social and cultural values associated with land ownership (extra benefits);
- protection of infrastructure such as roads, tramways, bridges, weirs, underground or overhead services (extra benefits);
- environmental losses associated with bank lining - where erosion processes are natural in origin the reworking of bank sediments and riparian land is part of the natural ecosystem; suppression of these processes may have detrimental effects through interruption of downstream sediment delivery, exacerbation of alternative (possibly catastrophic) erosion processes, ecological simplification etc. (extra costs);
- protection of remnant intact indigenous riparian zones (extra benefits).

4. NON-STRUCTURAL OPTIONS

Non-structural approaches to management are advocated for consideration in situations where major assets and the highest value farmland are not threatened.

The non-structural approach is not a do-nothing approach. It is a redirection of effort and resources. Two examples of proactive non-structural management of channel instability are outlined: 1) erosion hazard mapping, and 2) "Buy-back-lease-back" arrangements. This discussion is not intended to be an exhaustive review of non-structural options.

Inundation hazard mapping is a widely accepted tool in the management of flooding. Dunne (1988) outlined a North American example where information on areas likely to be affected by future channel migration was incorporated into land use planning. Erosion hazard mapping for the management of bank erosion would involve the identification of areas subject to various levels of risk of meander migration and other channel processes. Land uses could then be zoned in such a way that they are compatible with risk levels, and prospective purchasers of properties bordering waterways could be warned of inherent risks. In the case of land which is currently privately owned, considerations of fairness and equity indicate that mapping and zoning would need to be accompanied by financial offsets for any reduction in property values. An understanding of geomorphological processes is crucial to effective and credible erosion hazard zoning.

"Buy-back lease-back" arrangements have been used in Australia and overseas in the management of land subject to inundation. Such a system has potential for application to the management of land currently in private ownership which is subject to meander processes. It would involve the purchase of land by interested parties (possibly but not necessarily the waterway management authority; other potential sponsors could be community organisations such as conservation groups). The land could be leased back to adjoining landholders for cane production at a rental which reflects the risk of erosion, on the proviso that erosion losses could not be claimed. Alternatively, it could be leased back for environmental enhancement purposes.

A lease-back system would also help address the problem that when a stream migrates, land is "lost" on the outer bank of the bend, but "gained" on the inside bank. Under a lease arrangement, the landholder on the outer bank does not sustain as great a loss as they would if they owned the land, and the landholder on the inside bank has the option to lease the additional land "gained" as the result of meander processes.

5. A PREFERRED MANAGEMENT STRATEGY

A preferred strategy for managing lateral instability would be based on the premise that the most appropriate land use for stream banks and verges is as a zone of indigenous vegetation, but would also take into account precedents set by past management operations, as well as current physical, economic and social constraints. Such a strategy includes the following key elements:

1. Encouraging gradual withdrawal of intensive cultivation from those parts of the floodplains which are subject to active erosion and deposition.
2. Encouraging regeneration of indigenous vegetation in the riparian zone and on the active parts of the floodplains. Limited clearing of fast growing vegetation in the channel may be necessary to reduce the probability of splays or avulsions.
3. Employing erosion control works only where significant assets, high value farmland, infrastructure, or remnant riparian vegetation are threatened, or are likely to be threatened in the short-term by continuing meander progression.
4. Utilizing savings from any reduction in structural works activities to support landowners/occupiers whose livelihood may be threatened from time to time through progress of ongoing stream processes.

6. CONCLUSIONS

Many rivers and streams in north-eastern Queensland are naturally subject to lateral instability due to meander migration, cutoffs, avulsion, and fluctuations in channel width related to flood activity. This paper has focussed on options for the management of meander migration, with particular reference to Cattle Creek. It is argued that a preferred management strategy for Cattle Creek and similar streams should include structural and non-structural measures. Structural works are necessary for protecting valuable assets (including high value farmland) and infrastructure. However, proactive non-structural approaches should be considered in situations where economic or environmental considerations contraindicate the use of structural works. Appropriate non-structural measures may include: 1) erosion hazard mapping, or 2) "buy-back lease-back" arrangements for land subject to stream erosion hazard but currently in private ownership. Overall, this analysis reveals the need for systematic multidisciplinary evaluation of river management options, including structural and non-structural approaches, in agricultural settings.

7. ACKNOWLEDGMENTS

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ON THE ESTIMATION OF BENEFITS OF STREAM MANAGEMENT

Lindsay J. White* and Neil. H. Sturgess**

ABSTRACT

State funding of stream management in Victoria is shrinking in real terms. One possible explanation for this is the lack of hard data supporting claims for increased funding.

This paper reviews and makes comment on techniques for estimating the benefits of stream management, with particular reference to the management of erosion and sedimentation. Reference is made to benefit analyses that have been undertaken in Victoria for reducing the risk of an erosion head progression upstream in Bruthen Creek, and reducing the risk of a breakaway occurring in the Ovens River.

1. CONTEXT

The Victorian State government has been the primary source of funding to stream management since River Improvement Trusts started to form in the 1950's.

State funding to stream management is steadily decreasing in real terms per unit area despite increased expectations of functions and performance. In 1984, the functions of stream management authorities were confined to working towards the stability of bed and banks. In 1995, stream management authorities are expected to adopt far broader functions including management of sand and gravel extraction, community education and monitoring of water quality. Yet, although the percentage of Victoria in stream management districts increased over threefold between 1984 and 1995 (from 9 % to 32%), State Government funding has decreased in real terms (from $3.6m in 1984 to $3.0m in 1995). Why? One of the main reasons of the reduction of funding is believed to be that river managers are not selling the benefits of stream management well enough and that there is a lack of hard data supporting claims for increased funding.

This paper will satisfy its purpose if it provides river managers with:

- an awareness or reminder that methods for estimating benefits of stream management exist;
- an overview of the methods currently available for estimating benefits from stream management; and
- some detail on the estimation of benefits from management of erosion and sedimentation, illustrated by examples.

2. WHY ESTIMATE BENEFITS FROM STREAM MANAGEMENT?

Reasons to estimate benefits of stream management follow.

1. **Justification of expenditure of public moneys.** Rivers are public goods, and stream management is an investment for the future of streams for the whole community. As with all investments, it is important to be confident that the project will yield a net benefit.
2. **Ranking of projects.** As funding is limited, it is useful for funding agencies to be able to compare the return for an investment in a number of possible projects.
3. **Professionalism.** Illustrates that the organisation seeking funding has a professional approach.
4. **Identifies key issues.** As Sinden (1994) states:

> *... analyses help to define issues, focus debates, formulate problems, provide orientation, provide a framework for thought, expose fallacious arguments, and raise the general level of debate over particular issues.*

As a note of caution, benefit-cost analysis of stream management is difficult because of the many difficult-to-value benefits that are involved. For this reason, great care is needed both in applying techniques and interpreting results. Furthermore, benefit-cost must never be allowed to monopolise the analytics used in the decision-making process. Stream management itself, and the economic analysis of it, are highly uncertain matters and there will always be a role for wise judgement in assessing all the intangible issues. However,

* ID&A Pty. Ltd, Sale, Victoria, *Telephone: (051) 43 1822 Fax: (051) 43 1828*
** Read Sturgess and Associates, Kew, Victoria, *Telephone: (03) 9751 2300, Fax. (03) 9751 2995*

unless some considered attempt is made to quantify these benefits in monetary or other terms, these benefits could be easily ignored or trivialised and stream management may not be funded to the extent that the issues demand.

3. GENERAL COMMENTS ON BENEFITS FROM STREAM MANAGEMENT

The essence of stream management is to change the river from what it would be without management to some better state. The economic benefit of management, that which we wish to identify in a benefit-cost analysis, is the difference in total economic value between these two states - with and without management.

The economic value of a river and its environs is made up of a number of different types of components. First, we can point to those values of the river which stem from the use which is made of the river. **Use values** include both consumptive and non-consumptive considerations and may be differentiated into values such as:

- direct productive uses such as use of the land surrounding the river for agriculture;
- direct consumptive uses, such as recreational fishing; and
- non-consumptive uses, such as sightseeing and camping.

Second, we note that use values can be distinguished from those values which people may associate with the river even though they do not use it, the latter are referred to as non-use values. The assessment of **non-use values** is more controversial than use values and is associated, amongst other things, with the value people might derive from knowing that the river or some attribute associated with it exists.

The goods and services provided by a natural asset can be classified into those which are traded in markets and those which are not. The former are called **priced**, or market values, while the latter are referred to as **unpriced**, or non-market values.
As a general rule, those goods and services produced by a natural asset which are traded in markets are associated with the use of the asset but, of course, not all use values are priced. For example, streamside agricultural land can be traded in a market but there is no market for the sight-seeing opportunities provided by the river. Non-use values do not have prices.

In broad terms, then, the total economic value of the asset (measured in present value terms) can be considered as the sum of these types of values, that is:

total economic value =

use values (priced + unpriced) + non-use values (unpriced).

3.1. USE VALUES

The basic approach to valuing the priced goods and services (eg. protection of agricultural land, bridges, roads) is the simple one of multiplying the quantity by the price, and capitalising by converting to a present value using an appropriate discount rate. The valuation problems associated with priced attributes are usually less severe than those associated with unpriced attributes. Apart from the ever-present problem of measuring the quantities of such goods and services, most such problems arise when the prices are administered in such a way that they do not reflect the true willingness to pay for that good or service, for example, if the government subsidises or taxes the good or service.

Unpriced values involving past or present use are often fairly easily delineated and can be associated with those recreational activities which people undertake on or near the river, walking by the river, picnicking, camping, fishing and swimming. Use values can also be associated with the act of merely experiencing the environment of the river, that is, sightseeing.

3.2. NON-USE VALUES

The umbrella term for non-use values is the concept of **existence value**. This is the value obtained from knowledge that some attribute of the environment exists. Such a value is independent of any present or future use; indeed, people can value the existence of the attribute even though the idea of actually visiting the river may be repugnant to them. The evidence for the notion of existence values is the fact that people will contribute to funds to protect environmental assets in remote areas which they would never expect to visit. While these assets could be used vicariously through film or television (eg. The Man from Snowy River), such use is unlikely to explain the substantial support given to preservation activities.

Existence values are difficult to define and some economists have suggested that various altruistic motives may account for existence value, namely: bequest motives, philanthropic motives and sympathy motives.

4. GENERAL TECHNIQUES FOR ESTIMATING UNPRICED BENEFITS OF STREAM MANAGEMENT

Three broad classes of methods have become accepted by environmental economists and others for the evaluation of unpriced values:

- contingent valuation methods (see Wilks 1990);
- related market methods (see Sinden and Worrell 1979); and
- value transfer (see Read Sturgess and Associates *et al* 1992).

These classes of methods are described in the sections below.

There is also a set of methods by which values may be approximated (that is, methods of "partial" valuation) for a comparison with the costs of a management program. These methods, such as assessing the opportunity cost or the replacement cost of an environmental asset, or evaluating cost savings or interpreting past decisions have been discussed in Read Sturgess and Associates *et al.* (1992) and Sinden (1994).

4.1. CONTINGENT VALUATION METHODS

The contingent valuation methods are implemented through surveys or experiments and rely on what people say they would be willing to pay (or the compensation they would be willing to accept) for the items in question, that is, the methods measure their behavioural intentions. The term "contingent" is used because the subjects' responses are contingent upon the hypothetical choice situations that are described. Contingent valuation methods can be employed to measure any type of unpriced value, whether it be a use value, existence value or total economic value. With the present state of knowledge, existence values can only be estimated using contingent valuation methods. Most of the controversy surrounding the methods arises from the fact that the accuracy cannot readily be verified empirically. However, Sinden (1988) found that biases due to the hypothetical nature of the procedure are not inevitable.

It is not proposed to reproduce here a detailed description of the methods and a discussion of the problems and biases which can arise in their use. These are readily available elsewhere (Sinden 1994). We note, however, that the controversy surrounding the methods stems from the fact that they deal with intended behaviour in hypothetical situations rather than observations of actual behaviour.

4.2. RELATED MARKET METHODS

The related market methods include the travel cost method and the hedonic price method. The related market approaches deal with actual behavioural responses.

The hedonic price method relies on investigating differences in the price of some marketable good which may result from differing exposures to some natural asset. For example, real estate value can be examined to detect any premium paid for locations with superior views. This may be difficult to apply to most stream management issues because of the small, localised markets involved.

The travel cost method uses observations on the expenses that people incur in visiting a location, and derives economic values by simulating how visitor numbers would respond to different entrance fees. It assumes that consumers of recreation would react to changes in the admission price in the same way that they do to the observed changes in travel or trip cost.

The problems with these methods centre around the fact that the markets which are used are only "related" and are not the market for the asset in question, which, by definition, does not exist. Thus, the "prices" may be real but they are only an indirect measure of the value in question. Nevertheless, because they provide values that are based on people "putting their money up", the related markets approaches, particularly the travel cost method, have appeal.

4.3. VALUE TRANSFER

The main difficulty with contingent valuation and the related market approaches is that they are expensive to apply. If these methods have been applied for one stream management issue, there is potential for the result to be transferred to other similar issues.

The process of transferring unpriced use values has been discussed extensively elsewhere and need not be repeated here (see Read Sturgess and Associates *et al.* 1992, I.D. &A. Pty. Ltd, 1995). We need only mention that it is the process of transferring values determined at one site (by one or other of the above methods) to the site of interest for the evaluation of a particular management program.

Desvouges, Naughton and Parsons (1992) suggest four criteria that must be satisfied before values are transferred from an original study to the site of interest.

1. The original study must be based on adequate data.
2. The original and new locations must offer similar recreation opportunities to a similar spectrum of households.
3. The benefits to be valued at the new site must be similar to those valued at the original site.
4. The original study must contain regression analysis of value (measured by willingness to pay), as a function of socio-economic and environmental variables.

The essence of these criteria is that the sites satisfy the common-sense requirement of being "comparable" and that there be sufficient information to allow systematic adjustment for differences between the sites. Applications of these criteria are discussed by, Loomis (1992) and Read Sturgess and Associates *et al* (1992).

The method is cheap and easy to use. It is the basis of a rapid appraisal method (RAM) of the benefits of stream management (Read Sturgess and Associates *et. al.* 1992). The validity of values obtained in this way has been scrutinised by Smith (1992) and Desvouges, Naughton and Parsons (1992), amongst others.

As an aside, the authors are surprised and somewhat disappointed that the RAM has not found more use since it was developed nearly four years ago. There may be many reasons for this situation but we do not believe lack of relevance is one of them. Is it possible that the funding situation is not as tight as we imagine? Or, has it just been forgotten as the personnel of relevant Government Departments change and the departments themselves undergo massive change? In the interests of decision making which uses all relevant information, we hope there may be a revival of interest in the approach.

The problem for the evaluation of stream management programs in Victoria is that there is only one study from which values might be legitimately transferred, namely Sinden's evaluation of recreational activities in the Ovens and King River catchments (Sinden 1988). That study is now getting "long in the tooth" and there is a need for more studies of that type. In fact, just one well-designed study to suit the requirements of value transfer will go a long way to assisting the next generation of economic evaluations of management programs.

5. ESTIMATION OF THE BENEFITS OF MANAGING EROSION AND SEDIMENTATION

As the focus of the conference is the estimation of the benefits associated with the management of stream erosion and sedimentation, examples of two past analyses are included in this section. It is important to note that management of erosion and sedimentation is but one of the spectrum of roles of stream management authorities in Victoria.

The benefit of managing erosion and sedimentation is often measured as the value of avoiding the various types of damage that might result without management.

In broad terms the benefits of stream management in terms of avoidance of damage can be classified into the following categories:

- avoiding a reduction in the flow of services (eg. progressive build-up of silt reducing pasture production or progressive degradation of scenery);
- avoiding a shortened life of assets (eg. fences or bridges may require replacement before normal time due to siltation or erosion); and
- avoiding the loss of assets (eg. agricultural land or fish habitat).

In some cases, of course, management of sedimentation and erosion will produce additional benefits because it enhances the flow of services from the river and its environs (eg. stream-side revegetation for stabilisation also can provide increased scenic amenity). Two examples of the estimation of benefits in Victoria follow.

5.1. EXAMPLE 1: MANAGEMENT TO PREVENT THE UPSTREAM PROGRESSION OF AN EROSION HEAD: BRUTHEN CREEK

Bruthen Creek is located in South Gippsland.

A rock chute in Bruthen Creek was severely damaged by a flood in September 1993. A subsequent investigation revealed that the average recurrence interval of the flood was approximately 100 years, considerably higher than the design average recurrence interval of 30 years.

A cost benefit analysis was undertaken to assist Treasury to decide whether it was worthwhile to allocate Natural Disaster Funding to repair the rock chute and surrounding channel. A comparison was made of stabilising Bruthen Creek now, in the future when a bridge was threatened, or not at all. The main source of benefits from stabilising Bruthen Creek would derive from extending the life of assets (particularly a reasonably new bridge worth $400,000) based on an average rate of progression of the primary erosion head. The rate of erosion head progression was estimated using 90 years of data.

The cost of the works was estimated to be $377,000. The marketable benefit to cost ratio of the project was calculated to be 0.8, with public marketable benefits providing 3/4 of these benefits. The unpriced benefits were described in the funding application.

Funding to stabilise Bruthen Creek has been approved by Treasury.

5.2. EXAMPLE 2: MANAGEMENT TO PREVENT RISK OF A BREAKAWAY: OVENS RIVER

The Ovens River is in North Eastern Victoria. There is a threat of an avulsion into Happy Valley Creek, near Myrtleford.

The benefits of reducing the risk of an avulsion into Happy Valley Creek were estimated. It was judged that:

- without works, the occurrence of two twenty year floods and a 100 year flood, irrespective of order, would cause the breakaway during the next 30 years (the planning horizon chosen) in the absence of management; and
- even if the works were undertaken the breakaway would occur in a flood with a 500-year return period.

Benefits were derived by deferring the replacement of public and private assets. The benefits of reducing the risk of the breakaway were discounted by both a discount rate and the probability of the floods judged to cause the breakaway. A sensitivity analysis was also undertaken.

The conclusions of the analysis were:

- the present value of the quantifiable benefits of the works to prevent the breakaway is $0.1 million; and
- the present value of the cost of the works program is $0.57m.

For the program to break even the quantifiable benefits would need to be valued at $0.47m (based on discounted probability).

6. CONCLUDING COMMENTS

Techniques are available estimate the benefits of stream management works, some of which have been reviewed in this paper. The detail and cost of the analysis should be commensurate with the required accuracy of the results.

A considered but yet imperfect estimation of benefits is likely to result in better decisions by river managers and funding agencies than no estimation of benefits at all.

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The Role of a Professional Association

*John Senior**

ABSTRACT

The River Basin Management Society is a unique organisation offering an independent multi-disciplinary forum for integrated catchment management in Australia. No other body has attempted (let alone succeeded) to bring together the whole spectrum of professional and community interests involved in catchment management.

The paper outlines the techniques and approaches successfully used by the RBMS to bring varied interests together, to broaden understanding, to seek resolution of apparent conflicts, to facilitate outcomes, to generate change and to stimulate thinking.

1. INTRODUCTION

From a modest beginning at Sale in eastern Victoria late in 1984, where it was conceived, the River Basin Management Society has evolved into a diverse yet cohesive group exceeding 300 in membership.

After a formative period of two years the Society was officially born on 26 November 1986 and incorporated a short time later.

The Society's aim remains "to facilitate communication between the many and varied disciplines and interests involved in river basin management, for the benefit of the community".

2. PHILOSOPHY

The guiding principles on which the RBMS operates are based on independence, affordability and responsiveness.

Membership is restricted to individuals in order that the Society remains free to comment on the activities of authorities and organisations without embarrassment or prejudice. Corporate support is welcomed through patronage or sponsorship.

Recognising that many potential members already belong to a single discipline body the policy has been to maintain a modest scale of fees and subscriptions.

As advocates of a co-operative approach rather than a specific industry, the RBMS has less need to provide for formal professional development and representation.

Particular emphasis has been placed on providing "value for money". Member surveys (regularly conducted as part of seminar gatherings) have been used to identify topics for conferences, ideas for new initiatives and to indicate levels of satisfaction with:

- newsletter frequency, style and content
- seminar and subscription costs
- the way in which particular Society projects are being handled
- member services generally

3. MEMBERSHIP

Since its inception the RBMS has grown intermittently to its present level of just over 300 (Figure 1), spread across all states. What is particularly rewarding is the substantial increase in the last three years. This represents the attraction of a wider audience to the twice-yearly Seminars and indicates an increasing awareness of, and value placed on, the Society's endeavours.

The range of member backgrounds continues to widen whilst understandably dominated by science and engineering interests. Membership contains a good balance between academics and practitioners, and between public and private sector backgrounds. The amount of other interests is encouraging (Figure 2). It is vital that overall membership and conference delegates are representative of the wider community if integrated understanding is to be achieved. It is also pleasing to see improving student involvement and a growing proportion of female participants.

The RBMS is managed by a Committee of ten, elected annually. This arrangement enables the continual introduction of "new blood" whilst allowing for continuity. It has provided regular opportunity for members to show their satisfaction with general administration through nomination and at the ballot box.

* President, River Basin Management Society, 425 Porter Street, Templestowe, Victoria 3106
Telephone: Bus. (03) 9816 6857 Home (03) 9846 4749 Fax (03) 9816 6898

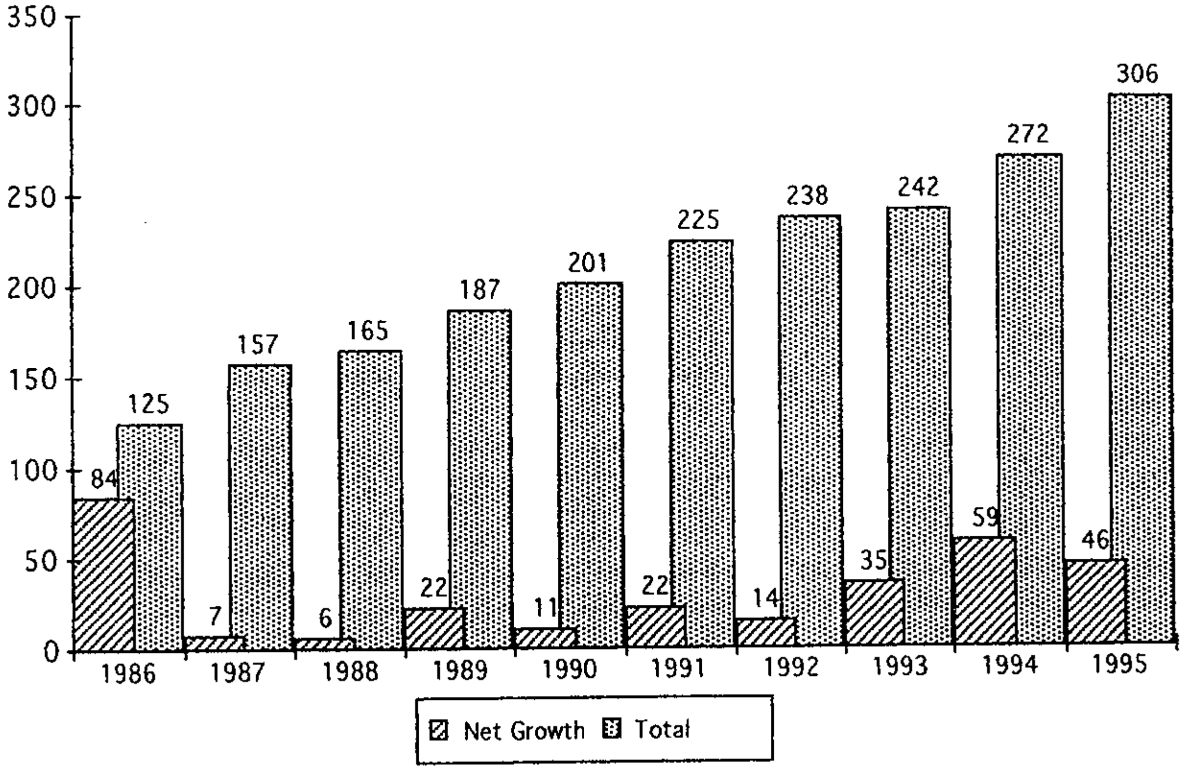

Figure 1 Net Growth per year & Net Membership

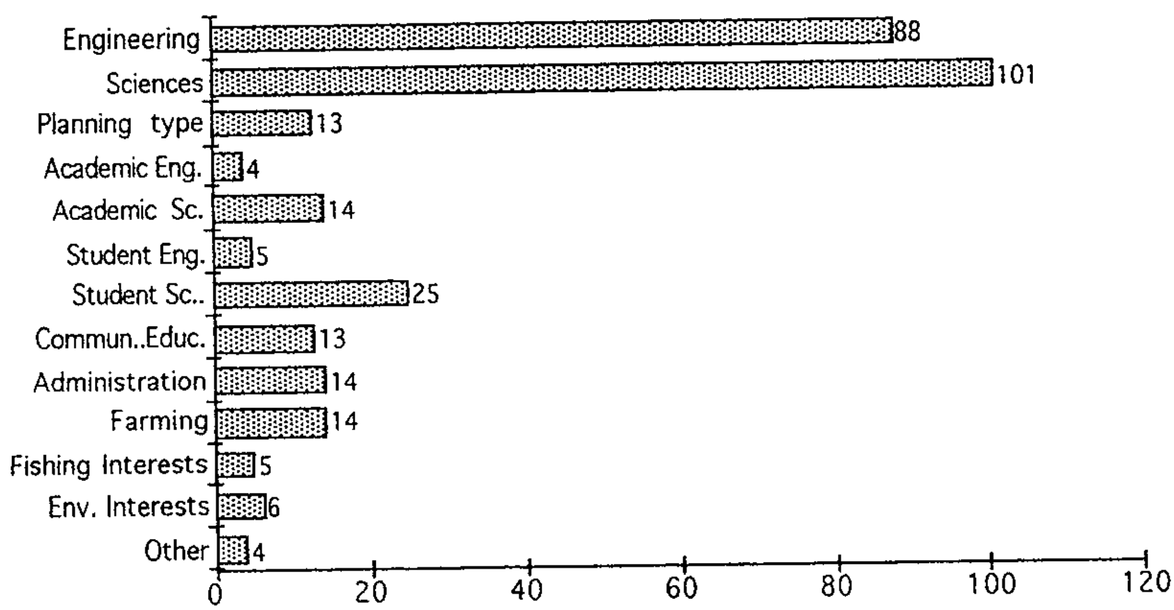

Figure 2 Current Membership X training

4. FINANCIAL

As indicated earlier, subscription levels have been held to the minimum (Figure 3). This has only been achieved by a combination of initiatives. Voluntary help is fundamental to any such body and the amount of such effort is a reflection of the strength of member commitment to the Society's aims and objectives. The Society has obtained a tax deductible status for fees and subscriptions.

In-kind support received from key agencies to enable basic administration to occur and to provide small financial assistance with newsletter printing is indicative of common goals and principles. The current trend towards more commercial (business) approaches in traditional public sector organisations means such sources can no longer be relied upon. Indeed the future credibility of the RBMS will be dependent on it demonstrating a more resonsible, "professional" approach itself.

Major sponsorship sought from government bodies has facilitated the organisation of a number of seminars of special value to those agencies. It has been a case of making and taking opportunities that present themselves. To do so necessitates the need for forward thinking and strategic positioning. For most events, to minimise costs, support is sought mainly from government bodies with local commercial companies often assisting in a range of minor ways particularly for non-metropolitan venues.

Additionally a small number of opportunities for "consultancy" assignments have arisen where agencies have valued the unique "collective wisdom" that the RBMS can offer. In a small budget base these assignments have brought in useful income. By voluntary resourcing through retired members at minimal actual cost quite significant income can be derived. This will not always be possible, it depends on personal sacrifices, a strong belief in the project and the need for additional support whenever required.

Presently the RBMS has an annual operating budget of almost $50,000, with cash and invested reserves of over $60,000. Wise investment of surplus funds has been carefully pursued.

5. ACTIVITIES

Since 1990 a major commitment to establishing and maintaining student research grants has been made. Now entitled the "Ernest Jackson Memorial Research Grants" (after "Watershed" Jackson, often viewed as the father of total catchment management) over $20,000 has been awarded to 25 recipients in four states. This approximates to 60% of income received through member subscriptions in the same period!

A smart, simple, regular and informative newsletter keeps members abreast of current issues and developments, and is highly rated by members.

Topics for the twice yearly, one/two day seminars have ranged from the general to the specific, from technical and scientific knowledge to community expectations, from legal and institutional aspects to cost benefits (Appendix). Many have included workshop sessions and site visits to involve participants and improve understanding at first hand. Proceedings of all seminars are provided free to delegates and are generally available for purchase at a small cost. Attendance is usually evenly split between memmbers and non-members. A major value, consistently highlighted in seminar survey evaluations, is the networking opportunity at and following the events themselves. In programming each event every effort is made to facilitate such opportunities.

Occasional evening seminars are arranged to take advantage of visiting experts and to enable grant recipients to present the outcomes of their research.

More recently the RBMS has sponsored member presentations to, or attendance at, conferences of significance. These initiatives promote further awareness of and respect for the Society and provide a "promotional" opportunity.

The perceived credibility and independence of the RBMS are the reasons why it is often invited by government bodies to:

- conduct seminars to add value to draft policies or guidelines
- undertake paid consultancy assignments to provide to strategy development
- participate on consultative committees to provide advice and comment on draft strategies
- review draft reports.
- act as an "honest broker" with other interest groups

Involvement in these activities is resourced through the wide base of member experience and knowledge (Ref.).

The RBMS is also represented on the industry steering committee advising the East Gippsland College of TAFE on the re-accreditation of Resource Management Diploma and Advanced Certificate courses.

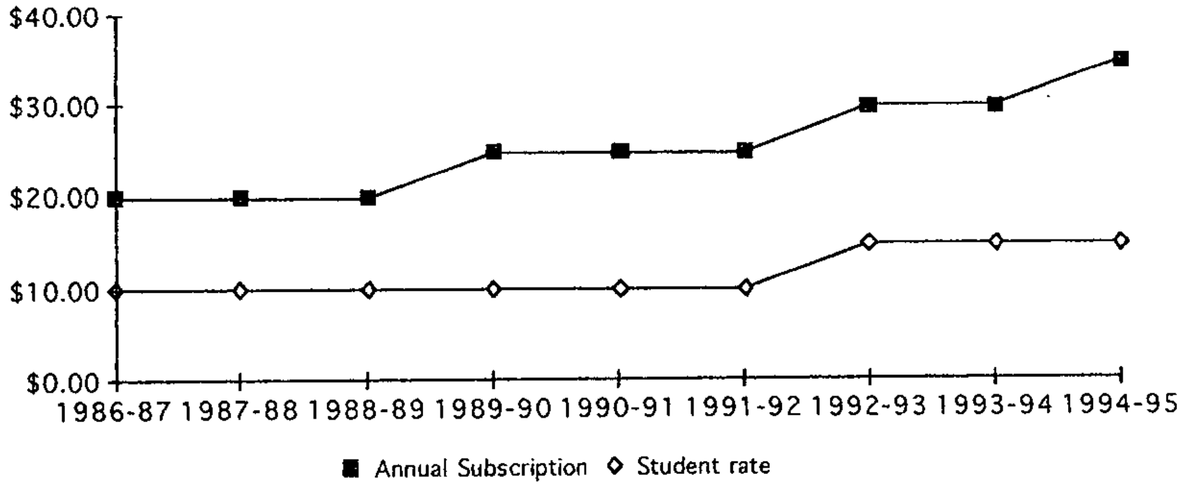

Figure 3 RBMS Annual Subscription Rates

Information on Research Grants

First Made in 1990 year -
Since that time Grants of $21,425 have been made with a current provision for this year of another $7000 .
These have made to 25 recipients in 4 states (Vic.;S.A.;N.S.W; & W.A.) and the A.C.T.
During this period the revenue from annual Subscriptions has been approximately $33,000.

6. SPECIAL PROJECTS

6.1 Catchment & Land Protection

The established reputation of the RBMS was the reason why it was invited by the Victorian Department of Conservation & Natural Resources to participate in the consultation process for the development of inaugural Catchment and Land Protection legislation. In particular, it was asked to organise a two-day Seminar in November 1993 as part of that process. This highly successful event attracted 159 delegates including a number from inter-state.

Subsequently the RBMS prepared a booklet "Catchment & Land Protection - Ideas to Make it Work" (Ref.) as its contribution to the induction program for members of the ten new Regional Catchment & Land Protection Boards established by the legislation. Whilst particularly aimed at this audience, the principles and ideas it contains are by no means limited to the Victorian scene and have much wider application. The booklet is available for purchase.

A complementary initiative has been to offer to conduct associated presentations to the Boards and other relevant groups on a fee for service basis.

6.2 Melbourne's Sewerage Strategy

A further example of the esteem it which the RBMS is held is the consultant role it has played with Melbourne Water Corporation. Under this arrangement it has contributed to the development of a "Sewerage Strategy" for the greater Melbourne area. The constructive technical input and "honest broker" role that has been provided over the three and half year period of its involvement to date has further enhanced the Society's standing.

7. FUTURE

The RBMS is now at a stage of growth and evolution that require alternative solutions to increasing administrative needs. Accordingly a bid has been made for Federal funding under the "Program of Grants to Voluntary Conservation Organisations" to assist with operating costs.

As part of special initiatives to recognise its imminent 10th anniversary, the Society is exploring the potential to establish a Foundation to provide surety and greater levels of funding for the research grants program.

8. CONCLUSION

The professional approach adopted to address the latent need for "bridging gaps" between different disciplines and other interest has proved an outstanding success. It is evident that the unique role played by the RBMS in the field of integrated catchment management is one that is becoming increasingly relevant to both individuals and authorities.

The RBMS experience is an example to all who seek to bridge similar gaps.

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Saltwater Intrusion, Lower Mary River, Northern Territory Australia.

David K. Williams.

ABSTRACT.

The floodplains of the Lower Mary River lie close to Darwin and are a valuable cultural and economic resource. The floodplains support a wide variety of plant and animal communities that are dependant on the extensive freshwater system. This area has been extensively degraded by saltwater intrusion and as the extent of the intrusion increases to expand much more of the freshwater habitat is under threat. This paper gives a brief overview of the studies that are being conducted in order to limit further saltwater intrusion.

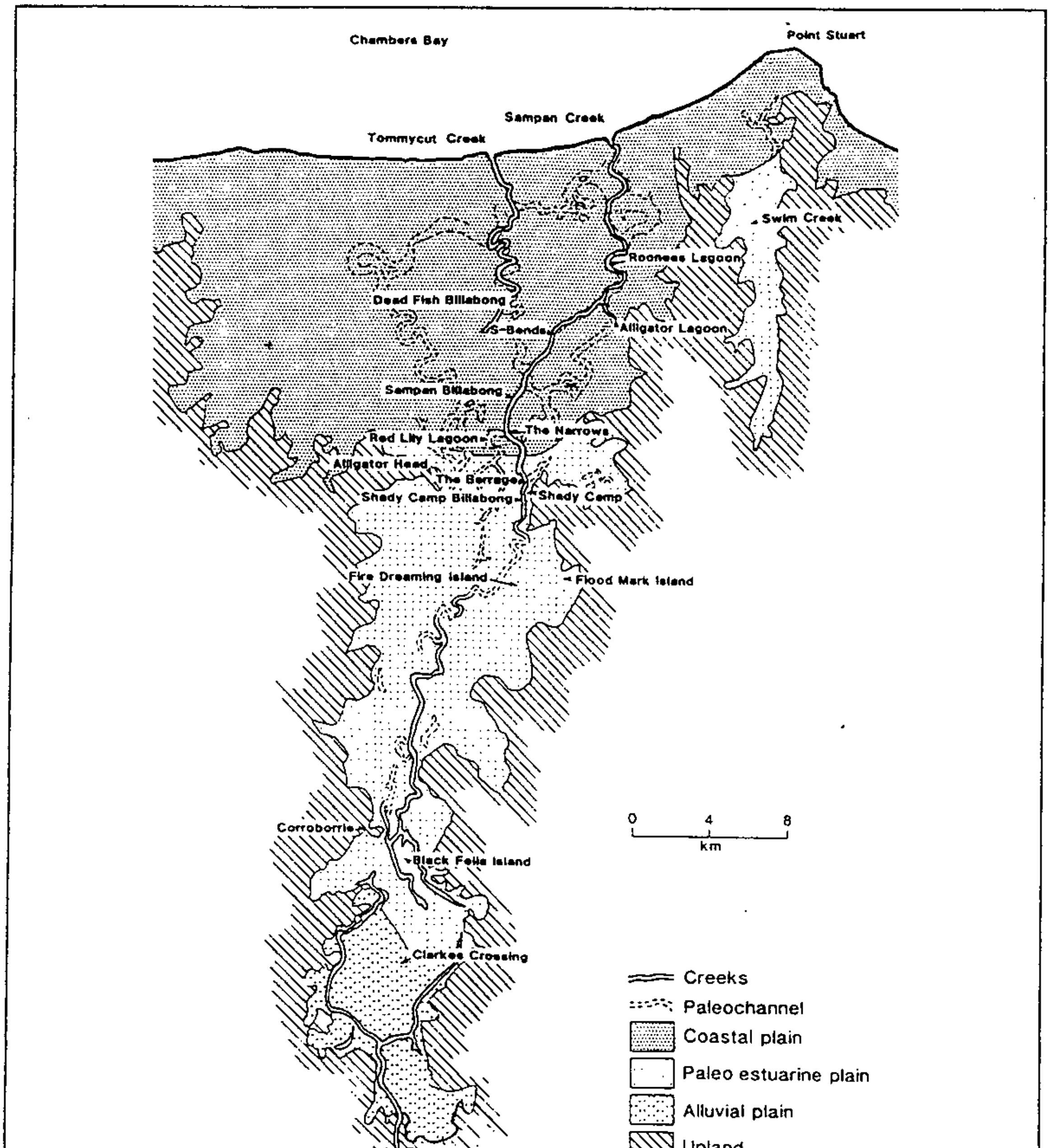

Figure 1. The Lower Mary River floodplains.

Power and Water Authority, Water Resources Division. P. O. Box 1096 Darwin, 0801. Northern Territory.

INTRODUCTION.

The Mary River has a catchment area of 9000 square kilometres and drains northward into Chambers Bay via two tidal tributaries (Sampan and Tommycut Creeks) 80 kilometres to the east of Darwin (fig 1). The last 100 kilometres of river form the wetlands and 35 kilometres are under tidal influence. The wetlands cover an area of 3000 square kilometres and comprise a large area of salt marsh and an equally extensive area of fresh water billabongs. The climate is wet dry monsoonal and the average annual rainfall is 1500 millimetres, which falls in the wet season from November to March.

These wetlands support a great variety of life. They contain ecologically significant stands of paperbark (Melaleuca) forest, perhaps some of the largest in area in the top end of the Northern Territory. At present the region supports agriculture, commercial and recreational fishing, tourism and conservation parkland. It is the breeding ground for fish (especially barramundi) and many species of water birds. It has the densest population of saltwater crocodile per river kilometre in the Top End and is a valuable beef producing area.

The floodplains are unique amongst Northern Territory coastal floodplains as until recently there has been no significant estuarine development. This lack of estuarine development has not provided a distinct outlet for the annual wet season flood waters to escape to the sea. Annually this vast expanse of water spread out over a large area where it slowly evaporated and infiltrated. The floodplains have had several channels formed on them during the rapid progradation that began in the Holocene (Woodroffe et al 1993). Evidence from drill cores suggests that these channels were wider and shallower than those that are forming at present. Flow paths have changed their course on the floodplains over time and the mechanism of channel switching is not well understood. It is probable that the channel switching occurred concurrently with the formation and breaching of chenier ridges at the previous coastlines. When a chenier ridge forms it can create a barrier that limits the entry of tidal waters onto the floodplain. During this time the channels can fill with alluvial sediments carried by the wet season floods. If a chenier is breached a new flow pathway is formed and the channels may change their course. Chenier formation has been episodic over the evolution of the floodplain with the last cheniers being formed between 1000 to 2000 years ago (Woodroffe et al 1993).

SALTWATER INTRUSION.

Saltwater Intrusion has been increasing in the Lower Mary River wetlands since at least the 1940s. This is evident from an examination of aerial photographs and the water level recording station that existed at Roonees Lagoon (14 kilometres inland) from 1958. The main channel of Sampan Creek was at that time narrow and discontinuous. A survey of the channel form of Sampan Creek at Roonees Lagoon in 1963 shows that the width of the stream was 25 metres and the maximum depth was 1.5 metres. The 1994 survey shows that the stream is now 90 metres wide with a maximum depth of 7 metres (fig 2). It is evident from the available air photography that many changes have occurred to the network of channels on the Lower Mary floodplain. Most noticeable has been the growth in density of tributaries and the widening and deepening of the main channel. Associated with the increase in channel dimensions has been a marked increase in tidal range. In 1959 the tidal range at Roonees Lagoon was only small (a maximum of 0.3 metres) (fig 3) and the channel networks were only beginning to branch out onto the floodplains. When compared to Darwin Harbour tides which are indicative of the deep ocean tides it can be seen that spring tide conditions forced more water inland and that the Roonees Lagoon tide levels in 1959 are composed of two superimposed tides. One component of the tide shows the monthly spring and neap cycle while the other component shows the semidiurnal cycle. This indicates that some barrier may have been present that restricted the exchange of tidal waters between Roonees Lagoon and Chambers Bay. Current recorded water levels show that the tidal variations at this location are now at a maximum of 4 metres. It can be shown that the top of the main channel's banks are regularly overtopped by spring tides and that tides flow into the tributaries under all conditions (fig 4).

figure 2. Change in cross sectional form.

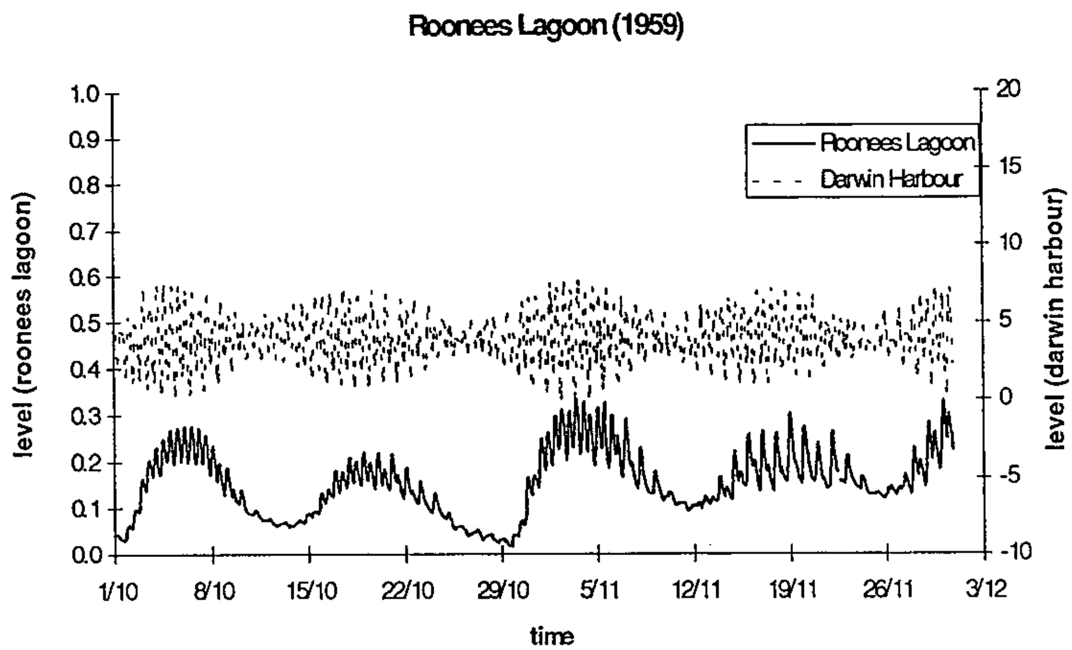

figure 3. 1959 tides at Roonees Lagoon compared to ocean tides (note difference in scale).

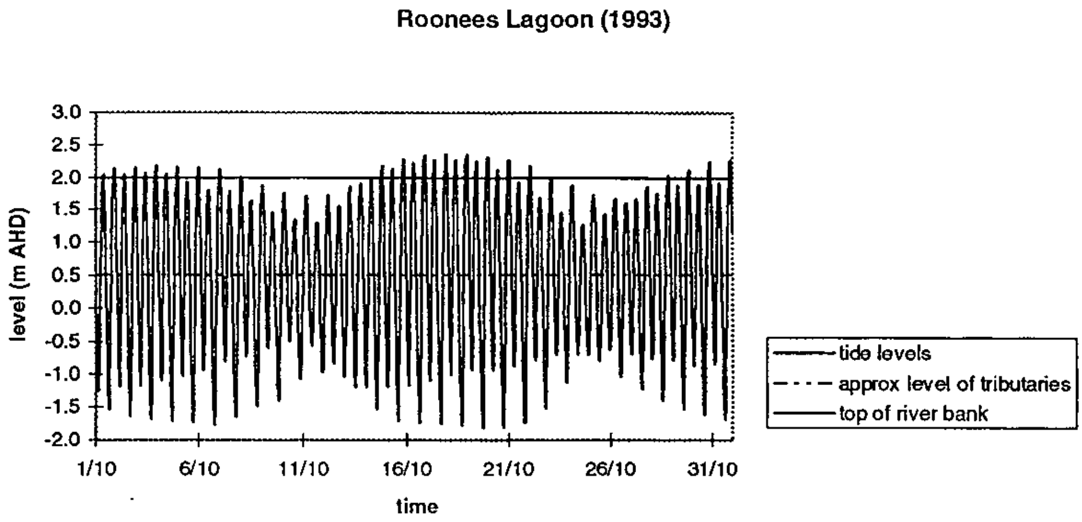

figure 4. 1993 tidal ranges at Roonees Lagoon.

Tidal variations were not seen at Shady Camp (35 kilometres inland) until 1980 where the maximum variation was 0.1 metres. This variation had increased to 0.5 metres by 1989 and in 1994 had reached a maximum of 2 metres. A barrage was constructed at this location in 1989 to prevent the saltwater from moving further upstream.

Tidal energy is persistent and the existing barriers that were at the coastline have deteriorated with time. Once these barriers, which are believed to be the chenier ridges, are breached their cemented resistant outer layer is severely weakened exposing them to erosional forces. As a result of this erosion more tidal energy is allowed to enter the Sampan and Tommycut Creek systems. This results in an increase in the volume of saltwater that can move into the channel networks. The channels respond by widening and deepening to accommodate the increased volume and this in turn applies more erosional stress on the system. Coupled with the increase in tidal volumes is the annual wet season flooding, the majority of which is borne by Sampan Creek. The additional concentration of energy results in the rapid erosion of the channel networks.

Bank slumping is prevalent throughout the tidal creek network. The large tidal range ensures that the banks remain saturated for much of the time. The banks have negligible shear resistance and continual positive pore pressures cause them to eventually slump into the river. This destroys the minor levees that have formed and the ensuing tides flood overland. The floodplain soils, which are black cracking clays, eventually sodify and lose coherence. The soil texture becomes peppery and is removed by wind and tidal movement. Small tributaries form in these areas and extend by tidal gullying, which consists of headward retreat and bank undercutting.

At present the mouth of Sampan and Tommycut Creeks experience the same tidal range as the offshore ocean tides and show no sign of reaching equilibrium conditions in the near future as they are still actively eroding. The tributary networks continue to expand and the channels widen and deepen. This allows more saltwater onto the floodplains and the erosion hazard increases. It is not possible to predict what the system may evolve to if left unchecked but the worst case scenario is that Shady Camp will experience much larger tides which will result in the overtopping or sidestepping of the barrage and the invasion of the extensive upstream freshwater habitat by saltwater. Additionally, based on the rate of growth of the tributary network, the area between Sampan and Tommycut Creeks could become a large shallow tidal inlet and the extensive floodplains and freshwater habitats to the west of Tommycut Creek could be invaded.

The growth of the main channel and the tributary network has altered the drainage characteristics of the floodplains after the wet season. When the Lower Mary River was a discontinuous channel, with only a small opening to the sea, wet season floods would remain on the plains for long periods of time until the water was eventually removed by a combination of drainage, infiltration and evaporation. Now with an extensive network of tributaries, a continuous larger main channel and a much wider interface with the sea, wet season floods drain more rapidly. Water level records show that in the 1960s the floodplains would be inundated for up to 8 months. Since the mid 1990s the floodplains are only remaining inundated for up to 4 months. It is likely that the expansion of the channel system is caused by the erosion of the chenier ridges at the coast. The degradation of the coastal barriers may possibly be the result of major coastal storms, cyclones or flood events which had sufficient energy to transport the nearshore sediments offshore to be lost from the littoral system. Alternately the instability of the estuary may be linked to the instability of the coast caused by high wave energies during a major coastal event. To investigate this matter further all available aerial photographs and satellite images need to be reviewed to examine the history of the entrance condition, with the objective of correlating the entrance degradation to known coastal storms, cyclones and flood events. It has also been suggested that overgrazing of buffalo on the floodplains this century created swim channels between billabongs that enhanced erosion of the channel network. Anecdotal evidence has alleged that commercial fishing enterprises dynamited the entrance in the mid 1950s to gain anchorages for their vessels.

MONITORING AND MODELLING.

In November 1991 a monitoring program was initiated to gain an overview of the fluvial, estuarine and coastal processes operating in the Lower Mary River catchment. The network is aimed at effectively and efficiently collecting data to allow construction and calibration of a numerical model to describe the hydrodynamics of the lower floodplain.

Gauging stations have been installed to represent different parts of the main channels and representative tributaries on Sampan and Tommycut creeks.

To calibrate and verify the model tidal flow gaugings are performed simultaneously at gauging stations over complete tidal cycles. Gaugings commence as close as possible to the peak of the flood tide and continue to the peak of the next flood. Velocities are measured by profiling with a directional impellor type current meter suspended from a boat. Between 5 and 10 observations are made across each gauged section, taking care to ensure that the tidal stage does not change significantly during the gauging and so affect the accuracy of the measurement. Vertical profiles are observed at 0.2, 0.6 and 0.8 of the total depth below the water surface. A submersible pump is attached near the current meter and samples are collected at each vertical and analysed for sediment concentration, temperature, pH and conductivity.

The monitoring and modelling program aim to assist in the understanding of the hydrodynamics which are now responsible in the rapid expansion of the tidal network.

Another component of the program is monitoring and modelling the changes to the channel forms. As the tidal effect continues to encroach further inland the channel form readjusts in response to the changing energy. Mapping these changes gives a clear indication of the state of the creek system. Regular cross section surveys over the length of Sampan Creek and its tributaries commenced in 1991 and have continued on a yearly basis. Parameters that are examined are width, area, hydraulic radius and width-depth ratio. Tidal channels tend to form fairly constant relationships between these parameters and distance from the mouth of the creek. It can be shown that Sampan Creek is changing in response to the increase in tidal energy. In 1991 Sampan Creek showed a regular pattern up to the S-Bends (23 kilometres from the coast) except for an anomaly near the entrance. This anomaly was mapped as a shoal in the creek. Upstream of the S-Bends the pattern became more erratic especially in terms of the width and width-depth ratios. Upstream of the S-Bends is a series of billabongs that have now been connected to the tidal system. The 1993 surveys show that a more regular pattern is beginning to form in this reach as the tidal energy incises a new channel. The anomalous area near the entrance now conforms more closely to the regular pattern as the bar is being removed.

REMEDIAL OPTIONS.

If the triggering mechanisms to saltwater intrusion of the floodplains were anthropogenic due to a combination of overgrazing and other destructive activities then remedial action is required. To combat the advance of saltwater, barrages have been constructed on several of the tidal tributaries. While this has successfully slowed the saline invasion of the floodplains it has done nothing to alleviate the problem of the continual increase of tidal energy entering the system. In any estuarine system the dominant energy comes from the twice daily tide cycle. Even during periods of flooding the semi diurnal tides advance upstream underneath the flood waters. As long as the main channel continues to erode at the mouth greater volumes of saltwater will enter the system resulting in greater advance of saltwater over the floodplains resulting in a continued expansion of the tributary network. The only means by which this mechanism can be arrested is to reduce the tidal energy and hence volume of water that enters the creeks from the ocean.

The aim of the preliminary modelling exercise was to examine various remedial options and their relative merits in terms of impacts on tide levels and flows along the main channel. These levels and flows are critical to the conveyance of saline waters onto the floodplain.

Options that have been modelled include :

- Construction of one or more constrictions at the entrance of the main channels.
- Raising the bed levels at the entrance of the main channels (submerged weir).
- Construction of an offshore bar.

Preliminary results indicate that :

- The constriction at the entrance will certainly be effective in generating turbulence and hence a head loss, however both the banks and bed for some distance upstream and downstream may require protection. The turbulence and velocity regime downstream of the constriction during peak ebb and flood flows could scour the bed and banks if unprotected. The constriction configuration and required protection scheme may need to be tested using a scaled physical model.

- Raising the bed level by the construction of a submerged weir again would generate turbulence but significantly less than the constriction. Raising the bed level to a maximum of 0.5 metres below low tide was considered acceptable considering the draft of boats which operate in the estuary. The raised bed again may generate velocity regimes causing bed and bank scour.

- Recharging of offshore shoals is an efficient means of reducing the tidal energy that enters the estuary. It is similar to the construction of a submerged weir but does not produce the same turbulence within the channel. Nearly all creeks and rivers have an associated offshore shoal. These shoals effectively reduce much of the ocean tidal energy from entering the estuary. Further modelling and survey of stable estuaries is required to determine the optimum placement and shape of the shoal.

CONCLUSION.

Saltwater intrusion has been occurring in the Lower Mary River since at least the 1940s and has been responsible for the degradation of much of the freshwater habitat. The main channel and tributary network continue to expand at a rapid rate and a large proportion of the floodplain previously unintruded is now under threat. The triggering mechanisms of saltwater intrusion are believed to have been a combination of coastal, fluvial and anthropogenic causes. Monitoring and modelling programs have been initiated to study the hydrodynamics of the floodplains with the aim of constructing and verifying a numerical simulation model. The model will be used to evaluate a range of remedial options. Preliminary modelling has suggested that the most effective action in remediation will be the construction of either entrance constrictions, raising channel bed levels or the recharge of offshore shoals.

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Imports Can Be Dangerous - Appropriate Approaches to Australian Rivers and Catchments

R.J. Wasson*, T.H. Donnelly* and A.S. Murray*

ABSTRACT: *Some of the reasons are offered why Australian streams and catchments are or might be different from those in other parts of the world, and examples are provided. The example that is discussed most in this paper is the relationship between land use and exports of sediment and phosphorus. The appropriateness of current models of this relationship are explored using data from the Upper Murrumbidgee River Catchment.*

1. INTRODUCTION

In 1984 the Ecological Society of Australia organised a symposium entitled: 'Are Australian Ecosystems Different?' (Dodson and Westoby, 1985). The answer to the question is both yes and no, depending not surprisingly on the ecosystem under examination. Aquatic ecosystems received little attention at the symposium, a situation that has only been redressed since 1984 by Harris (1995).

If the natural resources of this country are to be managed effectively, the question posed in the title of the Ecological Society's Symposium needs to be answered. Without an answer, we will continue to import ideas and models from other places without determining their appropriateness for Australian conditions.

In this paper, some of the features that may make Australian catchments and rivers different from those in other parts of the world are explored, although the degree of difference is not always obvious. We then explore one particular way in which at least some Australian catchments and rivers are different from those where many of our concepts of catchment behaviour were developed. It is hoped that this paper will stimulate others to explore the degree to which Australian fluvial systems differ from those in other lands.

2. AUSTRALIAN DIFFERENCES

Of all the continents, Australia is the driest, has the lowest relief and least elevation (Garrels and Mackenzie, 1991). Sheet and rill erosion rates are on an area-weighted basis higher than the global average, but the sediment discharge to the oceans is lower than the global average. The continental sediment delivery ratio is <3%, much lower than the global average (Wasson, Olive and Rosewell, in press). Much of the flora and fauna is endemic, and human population density is on average very low with concentrations around the coast. A large fraction of the soils are sodic and/or saline (Isbell et al, 1983), the continent's specific runoff is low, and both rainfall and runoff are the world's most variable (McMahon et al, 1992).

The major disturbance to the land caused within the last 200 years by the introduction of European agricultural practices is one of the most recent in the world, and since this disturbance there have been no major excursions of climate. The most recent significant climatic excursion occurred about 6,000 years ago when the continent was both warmer and wetter than present. Since then, climate has on average become drier and cooler. The massive perturbations to climate, soil and biota associated with the major ice sheets of the Northern Hemisphere did not occur in Australia. The major post-glacial environmental shift was largely driven by changes to available moisture rather than temperature (Wasson and Donnelly, 1991).

The very general statements listed above do not allow assessment of the degree of difference of Australian fluvial systems, or other ecosystems. They simply suggest reasons why we might search for differences. Differences worthy of more detailed consideration follow:

- The specific water yield of Australian catchments is low by world standards (McMahon et al, 1992). River channels are therefore likely to be smaller per unit of catchment, and under natural conditions dried out frequently. Paradoxically, many inland streams like the Darling River probably flow more often as a result of reservoir construction. Australia stores more water per capita than any other nation (Department of Environment, Sport and Territories, in press), to secure a water supply in the world's most variable rainfall regime.

*CSIRO Division of Water Resources, GPO Box 1666, Canberra, ACT, 2601, Australia.

- Long periods of weathering, uninterrupted by uplift and major mechanical erosion, have produced highly weathered soils (eg, McLennan, 1993). As a result suspended and deposited sediments in inland streams contain a large proportion of clay minerals (typically <2μm; eg, Woodyer, 1975). In addition, long periods of dry climate have allowed the accumulation of salts in soils (Chivas et al, 1991). These salts, and very fine clays, make the interior streams naturally saline and turbid (Williams, 1982). Phosphorus is strongly attached to suspended sediments and the major loads of this nutrient therefore move with the sediment during floods (Donnelly, 1995). Most of this phosphorus is natural (or native), derived from weathering.

- Sodicity, a characteristic of soils also related to aridity, produces highly dispersible subsoils that, once surface soil horizons are breached by erosion, suffer rapid and often deep gullying. Subsurface tunnel erosion occurs in these soils, also contributing to gully formation (Ford et al, 1993). This form of erosion liberates both fine sediments and native phosphorus.

- The low specific discharge of inland streams, combined with their low gradient, produce rates of lateral migration of rivers such as the Murrumbidgee and Barwon that are much lower than the global pattern identified by Hooke (1980). By contrast, coastal rivers with higher specific discharges, migrate laterally at about the global average rate (Rutherfurd, in press).

These few examples are merely indicative of the characteristics that distinguish Australian fluvial systems.

3. THE BALANCE OF SEDIMENT SOURCES

Golosov (1988) measured the fluxes of sediment in the 3,640 km^2 catchment of the Protva River near Moscow. Careful measurements have produced a sediment budget (Fig. 1) that exemplifies, it will be argued, the paradigm underlying most catchment management in Australia. In the Protva landscape of low relief, gentle slopes, erodible chernozems, and cultivation, about 94% of the annual average mobilisation of sediment is by sheet and rill erosion. The remainder is mobilised by channel and gully erosion. Only 11% on average leaves the catchment, and fully 83% of the mobilised sediment is stored on footslopes as colluvium each year.

A reasonable extension of this model of landscape behaviour is that land use substantially modulates the flux of sediment by affecting the rate of sheet and rill erosion. In this model, land use is a key driving force, and so is used as the pre-eminent variable in catchment modelling. At its simplest, land use affects fluxes by changing export coefficients of water, sediment, phosphorus and nitrogen (eg Young et al, in press; Phillips et al, 1992). In more mechanistic models, land use changes the vegetation cover and therefore sediment fluxes.

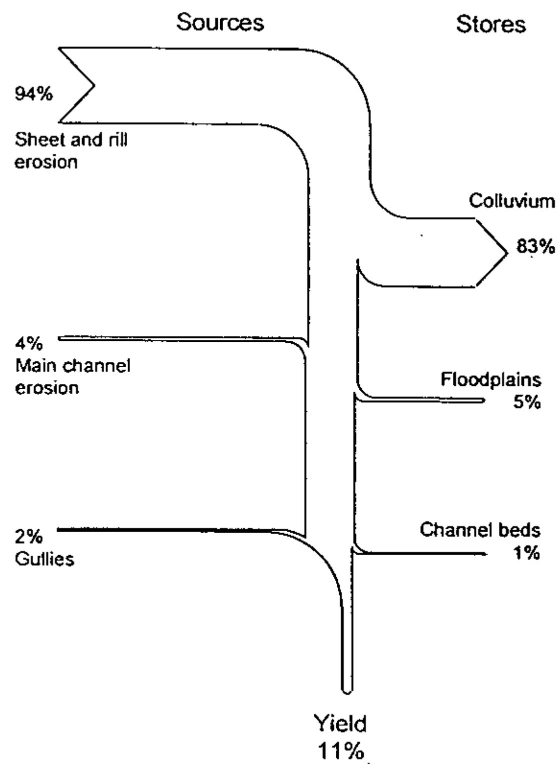

Figure 1: Protva Catchment

In landscapes where sheet and rill erosion rates are low and channel incision pervasive, a different model of landscape behaviour prevails. In the Jerrabomberra Creek catchment near Canberra, Wasson (1994a) and Wasson et al (in press) have shown that channel and gully erosion mobilised about 96% of the sediment moved in this 130 km^2 catchment since 1850 A.D. (Fig. 2). Here about 49% of the mobilised sediment leaves the catchment in an average year, a higher figure than in the Protva case because the Jerrabomberra catchment is smaller and the channels not only supply most sediment but also act as efficient conduits for its transport. Most of the mobilised sediment that does not leave the catchment is deposited on floodplains, near the sediment sources - unlike the Protva case where hillslopes both produce and store most mobilised sediment.

The two models (Figs 1 and 2) are probably end members (Wasson, 1994; Wasson and Sidorchuk, in press), and each requires radically different management strategies to control sediment flux. Additional evidence in support of Fig. 2 as a model for Australian catchments is now presented.

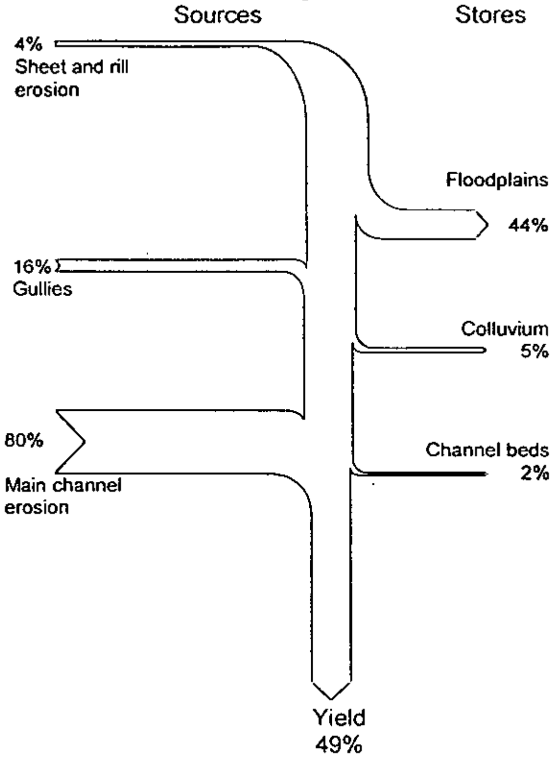

Figure 2: Jerrabomberra Catchment

Surveys of farm dams on the Southern Tablelands of NSW and the ACT have shown that ungullied catchments yield on average 5 ± 3 to 21 ± 15 times the amount of sediment leaving native forested catchments of ≤ 10 km^2 (Table 1). Gullied catchments yield 40 ± 26 times the forested catchments, between 8 and 2 times ungullied pasture and cropped catchments. These results come from small catchments, and Wasson (1994b) has shown that drainage density is a useful explanatory variable of sediment yield and land use is often not. Wasson (1994b) also summarised data from other parts of the country showing that gullies are a significant and often dominant source of fluvial sediment.

In larger catchments, the currently available test of the idea that channels dominate the sources of sediment is provided by the surface soil radionuclide tracers ^{210}Pb and ^{137}Cs (Wallbrink and Murray, 1993). These radionuclides are at their highest concentrations in the top few centimetres of soil. If diluted by unlabelled soil during transport, their concentrations in river sediments fall dramatically. Using this reasoning, Wallbrink et al (this volume) showed that about 90% of the suspended sediment in transport in the lower Murrumbidgee River comes from channel and gully erosion; that is, erosion of subsoils unlabelled by surface soil tracers. In the upper Murrumbidgee catchment, Wallbrink and Fogarty (in prep.), using this technique, have shown that in the Molonglo sub-catchment 96 ± 11% of the fine sediment in transport

Table 1: Mean annual specific sediment yield from catchments ≤10 km^2 on the Southern Tablelands (based on Neil and Fogarty, 1991; Lawrence, pers. comm.).

Catchment class	n	Mean annual specific sediment yield (t/km^2/yr)	Multiple of forested sediment yields
Native forest	5	4 ± 2	1
Native pasture	17	19 ± 5	5 ± 3
Native pasture with discontinuous gullies	5	31 ± 2	8 ± 4
Cropped	4	57 ± 15	14 ± 8
Overgrazed native pasture	2	68 ± 19	17 ± 8
Pine plantation	7	84 ± 42	21 ± 15
Established urban (industrial)	1	160	40
Native pasture with continuous gullies	10	161 ± 68	40 ± 26

Uncertainties are standard errors

in the rivers comes from channel and gully erosion, an estimate consistent with either a very small or zero surface soil input. Whenever a catchment is gullied, the sediment yield increases and the surface soil component is relatively small in catchments between 8 and 100,000 km^2 in area (Wallbrink et al, this volume).

4. MODELLING OF SEDIMENT AND PHOSPHORUS FLUXES

4.1 Modelling of Sediment Fluxes

Most mathematical and statistical models of sediment movement through catchments, that are suitable for routine use, are based on the concept of Fig. 1. ANSWERS, for example, has no channel erosion component, nor does TOPOG or CMSS. We take as our detailed example AQUALM, a model designed to assist planners, designers and managers (Phillips et al, 1992). This model has been applied to the upper Murrumbidgee River catchment (National Capital Planning Authority, 1994), thereby affording an opportunity to compare results with those available from field measurements and tracer studies.

The EXPORT mode of AQUALM generates runoff and pollutant exports using daily time steps, and then routes the pollutants through a stream network. The pollutant exports depend on land use type, and so the model does not explicitly produce pollutants from channels and gullies.

A test of AQUALM is to compare the model results with those estimated from reservoirs, lakes and sediment traps in the same area (Wasson, 1994a). Table 2 shows the comparison between the modelled median annual load of sediment, for a number of subcatchments in the Upper Murrumbidgee catchment, and the mean annual load calculated from the regression equation relating catchment area and load for this region. For the near-natural catchments, the pre-European settlement regression relationship of Wasson (1994a) has been used.

With only two exceptions, AQUALM underestimates the load for disturbed catchments and overestimates it for the near-natural catchments - by factors up to nearly eight. Mean and median loads are likely to be different by no more than about 50% from calculations done by C. Barnes (pers. comm.).

The underestimation of loads in disturbed, often gullied, catchments could result from: the failure of AQUALM to generate sediments from gullies and channels; or inadequate model runs to produce reliable median values to compare with the long-term means in the 'observed' data.

4.2 Modelling of Total Phosphorus Fluxes

There is an extensive literature on the factors that control TP export from catchments (eg. Chang et al,

Table 2: Modelled and Observed Suspended Sediment Yields in the Upper Murrumbidgee Catchment

Catchment	Area (km^2)	Median model yield (t/yr)	Mean 'observed' yield (t/yr)	Difference between modelled and 'observed'
L. Goodradigbee*	625	1990	260	- 8
L. Yass	1110	9250	24000	- 3
Woodstock	42	260	1110	- 4
Sturt	9	120	260	- 2
L. Queanbeyan	91	330	2290	- 7
Uriarra	249	930	5900	- 6
Williamsdale	107	1130	2660	- 2
Buchan	152	400	3710	- 9
L. Numeralla	37	1380	980	+ 1
Adaminaby*	1110	800	410	+ 2
Yaouk	378	40	170	- 5

* Near-natural

1983, Hill, 1981, Hartley et al, 1984, Young et al, in press). There is a general opinion that land use controls the export, modulated by topography, runoff, and soil type. This opinion in the case of TP is the equivalent of the conceptual model shown in Fig. 1, and AQUALM reflects that model. It is interesting, however, that for Australia Young et al (in press) show considerable overlap between TP generation rates for native pasture, improved pasture, and dryland cropping, the three major rural land use types in the Murrumbidgee catchment. This indicates that, in small catchments, land use does not correlate strongly with TP yields.

Most studies of phosphorus movement in catchments has been carried out in areas of intensive agriculture in western Europe and/or North America. In these landscapes, land use and fertiliser applications are likely to be important sources of TP, along with urban and industrial wastes. So the conceptual model based on intensive agriculture in a system resembling Fig. 1 is unlikely to apply to Australian catchments where broadacre agriculture, active channel incision, small areas of intensive agriculture, and small quantities of urban and industrial wastes are the norm. Yet there are few explicit tests of the appropriateness of the conceptual model.

Table 3 presents the calculated mean annual specific yield of TP for the same catchments documented in Table 1. The TP yield is calculated by multiplying the sediment yield by the mean concentration of TP in the soils of the catchment; ie. 0.03 ± 0.001°/₀ TP. Not surprisingly, gullied catchments yield most TP (48.3 ± 22.0 kg/km^2/yr). This result indicates that catchment managers attempting to reduce TP impacts to waterbodies should pay more attention to channel erosion as a source of native TP.

5. CONCLUSIONS

In this paper, reasons have been given to support a search for differences between Australian fluvial systems and those in other parts of the world. The motivation for this search is to ensure that we only import and use ideas and models that are appropriate to this landscape. The use of inappropriate imported ideas and models is dangerous (cf. Harris, 1995).

Some specific examples are given, and one is developed in some detail. A model (AQUALM), built on an idea derived from other parts of the world, is shown to poorly estimate observed yields of sediment. The model underestimates the observed data, possibly because the model did not include the key sources of sediment, namely gullies and channels.

From first principles, it is expected that models of phosphorus sources developed in more intensely used catchments in other countries will not apply to most Australian catchments. Some evidence is offered to support this view. More importantly, there is currently little effort in Australia to test the appropriateness of the phosphorus models, or indeed any other catchment models.

Table 3: Calculated mean annual specific Total Phosphorus (TP) yield from catchments ≤ 10 km^2 on the Southern Tablelands.

Catchment class	Mean annual specific TP yield (kg/km^2/yr)
Native forest	1.2 ± 0.6
Native pasture	5.7 ± 1.7
Native pasture with discontinuous gullies	9.3 ± 0.9
Cropped	17.1 ± 5.1
Overgrazed native pasture	20.4 ± 6.4
Pine plantation	25.2 ± 13.4
Native pasture with continuous gullies	48.3 ± 22.0

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COVER PHOTOGRAPHS

The King River, S.W. Tasmania (flow toward the viewer). The Mt Lyle Copper Mine at Queenstown has released an annual average of 1.2 million tonnes of tailings into the Queen River since the 1880s. The Queen transports the tailings (mean particle size 11 microns) to the King River where they have been deposited on the channel bed and banks, but predominantly in a delta in Macquarie Harbour. Copper in the tailings has killed riparian vegetation. Tailing releases from the mine ceased in October 1994 (see the paper in this volume by Locher). (Photograph: Ian Rutherfurd)

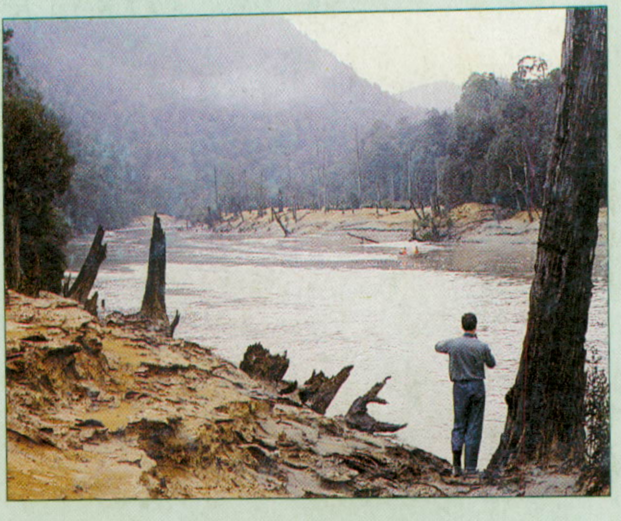
A large unnamed incised stream north of Adelaide, South Australia. This 12m deep gully was eroded in only two major storm events. It is suspected that, in common with most large incised streams in SE Australia, the trigger for the incision was clearing and drainage of swampy valley floor vegetation. (Photograph: Jason Carter)

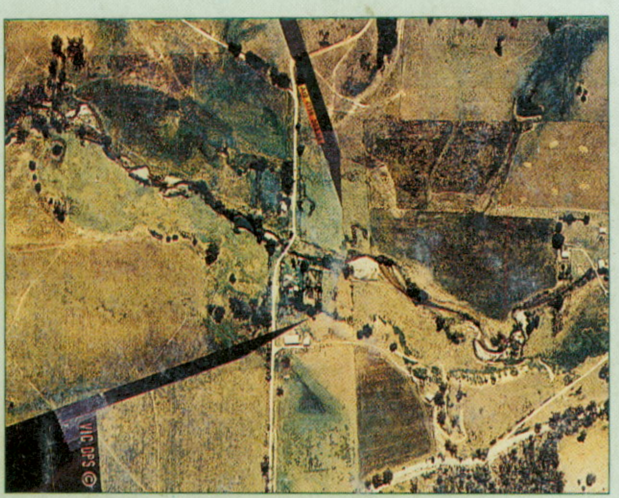
Black Range Creek, a tributary of the King River, NE Victoria (North to the top, flow right to left). This aerial photograph, taken in 1991, can be compared with the photograph opposite, showing the same creek after the October 1993 floods. (Note that the post-flood photograph has been printed upside down, with flow from left to right). (Photograph: Victorian Dept. of Property Services, used with permission).

Black Range Creek after the October 1993 flood. Erskine estimated that the flood had an average recurrence interval of at least 500 years (Rutherfurd & Erskine, 1994 (report to Broken River Management Board)). In places the channel was widened from 10m to over 100m, with the sediment being deposited on an unconfined section of floodplain downstream, and as a sand wave in the lower reaches of the channel (see paper by Rutherfurd, this volume). Over 12ha of land was eroded. (Photograph: Aerial photographs commissioned by the Broken River Management Board).

Bega River, S.E. NSW, near Bega, looking upstream. Before 1850 the Bega was a low sinuosity, laterally stable channel lined by river oaks. By 1926 the channel had widened from less than 50m to over 200m. Brooks (1994, "Veg. & channel morphodynamics along the Lower Bega R." Macquarie Uni. Honours Thesis) argues that the widening was due to a series of large floods combined with the hydrological effects of clearing 70% of the vegetation from the catchment. Since the 1960s the channel has been constricted by willows, reducing channel capacity by up to 50%. (Photograph: Ian Rutherfurd)

A small saline creek in the Kalgan River catchment, S.W. Western Australia. Note that the fluctuating saline water level has killed a swathe of riparian vegetation along the creek leading to erosion of the bed and banks. Dry-land salinity is a major complicating factor in many streams of the SW corner of the continent (Williams, P. (1992) The state of the rivers of the South West, W.A., W.A. Water Resources Council, Perth). (Photograph: Ian Rutherfurd)





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