Sand Slugs and Stream Degradation: The Case of the Granite Creeks, North-east Victoria

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Acronyms

ACS	average catchment slope
AHD	Australian height datum (height above sea level)
CR	circularity ratio
DNRE	Department of Natural Resources and Environment
GBCMA	Goulburn-Broken Catchment Management Authority
HCC	hillslope channel connectivity
HI	hypsometric integral
LSF	Land Selection Files
LWD	large woody debris
MSL	main stream length
NRE	see DNRE
PROV	Public Records Office of Victoria
PTC	Public Transport Corporation
RRR	relative relief ratio
RWC	Rural Water Corporation (or Commission)
SCA	Soil Conservation Authority
SRWSC	State Rivers and Water Supply Commission

Explanation of some terms

Bioturbation	disturbance or mixing of soil by organisms (animals living both above and below ground)
Drape	an overbank deposit of sediment, usually sand
Flocculation	process in which smaller particles join together to form larger particles
Pedogenesis	the process by which soil is formed or develops
Regolith	loose rock material that is the subject of weathering. Soil is the surface component of regolith.
Scour chain	a chain (of the order of 1 m long) partially inserted vertically into the bed of a stream. The remainder of the chain is laid horizontally on the streambed and measured. Changes in the lengths of the horizontal and vertical parts of the chain indicate the extent of scour and fill at that particular site.

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1. INTRODUCTION

1.1. Background and context

Stream and land degradation have occurred throughout south-eastern Australia since European settlement, resulting in gullying, channel incision and channel widening, and the release of large volumes of sediment (Rutherfurd 2000).

The fate of the sediment depends to a certain extent on its particle size distribution. Fine sediments (clays and fine silts) remain entrained in flow for sufficient time to be transported significant distances downstream from the site of erosion or out onto floodplain units where they are stored for long periods of time (Meade 1988). To transport the sand and gravel fraction, on the other hand, requires much more energy. As a result, this fraction remains in the stream channel and is transported slowly downstream in an episodic manner by large flood events. If the material eroded from a catchment is predominantly fine the major form of degradation is a deepening and widening of the channel, as well as sedimentation downstream on the floodplain. If the eroded material is predominantly coarse, degradation takes the form of changes in channel dimensions and stream sedimentation, or sand slug development.

A sand slug is a discrete body of sand deposited in a stream channel. Sand slugs were first described by Gilbert (1917) in relation to hydraulic mining debris deposited in the Sierra Nevada, in California. Since then, sand slugs have been reported in a variety of locations, both in Australia (e.g. Knighton 1989; Erskine 1994; Rutherfurd & Budahazy 1996) and throughout the world (e.g. Pickup, Higgins & Grant 1983; Lewin & Macklin 1987; Madej & Ozaki 1996).

Nicholas *et al*. have described slugs as ‘bodies of clastic material associated with disequilibrium in fluvial systems over time periods above the event scale’ (Nicholas *et al*. 1995 p. 502). In other words, a slug is a discrete volume of sand and/or gravel material that is released into a stream channel and only very slowly transported out of the stream network by the stream flow. The slug can fill the width of the channel to depths of the order of metres, and extend over distances of hundreds to thousands of metres. The front of the slug is referred to as its ‘snout’, and this can be a well-defined face or front, downstream of which negligible deposition is apparent.

The physical impact of a sand slug is to drown the stream’s natural bed form (e.g. submerge pool and riffle sequences)and alter the channel form (Nicholas *et al*. 1995). In many instances a sand slug will transform a stream channel, producing a shallow flat bed. This alters the channel roughness and reduces the channel capacity, altering the stream hydrology and hydraulics. The stream will break out of the channel more frequently, low flows may occur beneath the sand and pools will no longer persist during dry spells. Large woody debris is submerged by the sand and the channel boundary material is often altered. Such changes have an impact on in-stream habitat and thus the stream ecology. Alexander & Hansen (1986) found that the introduction of sand into a stream in the upper midwest of the USA resulted in the channel becoming shallower and wider. As a consequence the static water volume decreased, channel diversity was reduced, fish cover was reduced and velocities increased, all of which contributed to a more stressful environment for fish. Stream temperatures also increased slightly and benthic invertebrates were reduced to half. All these factors were found to contribute to a significant reduction in brook trout (*Salvelinus fontinalus*).

In south-eastern Australia sand slugs derived predominantly from stream erosion have tended to be associated mostly with granite catchments (Rutherfurd 1996). Granite catchments produce sediment that is dominated by sand-sized particles and so it is no surprise that when stream erosion and gullying occur in these catchments, sand slugs usually result. Large areas of south-eastern Australia are dominated by granitic geologies (Russell & Coupe 1984; Douglas & Ferguson 1988), and the influence of European settlement has been felt throughout the region, so stream degradation in the form of sand slug development is probably more widespread than is currently recognised. While sand movement in granite catchments has been studied at several sites in south-eastern Australia (e.g. Erskine 1994; Rutherfurd & Budahazy 1996; Brooks & Brierley 1997, 2000), those studies have been confined to large catchments (of the order of 1000 km^2 in area) and have been concerned primarily with the physical impact of sediment slugs on the streams. Similarly, the international literature detailing sand slugs is still limited and concentrates on gravel slugs or slugs resulting from mining waste (see review by Nicholas *et al*. 1995). Madej & Ozaki (1996) describe a sand slug derived from catchment erosion, but the Redwood Creek catchment in USA is very steep compared with the low gradient catchments common in Australia.

The work presented in this report is concerned with the development and movement of sand slugs in several small anabranching streams in central Victoria (the Granite Creeks, tributaries to the Goulburn River), with an emphasis on the effects on stream ecology and rehabilitation. We believe that similar conditions apply in small catchments elsewhere in Australia so that the lessons from this project should be useful to landholders, Landcare groups and river managers.

This report not only provides an insight into the triggers for sand slug development in small granite catchments, but also looks at the influence of anabranching on sand slug migration. The results from the investigation are also considered in relation to the probable effects on stream ecology and the implications for ecological restoration. The methods associated with the investigation are clearly described and so provide a template on which investigations of a similar nature might be modelled. Such a template could be of particular use to community groups contemplating stream rehabilitation activities.

1.2. Objectives and approach

This report presents some outcomes from the project called ‘Restoration of Degraded Rural Streams: the Granite Creeks Landcare Project, North-East Victoria’ (the Granite Creeks Project). The Granite Creeks Project has been developed to investigate the potential for ecological restoration of rural streams degraded by sand slugs. The Granite Creeks area has been chosen as the main field site for a variety of reasons, including the involvement of the local Landcare groups, the fact that preliminary ecological work has been carried out previously (O’Connor 1991) and because the site is readily accessible to researchers, being just two hours drive from Melbourne. The other advantage offered by the Granite Creeks site is that there are a number of streams with sand slugs which provide replicates and facilitate experimental investigations.

The project is multidisciplinary in nature and requires both ecological and geomorphological input. As a result the project has two components: an ecological component and a geomorphological component. This report gives the results of the geomorphological investigation.

Before restoration works can be planned, it is necessary to determine where the sand comes from and how it moves. Consequently the objective of the geomorphological component of the project was:

> to determine the levels of sediment input into selected streams from the catchments of the Strathbogie Ranges, and the movements of such sediments within the streams.

Two key hypotheses were developed to investigate this objective:

1. that increased inputs of sediment (sand) to Strathbogie Range streams have resulted from post-settlement catchment land use;
2. that downstream sedimentation associated with accelerated erosion in the catchments, post-settlement, is mitigated through sediment storage in the catchment slopes and tributary valleys.

There are more than ten creeks that could be considered part of the ‘Granite Creeks’ because they flow off the Strathbogie Ranges and across the Riverine Plain into the Goulburn River, but only three were selected for study in this project. Castle Creek, Creightons Creek and Pranjip–Nine Mile Creek are being studied during the ecological component of the project, and thus these three creeks have also been the subject of the geomorphological investigation.

The tasks required to address the two key hypotheses can generally be categorised as those associated with identifying historical stream condition and those associated with assessing present stream and catchment condition. In essence, the historical analysis was concerned with identifying the forms of the creeks at the time of European settlement, how those forms have adjusted since European settlement and the factors driving that change. The main objectives of the analysis of present condition were to find out if the processes driving change in the past are still active and whether or not the creeks are starting to stabilise. It was necessary to understand why the creeks are in the state they are in today before the fieldwork associated with current assessment was finalised and this led to the project being split into two parts. The first part, which consisted of the historical analysis, was carried out in the first half of 1998; and the assessment of present condition was conducted in the second half of 1998 and the first half of 1999.

1.3. Report outline

Chapter 2 of this report describes the physical attributes of the three selected catchments, and Chapter 3 details the methods associated with the historical analysis and the assessment of present condition. Chapter 4 presents the results of the historical analysis, and Chapter 5 gives the results of the assessment of present condition. The outcomes are discussed in relation to the overall project in Chapter 6 and final conclusions are presented in Chapter 7.

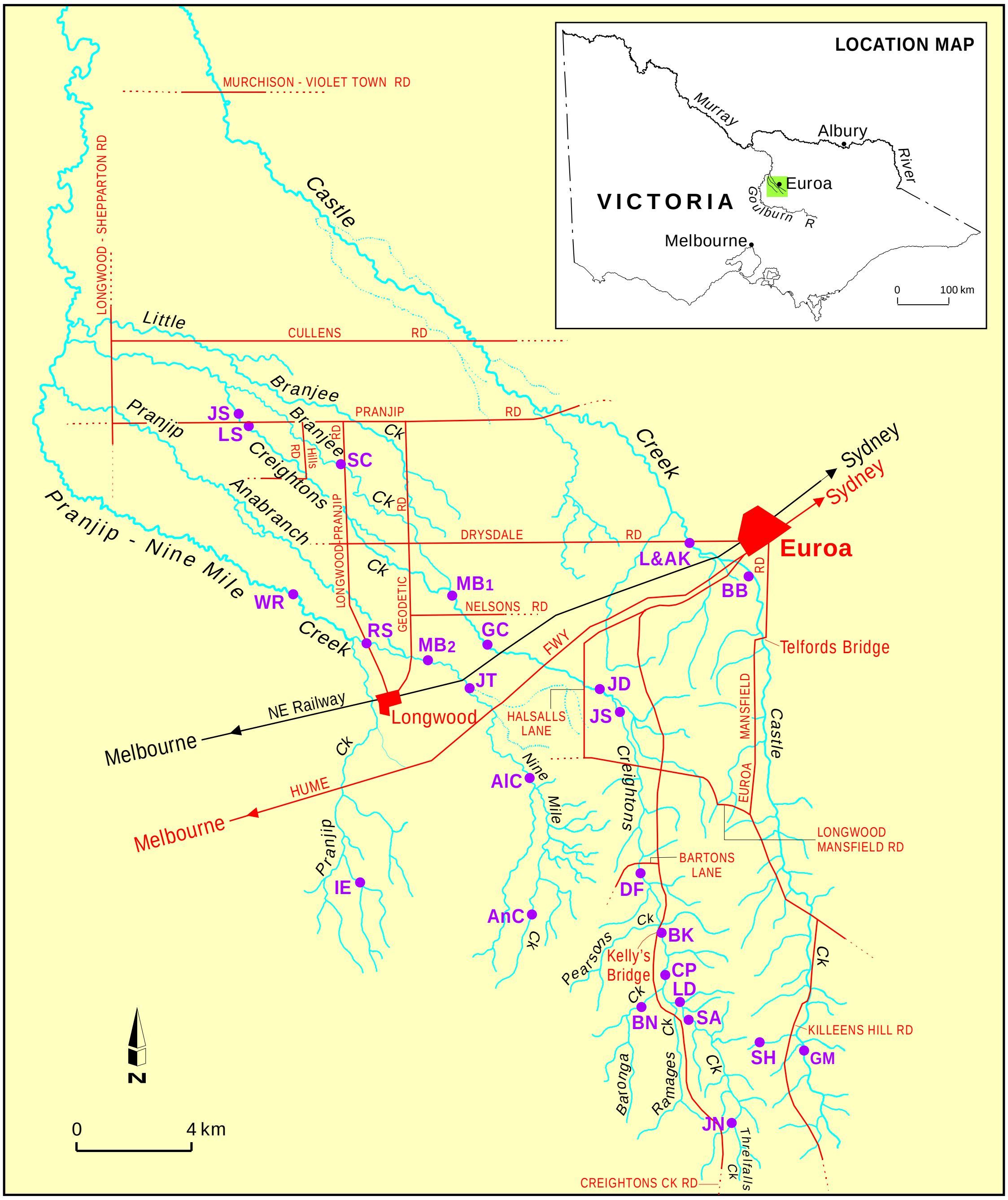


Fig. 2.1. Granite Creeks location map. Flow is from south to north.

Sites on map denoted by solid circles indicate locations referred to in the text. The letters next to each circle are the initials of one of the relevant property's owners. The abbreviations are as follows: AIC – Alastair Cameron, AnC – Andrew Cameron, BB – Brian Bamford, BK – Brian Kelly, BN – Barrie Noye, CP – Claire Penniceard, DF – Dino Furlanetto, GC – Greg Carlsson, GM – Geoff McLean, IE – Ian Elder, JD – Jim Dunn, JN – John Nielsen, JiS – Jim Shovelton, JaS – Jack Stevens, JT – Jim Threlfall, LK – Leo Kubeil, LD – Laurie Davidson, MB – Maurie Brodie, RS – Roy Seach SA – Stan Artridge, SC – Sue Caldwell, SH – Sue Haggard and WR – William Rennie.

2. CATCHMENT DESCRIPTIONS

2.1. Introduction

The physical attributes of Creightons Creek, Castle Creek and Pranjip–Nine Mile Creek are described in this chapter. The information sets the scene for the remainder of the report and provides the detail necessary for the reader to follow some of the descriptions and results presented later in this report, especially in relation to localities.

The physical descriptions provided here should enable the reader to understand these creek systems and how they compare with other more familiar systems. This chapter also discusses a number of extra physical characteristics that allow us to examine how similar the three creeks are to one another. Such an investigation also provides a method by which nearby creeks can be compared to the three creeks examined here, to determine if and how the results presented in this report apply to the other ‘Granite Creeks’.

2.2. A general description

Castle Creek, Creightons Creek and Pranjip–Nine Mile Creek all run off the Strathbogie Massif, in central Victoria, and flow in a north-westerly direction until they meet the north flowing Goulburn River (Fig. 2.1). Pranjip–Nine Mile Creek is the most southerly of the three creeks being studied, rising in the hills immediately above Old Longwood. Maps of the area show Pranjip Creek extending from its headwaters near Old Longwood, across the Riverine Plain to its confluence with a number of southern tributaries, before turning north and picking up Creightons Creek and Little Branjee Creek as tributaries. It then continues north and meets the Goulburn River north-east of Murchison. For the purposes of this study, Pranjip–Nine Mile Creek refers to that part of the system upstream of the Creightons Creek confluence, and does not include any of the southern tributaries, i.e. Wormangal Creek, Burnt Creek, Muddy Waterhole Creek, Charles Creek or Reedy Creek. Consequently the Pranjip–Nine Mile Creek system here consists only of Nine Mile Creek, Pranjip Creek above the Creightons Creek confluence, and the Anabranch of Pranjip. In total the area of the Pranjip–Nine Mile Creek catchment is approximately 206 km^2 (Thompson & Associates 1992).

The Creightons Creek catchment, which sits between the Pranjip–Nine Mile and Castle Creek catchments, is approximately 174 km^2 in area (Thompson & Associates 1992). The creek itself has four main upstream tributaries and two downstream tributaries that are considered to be anabranches. The upstream tributaries are Threlfalls Creek, Ramages Creek, Baronga Creek and Pearsons Creek. The downstream anabranches are Branjee Creek and Little Branjee Creek. It is important to note that if one is to describe a creek by its low-flow course then between Nelsons Rd and the Creightons–Branjee confluence, Branjee Creek forms the main channel because the Creightons Creek segment has effectively been abandoned.

Castle Creek is the most northerly of the three creeks. It flows through the southern outskirts of Euroa. At a glance Castle Creek appears to differ from both Creightons Creek and Pranjip–Nine Mile Creek because it flows directly into the Goulburn River without merging with another creek system, and it does not have any obvious anabranches. The Castle Creek catchment covers an area of approximately 282 km^2 (Thompson & Associates 1992).

2.2.1. Climate and hydrology

The Granite Creeks area generally experiences hot dry summers and cool wet winters (LCC 1984). Monthly rainfall data for Euroa (representing the ‘flats’, the plains on the north-western or downstream side of the Hume Freeway) and for North Strathbogie, 20 km south-east of Euroa in the Strathbogie Ranges (representing the highlands), suggest that the local rainfall regime has a moderate winter maximum. For example, rainfall in Euroa is at minimum in February (33 mm) and at maximum in June (77 mm). Similarly rainfall at North Strathbogie is at a minimum in February (35 mm) and at a maximum in July (123 mm) (LCC 1984). In terms of the rainfall distribution, it is lowest on the flats (550–630 mm per year) and increases with altitude; rainfall may be as high as 800 mm per year in the headwaters of Castle Creek, Creightons Creek and Pranjip–Nine Mile Creek (LCC 1983, 1984). The mean daily maximum temperature for Euroa varies from 15.2°C in July to 30.2°C in January. The mean daily minimum for Euroa ranges from 3.5°C in July to 11.9°C in January (LCC 1984).

Heavy frosts (i.e. <0.0°C) occur most frequently in the Strathbogie Ranges, but they are also relatively common on the flats. Data from White (1990) indicate that on average 53 heavy frosts are recorded at Strathbogie between April and November each year, and that on the flats at Euroa 10 heavy frost days per year are recorded, primarily between May and September.

According to wind rose data (White 1990) for Euroa for January and July, 50% of wind observations in summer are from the south-east, south or south-west, but in winter more than 50% of observations are recorded in the north-west quadrant.

There are no flow regulation structures on Castle Creek or Creightons Creek, but water is pumped from both creeks for stock and domestic use. Pranjip–Nine Mile Creek provides a domestic water supply for Longwood as well as stock and domestic supply for those landholders with riparian rights. The water supply for Longwood is pumped from a dam on Nine Mile Creek which is situated on the edge of the Strathbogie Plateau.

There are flow gauging stations on Castle Creek at Arcadia (commenced in 1970) and Pranjip Creek at Moorilim (commenced in 1957), but the gauging station at Creighton, on Creightons Creek, was discontinued in 1989 (commenced in 1976) (RWC 1987; pers. comm. Steve Noble, TES Hydrographics, April 1998). All three creeks are spring fed, but the strength of the springs varies. Both Castle Creek and Pranjip–Nine Mile Creek cease to flow in summer, whilst Creightons Creek continues to flow all the way to its confluence with Pranjip Creek, in all years except drought years (O'Connor 1991). Even in drought years when Creightons Creek has ceased to flow on the flats, it has not dried up beyond the Longwood–Mansfield Rd at any time over the last 120 years (pers. comm. Brian Kelly, landholder, Feb. 1998; Stan Artridge, landholder, Feb. 1998).

2.2.2. Geology, geomorphology, pedology and stream condition

The Granite Creeks catchments contain two distinct geologies. In the headwater reaches of the Castle, Creightons and Pranjip–Nine Mile Creek catchments the geology is dominated by the granitic Strathbogie Massif. The Massif is a broad plateau with an undulating granite surface (LCC 1984). The creeks flow out of their granite-controlled headwaters and onto the lowlands where the geology is dominated by alluvial sediments (Geology Map Sheets, Geological Survey of Victoria, 1:250 000, Sheets: SJ 55-1 & SJ 55-2). Between the headwaters and the Goulburn River the creeks flow across the Riverine Plain, which consists for the most part of alluvial material, clay, silt, sand and gravel laid down in the Quaternary (Pleistocene and Pliocene). More recently deposited Quaternary alluvial sediments (Recent and Pleistocene) can be found immediately adjacent to the creeks. Small pockets of Lower Devonian sandstone and siltstone can also be found on the Riverine Plain (Geology Map Sheets, Geological Survey of Victoria, 1:250 000, Sheets: SJ 55-1 & SJ 55-2).

Castle Creek, Creightons Creek and Pranjip–Nine Mile Creek all rise at altitudes of over 500 m AHD. The long profiles of the creeks (Fig. 2.2) are quite similar, dropping steeply from 500 m to 200–250 m over less than 10 km, resulting in gradients of 0.05 up to 0.2. Once the creeks leave the foothills and enter the Riverine Plain their grade is reduced (0.002–0.004). The gradient of Castle Creek declines to approximately 0.001 at 40–50 km from its headwaters, but the gradient of the

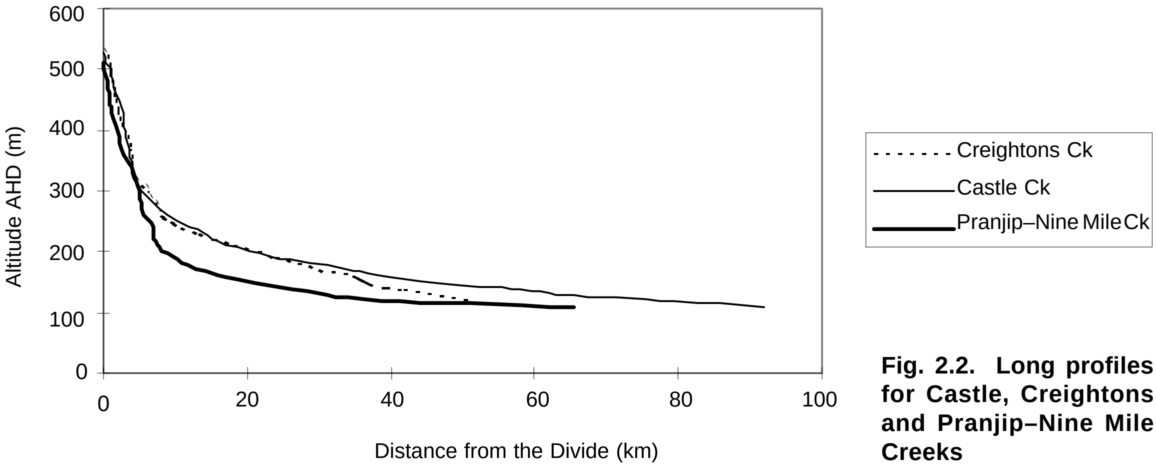


Fig. 2.2. Long profiles for Castle, Creightons and Pranjip–Nine Mile Creeks

lower reaches of Pranjip–Nine Mile and Creightons Creeks remains similar to that observed just below the foothills, i.e. approximately 0.002.

The headwater streams rise on the top of the Strathbogie Plateau in rolling country bounded by scarps, which form the Strathbogie Land System. Soils in this area vary from red duplex soils to weakly bleached friable gradational soils. The erosion hazard for this land system is generally low, although the streambank erosion hazard is moderate (LCC 1984). The streams move down the catchments into the Moonee Moonee Land System. This system is characterised by dissected granitic slopes of high relief, with soils varying from friable brown gradational soils to red gradational soils with weakly structured sub-soils. The erosion hazard here is generally low to moderate; the sheet erosion hazard on the steeper slopes and foothills is moderate (LCC 1984). Further downstream the creeks flow through the Swanpool Land System, which consists of rolling granitic hills and valley slopes and floors comprising Quaternary alluvium. Soils found in this system include yellow duplex soils, weakly bleached friable soils and massive gradational soils. The erosion hazard in the Swanpool Land System is generally low, although the hazard is probably higher (moderate) in the Granite Creeks area because it is drier (LCC 1984).

Several land systems are found on the flats. They include the Lurg Land System, the Benalla Land System, the Slopes Colluvial Land System and the Riverine Plain I Land System (LCC 1983, 1984). The Lurg Land System consists of undulating to rolling hills that have developed on Palaeozoic sediments. On western slopes, undifferentiated stony loams are common, while on eastern slopes red duplex soils and weakly bleached friable and massive gradational soils are found. On the Lurg Land System the streambank and gully erosion hazards are moderate, and the sheet erosion hazard is moderate to high (LCC 1984). The Benalla Land System, which consists of outwash fans, terraces, flats and swamps, is founded on Quaternary alluvium. Soils vary from yellow duplex soils (with some gilgai) to red and brown gradational soils with weakly structured sub-soils. The erosion hazard is generally low although the gully erosion hazard is moderate on gentle fan slopes (LCC 1984). The Slopes Colluvial Land System describes colluvial slopes developed on Quaternary granitic colluvium. Red duplex soils have developed where drainage is relatively good, and yellow to grey duplex soils have developed where drainage is poor. The gully erosion hazard is moderate (LCC 1983). The Riverine Plain I Land System consists of a flat plain sloping towards the north-west, with some prior stream levèes. Where drainage is good, yellow sodic soils develop on the Quaternary alluvium; otherwise the soils are generally grey calcareous sodic uniform clays. The main hazard on this land system is waterlogging.

In a survey of the environmental condition of Victorian streams Mitchell (1990) classified the upper reaches of Creightons Creek as very poor and the middle reaches as poor. The report describes the upper reaches of Creightons Creek as being ‘in very poor condition with heavily cleared eroding banks and sediment build up' (Mitchell 1990, p. 29). The upper reaches of Castle Creek are classed as being in a poor condition and the middle reaches as moderate. Of Pranjip Creek, Mitchell surveyed only the section below the Creightons Creek junction. No detail is provided for any of the other sites.

A more comprehensive survey of stream conditions in the area was carried out in 1992 as a part of an investigation into the Euroa catchments for the Euroa–Nagambie Regional Water Authority (Thompson & Associates 1992). In this survey substantial lengths of waterway in the upper sections of Pranjip, Nine Mile, Creightons and Castle Creeks were classified as unstable or showing severe instability, and some old incision was also noted. Conversely, the lower sections of these creeks were found to be subject to sedimentation, although some old incision and present instability was noted.

2.2.3. Land use and vegetative cover

The main land use in the Granite Creeks catchments is grazing of cattle and sheep (LCC 1983, 1984; Thompson & Associates 1992; Martin 1994). Some cropping occurs on relatively good agricultural land on the flats, whilst other agricultural activities include horse studs (personal observation), vineyards and apiculture (Thompson & Associates 1992; Martin 1994).

The conditions of land selection in Victoria in the 1800s led to the large-scale clearing of vegetation from the Granite Creeks catchments, so that by the 1920s there was little commercially valuable timber left on the flats and only small areas remaining in the hill country (see Section 4.4). Today remnant native vegetation can still be found in the area but it is restricted to some of the rocky ridges in the headwaters, reserves and road reserves. Up on the Strathbogie Plateau, messmate–stringybark open forest, narrow-leafed peppermint open forest and swamp gum open forest are common (LCC 1984). Downslope, the dominant vegetation varies slightly, with broad-leafed peppermint–red stringybark open forest and red stringybark–long-leafed box–red box open forest becoming more common (LCC 1984). The understorey is made up of a variety of shrubs and grasses, including Austral bracken, and there are soft tree ferns in the drainage lines (LCC 1984). In the broad valleys and foothills, red stringybark–long-leafed box–red box open forest is common and red gum open forest is also found. The understorey is dominated by silver wattle, Austral bracken and blackberries (LCC 1984). On the Riverine Plain, open forests/woodlands comprising grey box, yellow box, red gum and bulloak are found, with red gum common along the drainage lines (LCC 1983).

A survey of riparian vegetation in the area in 1992 by Thompson & Associates (1992) indicated that although there were areas where the riparian vegetation was in good condition with a good overstorey and some understorey, for the most part the vegetation was light and discontinuous. There were some segments in the upper catchment of Pranjip–Nine Mile Creek with relatively good riparian vegetation; but on Creightons Creek and Castle Creek the best sections of riparian vegetation were on the Riverine Plain.

2.3. Other physical characteristics

A number of catchment-based physical characteristics have been measured for all three catchments (Table 2.1) to compare the three creeks and determine how similar they are, and to provide further information about the nature of the creeks, e.g. their ability to transport and store sediment. The characteristics measured were catchment area, main stream length (MSL), minimum relief, maximum relief, relative relief ratio (RRR), circularity ratio (CR), average catchment slope (ACS), hypsometric integral (HI) and hillslope channel connectivity (HCC). The RRR is the average slope of the stream channel and the CR is a measure of how close the catchment area is to a perfect circle: the closer the CR to 1, the closer the catchment shape to a circle. The HI is the slope of the hypsometric curve at the point of inflection, where the hypsometric curve represents the way in which mass is distributed within a drainage basin (Strahler 1952). The HCC is a measure of how well the catchment is connected to the drainage network: in other words, how efficiently sediment can be delivered from

Table 2.1. Physical catchment characteristics for the three Granite Creeks catchments and for a number of other catchments in south-eastern Australia

Catchment	Area (km^2)	MSL (km)	Max relief (m)	Min relief (m)	RRR	CR	ACS	HI	HCC
Granite Creeks catchments									
Pranjip–Nine Mile[a]	206	36	510	123	0.011	0.60	3.74°	0.28	~11%
Creightons[b]	174	52.6	545	120	0.008	0.23	4.22°	0.31	~7%
Castle[c]	282	92	530	110	0.005	0.24	3.57°	0.21	~3%
Other catchments									
Lake Eildon	~2500	61	1805	290	0.025	0.31	20.1°	0.34	90%
Candowie Res.	18	5	240	60	0.036	0.63	12.5°	0.47	63%
Lance Ck	17	7	260	70	0.027	0.53	10.4°	0.43	51%
Melton Res.	1155	68	876	70	0.013	0.61	6.2°	0.42	49%
Pykes Ck Res.	120	18	840	360	0.022	0.39	7.3°	0.44	43%
Jerrabombera Ck	133	30	1194	550	0.021	0.35	7.7°	0.30	17%
Lake Eppalock	2028	70	1001	195	0.010	0.50	4.9°	0.30	9%
Lake Albert	77	17	480	195	0.017	0.75	4.4°	0.27	8%
Pekina Res.	135	19	782	440	0.018	0.65	4.5°	0.34	2%

Catchment outlets: [a]Pranjip anabranch confluence, [b]Pranjip Creek confluence, [c]Goulburn River confluence

hillslopes to the catchment outlet (Davis 1996). The higher the HCC value the better the connection, and thus the more efficient the sediment delivery.

A comparison of the characteristics of the Granite Creeks catchments with some other catchments in south-eastern Australia (Table 2.1) suggests that the three Granite Creeks catchments form a distinct group. Rivers with main stream lengths similar to those of the Granite Creeks have much larger catchments, and this is reflected in the unusually low circularity ratios of the Creightons Creek and Castle Creek catchments. It is generally accepted that as catchments increase in size the average slope in the catchment declines and sediment storage within the catchment increases (Walling 1983); consequently stream networks become more poorly connected. The three Granite Creeks catchments studied here are moderately small in size and, on the basis of the model just descibed, would be expected to be relatively steep and well connected. However, the data presented in Table 2.1 show that the Granite Creeks catchments are flat and poorly connected.

The HI can be useful for identifying the extent of geomorphic development of a basin. Strahler (1952) suggests that where HI is greater than 0.60, a basin is in the inequilibrium phase and there is considerable mass at relatively high elevation, while HI between 0.35 and 0.60 represents a basin that has a more uniform distribution of mass across the elevation range. Values of HI smaller than 0.35 occur where most of the basin is at low elevation. The data presented in Table 2.1 indicate that it is relatively common for catchments in south-eastern Australia to have HI values of 0.35 or less, indicating an overall low elevation, and therefore low gradient, landscape. However, the Granite Creeks catchments appear to have HIs among the lowest measured here. Similarly the Granite Creeks catchments have some of the lowest HCC values.

This brief analysis of catchment characteristics for the three Granite Creeks catchments investigated suggests that they have distinctive elongated catchments, dominated by low relief and low gradients. The HIs indicate that the catchments are dominated by extensive low elevation surfaces with isolated relief features, while the HCC values suggest that delivery of sediment from hillslopes in the catchments is inefficient and that the main sources of sediment for the Granite Creeks are the drainage lines.

3. METHODS

3.1. Introduction

When the Granite Creeks Project was conceived it was envisaged that the key hypotheses (see Section 1.2) could be addressed by undertaking the following tasks:

- investigate the history of erosion (gully, sheet and streambank) and stream sedimentation using aerial photos, archival information and local consultations;
- determine present catchment condition with regard to erosion hazard and location of sediment stores, using aerial photos, on-ground fieldwork and local consultations; attempt to map the location of PSA (post-settlement alluvium) using stratigraphic techniques;
- apply sediment tracing techniques to determine potential sediment sources;
- install scour chains to determine the degree of streambed disturbance associated with high discharge events;
- investigate past efforts to control erosion and sedimentation via SCA/DNRE files, on-ground fieldwork and local consultations.

Most of these tasks have been carried out in this study. The mapping of PSA and investigation of past attempts to control erosion were initiated but not completed, because of physical constraints (i.e. difficulties associated with differentiating between modern and old depositional material) and insufficient data (i.e. insufficient data available on past erosion control efforts). Other tasks were substituted for these, so that the study's capacity to address the key hypotheses was not compromised. The substitute tasks included measuring bedload transport rates and monitoring sand movement in the water column at high flows, and both of these have given insight into how sand migrates down the Granite Creeks.

The research questions that are addressed in this study require two distinct methodological components, as outlined in Chapter 1: historical analysis, and a field-based assessment of present conditions. This chapter describes the methods used for the historical analysis and assessment of present condition.

3.2. Historical analysis

The historical analysis used three sources of evidence: (i) documentary evidence, i.e. written historical records; (ii) anecdotal evidence; and (iii) historical cross-section data. For each main source of evidence the specific sources of data are detailed, and where appropriate the methods by which these sources were identified are described.

3.2.1. Documentary evidence

For the purposes of this study an attempt was made to identify all written records which might provide information relating to the form and state of Creightons Creek, Castle Creek and Pranjip–Nine Mile Creek, at any time in the past. The following potential sources of information were investigated: local histories, diaries (e.g. belonging to local squatters, explorers, overlanders); historical maps and plans, and the relevant surveyors' notebooks; Land Selection Files; local paintings and drawings; Shire records; and files held by the Department of Natural Resources and Environment (DNRE) (e.g. local Soil Conservation Authority files and Water Course files). Relevant information on creek morphology was found in all these sources with the exception of paintings and drawings of the creeks because no paintings or drawings were located.

There was a large amount of information and a limited amount of time available to analyse it, so a decision was made to concentrate on one of the three creeks. Creightons Creek was selected, for two reasons: (i) there were more data and information available for Creightons Creek than the other two creeks; and (ii) Creightons Creek was the creek of greatest interest to the researchers working on the ecological component of the project. This meant that although information was collected for Castle Creek and Pranjip–Nine Mile Creek, the Land Selection Files for those two creeks (a main data source) were not investigated.

3.2.2. Anecdotal evidence

To supplement the written information gathered on Creightons Creek, Castle Creek and Pranjip–Nine Mile Creek, local landholders were interviewed to collect undocumented information, such as observations of changes in the creeks over the years. To identify landholders, past and present, who would have such information an article was published in the local newspaper together with a request for information about the creeks. Contacts in each of the catchments also helped identify landholders who might have relevant information. Again, because of time limitations, the information collection focused on Creightons Creek, although landholders living along Castle Creek and Pranjip–Nine Mile Creek were also interviewed. In total 30 people who live or have lived adjacent to the three creeks were interviewed, six from Castle Creek, 20 from Creightons Creek and six from Pranjip–Nine Mile Creek.

In all but four instances the interviews were conducted face to face, generally while walking along the relevant parts of the three creeks. The interviews were not formal in the sense that set questions were given; instead the interview was based on the general question, ‘How has the creek changed over the years and what do you think has contributed to that change?’

While anecdotal evidence can be very useful because it can provide information that cannot be obtained from other sources, its usefulness can be compromised by the interviewee’s ability to clearly recall events in the past, and the potential for exaggeration; and stories that have been passed down through a family can have become distorted over time. Therefore, anecdotal evidence must be treated with some caution. The anecdotal information collected during this study was cross-checked with physical evidence and/or documentary evidence wherever possible, and if the veracity of the information could not be confirmed in some way, it was ignored.

3.2.3. Historic cross-section data

To determine if and how creek morphology has changed since European settlement, historical cross-section data were sought for Creightons Creek, Castle Creek and Pranjip–Nine Mile Creek. Creek cross-section data are often collected in relation to the construction of bridges, and relevant data for this study were held by the Public Transport Corporation (PTC) (railway bridges), the Strathbogie Shire Council (local road bridges) and VicRoads (Hume Freeway bridges).

Cross-sectional data were located for four sites on Castle Creek (Old Hume Highway, North-Eastern Railway, Pranjip Rd, Murchison–Violet Town Rd), five sites on Creightons Creek (Hume Freeway, North-Eastern Railway, Creightons Ck Rd, Longwood–Mansfield Rd, Longwood–Pranjip Rd), and three sites on Pranjip–Nine Mile Creek (Hume Freeway, North-Eastern Railway, Longwood–Pranjip Rd).

At all bridge sites at which historic cross-sectional data were available the creek cross-sections were resurveyed in 1998. The historical data were then plotted against the 1998 survey data to determine if there had been any change in bed level over the periods for which data were available. In interpreting any changes that are apparent from cross-sectional comparisons it is very important to consider local conditions and activities. For example, bed level changes that threaten the integrity of the bridge, either by undermining bridge supports (degradation) or by blockage of the channel (aggradation), would initiate a maintenance program to address the ‘threat’, i.e. the bridge ‘owner’ might place rock beaching in the channel or extract material from the bed in order to protect the bridge. Records of such action are not always available, so in interpreting changes in bed levels one needs to recognise that such activities may have taken place. There was both documentary evidence and physical evidence to suggest that material had been extracted from beneath a number of the bridges under consideration; consequently all bed level changes were interpreted with this information in mind.

3.3. Assessing present condition

When assessing present condition one can use a range of techniques. The type of information sought and the resources available to the project determine which technique is used. This study needed information about the source of sand in the channel, the rate and means by which sand is moving downstream, and the depth of scour and fill associated with downstream movement of sand. Information on the source of sand for the creeks was obtained using field inspections, an approximate sediment budget, and variations in particle size distribution across the catchment. The rate at which sand is moving down the creeks was estimated by measuring bedload transport. An attempt was made to sample the sediment being transported in the water column during high flow events, to determine how sand is moving down the creeks (see Section 3.3.5), but there were no suitable flow events during the monitoring period. Scour chains were installed to measure the extent of cut and fill associated with sand mobilisation along the creek bed.

Just as for the historical analysis, time limitations precluded assessment of all three creeks; hence present condition was assessed for Creightons Creek only.

3.3.1. Field inspections

Field inspections simply involved inspecting a substantial proportion of the creek and its catchment to identify potential sediment sources, i.e. erosion heads, channel widening, tunnelling and sheet erosion. During fieldwork, sediment deposition zones were also inspected.

3.3.2. Sediment budget

To determine where most of the sand in the channel might have come from, an approximate sediment budget was developed. During field inspections, sediment sources and sinks (channel and floodplain or bank storage) were identified and the size of each was estimated. Particle size analyses of channel material and sand drapes along Creightons Creek indicated that fine sediment, i.e. silts and clays (diameter less than 63 mm) are washed through the system. Therefore the budget considered only material that was sand-size and larger. Consequently, all the source material volumes were adjusted to give the sand and gravel content only (the adjustments were based on particle size analyses of bank and hillslope material).

The two main difficulties associated with applying this method were: (i) identifying modern sediment deposits; and (ii) estimating the volume of sediment deposited in the channel. In the initial field inspections, as noted in Section 3.1, it was not always clear if the depositional material that was evident on floodplains and the Riverine Plain had been deposited recently (i.e. post-European settlement, referred to here as Modern alluvium) or before European settlement. In many environments Modern alluvium is easily distinguished from surrounding soil and sediments because it is different in colour and texture, and it usually overlies the old A horizon. On the Riverine Plain, deposition is the dominant process and therefore, while different depositional layers can be seen in exposed creek banks, the age of each layer cannot be readily determined. Where the age of depositional material was unclear, it was assumed to be old.

Estimation of the volume of material deposited in channels is difficult because the original level of the bed prior to deposition cannot always be identified. Two sets of data were used to estimate the original depth of the creek relative to the banks: (i) anecdotal evidence regarding the original depth of pools in the creek; and (ii) probe depths (a steel rod pushed into the creek bed until it reaches a resistant layer which is assumed to be the original creek bed). Neither data set is free of error or complete, so both were used to estimated recent channel storage. Based on estimates of the depth of deposition in pools and on runs or riffles, an average depth of sedimentation was estimated for the width and length of the channel. Deposition of material in old or inactive channels has not been considered because, like the rest of the Riverine Plain, these channels are depositional features and old depositional material and Modern alluvium cannot be differentiated readily.

As a result of the problems associated with estimating the volume of Modern alluvium stored on the Riverine Plain this budget underestimates the stored volume of sediment. In an attempt to adequately account for the stored volume the calculated total deposition volume was doubled to give a final total, in other words a positive error margin of 100% was assumed. This estimate was thought to be reasonable because the Granite Creeks' catchments narrow at the bottom end, indicating that potential storage areas do not increase significantly at the downstream end of the catchments.

3.3.3. Sediment tracing using particle size distributions

Descriptions of techniques

Particle size distributions can provide useful information about sediment movement without the expense associated with some other sediment tracing techniques (e.g. use of radionuclides). Comparison of the particle size distributions of sediment samples taken from different parts of a catchment can tell us something about the origin of material found in sediment sinks. Hence in this section of the investigation, possible source/sink relationships within the Creightons Creek catchment were identified on the basis of particle size distributions.

Four methods were used here to provide information about sediment transport in the catchment, based on particle size distribution data. The Fine Fraction method tracks the proportion of fine material (sediment finer than 63 mm in diameter) in samples taken along a transect of the catchment. The fine fraction at any given site (source or sink sites) is the first fraction to be eroded, so variations in the percentage of fine material between samples from a small area can be interpreted in terms of sediment transport locally.

The Comparison of Histograms method is similar to the Fine Fraction method, but it tracks all sediment larger than 63 mm. The method consists of comparing histograms for sand-size and gravel-size material between nearby samples. By again assuming that finer particles will be mobilised first, patterns of sediment movement can be identified.

The Coarse Fraction method measures the distribution of the coarsest material in the catchment, which in this case is sediment with a particle-size diameter between 6.7 mm and 19 mm. If this material is found in sediment deposits, then its source must also contain such coarse material. This method was used here to narrow down the list of potential sediment sources.

The fourth method employed here was the McLaren technique (McLaren 1981; McLaren & Bowles 1985) which uses trends in particle size parameters to suggest possible sediment sources and sinks for a suite of samples. The technique is based on work conducted primarily in the marine environment which suggests that when the particle size measures (namely, the average particle size, standard deviation and skewness) of a source and a deposit are compared, there can be three outcomes: (i) lag (Case 1); (ii) sequential deposit A (Case 2); and (iii) sequential deposit B (Case 3). The three cases produce two possible sets of trends in measures of particle size (McLaren & Bowles 1985). Material remaining as lag (Case 1) is relatively coarse, relatively well sorted and relatively positively skewed. Sequential deposit A (Case 2) is indicated if the material is relatively fine, relatively well sorted and relatively negatively skewed,and sequential deposit B (Case 3) is probable if material is found to be relatively coarse, relatively well sorted and relatively positively skewed. Case 1 and

Case 3 produce the same trend. Although this technique was developed for use in marine conditions, it has been tested in fluvial conditions and found to be appropriate (e.g. Haner 1984; McLaren & Bowles 1985; Davis 1996).

Four exceptions or limitations associated with use of the McLaren method (McLaren 1981) need to be carefully considered, because if they apply to a case study they render the results of the analysis invalid.

First, when there is more than one source contributing sediment to a sediment sink the technique may fail. This will occur when the relative contributions of the sources are the same, i.e. no one source is dominant. However, it has been hypothesised that where there is one dominant source of sediment to a particular sink the trends will still be visible and valid (Davis 1996). This limitation needs to be carefully considered when the results of the investigation are interpreted.

Second, McLaren (1981) recognised that individual particle size does not always determine sediment transport characteristics, i.e. the assumption that a small particle will be transported farther than a larger particle can be false if flocculation occurs. In this situation, the clay flocs may not be transported as far as they would have been transported as individual clay particles. Hence a comparison of the sediment characteristics of the sediment source and sink may result in the relationship that might have been expected had the source material been coarser. It is difficult to determine whether or not flocculation would have occurred in the field, and so it is important to be aware of this problem as a potential source of error.

The third exception described by McLaren (1981) is closely related to the second exception, but relates to soil aggregates rather than flocculated clay particles. An aggregate can be transported and deposited as a single large particle, but when a sample of sediment is analysed the aggregate may break up (disperse) and be treated as a number of smaller particles. To determine the relevance of this limitation the presence of undispersed aggregates was noted during the laboratory analysis of the samples and is discussed in conjunction with the results in Section 5.3.

The fourth exception recognised by McLaren again relates to changes in grain size during transport. In this case, abrasion during transport, pedogenesis or bioturbation could result in particles becoming finer or coarser.

The relative importance of abrasion and selective transport processes for a given river system is the subject of debate. A number of studies find that abrasion is the dominant process (e.g. Shukis & Etheridge 1975; Kodama 1994), while others find that selective transport is the more important process (e.g. Breyer & Bart 1978; Brierley & Hickin 1985). Not only is this lack of consensus confusing, but most of the work done on abrasion has not considered small systems such as Creightons Creek. Recent work by Dyer (1998) on soil samples taken from a catchment just west of Melbourne indicates that when granite-derived soils are transported along a stream system for a distance of approximately 8 km, sand and gravel material (i.e. material larger than 63 mm in diameter) is abraded, resulting in a reduction of 3–30% in the total mass of coarse material. Most of the abraded material is converted to particles with a diameter of less than 10 mm. These data suggest that the movement of sand and gravels along Creightons Creek may result in abrasion, which is a potential source of error for the McLaren Technique.

The precise effects of bioturbation and pedogenesis on the particle size distributions of soil samples is unclear. These two processes can either fine or coarsen soil material. Bioturbation affects particle size distributions mainly via mixing (Hole 1981; Conacher & Dalrymple 1977), whereas pedogenesis has a less clear effect and thus is very difficult to predict, because although fining generally results, coarsening can also occur in some parts of the soil profile (Brady 1984).

The effects of bioturbation and pedogenesis on the particle size distributions of the samples taken in the Creightons Creek catchment may only be important where these processes have different effects on the samples. For example, it is probable that bank samples taken throughout the sub-catchment are affected to the same degree by bioturbation and pedogenesis, but the effects on samples from the hillslopes, creek bed and sand drapes can be different. It could be assumed that creek bed and sand drape samples would not be affected significantly by either bioturbation or pedogenesis because they have been recently deposited. Conversely samples on the hillslopes might be differentially affected by bioturbation and/or pedogenesis. Therefore, for example, it may not be correct to attribute fining in the footslopes to deposition of material from upslope. However, it appears unlikely that either would have any substantial effect. Bioturbation, for example, can result in the mixing of the A and B horizons. However, the deeper horizons consist of weathered regolith and then bedrock — that is, the soil material coarsens with depth — so mixing normally results in coarsening of the sampled footslope material. Because the samples were not taken in obviously bioturbated areas, it may be possible to assume that bioturbation did not have a significant influence on comparative results.

Similarly pedogenesis may not have a significant effect on the particle size distributions of the hillslope samples. Although one might expect pedogenesis to result in differences in the particle size distributions of samples found on different parts of the hillslope, the literature suggests that these differences may be the result of lateral slope processes (e.g. Dalrymple *et al.* 1968; Conacher & Dalrymple 1977; Paton 1978). Hence the effect of pedogenesis on the particle size distributions of the hillslope samples is probably of minor significance when compared with the impact of sediment transport processes, particularly in relation to the time period of relevance here, i.e. just 150 years.

It is concluded that neither bioturbation nor pedogenesis would have had a significant impact on particle size distributions in the Creightons Creek catchment. However, abrasion may be significant during creek transport and thus may be a source of error for the McLaren technique. In this study, to reduce the impact of abrasion-related errors, potential source/sink relationships were limited to those in which sediment transport distances were relatively small, i.e. only local samples were compared.

To apply the McLaren technique the three particle size distribution parameters (average particle size, standard deviation and skewness) must be calculated for each sample. For the purposes of this analysis moment measures were used to derive these parameters. The phi mean, standard deviation and skewness were calculated as described by Krumbein & Pettijohn (1938) and used to set up a sediment trend matrix, as indicated in Table 3.1.

Each sample was listed across the top and down the left side of the matrix. Every sample was then compared and classified in terms of particle size (coarser or finer), standard deviation (poorer or better sorting) and skewness (more positive or negative). The results contained in each cell were compared to the two transport indicative trends described by McLaren & Bowles (1985).

Relationships that did not fit one of these two trends were discarded. For each of the remaining cells the proposed relationship was examined, and impossible or highly improbable relationships were also discarded (e.g. the creek bed as a source for the top of the hillslope). To reduce the effect of abrasion and multiple sources on the application of this technique only local source/sink relationships were considered; in other words, only immediate downslope or downstream sinks were considered for a given source. The remaining relationships indicate probable sources, deposits and sediment transport paths.

Clearly all four methods (i.e. the Fine Fraction method, the Comparison of Histograms, the Coarse Fraction method and the McLaren technique) are subject to assumptions and limitations, the effects of which cannot be readily assessed. However, because four independent techniques were applied and assessments are based on *all* the results, the errors associated with the assessment should be minimal. Furthermore the results derived from particle size analyses are combined with sediment budget data and field observations to give an assessment of the primary sediment source. By using a range of techniques in this manner it is possible to qualitatively assess the validity of the results.

Table 3.1. Sediment trend matrix format

		Source			
	Sample	**A**	**B**	**C**	**D**
Deposit	**A**				
	B				
	C				
	D				

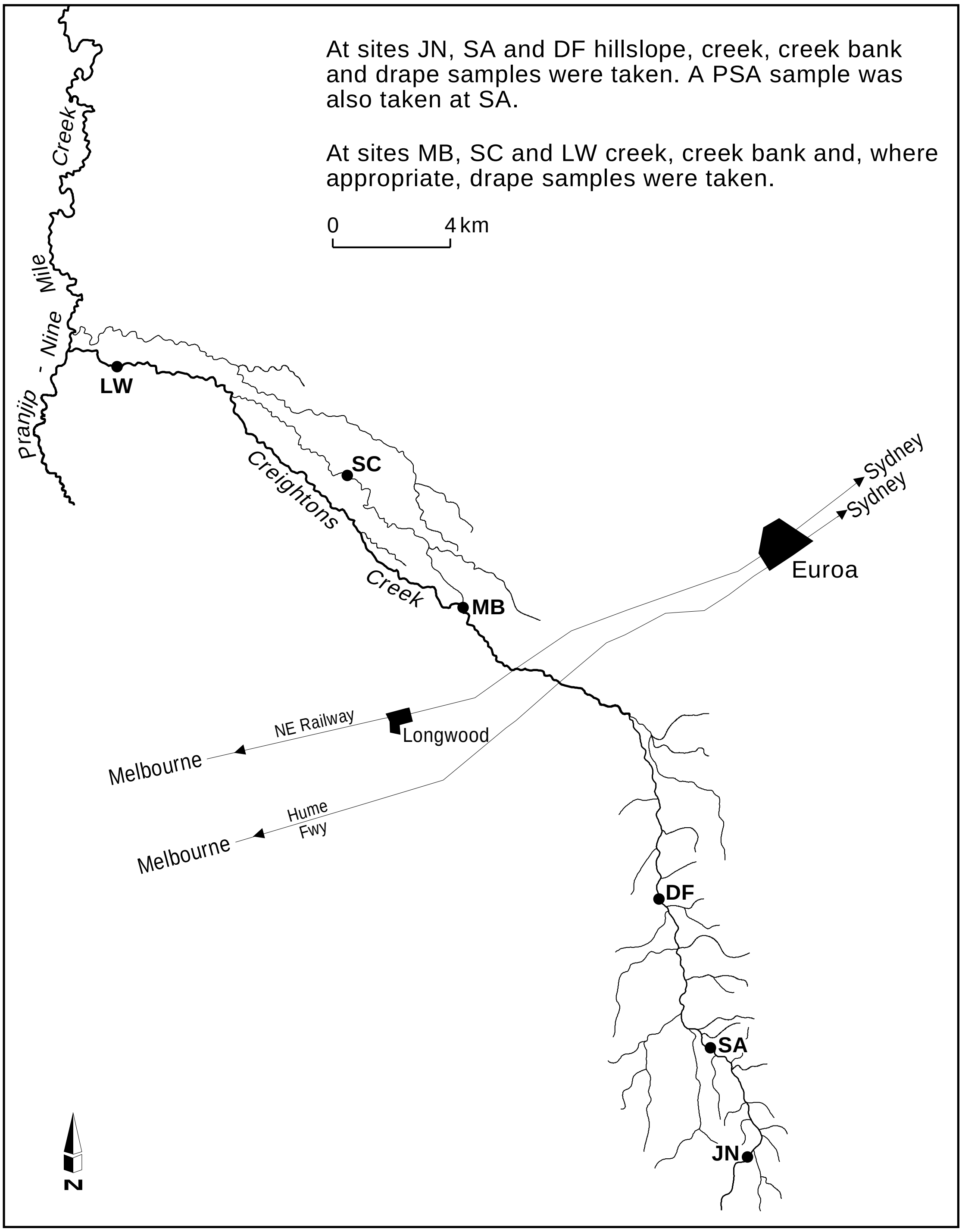
Sediment sampling and analysis procedure

To help identify the possible sources of sediment for various sinks in the Creightons Creek catchment, a sampling scheme was devised which recognised all possible sediment sources (hilltop sites, mid-slope and footslope sites, creek bed and banks) and sinks (creek bed, sand drapes, mid-slope and footslope sites). Figure 3.1 shows the locations of sampling sites. At the three upstream sites (i.e. JN, SA and DF), hillslope, streambank, creek bed and drape samples were taken. At the three sites down on the flats (i.e. MB, SC and LW) where there are no hillslopes, only streambank, creek bed and drape samples were taken. Sand drapes were not present at all sites, so drape samples were not taken at every site.

Two aspects of sampling techniques need to be considered. The first is sample size in relation to mass: this is a statistical problem. From an engineering point of view, the sample should be of sufficient size that ‘accidental exclusion or inclusion of a single large particle will not significantly affect the result’ (SAA AS 1289.1 1991, p. 5). The samples taken in this study were between 400 g and 3 kg, as prescribed in Australian Standard 1289.1. The second aspect to be considered is the depth of sampling because it will affect the time resolution of the study. This is not such a problem in source areas where depth variations are not very critical and a sample of 5 cm will suffice. However, in depositional areas different sampling depths may result in the collection of samples derived from different sources, e.g. drape sediments. In some places it may be useful to sample to different depths to detect changes in the sediment source, but because of the time constraints associated with this exercise it was necessary to limit the sediment path tracing investigation to recent movement. Hence sediment samples from the creek bed and the drapes were taken from deposits thought to be of most recent origin; e.g. creek bed samples were taken in the main channel, within 5 cm of the bed surface.

One other issue that needed to be addressed was representative sampling. For hillslope samples and creek bed samples, this issue was dealt with by taking three widely spaced samples at each site and bulking the samples. As a result of this procedure, and the need to sample the active channel when taking creek bed samples, a method was required which allowed samples to be taken beneath flowing water without the loss of the fine fraction that is trapped in the sediment matrix. This problem was overcome by used a yabby pump to draw up sediment and pore water, thus retaining the fines. Representative bank samples were difficult to obtain because of the variability of bank material in some parts of the catchment. Exposed banks allowed bank material to be observed; it was relatively homogeneous in some areas, but quite variable in others (e.g. at site SA). The noted variability has probably arisen where valley fill has been incised. The valley fill would be expected to consist of material deposited under a variety of climatic conditions, resulting in a range of particle size distributions.

To overcome this difficulty, each of the apparent bank sediment types was sampled and then all were bulked together. In each instance, the proportion of each bank source was estimated relative to another,


At sites JN, SA and DF hillslope, creek, creek bank and drape samples were taken. A PSA sample was also taken at SA.

At sites MB, SC and LW creek, creek bank and, where appropriate, drape samples were taken.

Fig. 3.1. Creightons Creek sediment sampling sites

and the sample size was scaled accordingly, i.e. where a bank was dominated by material type A, and only a small amount of material type B was available the bulked sample consisted mostly of material type A.

The samples were returned to the laboratory where they were analysed to determine their particle size distribution. The analysis procedure is described below and is based on procedures outlined in Australian Standard 1289 (SAA 1991).

1) All samples were air dried (at which time organic material was removed by hand).
2) Where appropriate, aggregates were crumbled with a roller and the sample was sub-sampled (using a sample divider) to provide two samples: one for oven drying and the second for particle size analysis.
3) The first sub-sample was placed in an oven at 105–110^{o}C until a constant mass was obtained on repeated weighing; the moisture content of the air dried sample was calculated.
4) The second sub-sample was weighed, then covered with dispersing solution (sodium hexametaphosphate ($Na(PO_3)_n.Na_2O$), agitated and left for one hour.
5) The second sub-sample was wet sieved using a 63 mm sieve; a sample of the wash solution (containing the fine fraction) was taken to allow further analysis if required, and the coarse fraction was oven-dried at 105–110^{o}C until a constant mass was obtained.
6) After oven drying, the coarse fraction of the second sub-sample was dry sieved using a mechanical shaker for 15 minutes, with the following sieve mesh sizes:

   19 mm (–4.25f); 6.7 mm (–2.75f); 4.75 mm (–2.25f); 2.36 mm (–1.25f); 1.18 mm (–0.25f); 600 mm (0.75f); 425 mm (1.25f); 300 mm (1.75f); 212 mm (2.25f); 150 mm (2.75f); and 63 mm (4f).
7) The weights of the samples collected in each sieve were used to calculate the percentage passing the 63 mm sieve (i.e. the percentage of clay and silt), as well the particle size distribution of the coarse fraction (>63 mm).

This procedure was applied to all except the hillslope samples. As is indicated by the above procedure, samples were generally not treated for organic matter. Most samples had a negligible organic content and the small amount of material could be removed by hand during processing. The hillslope samples, however, appeared to contain a significant proportion of organic material and manual removal was not judged to be sufficiently successful; consequently an extra step was added after step 5 for these samples. They were ashed to remove all organic matter by placing all the sample or a sub-sample into a furnace at 550^{o}C until constant weight was obtained (Franson 1995). Then the hillslope samples were dry sieved as described in step 6 and the data were analysed as in step 7.

3.3.4. Scour chains

Scour chains were used in this project with the objective of gaining information about the depth of scour and fill that occurs in the sanded sections of the creeks. Scour chains were installed in the creek beds at various locations and under a variety of flow conditions. The depth of scour and fill is of interest for two reasons: (i) it provides information about the way in which sand is being transported down the creeks, with respect to the size of bedforms; and (ii) it indicates the depth at which the bed material becomes mobile and thus the extent of habitat disturbance for benthic organisms.

Scour chains have been used in a range of fluvial environments to measure scour and fill during a flow event (Laronne *et al*. 1994). Although scour chains do not provide as much detail as continuous monitoring using a depth sounder for example, they are a low cost alternative. Their use involves placing a chain vertically in the creek bed with a small proportion of the chain protruding from the surface and lying on the creek bed (see Fig. 3.2). The length of chain protruding from the creek bed is measured. When the bed is scoured out, the chain drops down to the scour level and it is buried under the fill material. Consequently once the chain is relocated (i.e. after a flow event) the depth of scour and fill can be estimated simply by measuring the length of chain protruding from the bed at the bed level at which it is found and measuring the length of chain protruding from the bed after the area around the chain is refilled to the new bed height (see Fig. 3.2).

Twelve scour chains were inserted into the beds of the three creeks using a pipe inserter which allowed the chains to be inserted to a depth of 0.5–0.8 m with minimal disturbance to the bed, as

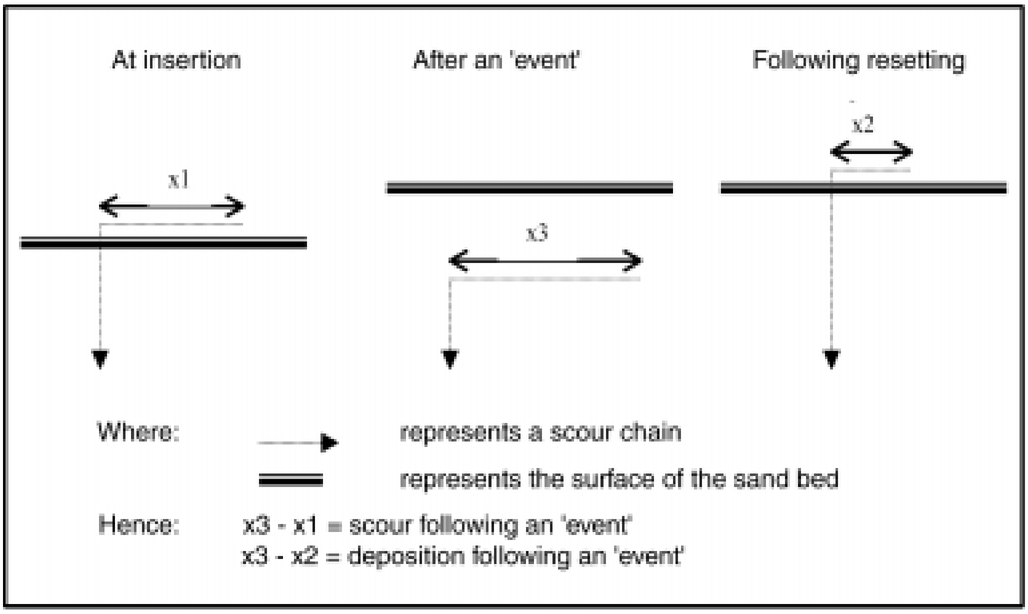


Fig. 3.2. Diagrammatic representation of scour chain measurements

follows. At each site a brass point was attached to a 1.2 m length of chain which was then fed into a pipe 1.7 m long with a collar halfway along its length. Extra chain was attached to the end of the scour chain so that it extended from the end of the pipe and could be pulled tight to keep the scour chain straight during insertion. A hollow post-hole driver was then placed over the pipe and used to strike the collar and drive the pointed end of the apparatus into the creek bed. Once the point had been driven far enough into the bed the pipe and driver were carefully pulled out, leaving the chain and point in place. The extra chain was disconnected from the scour chain and the protruding length of scour chain (surface chain) was measured. Upon return to the site following scour and fill activity the chain was located in the bed using metal probes and a hole was dug down to expose the chain sitting at the maximum scour level. The length of surface chain was then measured, the hole backfilled (while the chain was held vertical) to the new bed level and the remaining protruding chain length measured. The depth of scour was then calculated by subtracting the surface chain length measured after back fill on the previous visit (x_1) from the surface chain length measured at maximum scour level for the current visit (x_3). The depth of fill was calculated by subtracting the surface chain length measured after back fill on the current visit (x_2) from the surface chain length measured at maximum scour level for the current visit (x_3) (see Fig. 3.2).

Scour chains were placed at six sites on the three creeks, two chains at an upstream site and two at a downstream site on each creek. The sites were selected for two reasons: (i) to determine if scour and fill behaviour varied between sites at different locations on the sand slug; and (ii) to measure scour and fill at sites adjacent to biological sampling sites associated with the ecological component of the project. At each site a cross-section was selected on a straight section of stream (to avoid obvious sites of long-term degradation and aggradation) and two chains were placed in the creek bed along the cross-section to detect differential scour and fill. The locations of the six sites are shown in Fig. 3.3 and Table 3.2.

3.3.5. Suspended load sampling

Traditionally, suspended load sampling has been conducted to determine the rate at which fine sediment (i.e. silt and clay) suspended above the streambed has been moving down the stream. Clearly, fine sediments are not at issue in the Granite Creeks, but it is important to know if coarser

Table 3.2. Scour chain site locations

Site no.	Creek	Approximate location	Property owner
1	Castle Ck	Below the Hume Freeway	Bamford
2	Castle Ck	Below Drysdale Rd	Kubeil
3	Creightons Ck	Below the railway line	Carlsson
4	Creightons Ck	Below Pranjip–Longwood Rd	Caldwell
5	Pranjip NM Ck	Killeen (above Longwood–Mansfield Rd)	Cameron
6	Pranjip NM Ck	Above Longwood–Avenel Rd	Threlfall

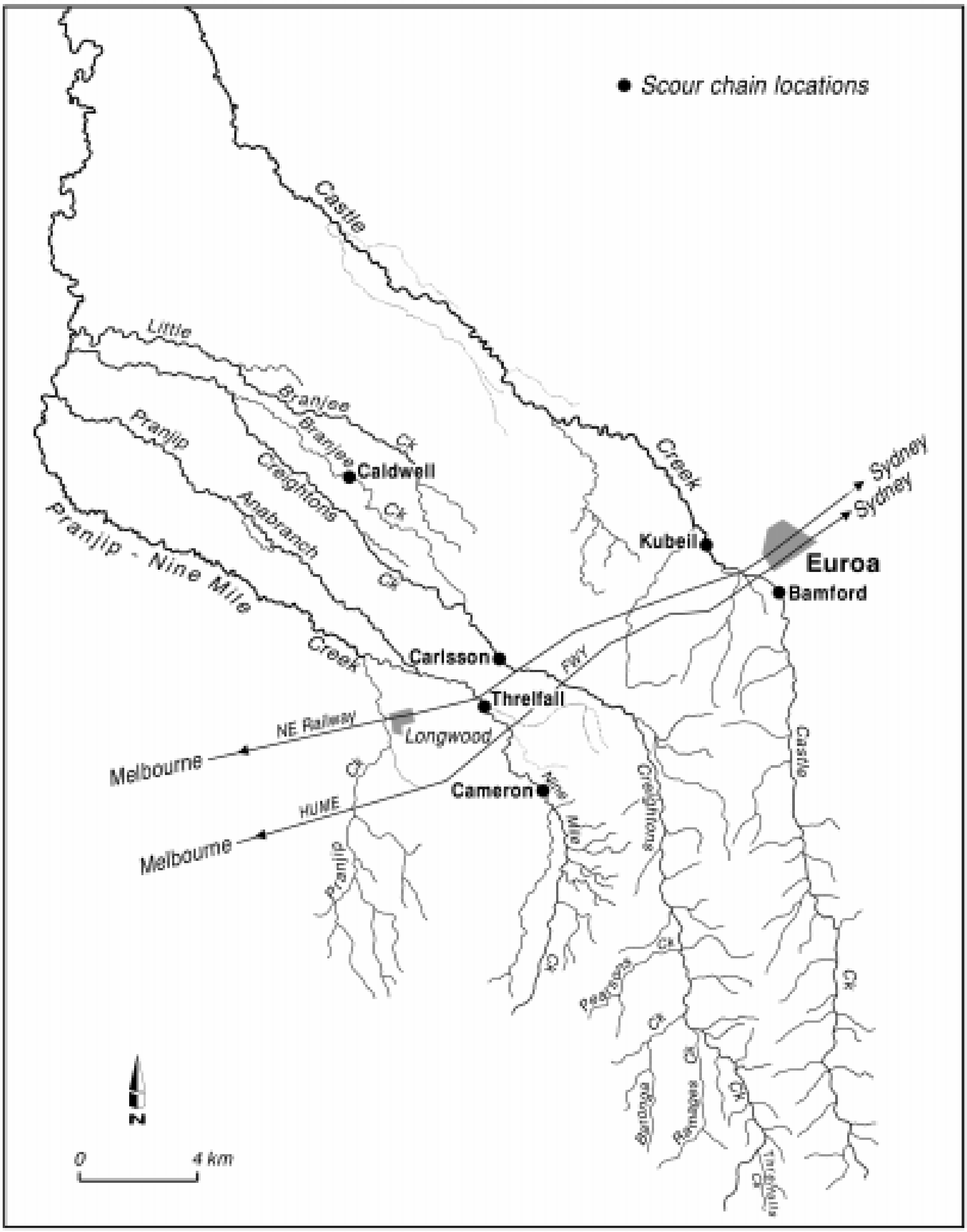


Fig. 3.3. Map of scour chain locations

Fig. 3.4. An example of a high-level sand drape

sediment (sand) is being transported suspended in the water column during high flow events, because this affects the places to which the system delivers the sand. As was noted in Chapter 2, once the Granite Creeks reach the Riverine Plain they begin to anabranch; therefore, during high flow events only a portion of the flow remains in the main creek channels, and the rest moves out into the anabranches. Many of the anabranch off-takes observed on the Granite Creeks are well above bed level and more often than not flow must overtop the banks to enter an anabranch. As a result, sand being transported as bed load would be unlikely to enter these anabranches. However, sand drapes visible on stream banks after high flows (Fig. 3.4) suggest that sand might be transported high in the water column during high flow events, in which case it could be expected that sand would be delivered to and possibly stored in the streams' anabranches, with implications for sand slug migration along the lower reaches of the Granite Creeks.

To better understand how sand migrates along a sand slug during high flows and the potential for anabranches to divert sand from the main channel, a suspended sediment sampling scheme was set up. This consisted of taking samples of water and suspended sediment at several levels above the bed during high flows and determining the average concentration of sand in the water column. While conceptually this sampling exercise was simple it was not easy to find equipment that could be used to sample sand-size sediment under the physical conditions described here. Most suspended sediment samplers, e.g. the P61, are designed to sample fine sediment and so have only a small inlet. Consequently a 'suspended sand sampler' had to be designed and built for the purpose.

The suspended sand sampler was designed as an open tube aligned with the flow, through which sediment and water pass until the ends are sealed simultaneously. The trapped water and sand provide a snap shot of the sediment concentration at a particular height above the creek bed at some point during a high flow event. The final design of the suspended sand sampler is depicted in Figs 3.5 and 3.6. Essentially the sampler consists of four pieces of 100 mm diameter PVC pipe held in a metal rack which sits above the creek bed. The lowest tube is 30 cm above the creek bed, the next two tubes are 60 cm and 90 cm above the bed, and fourth tube is 120 cm above the bed. One-way swing valves are attached to the ends of each tube and can only open out. A piece of elastic cord runs through the centre of each tube and is attached to the inside of each valve, the cord being tensioned so as to hold the valves shut and prevent all but minor water leakage.

Before installation a test sampler was tested for leakage. A set of sand samples with various particle size ranges was prepared: >64 mm, >212 mm, 64–150 mm, 150–212 mm and 212–600 mm. Samples were placed in the sampler (which was full of water) for 1 hour and 24 hours and the sediment that leaked from the sampler was collected to determine leakage. Sand losses for all particle size ranges and leakage periods were negligible — less than 1% on average.

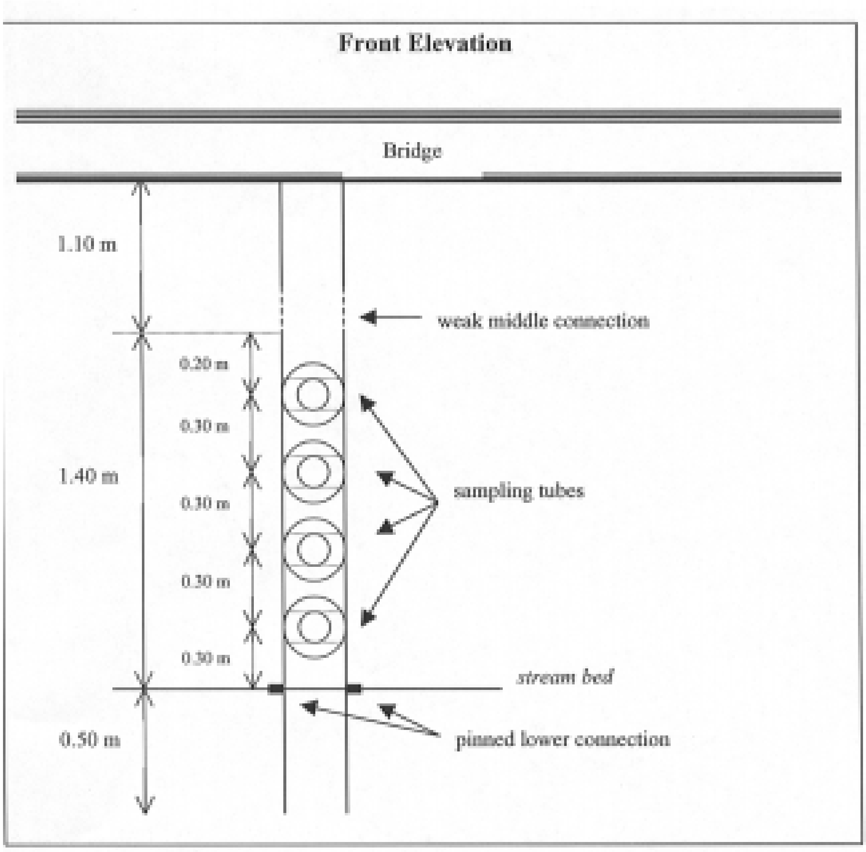


Fig. 3.5. A diagrammatic representation of the suspended sediment sampler

Fig. 3.6. Two views of the suspended sediment sampler

Fig. 3.7. A small Helley-Smith Bedload Sampler being used to sample bed load in Creightons Creek

The valves are pinned open prior to an event, with the pins attached to a mechanism that releases them all at once, thus allowing all four levels in the water column to be sampled at once. To prevent the apparatus being undermined, four support posts are inserted 0.5 m into the creek bed and the top of the rack is attached, via extension legs, to a bridge. During a storm event, debris might become caught on the apparatus, ultimately leading to the failure of the bridge, so the three connection points (Fig. 3.5, Points A, B and C) were either pinned or made relatively weak so the apparatus would collapse before a debris build-up caused damage.

Initially it was intended that the release mechanism would be triggered by a float; in other words the tubes would close when the flow reached a particular height. However, the load required to release all eight valves was found to be far higher than could be supported by a float and so instead the apparatus was set up to be triggered by a person from the bridge. A landholder who lives adjacent to the site agreed to trigger the sampler when preferred conditions occurred for triggering. Preferred conditions were: (i) on the rising limb of the storm event; and (ii) close to the peak of the event. The landholder would also record the time at which the apparatus was triggered so that the sampling stage could be estimated from continuous stage monitoring equipment that was installed at the site.

Despite the fact the sampler had been installed for more than six months (18/1/99–16/7/99) when the geomorphic study drew to a close, no appropriate high flow events had occurred and thus no data had been collected. While the sampler will continue to be monitored and data will eventually be collected, they could not be included in this report. It is anticipated that a separate report on the results of the suspended sediment sampling investigation will be released later, once sufficient data have been collected.

3.3.6. Bedload sampling

For estimating bedload transport rates there are two alternatives: direct measurement or estimation via bedload equations. Both alternatives are difficult and as a result bedload estimation is problematic. Hean & Nanson (1987) have reported that there are serious problems with using bedload equations to estimate bedload in south-eastern Australia, indicating that the equations cannot be used to provide reliable evaluation of catchment sediment yields. Measurement of bedload is complex (Gaweesh & van Rijn 1994) and accurate measurement is difficult to achieve (Gordon *et al*. 1992). Measurement is further complicated by the need to monitor bedload transport over a range of flow conditions which would require at least several years of data, and such a program could not be accommodated within the confines of this project. Given these difficulties it was not feasible to try to estimate average bedload transport rates, but it was clear that it would be useful to have some idea of the magnitude of bedload transport under various flow conditions. Consequently bedload transport was measured at two sites on Creightons Creek on several occasions: adjacent to Stan Artridge’s property (SA in Fig. 2.1) on six occasions and adjacent to Maurie Brodie’s property (MB1 in Fig. 2.1) on four occasions.

Bedload transport rates were measured using a Helley–Smith pressure difference sampler (Helley & Smith 1971) (see Fig.3.7). The Helley-Smith sampler is a portable device which sits on the streambed and captures bedload in a mesh bag, allowing water and fine sediment to pass through. This type of device is said to be most practical for measuring bedload (Hubbell *et al*. 1985) and the Helley–Smith bedload sampler is considered to be one of the most successful models (Richards 1982).

There are procedures available for using the Helley-Smith bedload sampler for measuring bedload at a given cross-section, but they are generally directed at sampling large rivers during high flow events (e.g. Gaweesh & van Rijn 1994; Locher 1997), so a modified procedure was devised for sampling in the Granite Creeks. The main sources of error for bedload sampling are: instrument error; spatial variability; and temporal variability (Gaweesh & van Rijn 1994), so effort was made to minimise these errors in the modified procedure. The problem of spatial variability was dealt with by inspecting bedload movement at each cross-section and splitting the cross-section up into segments in which similar rates of bedload movement were apparent. Bedload movement was then measured at each segment. Once (during a high flow event) the bed was obscured by turbid water; in this instance the cross-section was divided up on the basis of variations in velocity and depth (factors which influence bedload transport rates). The problem of temporal variability was addressed by resampling those segments at which bedload transport rates were highest (i.e. those segments which would contribute the most error).

Instrument error generally occurs because of disturbance of the bed, development of a gap between the sampler and the bed and scooping of the bed with the sampler (Gaweesh & van Rijn 1994). These errors were more difficult to address, but on most occasions the sampler could be watched during sampling and adjusted if such problems were observed. Each segment was sampled for 10 minutes. This period was found to give reasonable size samples when bedload transport rates were highest, without over-filling the sample bag, which can cause sampling errors (Gaweesh & van Rijn 1994).

After sampling, the bedload samples were washed into a sample bag and transported back to the laboratory where they were oven dried at 105–110^{o}C until constant mass was achieved. From these data, transport rates were calculated in the form of mass per unit time. Some samples were also analysed to determine particle size distributions.

4. ANALYSIS OF HISTORICAL EVIDENCE: ESTABLISHING BASELINE CONDITIONS AND POTENTIAL EROSION TRIGGERS

4.1. Introduction

In this chapter the historical data are presented and discussed as a way of discovering the form of the Granite Creeks at the time of European settlement, how they have changed over the last 150 years and what activities might have caused the observed changes.

4.2. Explorers and the Overlanders

The first Europeans to traverse the Granite Creeks were Hume and Hovell in 1824. It appears that they passed through the area not far from the present day location of the Hume Freeway, but unfortunately Hovell made his last journal entry the week before they arrived in the area, on their way back to the settled districts (Andrews 1981). Consequently we have no record of the area from this period.

More than ten years passed before Europeans returned to the area. Major Thomas Mitchell and his exploring party travelled from an encampment near Wormangul Creek to a camp on Castle Creek on the 10th of October 1836 (DCE 1990). Mitchell and his party were on their way back to Sydney after a journey that had already taken them through the present day locations of Swan Hill and Portland. In traversing this section of country, not far from what is now Pranjip Rd (DCE 1990), the party crossed numerous chains of ponds and one running stream before reaching Castle Creek (Mitchell 1839). It seems probable that Creightons Creek was the running stream to which Mitchell referred, and Pranjip, the anabranch of Pranjip, Branjee and Little Branjee Creek were ‘chains of ponds’. The party spent the night camped on Castle Creek, which Mitchell referred to as Violet Ponds because of flowers growing around deep pools in the running creek (Mitchell 1839).

One thing that is not clear is exactly what Mitchell meant by the term ‘chain of ponds’. He may have been referring to ephemeral channels with large pools in which water remained, or he may have been describing the true ‘chain of ponds’ form still evident along sections of Little Branjee Creek today.

Mitchell’s second-in-command, Granville Stapylton, was following Mitchell at this stage of the journey, with a second party. Stayplton, who was about two weeks behind Mitchell, discontinued his diary several days before arriving in the area, and thus does not provide any further information about the Granite Creeks (Andrews 1986).

Following Mitchell’s return to Sydney, his favourable descriptions of ‘Australia Felix’ instigated a wave of overlanding expeditions to the Port Phillip District along the track made by Mitchell’s drays on their return journey to Sydney. This track became known as the Major’s Line.

The Overlanders drove their stock, usually sheep and some cattle, from the settled regions around Goulburn to the Port Phillip District to take up land for pastoral pursuits. One of the first handful of overlanders to make the journey south was Alexander Mollison. Mollison’s diary indicates he first crossed the Granite Creeks in July 1837 and may have camped beside Castle Creek (Randell 1980). Whilst there is no description of the area, Mollison mentions that most of the creeks Mitchell referred to in his journal as ‘“chains of ponds” running’, were not running when his party passed through (Randell 1980). After settling in central Victoria (near Kyneton) Mollison returned to his station near Canberra to collect more stock. Mollison’s second overlanding trip south brought him back to the Granite Creeks in late October–early November of 1837. In his diary Mollison describes the country as follows (Randell 1980, p. 56):

> The country around, sterile and covered with scrubby bushes. On the immediate bank of the creek there is, at present, young grass thinly scattered over the ground. I observe that those creeks and chains of ponds which have large water ponds and a broad, shallow water course, are now full and running, while those which have deep channels, steep banks cut into the earth and ponds small in proportion to their channels, are now quite dry, with the exception of a few ponds in some of them in which there may be found a little muddy water.

The poor grass cover noted here may have been a result of the large numbers of stock which were being driven down the Major's Line at this time. The impact of overlanding parties on land in the vicinity of the Major's Line between Violet Town and the Goulburn River is best illustrated by the following description taken from a traveller's diary in 1838 (Walker 1838, pp. 33–34).

> When we had come to the said thirteen mile creek, we found, however that some time ago the grass all about it had been burnt, and that there was not a single bite for our cattle; this was therefore no place to holt at, so we determined to give the animals a drink, and proceed until we came to grass; to our great mortification, we found not a blade, nor any water nearer than this place (a further 7 miles on). The whole country has been burnt, and no rain having since fallen, not a vestige of grass is to be seen. We have within this last day or two, passed through a great deal of country in a similar state, and most dreary and miserable does it appear; at no time more so than to-day. The country was in itself scrubby and of bad soil, and superadded to that, we under the impression, in passing that we should have to halt in it for the night, without having food or drink for our cattle, ... From the experience I have now had, I should not again think of making an exploring expedition with a bullock-cart to say nothing of the hindrance it is to progression, how dependent it makes us on finding water every few miles, and in this country, how often we are disappointed in doing so.

Besides indicating the poor condition of land in the Granite Creeks area in 1838, this account suggests that burning probably had a significant impact on the landscape. It is not clear either how the fires were initiated (e.g. by the Overlanders, the local Aboriginal people or lightning) or the frequency of such events, but these factors have implications for the magnitude of the impact on the landscape.

4.3. Pastoral runs

With the influx of settlers to the Port Phillip District it was not long before several squatters had taken up runs in the Granite Creeks area. In 1839 William Creighton took up the Five Mile Creek pastoral run, including some 60 000 acres (Billis & Kenyon 1974), covering most of the Creightons Creek catchment, as well as much of the Pranjip–Nine Mile Creek catchment above the Burnt Creek confluence (CPO Run Plans 237 (1852)). The run carried 1200 cattle initially (Billis & Kenyon 1974), but this number appears to have halved by the middle of the 1840s (VPRS 5920). In 1840 William Creighton took up Wanghambeham, a run adjoining Five Mile Creek or Killeen (which may once have formed part of Five Mile Creek). Wanghambeham was situated on the upper reaches of Creightons Creek, comprised 16 000 acres and initially carried 4000 sheep (Billis & Kenyon 1974).

John Livingstone took up the Molka Pastoral Run in 1846. Initially comprising 30 000 acres and carrying 6000 sheep, the station covered the remainder of the lower catchments of Creightons Creek and Pranjip–Nine Mile Creek (Billis & Kenyon 1974, CPO Run Plans 237 (1852)).

The upper reaches of Castle Creek were included in the Seven Creeks run which was first leased in 1838. A.J. Templeton took up 70 000 acres on which he ran 35 head of cattle and 12 000 sheep.

The lower sections of Castle Creek formed the boundaries of a number of pastoral runs, including Arcadia, Noorilim, Croppers, Molka and Euroa. Arcadia was first leased in 1839 by Gregor McGregor, who took up 80 000 acres, running 6000 sheep. By 1858 the run had been subdivided; the southern portion, through which Castle Creek passed, retained the name Arcadia but it was reduced to

48 000 acres. Noorilim, which was taken up in 1840 by Fredrick Manton, comprised 44 320 acres and carried 8000 sheep (Billis & Kenyon 1974). Croppers Station, or Burrabirronga was first leased in 1844 by Charles Cropper. At this time 100 head of cattle and 2500 sheep were run on 19 200 acres (Billis & Kenyon 1974). Euroa, which comprised 80 000 acres and initially carried 500 head of cattle and 6000 sheep, was taken up in 1840–1841 by Roderick McKay.

Although neither the location of run boundaries in relation to catchment boundaries, nor the records of cattle and sheep numbers are accurately known, it is possible to conclude that by midway through the 1840s, all the land within the Granite Creeks catchments had been leased by squatters and may have been carrying up to 40 000 sheep and 1000 head of cattle. If 1 cow is the equivalent of 3 sheep (Powell 1970), then this equates approximately to 1 sheep to 9 acres.

Due to the nature of land tenure, i.e. lease, the pastoralists generally did not make substantial improvements on their runs (Powell 1976). Consequently, fencing, construction of water supplies and clearing were not common. Descriptions of land selected along Creightons Creek in the 1870s and 1880s suggest that improvements introduced into the area by the pastoralists were limited to boundary fencing and some paddock fencing (various Land Selection Files; see list on page 101). Thus by 1850, 26 years after Hume and Hovell first passed through the Granite Creeks catchments, the impact of European settlement had probably been limited to the introduction of hoofed animals and consequent light grazing pressure, as well as the development of a number of tracks across the district.

4.4. The Granite Creeks area in the second half of the nineteenth century

In terms of development, there was relatively little progress in the Granite Creeks catchments before the 1850s, but this changed in the second half of the 1800s with the construction of the North-Eastern Railway and the advent of Land Selection Legislation. A number of sources of information have been used to derive descriptions of the Granite Creeks catchments between 1850 and 1900, including old plans and the corresponding survey notes, Land Selection Files and anecdotal evidence. In particular, attention has been paid to changes in land use, and the impact of land settlement on the Granite Creeks.

General descriptions of the Granite Creeks area can be obtained from the notes of surveyors who conducted surveys in the area in the 1860s to allow the original Parish Plans to be drawn up. Notes by J. Hardy on the Branjee feature survey indicate the area was covered by open forest, chiefly of box, though some areas (predominantly on clay soil) were thickly covered by heath. The soil was generally clayey and quite wet in winter, and considered to be poor (CPO Survey Book 156, Bundle 11). Marchant surveyed an area taking in some parts of the lower catchments of Pranjip–Nine Mile Creek and the anabranch, as well as Creightons Creek. Notes from his fieldbook indicate that the area was lightly timbered with box, gum and wattle, with an understorey of thick scrub. The soil was a light sandy soil. Marchant’s notes also indicate that the creeks were between 10 and 40 links wide (2–8 m) (CPO Survey Book 922).

Information can also be gleaned from some of the original parish and town plans. The Pranjip Parish plan, surveyed in 1862, indicates the area was covered by a sandy soil of very inferior quality, which was timbered with box and scrub (CPO Putaway Plans, P123). Plans of the Euroa township indicate that the soil near Castle Creek was a loamy sandy soil (1862) and consequently there were a number of sand and gravel pits on town allotments in 1906. Town plans from 1909 also indicate that the channel of Castle Creek was realigned, probably in relation to the construction of a bridge for the Sydney Road (CPO Putaway Plans E81(2), E82(A), E82(O) (1909, 1862, 1906)). Soils in the Parish of Gooram Gooram Gong, in the vicinity of Castle Creek were shown as being stony, sandy and medium (CPO Putaway Plans G149 (1862)). On the other hand, notes on the original Parish Plan for Longwood indicate that the area was timbered with stringybark, box and gum, and that whilst in some areas the soil was poor and sandy, other areas were considered to be good agricultural land (CPO Putaway Plans L92(A) (1862)). Plans for the Parish of Molka indicate that some parts of the parish could be described as low crabholey ground that was openly timbered with grey box, white gum and bulloak (CPO Putaway Plans M519 (1921)). Other parts of the parish have been described as having indifferent soil and timbered with box and black acacia (CPO Putaway Plans D155(A) (1866)). The Parish Plan for Miepoll indicates the area was covered by open box forest on inferior clayey land (CPO Putaway Plans M418 (1863)).

Clearly both soil types and vegetative cover varied throughout the catchments, prior to widespread clearing. Taking descriptions from the Land Selection Files for allotments along Creightons Creek, it is possible to loosely describe the two broad areas that make up the Granite Creek catchments, i.e. the flats and the hill country, where the flats constitute the land below the Hume Freeway and the hill country is that part of the catchment above the highway.

Land on the flats surrounding Creightons Creek was generally described in the 1880s as being unfit for cultivation, because the land was too crabholey and wet. If cultivation did take place, usually wheat, oats, barley and hay were grown, although yields were never usually very high. Most of the trees in the area had been ring-barked (rung) and some of it cleared by the 1890s, and by the 1920s there was little commercially valuable timber left (PROV VPRS: 5714/344/288; 5714/364/458). The original vegetation was variously described as ‘thick box forest’ or some combination of box, gum, bulloak, she-oak, wattle and cherry. Tea-tree and red gum were said to be found along the stream banks. The soils in the area were often described as either clayey or clay–sand loam.

Although physically the hill country was distinct from the flats it also was considered unfit for cultivation in the 1880s. The reasons given by selectors for not cultivating the required 10% of selected land in the hill country were related to land either being too sandy, too rocky or too wet. (When land was taken up by selectors under the various Land Selection Acts there was a requirement that the land be improved before the selectors could be issued with freehold rights to the land. One of the improvements required by the government was that at least 10% of the land be cultivated.) Where cultivation did take place wheat, oats and hay were grown, but it was not unusual for black wattles to be cultivated for their bark (Land Selection Files; pers. comm. Stan Artridge, landholder, Feb. 1998). With the exception of some of the steeper country, ringing was completed by the 1890s, but timber still remained on a number of allotments in the area through to at least the 1920s (PROV VPRS: 5714/305/101; 5714/351/281). The native vegetation cleared by the selectors was described by the surveyors as some combination of grass, fern, honeysuckle (possibly a banksia), gum, box, peppermint, stringybark, cherry, wattle and oak. The soils in the area were generally described as sandy loams.

4.4.1. Creek morphology

Early plans and maps of the area suggest that the anabranch of Pranjip Creek existed in 1851, but that Branjee Creek was apparently not connected to Creightons Creek by a distinct channel during this period (CPO Historic Plans, Goulburn 22 & 68 (1851 & 1852)). A survey carried out in 1862 for the preparation of the first parish plan for the Parish of Branjee, shows Branjee Creek only extending to within 2 km of the present divergence point (CPO Historic Plans, Features 3, Parish of Branjee (1862)).

Plans based on a survey conducted in 1849 suggest that while only short sections of the upper reaches of Nine Mile Creek and Castle Creek were swampy, much of the area adjoining Creightons Creek, above the present location of Kelly’s Bridge, was swampy (CPO Historic Plans, Goulburn 72 (1849)).

Much more detailed information has been collected about the morphology of Creightons Creek from anecdotal evidence and Land Selection Files (for the reasons discussed in Section 3.2.1). This information is presented below, in two parts for clarity; first the hill country (i.e. above the Hume Freeway) is described, and then the flats (i.e. below the Hume Freeway).

Creightons Creek: the hill country

Survey notes are available for the surveys of six allotments along Creightons Creek in the hill country. The survey notes, which include information on the planform of the creek, cover most of Creightons Creek between Halsalls Lane and Bartons Lane. The descriptions and bank widths given in the notes suggest that the channel was well defined below Bartons Lane, with bank widths of between 8 m and 10 m. The surveyors' notes for two allotments in the area indicate that some sections of the creek below Bartons Lane were quite shallow and sandy, with no pools (PROV VPRS: 626/2095/3774; 625/365/25452), which may well be indicative of aggradation or simply the natural form of the creek.

Information from several Land Selection Files also provides evidence of possible sources of sediment. For example a surveyor noted in 1874 that where the Gobur Road crossed Creightons Creek (at Kellys Bridge) there were two deep ravines cutting through the swamp. This description suggests that two channels had eroded into the swamp at Kellys Bridge (PROV VPRS: 626/2021/610).

Similarly, in 1880, a surveyor who was responsible for surveying CA 15 of H Longwood (the road-front allotment at Baronga) noted that two channels were cutting back across the designated road reserve into the selector's allotment. The low lying area on the allotment was referred to as 'swampy flats' and the channels were said to be cutting farther back into the these flats each year, forcing travellers on the Gobur Road to travel into the selector's allotment to avoid having to cross the channels (PROV VPRS: 626/2058/2287).

A possible third example of erosion in the upper catchment was evident in Creightons Creek near the boundary of the Artridge property and an allotment now owned by the MacDonalds. In 1884 the surveyor responsible for surveying the upstream allotment (MacDonalds) noted that the stream morphology changed near the property boundary. According to him, downstream of the boundary the creek was wide, up to half a chain (10 m) in places, whilst further upstream the creek was so small it could be stepped over in places. Whilst this is not strong evidence it does suggest that a head of erosion may have been moving up Creightons Creek as early as 1884 (PROV VRPS: 626/44/3079).

Anecdotal evidence suggests that a fourth site of erosion may have existed on the lower section of Ramages Creek. Stan Artridge recalls his grandfather telling him that incision on Ramages Creek started when the original selector, Mr Ramage, used a plough line to drain part of the swamp that existed on the lower reaches of the creek (pers. comm. Stan Artridge, Landholder, Feb. 1998). It is highly probable that this occurred towards the end of the 1800s.

Creightons Creek: the flats

On the flats, the Creightons Creek system consists of the main stem of Creightons Creek, Little Branjee Creek and Branjee Creek.

Little Branjee Creek is described by surveyors in several of the Land Selection Files in the early 1880s as non-permanent (PROV VPRS: 626/2055/2134; 626/2093/3713) and a 'mere depression' (PROV VPRS: 626/2119/4673; 626/2121/4740; 626/2096/3801; 626/2129/5116). During selection, two allotments on Little Branjee Creek were surveyed. The surveyors notes from these surveys suggest that the channel of Little Branjee Creek was, at least in parts, a continuous channel with an average width of 4–5 m, but with pools up to 10 m in width (PROV VPRS: 626/2084/3346; 626/2096/3793).

Note that the interpretation of the surveyors' notes presented here assumes that the surveyors were measuring the width of the stream banks and not the width of the water surface, which is a reasonable assumption (pers. comm. Tony Morabito, Central Plan Office, DNRE, March 1998). Distinct 'chains of ponds' have been observed by the author along Little Branjee Creek south of Curries Rd, and these may be relics of the form of Little Branjee Creek prior to European settlement. No Land Selection File survey was available for this area and thus it is not possible to determine how this

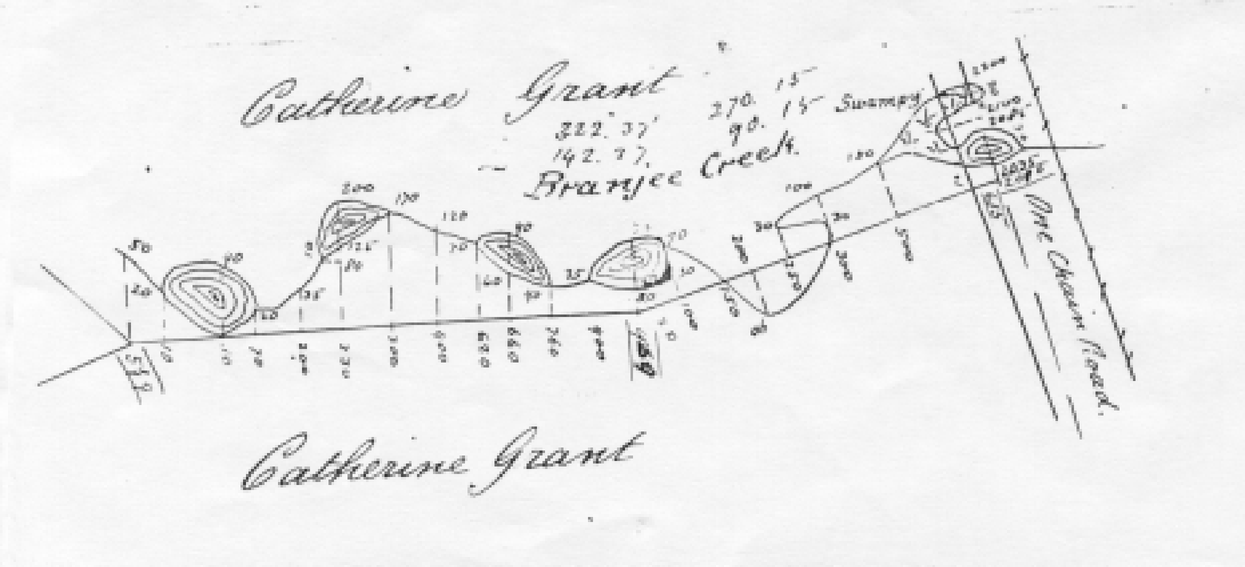
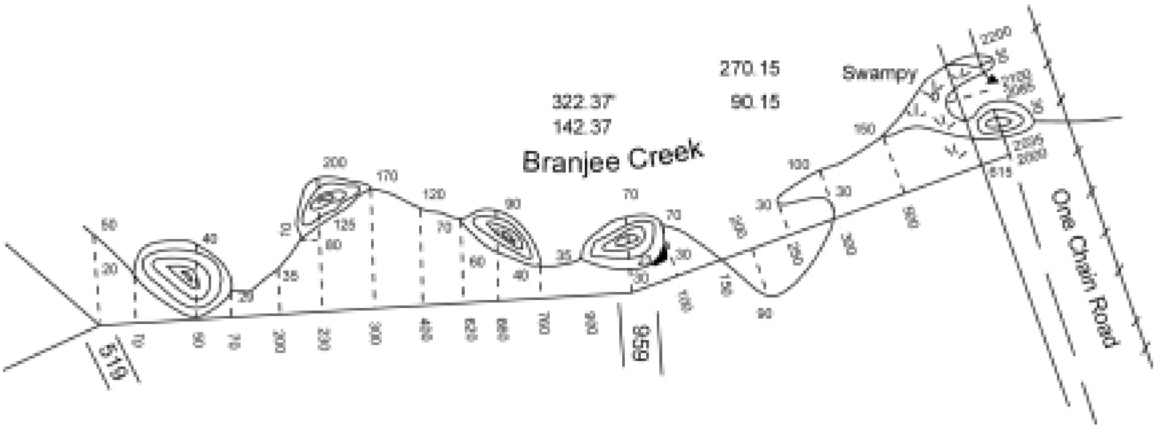


Fig. 4.1. Survey notes showing Branjee Creek in 1882. Note the narrow channel and large pools. Reproduced from PROV VPRS 626, Unit 2119, File 4671/20 (diagram taken from field notes of traverse of Branjee Creek) with the permission of the Keeper of Public Records, Public Records Office Victoria, Australia. A trace of the scan is reproduced below, for clarity.



form of stream was portrayed by the surveyors, i.e. as a distinct channel with regular width, or as a chain of ponds.

Branjee Creek was described in the early 1880s, in several Land Selection Files, as non-permanent (e.g. PROV VPRS: 626/2055/2134; 626/2119/4673). None of the Land Selection Files indicates that there was a swamp at the head of Branjee Creek, just north of Nelsons Rd, or that Branjee Creek received runoff directly from Creightons Creek via a distinct channel (PROV VPRS: 626/614/17419; 626/640/19003; 626/603/16872; 626/603/16871).

Five allotments were surveyed along Branjee Creek during the late 1870s and early 1880s, and as part of these surveys Branjee Creek was also surveyed (PROV VPRS: 626/2096/3793; 626/2054/2081; 626/2119/4671; 626/2137/5435; 626/2129/5120). Although it is necessary to be cautious about interpreting the results of these surveys, the notes suggest that Branjee Creek may have had two distinct morphologies. Downstream (below Hills Rd) it may have been a well defined channel, approximately 6 m wide. Upstream it is possible that Branjee Creek consisted of a narrow channel interspersed with pools, some 8 m wide and 50 m long (Fig. 4.1). The upstream channel area may have also tended to be swampy in winter.

The main stem of Creightons Creek was noted as being permanent during most of the surveys that took place on allotments along the creeks during the late 1870s and early 1880s (e.g. PROV VPRS: 626/2080/3171). Only one swamp was noted on the creek below the Hume Freeway during this period. Belton's Swamp, as it will be referred to, extended along the line of the creek from a point just north of the Pranjip Rd to the confluence of Creightons Creek and Branjee Creek (PROV VPRS: 626/2055/2134).

Survey notes for Creightons Creek were found for a large proportion of the allotments on Creightons Creek between the Pranjip Creek confluence and the Hume Freeway (19 in total). The notes suggest that Creightons Creek ran in a defined channel for most of its length except at Belton's Swamp where a small channel wound its way through the swamp. Upstream and downstream of the swamp the channel tended to be between 4 m and 10 m wide, with pools up to 20 m wide in places. The surveys indicate that the stream was probably at its narrowest (4–5 m) between the Geodetic Rd and the Longwood–Pranjip Rd, before appearing to double in width (~10 m) between the Geodetic Rd and the present Hume Freeway. This evidence indicates that the Creightons Creek channel may have been narrowing in the vicinity of the present-day location of the Branjee Creek off-take, in the early 1880s.

The North-Eastern Railway was constructed in 1873, substantially altering the hydrology of high flows from the hill country onto the flats by restricting flows to one or two specific drainage lines under the railway line. However, there is no evidence to suggest that channel incision resulted as might have been expected (see Section 4.7 for more information).

Anecdotal evidence suggests that there were several deep pools along Creightons Creek up to the beginning of the 1900s. There are stories of pools 12–14 feet (3–4 m) deep on Creightons Creek near the Pranjip Rd and an even deeper pool, 15–20 feet (4.5–6 m) deep, adjacent to the Longwood–Pranjip Rd (pers. comm. Jack Stevens, landholder, Feb. 1998). There is also a story about woodcutters leading their horses under the bridge on the Geodetic Rd near the beginning of the 1900s, which suggests the creek was at least 3 m deep at this point (pers. comm. Jack Stevens, landholder, Feb. 1998), but today there is not even a culvert — the stream simply no longer exists (Fig. 4.2). Thus it is possible that at the beginning of the 1900s Creightons Creek flowed in a well-defined channel with deep pools for much of its length below the present Hume Freeway. Figure 4.3 shows remnant pools in this section of Creightons Creek today.

Fig. 4.2. Former channel of Creightons Creek upstream of Geodetic Rd. Anecdotal evidence suggests that a deep pool (2–3 m deep) existed at this point towards the end of the 19th century.

Fig. 4.3. Remnant pools on Creightons Creek today. This stream form could be representative of the lower reaches of Creighton's Creek (i.e. below the present Hume Freeway) in the 1800s.

In summary, the channels of Little Branjee, Branjee and Creightons Creek on the flats differ from those apparent today. Little Branjee Creek was intermittent and probably comprised a narrow channel interspersed with pools. Branjee Creek was permanently linked to Creightons Creek only at its downstream end and had two distinct forms. Below Hills Rd, Branjee Creek was a well-defined, moderate size channel, while above Hills Rd the channel was narrow and interspersed with pools, and tended to be swampy. Creightons Creek flowed in a well-defined channel with deep pools, from the present Hume Freeway down to Pranjip Rd where the channel then became narrow and swampy.

4.5. The Creightons Creek area in the 20th century

The following is a chronological description of activities affecting Creightons Creek and its behaviour during the 20th century based on anecdotal evidence, agency files and some fieldwork. Creightons Creek is the only creek for which detailed information was sought, because of time constraints, but it is probable that the history of erosion and sedimentation outlined below for Creightons Creek is representative of the histories of the other Granite Creeks.

4.5.1. Creightons Creek: the hill country

From the description of creek morphology for the hill country between 1850 and 1900 it is possible to derive an approximate description of Creightons Creek at the beginning of the 1900s. Between the present Hume Freeway and Bartons Lane, at least, it is probable that Creightons Creek was relatively wide (~10 m), shallow and sandy. Above Kellys Bridge it seems likely that, while some swamp may have remained adjacent to the creek, the creek itself was contained in a distinct channel. Further upstream, above Stan Artridge's property, in the steeper reaches of the catchment, it is probable that the creek was channelised in some sections, but where floodplains exist the channel adjoined swampy flats. Bert Threlfall recalls much of Creightons Creek above the MacDonald property as flowing in narrow deep channels which were almost completely covered with the sword grass and fish fern that grew on the banks. In some areas the only indication that the stream was running was from the sounds coming from beneath the dense canopy (pers. comm. Bert Threlfall, former landholder, March 1998). Although it is possible that this stream form may have existed prior to European settlement, it seems likely that it co-existed with an unchannelised swampy form.

The state of the tributaries at the start of the 20th century is even more difficult to establish. For Baronga Creek it is probable that the lowest section of the creek (i.e. below the waterfall near Barrie Noye's house) was channelised but not deeply incised, and the flats surrounding the creek may have still tended to be swampy, particularly in winter. Ramages Creek was probably in a similar state with the lower reaches channelised but not deeply incised, and the surrounding flats swampy.

The first major changes in the upper catchment in the 20th century probably coincided with the 1916 flood, one of the largest on record (Sinclair Knight Merz 1997). Anecdotal evidence suggests that the flood resulted in massive channel incision (of the order of 8–10 m in places) on Creightons Creek above the Ramages Creek junction (Fig. 4.4) (pers. comm. Stan Artridge, landholder, Feb. 1998). This incision event can be traced upstream to a waterfall on Stan's property. Similar incision may have also occurred on Ramages Creek near Bill O'Connor's house (pers. comm. Bert Threlfall, former landholder, March 1998), and on sections of Creightons Creek above the Artridge property, e.g. on John Nielsen's property (based on observations made by author). This event must have excavated large volumes of sediment and had a catastrophic impact downstream; however, there is no evidence available of significant siltation above the present Hume Freeway at this time.

A second phase of channel incision appears to have coincided with the 1950s, which was a particularly wet decade. Over 1050 mm of rain fell in 1956 alone and there were three years between 1952 and 1956 in which more than 800 mm fell annually, compared with the annual average of 653 mm (based on rainfall data for Euroa published in the Centenary Edition of the *Euroa Gazette* December 1997). The process by which incision occurred is not clear, but it seems likely that a series of erosion heads moved up Creightons Creek during the 1950s and 1960s (e.g. pers. comm. Barrie Noye, landholder, Feb. 1998), resulting in incision throughout much of the system. Baronga Creek, for example, incised 4–5 m between the Creightons Creek Rd and the waterfall (pers. comm. Barrie Noye, landholder, Feb. 1998; Goulburn-Murray Water File: 2020 WW). Incision elsewhere does not appear to have been as severe (closer to 1–1.5 m), but it is clearly evident along the lower sections of Ramages Creek, as well as on Creightons Creek above the Ramages Creek junction.

The only evidence of stream incision downstream of Kellys Bridge during this period is at the present Hume Freeway where a highway bridge had to be replaced in 1957/8 because of stream enlargement (pers. comm. Paul Tucker, Vic Roads, Benalla, March 1998). A comparison of cross-sections measured on Creightons Creek at the Hume Freeway in 1957 and 1998 indicates that in that 40 year period the streambed at the bridge has dropped approximately 50 c m (Appendix Fig. B3). A bed control structure in the creek immediately below the bridge (Fig. 4.5) is holding another 30–50 cm erosion head from moving upstream. It is not possible to determine the timing of this incision.

Sediment deposition from this second major phase of channel incision was noted at a number of locations in the creek downstream of the Baronga Creek confluence. Sedimentation in the creek in the vicinity of the Creightons Creek Reserve was noted by Brian Kelly. According to Brian there were a number of large pools (approximately 6 m in diameter) along Creightons Creek just downstream of Kellys Bridge in the 1940s and 1950s which started to fill with sediment in the 1950s;

Fig. 4.4. Creightons Creek above the junction with Ramages Creek on Stan Artridge's property. This section of Creightons Creek has incised more than 10 m and anecdotal evidence suggests that most of this incision occurred during the 1916 flood.

Fig. 4.5. Creightons Creek at the Hume Freeway Bridge. The concrete sill visible in the photo is a bed control structure that is protecting the bridge piers from being undermined.

and within a few years they had disappeared altogether. Other changes during this period were also noted by Brian in, and just above, the Creightons Creek Reserve, as well as at Kellys Bridge. Throughout the decades that followed the 1950s, the creek in and just above the Reserve began to silt up, with up to 0.5 m of sediment deposited (pers. comm. Brian Kelly, landholder, Feb. 1998).

Just below the Reserve at Kellys Bridge, sediment deposition of 8–9 feet (2.5–3 m) occurred following the 1950s, engulfing the old road bridge (pers. comm. Brian Kelly, landholder, Feb. 1998). Downstream of Kellys Bridge, below the Longwood–Mansfield Rd, Jim Shovelton also has recollections of pools in Creightons Creek in the 1950s that were 3–4 feet (~1 m) deep, although he believes that the pools higher up the creek were not as deep. These pools filled in not many years after the 1950s (pers. comm. Jim Shovelton, landholder, Feb. 1998). These observations suggest that sediment deposition in this section of the creek commenced in the 1950s, starting further upstream, hence the shallower pools; and by the 1960s all the bed form above the Longwood–Mansfield Rd had been sanded out.

A third phase of incision may have moved through the upper reaches of Creightons Creek over the last 20 years, particularly affecting the lowest section of Baronga Creek, as well as much of Creightons Creek above the Hume Freeway. As mentioned above, according to Brian Kelly the old road bridge (Kellys Bridge) was almost completely buried in the decades that followed the 1950s, but over the last decade or so the sediment engulfing the bridge has receded and the creek, in the vicinity of the old bridge, is apparently at a similar bed elevation today to that prior to the 1950s (pers. comm. Brian Kelly, landholder, Feb. 1998). This anecdotal evidence is supported to some extent by information generated by comparing the original design of the current bridge (Strathbogie Shire Council Bridge Plan: 129 (1966)) with the current bridge cross-section. Such a comparison suggests that over the last thirty years Creightons Creek may have degraded by 1 m, lending some support to Brian Kelly’s claim.

Heads of erosion have also continued to move up Baronga Creek to the waterfall over the last two decades. Barrie Noye planted vegetation in the bed of Baronga Creek in the late 1970s, and today the streambed is, in places, 10 feet (3 m) below the vegetation (pers. comm. Barrie Noye, landholder, March 1998). However, comparisons of cross-sections measured at the Creightons Creek Rd bridge over Baronga Creek in 1988 (Strathbogie Shire Council Bridge Plan: 518 (1988)) and 1998, indicate that there has been limited change in bed elevation in this vicinity over the last ten years (1988–1998). This suggests that there has been limited bed movement at the lower end of Baronga Creek during the last decade.

Fig. 4.6. Creightons Creek upstream of Bartons Lane. This section of Creightons Creek would once have had a much smaller channel and would have flowed across a swampy plain. The stream is now incised and is continuing to incise in places (see headcut in channel bed).

Incision has also been noted upstream of Bartons Lane (Fig. 4.6.). Dino Furlanetto has noticed Creightons Creek incising over the last 25 years, with much of the incision occurring during flood events. The 1993 floods were particularly damaging, causing severe incision and widening immediately upstream of Bartons Lane, where the creek is now 3–4 m deep in places. To halt the incision Dino has put in two rock chutes to act as sediment traps. He claims they have caused the bed to rise about 3 feet (1 m), with most of the sediment being trapped within a year of chute construction (pers. comm. Dino Furlanetto, landholder, March 1998). It was interesting to note that the incision at the Furlanettos' has revealed the stumps of two large gum trees in the creek bed, suggesting that the creek has been at its current level in the past. This scenario is consistent with the filling and cutting of the creek bed at Kellys Bridge, 1–2 km further upstream, noted by Brian Kelly.

It is not clear if such incision extended down to the Longwood–Mansfield Rd. Conflicting bridge design records indicate the bed may have degraded up to 1 m in this vicinity over the last 30 years, or it may have degraded less than 0.2 m in total over the last 20 years.

Further downstream still, just above Halsalls Lane, Jim Dunn has also noted the creek deepening in recent years. The bed may have dropped a couple of feet (approximately 0.5 m) in this area, but it is also possible that some of the incision observed may be localised.

The legacy of the third phase of incision in the upper section of Creightons Creek has been another wave of in-stream sedimentation resulting in the infilling of some of the pools remaining in Creightons Creek above the Baronga Creek confluence. Sue Haggard, for example has noted that many of the pools that existed in the creek adjacent to her property (in the MacDonalds property) 25 years ago, have now filled (pers. comm. Sue Haggard, landholder, March 1998). Sedimentation has also continued in Creightons Creek adjacent to the Creightons Creek Recreation Reserve (immediately upstream of Kellys Bridge). The local landholders became so concerned about flooding resulting from this sedimentation that in the late 1980s the channel was dredged to increase the stream capacity locally (pers. comm. Brian Kelly, landholder, Feb. 1998). This action may, however, have caused incision. At the Recreation Reserve the creek has incised 1 foot (0.3 m) since dredging (pers. comm. Brian Kelly, landholder, Feb. 1998) and upstream of the Recreation Reserve it has cut down 5 feet (1.5 m) (pers. comm. Laurie Davidson, landholder, Nov. 1998).

While the three main phases of incision appear to have been responsible for many of the changes noted in the upper section of Creightons Creeks over the years, there have been other isolated cases of erosion in the upper catchment. Examples include channel avulsion, incision and an erosion head forming in the lower reaches of Ramages Creek, triggered apparently by significant local rainfall events in 1988/9 (pers. comm. Bill O'Connor, landholder, March 1998; Goulburn-Murray Water File 2020 WW), and gullying initiated during a wet 1973 (annual rainfall for 1973 was 1078 mm) (DNRE, SCA File: N/ 230). Inappropriate land management in the form of ploughing lands has been blamed for at least one gully on Jim Shovelton's property (pers. comm. Jim Shovelton, landholder, March 1998), and bushfires (1990–91) and drought (1982–83) are considered to be the disturbances responsible for triggering gullies on the properties of Dino Furlanetto (pers. comm. Dino Furlanetto, landholder, March 1998) and John Nielsen (pers. comm. John Nielsen, landholder, March 1998) respectively.

Bert Threlfall and Barrie Noye have both observed a number of small erosion heads moving up the headwater reaches of Creightons Creek and its tributaries in recent years, and they have attributed these heads to uncontrolled stock access to the streams, particularly by cattle (pers. comm. Bert Threlfall and Barrie Noye, landholders, March 1998). These erosion heads are said to be the source of sediment that is starting to fill some of the small pools remaining higher up the creek. The upper section of Creightons Creek has few segments that are today in a form similar to that which would have been seen by the first settlers over 150 years ago. Few swamps remain and the channelised segments are sanded out with little variation in bed form.

In summary it would appear that there have been three main phases of channel incision in the upper section of Creightons Creek. The first two phases appear to have been related to flood events or 'wet years', when stream power was sufficient to drive a number of existing erosion heads a great distance, and perhaps initiate some others. The combined result of these was a single incision event of the order of several metres. The third phase of channel incision does not appear to have had an obvious external trigger but it may be a combination of events over the period, e.g. 1982–83 drought, 1990–91 bushfires and 1993–94 floods, that have pushed a number of erosion heads quite quickly through the system. This implies that erosion heads are just as prevalent in the system now as they have been at any time in the past 100 years, but it may also be an artefact of greater stream awareness and the temporal proximity of these events in people's minds. Possible sources of disturbance for initiating erosion heads are explored in Section 4.7.

Bushfires and droughts, as well as land management activities, also appear to have had an impact on stream and drainage line stability at a local level.

4.5.2. Creightons Creek: the flats

Changes during the 20th century along Creightons Creek and its tributaries on the flats have been just as dramatic as those that occurred upstream of the present Hume Freeway, but they seem to be more closely linked to changes induced by sediment delivered from the upper catchment than to local activities.

At the beginning of the 1900s Creightons Creek was probably carrying all the low flows derived from the upper catchment. In terms of the creek form it is likely that for much of its length it was similar to the sections near the Longwood–Shepparton Rd today, i.e. with long deep pools as well as shallower 'run' sections (see Fig. 4.3). The only place in which it may not have had a well defined course was through Beltons Swamp, although there is anecdotal evidence to suggest that drains cut through the swamp around the beginning of the 1900s may have 'captured' the creek and allowed it to develop a more well-defined course (pers. comm. Jack Stevens, landholder, Feb. 1998). This incision, as well as possible incision initiated at the railway line by the channelisation of flow, may have been the most significant disturbances visible along Creightons Creek at the beginning of the 1900s.

Although the lower sections of Branjee Creek may have had a well defined channel, it is possible that the upper section was in the form of a chain of ponds which had no direct connection to Creightons Creek. The same may also have applied to Little Branjee Creek. Despite being 'disconnected' from Creightons Creek, and thus non-permanent, it is probable that both Branjee Creek and Little Branjee Creek carried overflow from Creightons Creek during flood events, thus behaving as anabranches of Creightons Creek.

Fig. 4.7. A section of Creightons Creek upstream of the Longwood–Pranjip Rd. This section of channel was dredged in 1969 and the dredge material placed in mounds on the creek bank. Since the early 1970s the channel has only carried flood flows.

It is clear that sedimentation commenced along the lower section of Creightons Creek in the early 1900s, but it took a number of years for significant impacts to accumulate. Changes apparently were first noted in the 1930s and 1940s, as Creightons Creek began to fill with sand, particularly in the section just north of Nelsons Rd. In 1935 it was recorded at a meeting of the Euroa Shire Council that siltation of Creightons Creek was causing damage to roads in the Pranjip area (Halsall 1980). Anecdotal evidence suggests that flow in Creightons Creek at the Pranjip Rd began to decline in the 1930s (pers. comm. Jack Stevens, landholder, Feb. 1998), suggesting that some proportion of flow in Creightons Creek was already being diverted into Branjee Creek. This is supported by the claim that Nelsons Swamp came into existence around the 1940s (pers. comm. Jack Stevens, landholder, Feb. 1998), which indicates that Creightons Creek began to have difficulty carrying flows at this time. A local landholder also recalls that Branjee Creek began to change following the 1940s. According to Jack Stevens, Branjee Creek consisted of a series of ponds or pools in the 1940s, but since then the ridges between the pools have been scoured out and the creek is now a continuous channel (pers. comm. Jack Stevens, landholder, Feb. 1998). The changes noted along sections of Branjee Creek after the 1940s may be consistent with the conversion of an ephemeral stream to a perennial stream.

By 1969 sedimentation was so severe under road bridges at Nelsons Rd and the Longwood–Pranjip Rd that the Shire of Euroa sought State Rivers and Water Supply Commission (SRWSC) funding to clear snags and vegetation from Creightons Creek in the vicinity of the bridges. This funding was granted (Goulburn-Murray Water File: 2020 WW) and in the months that followed sand was dredged from the creek at both bridges, and reeds and snags were removed from the bed (pers. comm. Maurie Brodie, landholder, Feb. 1998). Anecdotal evidence suggests that a hole 3 m deep and about 30 m long was dredged under the Nelsons Rd bridge, but this hole had filled again within 12 months (pers. comm. Maurie Brodie, landholder, Feb. 1998). In contrast, there has been very little change following the works conducted at the Longwood–Pranjip Rd bridge. The mounds of dredged silt are still visible on the banks and the channel remains clear of vegetation and relatively deep (Fig. 4.7). The contrasting responses can be explained by the fact that the Creightons Creek at the Nelson Rd bridge has continued to carry all the flow delivered from the upper catchment, while below Nelsons Swamp Creightons Creek was carrying only 14% of low flows in 1971, the remaining 86% being diverting into Branjee Creek (Goulburn-Murray Water File: 2020 WW). A short time after this breakdown in flows was measured, the diversion was completed with the construction of a drain by a landholder (pers. comm. Maurie Brodie, landholder, Feb. 1998), which resulted in 100% of low flows entering Branjee Creek. Consequently Creightons Creek at the Longwood–Pranjip Rd has carried little flow derived from the upper Creightons Creek catchment since 1969, and thus there has been little opportunity for this section of the creek to fill with sediment.

Since the diversion drain was constructed in 1971 all low flows have been carried by Branjee Creek, but it is not clear if some of the high flows are still carried by Creightons Creek below Nelsons Swamp. In terms of the creek's morphology, the original course of Creightons Creek has been obliterated by cultivation in the paddock where the creek has been diverted. Immediately below the paddock the channel has completely filled with sediment and is only discernible by vegetation patterns. The creek has a similar appearance at the Geodetic Rd, but by the time the creek reaches the Drysdale Rd a shallow course is visible.

Changes to Creightons Creek and Branjee Creek over the last couple of decades appear to relate to management activities in the creeks. For example the drain that was cut to divert all the flow into Branjee Creek was originally 18 inches (0.45 m) deep and 2–3 feet (~0.75 m) wide, but it is now approximately 1.5 m deep and 10 m wide (Fig. 4.8). Other activities affecting the creek in recent years include the cutting off of meander bends on Branjee Creek several hundred metres below the diversion point (1980s) and where the drain begins (1997), and desnagging and poisoning of cane grass (*sic*) in the bed of the creek (1997). The landholder carried out these activities to prevent sand building up in the bed and claims that the activities carried out in 1997 alone have led to the creek bed dropping 15 inches (~0.4 m) (Fig. 4.9) (pers. comm. Maurie Brodie, landholder, Feb. 1998).

At the bottom end of the Creightons Creek system, below the Branjee Creek confluence, sand deposition has been minimal, to date. This is indicated both by visual inspection and by a comparison of stream cross-sections measured at the Longwood–Shepparton Rd bridge. Observations of Creightons Creek below the Branjee Creek confluence indicate that although there is some evidence of sand deposition in this reach it is minor and comprised mainly of small deposits on point bars and in low velocity zones along the stream. Sand can also be observed in the bed, but, as discussed in Section 5.1.2, the local streambed and banks are the most likely source of this material. A comparison of the original bridge design for the Longwood–Shepparton Rd bridge (Strathbogie Shire Council Bridge Plan: 529 (1989)) with the present cross-section reveals that there has been little change in bed elevation over the last nine years.

To briefly summarise, Creightons Creek below the present Hume Freeway has changed dramatically since the start of the 1900s. Originally the channel contained deep pools and runs, and carried 100% of low flows. During high flows it is probable that overbank flows were captured by Branjee Creek and Little Branjee Creek which functioned as anabranches and had predominantly 'chain-of-ponds' forms. Since European settlement, change appears to have been driven by sediment being transported from the upper catchment to the lower catchment. Sedimentation has obliterated many of the pools in Creightons Creek above the Branjee confluence; it blocked the Creightons

Fig. 4.8. Branjee Creek between Nelsons Rd and Drysdale Rd. This section of Branjee Creek was originally a narrow drain cut to divert all baseflows from Creightons Creek into Branjee Creek. The channel has deepened and widened substantially over the last 30 years.

Fig. 4.9. Branjee–Creightons Creek meander cutoff, initiated in 1997

Creek channel to such a degree that over a period of about 30–40 years low flows began to divert into Branjee Creek. The diversion, which was assisted in 1971 by direct human intervention, has altered the form of Branjee Creek to that of a continuous channel, the pools of which are now filling with sand. While there is little doubt that such channel abandonment is a natural feature of these Riverine Plain streams, as is evidenced by the existence of sand filled channels on the flats (pers. comm. Len Stevens, landholder, Feb. 1998), it seems probable that this process has been accelerated by the effects of European settlement.

4.6. Evidence of erosion and sedimentation along Castle Creek and Pranjip–Nine Mile Creek

Castle Creek and Pranjip–Nine Mile Creek have not been considered in the same detail as Creightons Creek. Some information has been gathered for these two creeks, but it is patchy, and no clear picture of the timing and location of erosion and aggradation can be formed. However, the information provides an approximate means of comparing the history of stream morphology for all three creeks.

4.6.1. Castle Creek

There is evidence that erosion was occurring in the Castle Creek catchment not long after the beginning of the 1900s. A Soil Conservation Authority (SCA) file indicates that trees may have been planted along a gully in the catchment to stabilise it between 1910 and 1920 (DNRE SCA Files: S/1064). Since that time, the SCA has been called in by landholders on a number of occasions to address problems, primarily gullying. Most of the gullying problems were reported in the 1960s and 1970s, but in some instances the gully was old and was quite stable or had been reactivated in recent years. Therefore, it cannot necessarily be assumed that this was an especially erosive period (DNRE SCA Files: B/1282, H/573, H/1099, M/966, R/222, S/1064, W/519). It is also important to note that only a small proportion of landholders would have approached the SCA about erosion problems, and these landholders may not have been aware of the SCA prior to the 1960s.

One notable example of erosion in Castle Creek catchment has been recorded in SCA, NRE and RWC Files, namely the movement of an 8 foot erosion head (2.4 m) up Castle Creek during the 1970s. According to an SCA report between 1973 and 1977 the head advanced 80 m upstream, degrading the bed 2.5 m and widening the stream 5–15 m (S/1064). It is interesting to consider this rate of advance in relation to rainfall in this period. Annual rainfall in 1973 was 1078 mm, the wettest year since records began. This was followed by 897 mm in 1974 and 896 mm in 1975 (based on rainfall data in the Centenary Edition of the *Euroa Gazette*, 1997). The SCA report does not reveal what initiated the erosion head/s, but it indicates that the wet 1970s led to the rapid liberation of approximately 2000 m^3 of sediment from the bed and banks of Castle Creek.

The NRE/RWC Files for Castle Creek indicate that the 8 foot erosion head that moved through the upper reaches of Castle Creek in the 1970s incised a section of creek that had already been incised 10 feet (3 m) in 1961 (NRE/RWC File, 62/19071). Anecdotal evidence from a local landholder suggests that this reach of Castle Creek, i.e. above Killeens Hill Rd, was quite stable and relatively undisturbed until the 1960s when his father decided to move the creek so it was closer to the house for convenience (pers. comm. Geoff McLean, landholder, May 1998). He did this by using his tractor to dig a new channel for the creek, and he succeeded in diverting the creek over a length of 500 m. However, once the creek changed course it began to incise. On the McLean's property there have been two periods of incision, the first coinciding with the diversion of the creek in the 1950s–60s, and the second in response to the 1993 floods. Both periods of incision have reduced the bed elevation by about 2 m. The erosion head initiated by the diversion of the creek in the 1950s–60s migrated upstream until it reached a waterfall (several kilometres above the McLean's property). It appears that as the head migrated upstream it increased in height, incising into the streambed more deeply, and in fact it appears that the head has incised into the original creek bed up to 10 m, just below the waterfall (Fig. 4.10).

The material excavated from the upper reaches of Castle Creek by stream incision has been deposited over the floodplain between Geoff McLean's house and the lower boundary of his property, at a depth of 4–5 feet (~1.4 m) (pers. comm. Geoff McLean, landholder, May 1998). This information suggests that more than 500 000 m^3 of sediment may be held in this store. There is some evidence to support Geoff McLean's claims. For example the original creek is still visible on the floodplain, and it is relatively small (~0.5 m deep and 1.5–2 m wide) suggesting that it was stable prior to diversion. There are also several pieces of evidence suggesting that 1.4 m (4–5 feet) of sediment has been deposited on the floodplain. First, the authors observed a piece of milled timber sticking out of the stream bank about 4 feet below the top of the stream bank, which is consistent with it having been buried under the sediment deposited on the floodplain. Second, a number of red gums that were located along the creek have died, apparently because their trunks have been indundated by sediment. Further evidence supporting Geoff McLean's story is that soil layering exposed in the stream banks shows 1.4 m of lighter material overlying a darker layer that may correspond to the original A Horizon. The final piece of evidence relates to the stripping of the lighter sediment layer at several points along the creek by the 1993 floods. At a number of sites along the creek the floods stripped soil to create benches,

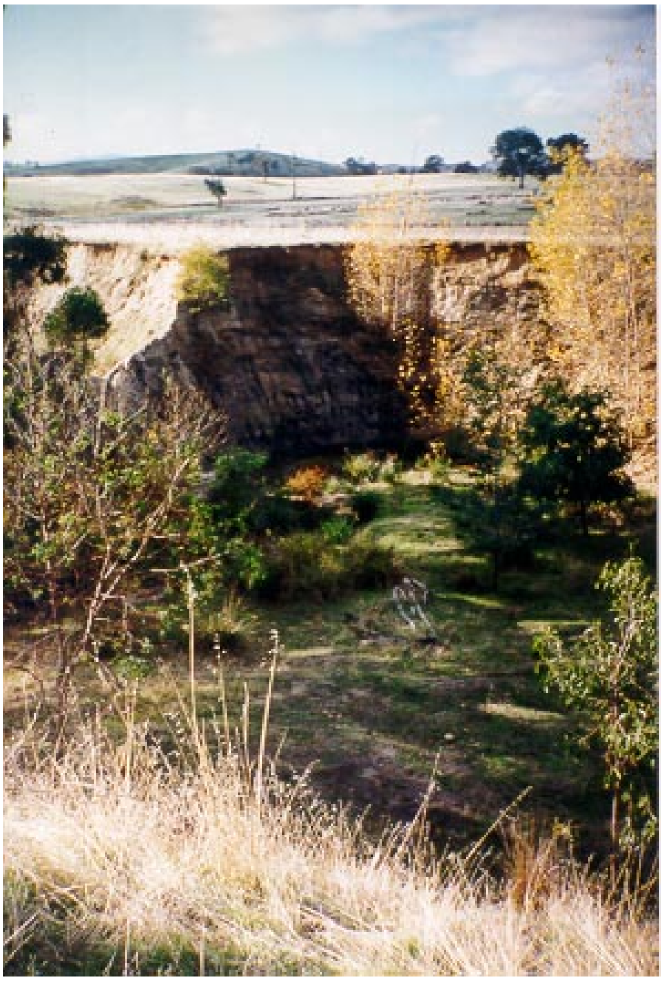


Fig. 4.10. Castle Creek upstream of the McLeans' property. Severe stream incision and widening has led to the formation of this chasm since the 1960s.

but in each case the soil was stripped to exactly the same level, which corresponded to the top of the darker soil layer just described, and following the floods a large number of native plants germinated on the exposed benches. All these observations are consistent with the original soil surface being covered by 1.4 m of sediment, which was predominantly sandy and lacked cohesion and thus strength, making it susceptible to further erosion.

Erosion has also been a problem at several other locations along Castle Creek, according to NRE and NRE/RWC Files. Erosion was recorded on Castle Creek at the Newtons' in 1963, when a short section of creek was abandoned and a new channel formed that was much deeper and wider (the original channel was 3 ft (0.9 m) deep and 6 ft (1.8 m) wide, and the new channel was 12 ft (3.7 m) deep and 20 ft (6.1 m) wide) (NRE/RWC File, 62/19071). Erosion was still a problem on this reach of Castle Creek 17 years later when deepening and widening was noted over a length of 0.5–0.75 miles (800–1200 m) (NRE/RWC File, 62/19071). In 1982, funding was granted for the construction of an erosion control structure in this reach to control the erosion head that was responsible for destabilising the creek. In the 12 months preceding 1982 the head had moved 300 m (NRE/RWC File, 62/19071). More recently, in 1993, funding was allocated for the construction of a floodway to prevent the creek abandoning a section of channel (NRE File, 85/22219).

In 1998 a drop structure was constructed on Castle Creek on John King's property to prevent several erosion heads by-passing the willows that were stopping the heads from moving further upstream (pers. comm. Wayne Tennant, GBCMA, May 1998). Another head of similar size (3–4 m) is located a short distance downstream and is presently caught on a bedrock bar. However, there is concern that the bar will soon be out-flanked and it is proposed that works be carried out to control this erosion in the future.

Stream erosion has also occurred downstream of Euroa. During a wet winter in the early 1980s, part of Castle Creek and some of the surrounding paddocks eroded (NRE/RWC File, 62/19071).

At three locations along Castle Creek the creek has been straightened to facilitate the realignment of roads. An historic map (CPO Putaway Plans E81(2) (1909)) indicates that a meander bend was cut off in about 1910, from Castle Creek near Sydney Road (the old Hume Highway) to allow the road to be realigned. Later, plans for road bridges over Castle Creek prepared by the Euroa Shire Council in 1959 (Cullens Rd) and 1970 (Geodetic Rd) (Strathbogie Shire Council Bridge Plan: 182 & 022 (1959 & 1970)), indicate that the creek was to be realigned to allow the roads to be realigned. In all three cases the creek realignment involved cutting off a substantial meander and in the process steepening the creek gradient locally, which may have had the potential to initiate erosion heads (Galay 1983).

Some of the earliest information readily available regarding the morphology of Castle Creek suggests that although deep holes were noted in the streambed near Sydney Road at about the start of the 1900s (Halsall 1980), the bed in this reach of creek was probably flat and sandy by the 1930s. Two pieces of evidence support this suggestion. One piece of evidence comes from a story about a railway ganger having to jump from the railway line in 1933 to avoid being struck by a train; it was said that he landed safely in the sandy bed of Castle Creek (Halsall 1980). The second piece of evidence comes from a photo of Castle Creek taken adjacent to the Euroa Golf Course sometime before 1947/8, which shows the bed to be shallow and sandy (Halsall 1980).

Aggradation in Castle Creek has been recorded in the RWC and NRE files as occurring primarily between the old Hume Highway bridge and the Drysdale Rd, although it has also been noted upstream between Euroa and the Euroa–Mansfield Rd bridge (i.e. Telfords Bridge). The deposition of sand in this area is said to have exacerbated flooding problems in parts of Euroa, and as a result desnagging and sand extraction have been authorised on a number of occasions. However, on at least one occasion (in 1982) sand extraction and the removal of all vegetation and snags from the creek resulted in the formation of a small erosion head just upstream of the old Hume Highway bridge (DNRE RWC File 62/19071).

Fig. 4.11. Sand deposition in Castle Creek downstream of the old Hume Highway Bridge

Comparisons of stream cross-sections measured at the railway line and the old Hume Highway suggest that the bed of Castle Creek in this vicinity accreted during the 1900s. A re-survey of the old Hume Highway bridge suggests that between 1938 and 1998 (60 years) the bed may have risen slightly (Fig. 4.11 and Appendix Fig. B4). A re-survey of the railway bridge at Castle Creek indicates that between 1926 and 1995 the bed may have accreted more than 50 cm, whilst between 1995 and 1998 it may have degraded slightly (Appendix Fig. B8). The degradation between 1995 and 1998 may, however, be related to the removal of sediment from beneath the bridge (PTC Bridge Files, Somerton to Wodonga Line, Index: 186). From these data it is possible to say that this section of Castle Creek has aggraded since 1926, but given the data for the old Hume Highway and the story about the railway ganger described above, it is possible to speculate that much of the aggradation may have occurred in the late 1920s and early 1930s. The evidence presented above regarding sand extraction from Castle Creek in the vicinity of the old Hume Highway bridge and the railway line, suggests that the rates of sedimentation estimated from the bridge cross-sections are probably substantial underestimates of the actual rate of sedimentation.

A comparison of bridge design cross-sections with present cross-sections at a number of other sites along Castle Creek indicates that bed elevations have risen, dropped, and remained stable at different points along the creek over the last 30 or so years. Cross-sections at the Euroa–Mansfield Rd (Telfords Bridge) for example, indicate that the creek was silting up prior to 1939 (Strathbogie Shire Council Bridge Plan: 002 (1939)), and between 1939 and 1991 it may have aggraded by more than 1 m (Strathbogie Shire Council Bridge Plans: 002 & 554 (1939 & 1991)). Since the bridge was replaced in 1991 the channel has adjusted its shape and may have experienced some aggradation (Strathbogie Shire Council Bridge Plans: 554 & 554-3 (1991 & 1991). Downstream at the Pranjip Rd bridge, Castle Creek appears to have scoured. Between the early 1960s and 1998 the creek bed may have degraded 1–1.5 m. Further downstream at the Cullens Rd bridge a comparison between the design cross-section, which was constructed sometime after 1959, and the present day cross-section indicates that the bed may have aggraded slightly (~20–30 cm).

The lowest cross-section available on Castle Creek is at the Murchison–Violet Town Rd bridge (Strathbogie Shire Council Bridge Plan: 076 (1961)). When the bridge was built in the early 1960s up to 10 feet (3 m) of material was removed from the streambed to form the present day channel.

Fig. 4.12. Pranjip Creek at the Hume Freeway. More than 0.5 m of sediment may have been deposited in this section of channel between 1958 and 1998.

Such a disturbance might be expected to propagate upstream via knickpoint migration, but an inspection of the reach upstream revealed no such degradation, with the narrow run–pool sequence intact. Even at the bridge site change has been minimal, with the bed elevation appearing to have dropped 10–20 cm at the most over 30 years.

4.6.2. Pranjip–Nine Mile Creek

The earliest evidence of erosion in the Pranjip–Nine Mile Creek catchment comes from Killeen on the Nine Mile Creek, in 1949, where a gully had formed in a cropped paddock (DNRE SCA File: C/18). Just as for Castle Creek, there were a number of instances of gully erosion reported in the Pranjip–Nine Mile Creek catchment in the 1960s and 1970s (DNRE SCA Files: B/1143, C/18, D/547, L/1168, O/102, P/682, T/418), but because not all landholders reported erosion to the SCA, and local landholders may not have been aware of the SCA before the 1960s, it cannot be assumed that this period was necessarily an erosive period.

In terms of possible disturbances capable of initiating erosion heads along Pranjip–Nine Mile Creek there is evidence of only one such event. According to road plans produced by the Euroa Shire Council in 1973 (Strathbogie Shire Council Bridge Plan: 099 (1964)), the Longwood–Avenel Rd was realigned in the vicinity of Threlfalls Lane. To facilitate the realignment of the road a section of Nine Mile Creek was straightened. Straightening of the creek increased the grade locally and may have initiated an erosion head.

Anecdotal evidence suggests that incision which has produced streams more than 8 m deep in some sections of the upper reaches of Pranjip Creek, has been caused primarily by cattle access to the creek and its tributaries (pers. comm. Ian Elder, landholder, May 1998). This conclusion is, however, based only on observations made in the area over the last 32 years, so it is not clear what may have initiated erosion before this period.

Whilst Nine Mile Creek has incised above the present Hume Freeway, it does not appear that incision is as extensive (in terms of volume of sediment eroded) as is seen on the upper reaches of Pranjip, Creightons and Castle Creeks.

Comparisons of stream cross-sections measured at the railway line and the Hume Freeway for Pranjip Creek (or Camerons Well Creek) and Nine Mile Creek indicate that aggradation and incision have occurred at different times. Cross-sections measured on Pranjip Creek at the Hume Freeway (Fig. 4.12) indicate that there may have been 50–70 cm of sediment deposited in the bed in this vicinity between 1958 and 1998 (40 years) (Appendix Fig. B1). The railway bridge (Fig. 4.13) cross-sections, in contrast, indicate that up to 1.5 m of sediment may have been deposited in the bed of Pranjip Creek between 1871 and 1922, but that since then the bed may have degraded back to its original level. The bed appears to have degraded approximately 50 cm between 1922 and 1947, a further 30 cm between 1947 and 1995 and perhaps another 40 cm between 1995 and 1998 (Appendix Fig. B5). Degradation over the last 15–20 years may, however, be related to at least two attempts to clear out sediment and vegetation from under the bridge (PTC Bridge Files, Somerton to Wodonga Line, Index: 143). These operations appear to have been quite extensive, judging from the size of the mound of sand adjacent to the bridge. These data may therefore be indicating that Pranjip Creek, in the vicinity of the present Hume Freeway and the railway, has filled (1871–1922), incised (1922–1947) and is in the process of filling again (1958–1998).

The data from Nine Mile Creek in the vicinity of the Hume Freeway and the railway line indicate that the bed elevation has been relatively stable. Cross-sections of Nine Mile Creek measured at the Hume Freeway indicate that a substantial pool (2–3 m deep), that was under the current bridge when it was built in 1927, was completely filled-in by 1958 (Appendix Figs B2a,b,c). Anecdotal evidence suggests that in fact the filling was complete by the 1930s (pers. comm. Bert Threlfall, former landholder, Feb. 1998). Comparisons of cross-sections for 1958, 1997 and 1998 suggest that there has been minimal change in the bed elevation since. This is reflected in a comparison of cross-sections measured at the railway bridge on Nine Mile Creek. Comparison of cross-sections from 1871, 1926, 1995 and 1998 indicates that there has been minimal change in the bed elevation of the creek in this vicinity over 127 years (Appendix Fig. B6). These data together suggest that with the exception of the filling-in of pools, possibly in the 1920s or 1930s, there has been no real change in the bed level of Nine Mile Creek in the vicinity of the present Hume Freeway and the railway line since at least the 1870s. This hypothesis is not supported by a comparison of bridge cross-sections measured at the Avenel–Longwood Rd bridge, where it would appear that Nine Mile Creek may have aggraded up to 1.5 m in the vicinity of the road bridge between 1973 and 1998 (Strathbogie Shire Council Bridge Plan: 038 (1973)). This evidence suggests that either aggradation is occurring in the vicinity of the Hume Freeway and the railway line in highly localised places, or that waves of sediment are moving through the area and the timing of cross-section checks at the Hume Freeway and railway line have failed to capture the oscillating behaviour of the streambed.

Below the railway line a combination of visual inspection and comparison of cross-sections at the Longwood–Pranjip Rd bridge over the Pranjip Anabranch, suggests that there has been only minor sand deposition in the vicinity. Observations of the Pranjip Anabranch in this area indicate that while some sand has been deposited through this reach, the narrow run–pool sequence remains

Fig. 4.13. Pranjip Creek at the railway line (Pranjip West Bridge). The stream bed in this vicinity has aggraded and degraded during the period since European settlement.

intact. Comparison of cross-sections measured at the bridge in the early 1960s (Strathbogie Shire Council Bridge Plan: 019 (1959)) and 1998 reveals that over the intervening 35–40 year period change at the cross-section has been limited to the channel adjusting to a form similar to that existing before the bridge was built, i.e. bed elevation has not changed.

4.7. Potential sources of disturbance

Quite clearly Creightons Creek has been severely affected by sedimentation derived apparently from drainage lines in the upper catchment. To have any chance of rehabilitating such a system we must consider the disturbances that might have initiated erosion in the upper catchment, i.e. factors that have caused the erosion heads. As was suggested earlier, floods and wet years have played an important part in driving incision, but it seems probable that these events have simply accelerated the movement of heads that were already in the system. From the information presented above and past experience, a number of potential sources of disturbance, and thus erosion heads, are now discussed with regard to their relevance to the Granite Creeks.

Goldmining

Historically, goldmining has been noted as highly detrimental to drainage line stability because of some of the practices employed. Gullies were dug up and puddling machines were used to wash sediment dug out of streams and hill sides, before flushing it downstream (Powell 1976). Later came the introduction of hydraulic sluicing in which miners used jets of water to displace alluvial deposits (Shakespear *et al*. 1887). These alluvial mining practices resulted in severe environmental degradation, usually in the form of downstream siltation (Powell 1976).

While the area from Mangalore to Wangaratta was not considered a ‘goldfield’ there were a number of isolated discoveries in the area. According to Flett (1970) gold was found near Benalla, as well as at Violet Town, Euroa and Avenel, though the exact location of these discoveries is not discussed. No mention is made of gold discoveries in the catchments of the Granite Creeks in any of the historic documentation relating to the area, and notes in many of the Land Selection Files indicate that land selection was only authorised after it was confirmed that the land was not auriferous. Shafts into quartz reefs were found on land at the head of Creightons Creek (PROV VPRS: 626/2025/782) and Castle Creek (Halsall 1980), but there is no evidence that any gold was found.

Consequently whilst gold mining can have a significant impact on drainage lines in particular, it appears that goldmining has not been a major activity in the Granite Creeks catchments.

Channelisation

The concentration of flow from a broad stream or several streams into one channel (‘channelisation’) has the potential to cause channel incision by increasing the shear stress acting on the streambed. A number of activities can result in the channelisation of flow, including construction of bridges, both road and rail, development of tracks and roads, and construction of drains. The impact of channelisation in relation to the initiation of erosion has been observed at a number of sites in Australia and overseas. For example, Bird (1980) reports that flow concentration via drain construction and river entrainment on the Lang Lang River in Victoria resulted in significant incision and stream erosion. Bird (1987) reports that channel incision in Bruthen Creek, also in Victoria, was initiated by the construction of drains and flow channelisation. At Wangrah Creek in NSW Prosser (1991) concludes that channel incision had commenced as a result of the construction of a road crossing the valley floor. Cooke & Reeves (1976) also recognise the important role flow concentration has played in channel incision in the south-west of the United States.

The potential of a range of ‘channelising’ activities that have taken place adjacent to the Granite Creeks are discussed below.

The railway line

The construction of the North-Eastern Railway through the area in 1873 had the potential to significantly affect the Granite Creeks. During the construction of the railway, bridges were built over many of the drainage lines crossing the Riverine Plain. However, because of the costs associated with the construction of these bridges they were only used where necessary and only made as wide as absolutely necessary. Thus the end result was a barrier to flow, which had a minimum number of openings and ran perpendicular to flow right across the Riverine Plain. The original survey carried out along the railway before its construction indicates the location and size of drainage lines on the Riverine Plain before the railway was built. Assessment of the survey in comparison to the position and size of drainage lines allowed by the bridge openings indicates that although bridges were built to span the main creeks, more often than not the small, high-flow channels and/or floodways running parallel and adjacent to the main creeks were filled in when the railway went through. Consequently, the hydrology of flood water movement on the Riverine Plain was significantly altered. During high flows that followed construction of the railway, Pranjip, Nine Mile, Creightons and Castle Creeks would all have been forced to take larger discharges than they had previously, increasing the shear stress on streambeds and thus increasing the potential for channel incision. Intuitively one would expect that stream incision would occur where flow was channelised, i.e. under the bridge and downstream of the bridge. Upstream of the bridge where flow was not channelised one would still expect incision to take place, but via progressive upstream migration of the erosion head/s that were formed at the initial point of incision.

In contrast to expectation, there is no direct evidence to suggest that incision occurred at the bridge sites. Comparisons between the original surveys (1871), bridge cross-section designs (1871–1872), pier depth checks (1922–26, 1947, 1995) (PTC Bridge Files, Somerton to Wodonga Line, Index: 143, 150, 160 & 186) and a re-survey carried out by the authors in 1998, suggest that there has been little change to the channels at the bridges over the last 125 years, and where change has occurred it has been in the form of aggradation rather than erosion (see Appendix Figs B5–B8). The Pranjip West bridge (over Pranjip or Camerons Well Creek) is the exception, but incision has only been apparent since 1922 (recent incision may also be related to the removal of sediment and vegetation from under the bridge during the last decade to maintain channel capacity), and prior to that the channel may have filled 1.75 m. Resurveys of the channel under the East Pranjip bridge (over Nine Mile Creek) suggest little change, in terms of average bed elevation, over the last 125 years. Similarly the resurveys carried out at the Creightons Creek bridge suggest minimal change in bed elevation over the last 125 years. At Castle Creek there would appear to have been minimal change between 1871 and 1926, followed by more than a metre of aggradation since, which has necessitated the clearing of vegetation and sediment from the bridge openings at least once in the last 10 years.

It is possible that the resurveys will not have necessarily picked up all episodes of cutting and filling; for example on Creightons Creek between 1871 and 1922 there may have been a major episode of incision, followed by a major phase of infilling, which effectively cancelled one another out. Consequently incision following the construction of the railway cannot be ruled out, but because such events would have been of great interest to the PTC, with respect to ensuring the integrity of the railway line, it is expected that such an incident would have been mentioned in the bridge file, and no mention is made. Thus it is unlikely that there was undetected incision at the railway line.

Road bridges

Road bridges were built in the area as early as the 1870s and even earlier (e.g. PROV VPRS 626/2043/1697, CPO Historic Plans, Features 3, Parish of Branjee (1862)). The impact of road bridges may, however, not have been as severe as that of the railway because high flow channels and the floodplain were not restricted by a continuous embankment as was constructed for the railway, and thus the creek could still follow its original high flow course to a certain extent. Nevertheless, flow channelisation in sensitive areas such as over a swamp may have caused incision, a possible example being incision in Creightons Creek where the Gobur Road originally crossed the creek or swamp (near the present site of Kellys Bridge). However, it is not clear whether there was a bridge at that site as early as the 1870s.

While old road bridge plans, particularly those for Sydney Road (the present Hume Freeway) can be, and have been, used to determine the extent of bed elevation change over time, the bridge plans that are available only relate to the most recent bridge; thus the impact of the original bridges and initial channelisation cannot be determined.

Tracks

Tracks or paths worn by constant use can be a source of disturbance because vegetation is worn away and a depression is formed which can capture and concentrate flow along the path, resulting in incision. There are two examples where this may have occurred along Creightons Creek. The first is where Gobur Road originally crossed the creek or swamp (near the present day site of Kellys Bridge) and incision was noted as early as 1874 (PROV VPRS: 626/2021/610). As mentioned above there may or may not have been a bridge at this site, but even if there was only a track traversing the swamp it may have provided an area with minimal vegetation where incision could commence. A similar situation may have arisen on what is now Baronga Creek in the 1870s, where the Gobur Track may have been the source of disturbance that initiated an erosion head (PROV VPRS: 626/2058/2287). It is possible that tracks may have initiated erosion heads at a number of other points along Creightons Creek, as well as along the other Granite Creeks.

Drains

Drains are probably the most obvious mechanism for flow channelisation and thus the introduction of erosion heads into the Granite Creeks, and there have been a number of examples of drains cut into or adjoining Creightons Creek and its tributaries. Drains were constructed by several selectors in the Creightons Creek catchment, primarily in wet areas, to drain the land and so make it more productive. Land Selection Files indicate that drains had been constructed by Clinnick in Beltons Swamp by 1909 (PROV VPRS: 5357/5502/2477), possibly by Worland or Earl on the flats just below the railway line by 1889 (PROV VPRS: 626/2068/2725), by Ramage through the swampy flats which formed part of Ramages Creek by 1901 (PROV VPRS: 5357/5428/2786) and by Cameron on land to the east of Kellys Bridge by 1880 (PROV VPRS: 626/2017/315). In most cases the drains built were 500–1000 m long. In more recent times a drain was cut to complete the diversion of flows into Branjee Creek at Nelsons Swamp (pers. comm. M. Brodie, landholder, Feb. 1998).

Anecdotal evidence suggests that drains constructed by Clinnick and Ramage had an impact on Creightons Creek. Clinnick's drain, for example, was reported to have at least partially channelised flows through Beltons Swamp (pers. comm. Jack Stevens, landholder, March 1998). Some of the drains constructed by Ramage are said to have channelised flows through the swampy flats of Ramages Creek, and subsequently led to substantial incision (pers. comm. Stan Artridge, landholder, Feb. 1998). Comparison between the dimensions of the drain cut by M. Brodie in 1971 and the dimensions of the drain today indicate that it may have initiated 1 m of incision in Creightons Creek.

A drain or creek diversion was also put in place on Castle Creek in the 1950s, initiating erosion heads that have resulted in the creek incising between 2 m and 10 m, upstream of the diversion (pers. comm. Geoff McLean, landholder, May 1998).

Clearly the construction of drains in the Creightons Creek and Castle Creek catchments has been an important source of disturbance and thus erosion heads.

Channel dredging, clearing and straightening

The dredging of sediment and removal of vegetation from channels can have two effects. First, the removal of vegetation allows flow velocities in the bed to increase, and reduces the resistance of bed sediments to erosion. Prosser & Slade (1994) report that vegetative cover can play a crucial role in determining the susceptibility of valleys to channel incision. Dredging of material from the bed can lead to both upstream and downstream progressive bed degradation (Galay 1983), i.e. the development of erosion heads that move both upstream and downstream. Consequently in a situation where sediment supply to a stream section is limited, channel clearing and degradation can initiate upstream and downstream degradation.

There have been several examples of vegetation clearing and dredging in Creightons Creek. Two attempts have had minimal impact on the creek. The local shire council carried out clearing and dredging at the Longwood–Pranjip Rd and Nelsons Rd. As discussed earlier, Creightons Creek at the Longwood–Pranjip Rd had virtually been abandoned by 1969, so dredging at this location had no impact on the creek as a whole. At Nelsons Rd, the impact on the creek overall was minimal because the sediment supply was sufficient to fill the hole within the year.

In contrast, the removal of snags and vegetation from Creightons Creek, just downstream of Nelsons Rd in 1997 has, in combination with a meander cutoff (see below), caused the bed elevation to drop 15 inches (~ 40 cm) (pers. comm. Maurie Brodie, landholder, Feb. 1998). Similarly, channel dredging in Creightons Creek in the late 1980s, adjacent to the Creightons Creek Recreation Reserve, has initiated 1–5 feet (0.3–1.5 m) of bed incision upstream of the Reserve (pers. comm. Brian Kelly, landholder, Feb. 1998; pers. comm. Laurie Davidson, landholder, Oct. 1998).

Similarly, in Castle Creek in the vicinity of Euroa, sand and vegetation removal from the bed of the creek initiated a small erosion head (DNRE RWC File 62/19071).

The construction of road bridges may have also initiated erosion heads because of associated clearing and possible dredging of the bed. In a Soil Conservation Authority report into the incision of Baronga Creek in the 1950s it is suggested that a secondary head in Baronga Creek in 1953 may have been initiated by bridge construction (DNRE SCA File: N/50). However, it is not clear which activity may have initiated the head — whether channelisation or machinery clearing/dredging the bed, for example, though the latter seems more probable.

It is appropriate to mention here the practice of channel straightening. Channel straightening can be carried out to increase the channel gradient and in-stream velocities, or it can be used to facilitate the siting of infrastructure such as roads. There is evidence to suggest that two attempts have been made to cutoff meander bends to increase in-stream velocities: one on Creightons Creek (just above the Branjee diversion) and one on Branjee Creek (halfway between the diversion and Drysdale Rd). In both cases the intention of the cutoffs was to reduce sediment deposition (pers. comm. M. Brodie, landholder, Feb. 1998). The increase in channel grade and thus the velocity locally can result in local erosion, as well as upstream progressive degradation (Galay 1983). Anecdotal evidence suggests that the Creightons Creek cutoff, together with desnagging and vegetation removal, led to the streambed dropping about 15 inches (~ 40 cm) (pers. comm. Maurie Brodie, landholder, Feb. 1998), but no direct evidence is available regarding the impact of meander cutoffs on Branjee Creek, although several erosion heads are visible in the creek above the lower cutoff.

There has also been channel straightening at several locations on Nine Mile Creek and Castle Creek to allow local roads to be realigned (Strathbogie Shire Council Bridge Plans: 182, 022 & 099 (1959, 1970 & 1964)). As noted above, this action increases stream gradients locally and has the potential to initiate the formation of an erosion head. There is no evidence available to indicate whether or not erosion heads developed here.

Agriculture

One of the most significant sources of disturbance for the Granite Creeks catchments was clearing. If the experience along Creightons Creek is anything to go by then it would appear that much of the Granite Creeks catchments would have been rung (ringbarked) by 1900, and most areas completely cleared. When land is cleared in this manner, and native vegetation is replaced by crops or grasses for grazing, there are substantial impacts on soil stability and hydrology (Burch *et al*. 1987; Chartres *et al*. 1992), which in turn affect the stability of drainage lines. Flashier flood events greatly increase stream power in drainage lines with reduced erosion resistance, potentially resulting in gullying and channel incision. Coupled with this are the effects associated with stocking and cultivation.

Stocking can have two impacts (e.g. Fig. 4.14). Away from drainage lines, hoofed animals have the capacity to compact soils and reduce vegetative cover, which can increase runoff rates and erosion potential. Along drainage lines, stock can potentially do far more damage, particularly when stocking rates are not managed appropriately. Stock can damage vegetation that has an important stabilising role along a drainage line, and also initiate erosion. Stock paths through drainage lines can form points of flow concentration and thus erosion heads. Stock, particularly heavier animals such as cattle, can also break down stream banks. A study in the USA found that uncontrolled grazing along streams by cattle caused six times as much bank erosion as was measured at ungrazed sites, due mainly to the trampling of banks by stock (Trimble 1994). The study concluded that uncontrolled grazing of streambanks in the eastern United States has played an important role in stream widening during historical time.

Anecdotal evidence suggests that stock, cattle in particular, have initiated and are continuing to initiate erosion heads and bank erosion on Creightons Creek (pers. comm. Bert Threlfall, former landholder, Feb. 1998; Barrie Noye, landholder, Feb. 1998). Cattle and general stock access to the upper reaches of Castle Creek and Pranjip Creek have also been identified as major contributors to stream instability in these areas (pers. comm. Geoff McLean, landholder, May 1998; Ian Elder, landholder, May 1998). It is not clear whether or not stock were a major destabilising influence historically, but it appears that in more recent times stock access to drainage lines has been a source of erosion heads and bank erosion.

Cultivation also has the potential to affect drainage line stability where used inappropriately. Two examples of the impact of cultivation in the Creightons Creek catchment have been brought to the authors’ attention. The first example relates to lands that were ploughed in the 1800s adjacent to Creightons Creek between the Longwood–Mansfield Rd and the present Hume Freeway. The ridges and furrows channelised surface runoff which enabled a gully to form (pers. comm. Jim Shovelton, landholder, Feb. 1998). While it is probable that cultivation may have resulted in the formation of several gullies in the Creightons Creek catchment, and possibly in other Granite Creeks catchments, it would not appear to be a major source of sediment or erosion heads. The second example is from a property near the top of the Creightons Creek catchment where cropping prior to the 1960s was not carried out on the contour, resulting in rilling of the cropped area (DNRE SCA File: L330). However, an isolated incident such as this, where the area is not in close proximity to Creightons Creek and its main tributaries, is unlikely to have had a major effect on the creek as a whole.

Fig. 4.14. Creightons Creek upstream of the Creightons Creek Rd. This photo shows examples of both on-stream (stream bank) and off-stream (natural spring discharge site) damage caused by stock.

The impact of agriculture, with regard to the modification of vegetative cover, and particularly the impact of grazing, has been exacerbated by the prevalence of rabbits in the area. Rabbits were in plague proportions in the area in and after the 1880s. The Longwood Railway Station received 986 dozen rabbit scalps in one month in 1889 (Halsall 1980). Rabbits greatly increase pressure on pastures and riparian vegetation, and this, together with their burrowing, can play an important role in erosion initiation. The advent of myxomatosis in the 1950s brought the local rabbit population under control (Halsall 1980), but rabbits are still a problem for local farmers today (Martin 1994).

Floods

The role of flooding in channel incision has already been briefly discussed. It is possible that flood events may initiate erosion heads by developing stream power greater than that which a saturated drainage line can withstand; this mechanism was suggested by the Soil Conservation Authority in connection with the initiation of several heads in a gully about 1 km west of Kellys Bridge (SCA File: N/230). However, it is more likely that the major contribution of floods and ‘wet years’ to channel incision is that they drive existing heads up drainage lines at a much greater rate than during drier periods. By so doing, high flow events allow several smaller heads to link up, thus causing substantial incision in a short time. Several examples of this have already been discussed, including the 1916 floods which resulted in the incision of Creightons Creek at Stan Artridge’s property and the ‘wet’ 1950s which led to incision along Baronga Creek at Barrie Noye’s property.

Bushfires

Bushfires can initiate erosion by removing all vegetation and organic matter from the ground, leaving the soil bare and exposed to raindrop impact. Removal of vegetation also removes barriers to overland flow, increasing the potential for erosion to occur (Leitch *et al*. 1983; Ronan 1986; Prosser 1990). In some circumstances soils may become hydrophobic following a bushfire, reducing infiltration and increasing surface runoff, again increasing the potential for erosion (Leitch *et al.* 1983; Prosser 1990). Thus intense bushfires, followed by high rainfall totals, can cause severe sheet erosion as well as gullying and possibly stream incision.

There have been at least two severe bushfires in the Granite Creeks area since settlement. The 1901 bushfires were extensive, starting near Locksley and running north-east through the upper catchments of Pranjip–Nine Mile Creek, Creightons Creek and Castle Creek (Halsall 1980). The Strathbogie fires in 1990–91 also affected a large area, moving through parts of the Creightons Creek and Castle Creek catchments (pers. comm. Sue Haggard, landholder, March 1998; Dino Furlanetto, landholder, March 1998).

In the autumn and winter that followed the 1901 fires there were four months in which 50–100 mm of rain fell. Similarly in January 1991 nearly 120 mm of rain fell (based on rainfall data published in the Centenary issue of the *Euroa Gazette*, 1997). Consequently conditions conducive to severe erosion were present in the upper catchments of several of the Granite Creeks in both 1901 and 1990/1. As mentioned in Section 4.5.1, there is only one example of erosion being initiated by bushfires, from the old Wanghambeham Pre-emptive Right, south of Bartons Lane in the Creightons Creek catchment, where the local landholder claims gully erosion was initiated by rainfall events following the 1990 bushfire (pers. comm. Dino Furlanetto, landholder, March 1998). However, this does not, preclude serious erosion having occurred elsewhere, particularly in relation to the fires of 1901.

Droughts

For reasons similar to those described in relation to the impact of bushfires, droughts can also provide conditions conducive to erosion. Like bushfires, drought conditions can lead to reduced vegetative cover and increased soil hydrophobicity (Leitch *et al*. 1983; Ronan 1986); consequently erosion resistance is minimised and, if the drought is broken by rainfall events with moderate to high intensity rainfall, surface runoff will be maximised and erosion potential will be high or

Fig. 4.15. A sand pit on Castle Creek downstream of the old Hume Highway Bridge. Sand has been extracted from this site in the past.

extreme. The most severe droughts in the area since settlement have been 1884–89, 1897–98, 1914–15, 1944, 1968 and 1982–83 (Centenary Edition of the *Euroa Gazette*, 1997; pers. comm. Stan Artridge, landholder, Feb. 1998). There are, however, no rainfall intensity data available for drought breaking rains and hence it is not possible to evaluate the potential for erosion following each of these drought events.

As noted in Section 4.5.1 only one example of erosion following a drought has been reported, on John Nielsen's property near the top of Creightons Creek, where several gullies on the property were either initiated or reactivated following the 1982–83 drought (pers. comm. John Nielsen, landholder, March 1998). However, this lack of reporting does not prove that droughts, especially those in the late 1800s and early 1900s, did not instigate severe erosion in the Granite Creeks catchments.

Sand and gravel extraction

The extraction of bed materials from a stream can be detrimental, for the same reasons that dredging of the streambed can be detrimental, i.e. it can initiate upstream and downstream progressive degradation (Galay 1983). Sand extraction from streams in the Granite Creeks area has only officially been carried out at four locations on Castle Creek: one site adjacent to the golf course, and three sites between the Old Hume Highway bridge (Fig. 4.15) and a point 1 km downstream. Extraction has been authorised only for stream management purposes and approximately 2500 m^3 of sand has been removed (pers. comm. Michael Kaponica, NRE, Seymour, Feb. 1998).

However, this is certainly not the only sand extraction that has been carried out. The authors of this report have observed probable sand extraction sites on Castle and Creightons Creeks. These sites are generally located immediately adjacent to roads and are probably illegal extraction sites, but the volumes involved are small. There is also evidence that both VicRoads and the PTC have extracted sand from areas adjacent to their bridges in the past. For example, at some time in the last couple of years VicRoads obtained permission to remove sand from Creightons Creek between the two Hume Freeway bridges, for use in road maintenance (pers. comm. Paul Tucker, VicRoads, Benalla, March 1998). Similarly PTC bridge files for bridges along the North-Eastern Railway indicate that vegetation and sediment have been removed from the vicinity of the Pranjip West (Pranjip Creek or Camerons Well Creek) rail bridge and the Castle Creek rail bridge (PTC Bridge Files, Somerton to Wodonga Line, Index: 143, 150, 160 & 186).

There is little to suggest that sand extraction from the Granite Creeks has been detrimental: only one erosion head appears to have been initiated by sand extraction activities (DNRE RWC File 62/19071). Nevertheless it cannot be entirely discounted as a potential source of erosion heads in the creeks.

Internal triggers

All the sources of disturbance discussed up to this point are external triggers, imposed on the system from the outside. However, erosion heads can be initiated by internal triggers, or natural adjustments to the stream system. For example, incision can result where a section of the creek has been over-steepened by sedimentation. Another potential cause of bed degradation is the passing of a sand slug. At a given site the response of a stream to the passing of a sand slug is to aggrade and then degrade (Nicholas *et al*. 1995). Rutherfurd & Budahazy (1996) describe bed degradation following the passage of sand slugs in the Glenelg River system. As is discussed in the next section, it is not clear if this model of sand slug behaviour fits the Granite Creeks, or if bed degradation observed at Kellys Bridge, Bartons Lane and the Hume Freeway represents the sand slug leaving these segments of stream. However, bed degradation at these sites could be due to the passing of the sand slug, and consequently bed degradation could occur elsewhere in the system as the sand slug passes.

4.8. Patterns of aggradation

In the previous sections, patterns of erosion and aggradation have been discussed in chronological order, but to understand the overall response of these systems to disturbance it is more useful to look at spatial patterns. In particular, the location and dynamics of sand slugs are important. Hence this section discusses spatial patterns of aggradation, and explores their relevance to the system's overall response.

When considering spatial patterns of aggradation, time-scales are of utmost importance. Sediment is rarely transported from an upstream erosion source out of a catchment within the timeframe of a single event. For example, the channel incision observed during the 1916 flood on Creightons Creek would have liberated a large quantity of sediment, only a small proportion of which would have been removed from the Creightons Creek catchment during the flood event. While the floodwaters may have been capable of entraining some of the finer material (i.e. clays and silts) and transporting them significant distances downstream, the coarser material (i.e. sands and gravels) would have travelled only a short distance from the point of erosion. This is because large amounts of energy are required to mobilise the larger particles, and as the floodwaters move downstream the physical characteristics that provide energy to the flow (e.g. steep stream bed slope, confined channel) change. The coarser particles are deposited where there is a reduction in energy. Even during the flood of 1916, ponding and storage of floodwaters on the Riverine Plain would have created conditions under which some of the finer material would also have been deposited, though much farther downstream. So it could be assumed that, following the 1916 flood, sediment would have been deposited in the middle and upper reaches of the catchments (sands and gravel) as well as in the lower reaches of the catchments (fine sands, silts and clays), while some of the finer sediments would also have flowed into the Goulburn River. These stores would have been temporary, with sediment being remobilised when flows adjacent to the store once again gained sufficient energy.

Essentially, the transport of sediment through a catchment is episodic and depends on factors such as particle size, local conditions (e.g. bed slope) and discharge. As a result, a single sediment particle will be transported, stored and remobilised many times before it leaves a stream system and clearly this means that patterns of aggradation will also change over time. This is particularly true of in-stream aggradation because these stores are subject to flow on most days and so changes in aggradation patterns can occur frequently. To study aggradation patterns in the Granite Creeks a number of 'snap shots' must be taken over time. While over-bank deposition of sediment forms an integral part of such patterns it is not directly relevant to this study and with few data available it is not directly discussed here. Instead this discussion focuses on in-stream transport of sand and gravel; in other words, the downstream movement of sand slugs.

A brief description of sand slugs was presented in Chapter 1, but to reiterate, Nicholas *et al*. (1995) define a slug as a body of 'clastic material associated with disequilibrium in fluvial systems over time periods above the event scale' (Nicholas *et al*. 1995, p. 502). In other words, a slug is a discrete volume of sand and/or gravel material that is released into a stream channel and only very slowly transported out of the stream network by the stream flow. The slug can fill the width of the channel to depths of the order of metres, and extend over distances of hundreds to thousands of metres. The front of the slug is referred to as its 'snout', and this can be a well-defined face or front downstream of which negligible deposition is apparent. An attempt is made here describe the location of the sand slug in Creightons Creek over time; there are insufficient data available to attempt this exercise for Castle and Pranjip–Nine Mile Creek.

Ideally it would be most useful to describe the location of the Creightons Creek sand slug at several points in time, but the erosion and aggradation data collated are insufficient to generate such a picture. From the data presented previously in this chapter it is possible to say that the snout of the sand slug was located between the Longwood–Pranjip Rd and Pranjip Rd on the old Creightons Creek channel in the late 1960s. After Creightons Creek was diverted directly into Branjee Creek below Nelsons Rd in the early 1970s the sand front advanced quickly down Branjee Creek. By the late 1980s the snout was located between Longwood–Pranjip Rd and Pranjip Rd in the Branjee Creek channel (O'Connor 1991). One of the difficulties associated with finding the location of the snout, both now and in the past, is that, unlike snouts described elsewhere (Rutherfurd 1996), the snout of the Creightons Creek slug is indistinct (this is also true of the sand slugs in Castle and Pranjip-Nine Mile Creek). The channel morphology slowly changes over several hundred metres, from completely sanded at the Longwood–Pranjip Rd to partially sanded above the Pranjip Rd and finally negligibly sanded at the Longwood–Shepparton Rd (see Section 5.1.2). A comparison of conditions in 1998 with those observed by O'Connor in the late 1980s (pers. comm. Nick O'Connor, AWT, May 1998) suggests that there has been little if any downstream movement of the sand slug snout between the late 1980s and late 1990s.

Identifying the tail of a slug is difficult and it is usually only possible to say when a slug has left a segment of stream. At a given site a sand slug is evident as bed aggradation followed by bed degradation (Nicholas *et al*. 1995). However, because of the prevalence of erosion heads in the channels of the Granite Creeks, it cannot be assumed that bed degradation in the sanded segments of stream is indicative of the removal of the sand slug. While bed degradation in Creightons Creek at Kellys Bridge (1990s), above Bartons Lane (1980s–1990s) and at the Hume Freeway (1950s–1990s) could be associated with the evacuation of the sand slug from these reaches, the presence of erosion heads, associated with activities such as channel dredging, makes it difficult to draw any conclusions.

It is useful to consider how the behaviour of sand slugs in the Granite Creeks compares with that observed elsewhere in the world. Gilbert (1917) was the first to describe a sediment slug, the movement of which he compared to a floodwave. In other words, the stream bed will rise and fall as the sediment wave passes, and the wave's amplitude is attenuated as it passes downstream. Many researchers have since found the wave analogy appropriate for slugs studied in various parts of the world (e.g. Pickup *et al*. 1983; Nicholas *et al*. 1995; Madej & Ozaki 1996).

The limited amount of data available makes it difficult to determine the timing and location of bed level changes in the Granite Creeks. The middle reaches of Creightons Creek may have experienced the passing of a sediment wave, with the channel aggrading and degrading between Kellys Bridge and Bartons Lane, for example. Further downstream, on the Flats, the creek bed has aggraded, but degradation has not been observed to date. The lack of bed-level data also makes it difficult to determine if bed-level changes decline in the downstream direction. Hence it cannot be readily determined whether or not the wave model is appropriate for describing sand slug movements in the Granite Creeks.

There are several reasons why the wave model may not be appropriate for describing slug behaviour in the Granite Creeks. First, there are several sources of sediment for the sand slugs, both spatially (e.g. Creightons Creek — adjacent to Stan Artridge's property and Baronga Creek) and temporally (e.g. Creightons Creek — 1916 flood event and wet period during the 1950s). Knighton (1989) concluded that the wave model was inappropriate for the Ringarooma River in Tasmania because there were multiple input points, and this could also be true for the Granite Creeks. Secondly the stream form characteristic of the lower reaches of the Granite Creeks, i.e. anabranches, is decidedly different to those referred to in the literature. The streams for which the wave model has been found appropriate are all single strand streams (e.g. Gilbert 1917; Pickup *et al*. 1983; Madej & Ozaki 1996). It can be hypothesised that the impact of multiple lowland channels would be to distribute material out onto the floodplain during flood events. Water distributed on the floodplain will evaporate, or find its way back into the main channel further downstream, or enter groundwater stores, but sand enters long-term storage on the floodplain. Not only does the channel lose sand to the floodplain but the rate of migration of the sand that remains in the main channel is slowed, because of reduced discharge. Such behaviour could certainly mean that the wave model is not appropriate for the lower reaches of Creightons Creek or the Granite Creeks in general.

Other than this, no real conclusions can be drawn regarding the behaviour of the sand slug in Creightons Creek, except to say that the snout appears to have moved little in recent years.

4.9. Pre-settlement erosion and aggradation

To place the preceding information in context it is important that occurrences of erosion and aggradation prior to European settlement are also examined. There is no direct evidence of pre-settlement erosion or aggradation rates, but there is some indirect evidence available that provides invaluable information.

There is evidence to suggest that gullying and stream incision occurred in the Creightons Creek catchment before European settlement. According to anecdotal evidence, the incision in both Creightons Creek (at Stan Artridge's property) and Baronga Creek has revealed old red gum logs, buried 10–20 feet (3–6 m) below the surface (pers. comm. Stan Artridge, landholder, Feb. 1998; Barrie Noye, landholder, Feb. 1998). This suggests that both Creightons Creek and Baronga Creek have incised to similar depths in the past, prior to European settlement.

Higher up in the catchment on John Nielsen's property there is a gully in the lower end of a drainage line which clearly shows sequences of alluvial material that had been laid down at the bottom end of this steep valley. The layers are each approximately 10 cm thick and alternate between a dark, swampy loam and coarser yellow sediment. At least six layers are clearly visible in the gully wall and they appear to correspond to different types of geomorphic activity. The dark layers appear to correspond to the deposition of fine sediment in a low energy swampy environment, whereas the lighter layers may be from rapid deposition of material eroded from upstream under high energy conditions (the higher energy indicated by the drainage line's capacity to transport coarser materials). Assuming these suppositions are correct then it could be concluded that although the drainage line is probably stable for periods of time, stability is interspersed with periods of instability in which sediment is flushed down the drainage line. This would be consistent with a system in which erosion was episodic and perhaps linked to high flows (i.e. high energy events). It cannot, however, be stated categorically, without dating the layers, that any of these layers predates European settlement. Similar patterns of aggradation have been observed in a small creek system on the Southern Tablelands in NSW (Prosser 1991). The dark, swampy material described by Prosser (1991) was referred to as a swampy meadow unit and was related to a period when the system was not channelised and deposition dominated. The other units found comprised either gravels associated with a channel bed or coarse material derived from floodouts.

A third piece of evidence indicating that incision in the Creightons Creek catchment is not peculiar to the post-European settlement period is the existence of terraces at the lower end of Ramages Creek, which were found by a survey carried out in 1882 (PROV VPRS: 626/2092/3665). Hence it could be concluded that stream incision took place at the lower end of the Ramages Creek valley before European settlement.

The evidence presented above indicates that the Creightons Creek, Baronga Creek and Ramages Creek have all incised in the past, before European settlement. It is also possible that one of Creightons Creek's first order drainage lines may have experienced episodic erosion prior to European settlement. The fact that there are sand-filled abandoned channels on the Riverine Plain (pers. comm. Len Stevens, landholder, Feb. 1998) indicates that the sediment released from such events may have been deposited on the flats. This evidence suggests that the Granite Creeks catchments may be sensitive to disturbance and it seems probable that the gullying and incision that occurred in the Creightons Creek catchment prior to European settlement was in response to specific events such as bushfires, or an intense rainfall event, and that therefore such erosion events were probably isolated and localised. However, the same cannot be said for the erosion and aggradation that has occurred since European settlement. In fact erosion in the Granite Creeks catchments since European settlement appears to have been synchronised across a wide area, and such synchronisation is undoubtedly due to European settlement. Observations of synchronised erosion in Australia, coinciding with European settlement have been noted previously by Prosser & Winchester (1996).

4.10. Conclusions

The first disturbances associated with European settlement imposed on the Granite Creeks catchments coincided with the overlanding expeditions that travelled south from the settled districts in the 1830s. The large herds of sheep and cattle, combined with fires in the area, reduced the vegetative cover; and other impacts such as damage to creek banks by hoofed feet can only be surmised. Between the arrival of the Overlanders and the 1870s the main activity in the catchments was light grazing, which was carried out by the local squatters who leased large areas of the catchments. However, the 1870s heralded the arrival of 'progress' in the Granite Creeks area, and the following decades saw major changes. Land selection commenced in the Granite Creeks catchments in the 1870s, dramatically affecting the area via the introduction of clearing and an increase in grazing pressure. The North-Eastern Railway arrived in the early 1870s, imposing a barrier to flow across the Riverine Plain but also providing a means of transporting produce, including firewood, to Melbourne, thus making the region attractive for farming and woodcutting. Consequently, by the beginning of the 1900s two of the most significant changes to be imposed on the Granite Creeks, i.e. clearing and the construction of the North-Eastern Railway, were already in place. Although some erosion had been noted by this early stage, no other signs of degradation were yet clearly evident.

In contrast to the 1800s, degradation was clearly evident throughout the 1900s. The following description of the response of a creek to European settlement comes from a detailed look at the history of Creightons Creek. However, the evidence presented earlier in this chapter suggests that Castle Creek and Pranjip–Nine Mile Creek may have behaved in a similar manner. Anecdotal evidence for other creeks draining the Strathbogie Ranges (see Appendix A), suggests that what has occurred in the Creightons Creek catchment may also be an analogue for the other Granite Creeks.

In the period since settlement the upper section of Creightons Creek (i.e. above the present Hume Freeway) has incised extensively, and gullying has also occurred. The incision and gullying have been the result of a number of erosion heads moving along the creek; they appear to be related to activities that have taken place in the Creightons Creek catchment, including clearing, agriculture, channelisation, channel dredging and clearing, bushfires and droughts. As a result of the extensive erosion of drainage lines in the upper catchment large quantities of sediment have been released into the creek and this has had a serious impact on the lower section of Creightons Creek (i.e. below the present Hume Freeway).

Below the present Hume Freeway, aggradation of the channel has eventually led to the diversion of low flows from Creightons Creek to Branjee Creek at Nelsons Swamp. While the abandonment of a section of channel in such a manner is probably not unusual for a stream on the Riverine Plain, it is likely that the process was greatly accelerated by the excessive release of sediment induced by activities associated with European settlement. In recent years, erosion heads have continued to move through Creightons Creek, and based on the available evidence it seems most probable that these heads are related primarily to stock access to the drainage lines, and channel clearing and dredging and the initiation of meander cutoffs. Although some episodes of incision and channel filling occurred before European settlement, it would seem that such events were isolated and localised, whereas the erosion and aggradation that has occurred since European settlement appears to have been synchronised over a wide area, and this would have been as a result of European settlement.

5. ASSESSING PRESENT CONDITION

This chapter presents the results of the assessment of present stream and catchment condition.

5.1. Field observations

5.1.1. Erosion

During field inspections three main types of erosion were observed: bed erosion, bank erosion and gullying. No tunnel erosion was observed by the authors, nor was there evidence of significant sheet erosion.

Bed erosion was evident in the main stem of Creightons Creek and several of the tributaries, in the form of erosion heads or knickpoints. These erosion heads were generally between 0.1 and 0.5 m high, though some were close to 1 m. Erosion heads were observed both above and below the Hume Freeway (i.e. in the hills and on the flats), with clusters evident at several locations, including on Branjee Creek, between Nelsons Rd and Drysdale Rd and on some of the headwater tributaries. Many of the erosion heads observed below the Hume Freeway were 'caught' on river rock (indurated river sediments) exposed in the bed of the creek (Fig. 5.1) and are consequently progressing very slowly upstream. The erosion heads observed above the Hume Freeway were in some instances caught on river rock, but were more commonly eroding through less resistant alluvial material (Fig. 5.2) and were, as a consequence, probably progressing upstream relatively quickly. Some work is currently being done by DNRE, the Goulburn-Broken Catchment Management Authority and a local land holder (Barrie Noye), which involves mapping erosion heads in the creek system to facilitate management.

Bank erosion was also observed along the main stem of Creightons Creek, both upstream and downstream of the Hume Freeway. At a large number of sites, bank erosion (channel widening) has followed bed erosion (channel deepening). Channel widening following incision was evident above the Hume Freeway, both in the middle reaches (Fig. 5.3) and in the upper reaches of the creek (Fig. 5.4), as well as below the Hume Freeway (Fig. 5.5). While channel widening processes associated with incision would appear to be the main cause of bank erosion on Creightons Creek there are some sites where bank erosion has occurred for other reasons. There are, for example, several sites where bank

Fig. 5.1. An erosion head in Creightons Creek caught on resistant river rock

Fig. 5.2. An erosion head in Ramages Creek moving through alluvial material

Fig. 5.3. Eroding streambanks in the middle reaches of Creightons Creek

Fig. 5.4. Eroding streambanks in the upper reaches of Creightons Creek

Fig. 5.5. Eroding streambanks in the lower reaches of Creightons Creek

Fig. 5.6. Bank erosion on Creightons Creek due to undercutting

Fig. 5.7. Bank erosion on Creightons Creek due to stock trampling

Fig. 5.8. A gully in the Creightons Creek catchment that has been fenced and planted with vegetation.

Fig. 5.9. A gully in the Creightons Creek catchment that has been fenced and planted with vegetation

erosion is occurring as a result of stream migration, where the creek is undercutting the stream bank. Such instances are localised and in general are not a significant sediment source, but where these processes are active within a deeply incised reach of stream (such as on Stan Artridge's property (Fig. 5.6)) the potential sediment yield could be large. Bank erosion is also occurring at several sites along Creightons Creek and its tributaries as a result of stock trampling the banks (Fig. 5.7).

The third type of erosion observed in the Creightons Creek catchment is gullying. Active gullying has obviously been a problem in the past, with regard to the sediment released and farm management, but in most instances landholders have taken steps to address the problem, usually by fencing the drainage line out and planting vegetation (e.g. see Figs 5.8, 5.9). This is not to say gullying will not be a problem in the future, because anecdotal evidence suggests that where gullying has occurred in the past it has been in response to an activity (e.g. ploughing) or an event (e.g. storm, bushfire) which could also occur in the future. Gully erosion releases large quantities of sediment and this could also occur in the future, under the right conditions.

Fig. 5.10. A completely sanded reach of Creightons Creek

5.1.2. *Aggradation*

Information on sedimentation in the Creightons Creek catchment (Chapter 4) indicates that since European settlement there have been a number of phases of incision and aggradation along Creightons Creek. Anecdotal evidence suggests that sediment may now be filling the remaining pools on the upper tributaries to Creightons Creek. However, other evidence, such as bed degradation (see Chapter 4) and channel lengthening (pers. comm. Claire Penniceard, landholder, April 1998), suggests that sediment transport and aggradation may be declining through the middle reaches of the creek, i.e. between the Hume Freeway and Stan Artridge's property.

Downstream of the Hume Freeway the creek can be split into three segments. From the Hume Freeway down to the Longwood–Pranjip Rd (Branjee Creek) the creek is completely sanded, the channel is almost rectangular in cross-section and there is no variation in bed form (Fig. 5.10). The reach between the Longwood–Pranjip Rd and Pranjip Rd is a transition zone. In this reach sand is certainly evident but the volumes are not yet so large as to drown out the pool–run bed form (Fig. 5.11). Below Pranjip Rd some sand is evident in Branjee–Creightons Creek, deposited as sand drapes on the banks and point bars, but the total volume of sand deposited is minor as is its impact on the morphology of the creek (Fig. 5.12). While sand transport is clearly evident in the sanded segment, via dune movement (Fig. 5.13) and saltation of individual grains, the rate of movement of the snout of the sand slug is difficult to assess. The only piece of evidence available comes from

Fig. 5.11. A partially sanded reach of Creightons Creek

Fig. 5.12. Creightons Creek below the sand slug

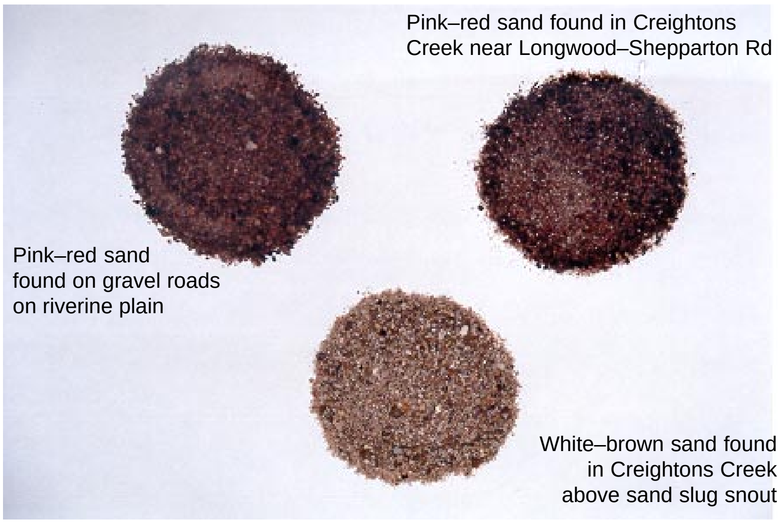
the description of the location of the sand slug by O'Connor (1991; pers. comm. Nick O'Connor, AWT, May 1998), and this suggests that there has not been significant downstream movement of the snout in the last 5–10 years (also see Section 4.8).

The features of the sand slugs in Castle and Pranjip–Nine Mile Creek are relatively similar to those of the Creightons Creek sand slug. All three sand slugs have indistinct snouts and tails that may be evacuating the middle reaches of their respective stream networks. Hence it appears that the Creightons Creek sand slug may well be typical of sand slugs found in the Granite Creeks.

The following observations were made in the laboratory and not in the field, but it is appropriate to discuss these observations here and to speculate about the possible implications. When creek bed sediment samples taken from Creightons Creek at the Longwood-Shepparton Rd were dry sieved it became obvious that a substantial proportion of the sand-sized grains were pink–red and not brown–white as had been observed for all the other samples (Fig. 5.14). Investigations in the field revealed that similar 'pink' sand was evident in Muddy-waterhole Creek at Kirwans Bridge Rd and on many of the gravel roads in the area. Discussions with the Works Foreman for the Strathbogie Shire Council revealed that the pink sand was not consistent with the gravel the council used on these roads. For the purposes of determining the source of sand in the lower reaches of Creightons Creek it was important that the origin of the pink sand be identified, so further investigations were carried out.

Fig. 5.13. Sand dunes migrating along Creightons Creek

Fig. 5.14. 'Pink' and 'white' sand samples taken from Creightons Creek catchment



When viewed under a microscope the pink sand grains appeared to be clear quartz grains with a pink–red surface coating. This was confirmed when several grains were cracked open. While the pink–red surface coating was visible on some of the fracture surfaces it was not visible on others, suggesting that the surface and the more open fracture planes had been stained. The mineral composition of the sand is consistent with it having been derived from the granitic Strathbogie Ranges but it has subsequently been stained. The most obvious explanation for the staining is that the sand has been stored on the Riverine Plain for some time and during this period it has been subject to flooding and waterlogging — conditions in which iron can be mobilised (Bloomfield 1981). When the sediments were exposed to oxidation during periodic lowering of the water table, iron precipitated (Bloomfield 1981) staining the quartz grains a red–pink colour. If this explanation is correct then the pink sand can be considered, in the management time scale, to be the material into which the channels on the Riverine Plain have been cut and is the material which, though originally derived from weathering and erosion of Strathbogie granites, has been in storage on the plain for a significant time span. One would also expect to find pink sand in other reaches of Creightons Creek on the Riverine Plain, but most reaches upstream of Pranjip Rd have been inundated with 'white' sand which would have substantially diluted the pink colouring and buried the underlying material.

The main implication of the above explanation for the existence of the pink sand is that the sand found in Creightons Creek at the Longwood–Shepparton Rd and in Muddy-Waterhole Creek at Kirwans Bridge Rd is derived locally. Since the pink sand found in these locations has not been diluted by 'white sand' released recently from the upper catchment, it can be assumed that the lower reaches of Creightons Creek and Muddy-Waterhole Creek have not yet been affected by the sand slug moving down the system.

5.2. Sediment budget

As described in Section 3.3.2, a sediment budget was developed to determine the main source of sand for the sand slug. Note that these calculations are based on very rough estimates of the volume of sediment eroded from the catchment and the amount of sediment deposited in the catchment (see Section 3.3.2). There are two main reasons for the approximate nature of these estimates: (i) it was not always easy to distinguish modern depositional material from old depositional material; and (ii) it was difficult to estimate the average depth of sediment deposited in the active channel. Given the errors associated with the sediment budget it was decided that the results would only be used to determine whether or not there was sufficient sand released from channel incision and gullying to account for the sediment deposited in the creek.

Three main sources of sediment were identified in the catchment, the three sites being incised reaches on Creightons Creek (adjacent to Stan Artridge and Laurie Davidson's properties), Baronga Creek (adjacent to Barrie Noye's property) and Ramages Creek (adjacent to Bill O'Connor's property). Minor examples of stream incision and gullying were also used to calculate the total volume of material liberated, but the three main sources accounted for more than 90% of the total. The total volume of material liberated by stream incision and gullying was estimated to be approximately 320 000 m^3. It was then estimated from the particle size analysis of bank samples that approximately 30% of the material would be finer than 63 mm, and in a worst case scenario all this would be washed through the system; hence only 70% would be retained in the catchment. Consequently it was estimated that approximately 225 000 m^3 of sand and gravel has been liberated from drainage lines in the Creightons Creek catchment.

The total volume of deposited sediment in the Creightons Creek catchment was estimated by assuming that on average 2 m of sediment has been deposited in the abandoned section of Creightons Creek, 0.75 m deposited in Branjee Creek above Pranjip Rd and 0.5 m of sediment deposited in Creightons Creek between the railway line and Laurie Davidson's property. Deposition was also estimated for the former swamp at Nelsons Rd (based on soil pit data) and overbank deposits adjacent to the creek at Stan Artridge's, Dino Furlanetto's and near Kelly's Bridge. Total deposition in these sinks was 113 000 m^3; this was rounded up to 120 000 m^3 to allow for in-stream extraction (see Section 4.7 for details). As no estimate could be made of overbank storage below the Hume Freeway the volume was doubled (increased by 100%) to give a final total. Hence it is estimated that approximately 240 000 m^3 of sediment is deposited in the Creightons Creek catchment.

A comparison between the estimated total volume of coarse sediment (larger than 63 mm) liberated from drainage lines in the Creightons Creek catchment (225 000 m^3) and the estimated total volume of sediment stored in the catchment (240 000 m^3) indicates that channel incision could account for the majority of sand and gravel deposits in the catchment.

5.3. Sediment tracing using particle size distributions

This study used sediment tracing to provide further information about possible sources and sinks for sediment in the Creightons Creek catchment (see Section 3.3.3). Particle size distribution was chosen as a method for tracing sediment movement, primarily because it is low cost. Four tracing techniques were used and the results are described below.

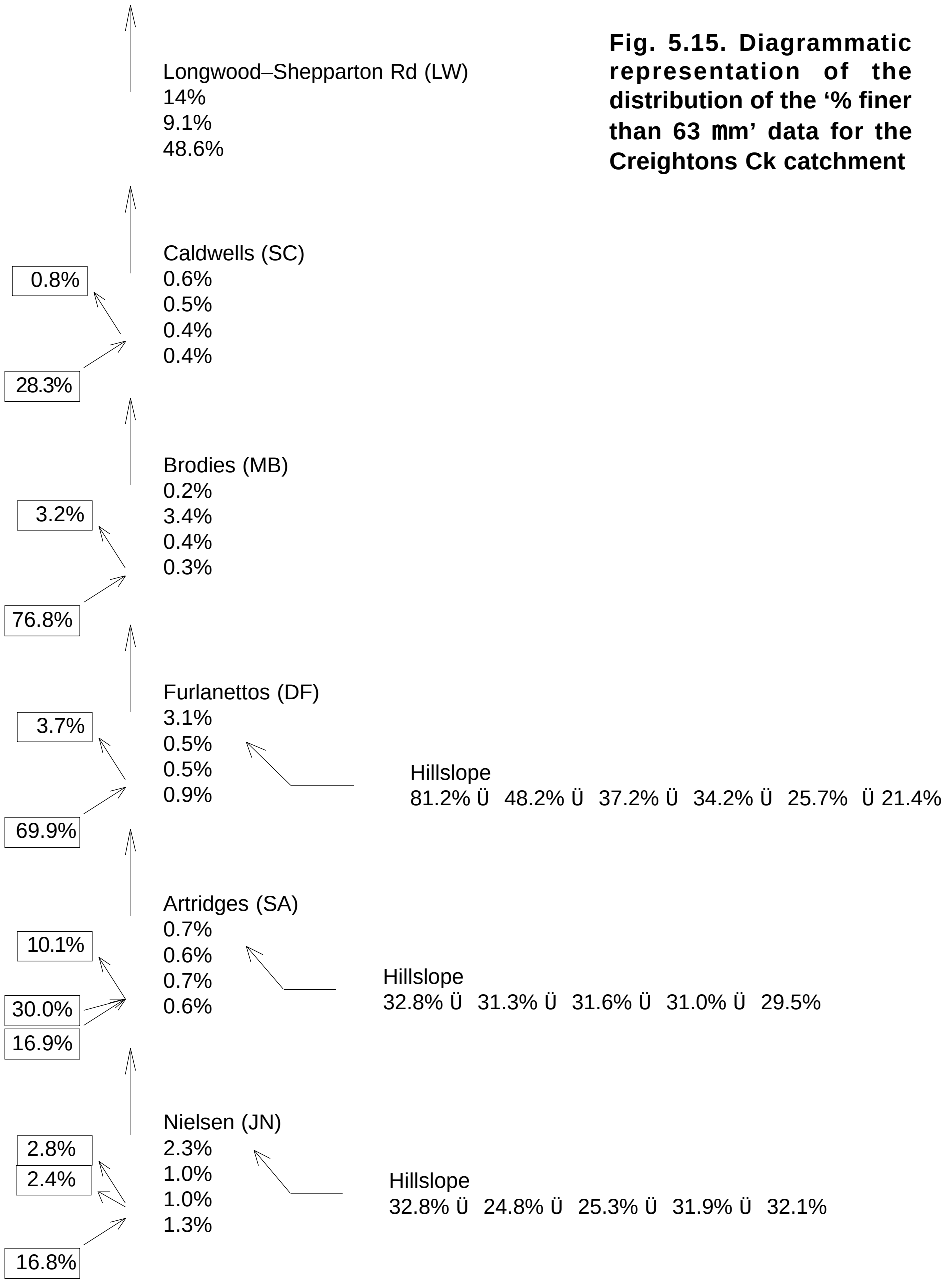
5.3.1. Fine fraction method

The results from the fine fraction method are summarised in Fig. 5.15. Because of concerns about abrasion (see Section 3.3.3) and the expectation that once the fine fraction enters the drainage network it is washed through, fine fraction transport patterns were only examined for the hillslope samples, although some general trends can be drawn out.

Several general patterns are visible in Fig. 5.15 (also see Fig. 3.1 for site locations) that are consistent with the expected movement of sediment that is less than 63 mm in size in a stream network. The percentage of fines is high on hillslopes and in the creek bed below the sand slug, low in creek beds and on adjacent banks (i.e. sand drapes deposited under moderate to high flow conditions) along the sand slug, and moderate or high in areas where deposition has occurred under low flow conditions (i.e. floodplain deposits that are now stream banks).

Examination of hillslope trends indicates that slightly different transport patterns may be occurring at each of the hillslope sites. The values of '% finer' at site JN are consistent with fines being eroded from the mid-slope area and being removed from the slope altogether. The '% finer' values from hillslope site SA could be indicating little movement of fine material and a fairly stable environment. The values of '% finer' from hillslope site DF indicate that the relative proportion of fines increases downslope,

Fig. 5.15. Diagrammatic representation of the distribution of the '% finer than 63 Mm' data for the Creightons Ck catchment



Key

Smiths (WS)
a%
b% represents samples taken in Creightons Creek on the Smith's property (location WS),
c% where the samples have a%–d% of their total mass finer than 63 mm
d%

Hillslope
e% Ü f% Ü g% Ü h% Ü i%

represents samples taken along a hillslope, where the uppermost sample has i% finer than 63 mm and the lowest sample has e% finer than 63 mm

k% represents a sample of material deposited adjacent to the channel, which is k% finer than 63 mm

j% represents a sample of potential source sediment from the channel walls, which is j% finer than 63 mm

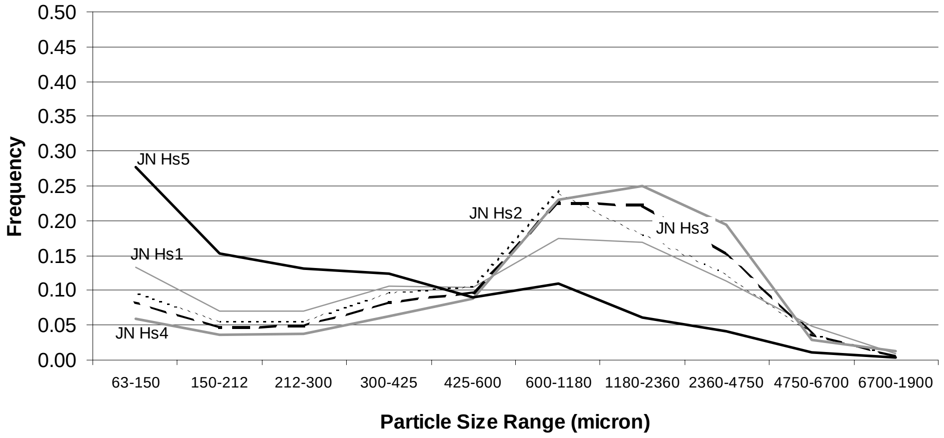


Fig. 5.16. Summary of hillslope particle size (mm) histograms for Site JN. Location ‘1’ represents the top of the slope and location ‘5’ is in the footslope.

which is consistent with fines being eroded from higher up the slope and being redistributed down the slope, with the greatest amount of deposition occurring at the toe of the slope.

These findings suggest that sediment less than 63 mm in size is being moved off some hillslopes in the Creightons Creek catchment. It may have been trapped high up in the catchment in the past (i.e. on floodplain/swampy meadow areas prior to incision) but is probably now being moved downstream, and either out onto the Riverine Plain (during high flow periods) or into the Goulburn River. However, the volume of material being removed from the upper catchment is not expected to be large.

5.3.2. Histogram comparison

It is important to recognise that abrasion (see Section 3.3.3) could be partially responsible for some of the potential source–sink relationships examined here. If abrasion has been an important process in producing downstream (or downslope) fining then the system’s ability to transport material, as identified here, is less than predicted.

As was stated in the methods section, histogram comparisons were only carried out for adjacent samples. Histograms were compared within groups (e.g. all the hillslope sample histograms taken on John Nielsen’s property (JNHs) were compared), but then group trends between adjacent sites were also compared if appropriate (e.g. creek bed histogram group trends were compared, but comparisons were not made between hillslope groups). No comparisons are made within creek sites because the purpose of taking four samples at each creek site was not to investigate sediment movement at a local scale, but to get an understanding of particle size distribution (PSD) variability at a single site and so allow a more rigorous assessment of variations in PSDs along the length of the creek.

Hillslope histogram comparisons

A comparison of the particle size frequency histograms for hillslope samples taken at site JN is presented in Fig. 5.16. Inspection of Fig. 5.16 indicates that, with the exception of the lowest sample site, as one moves downslope the PSDs become coarser and better sorted. The lowest hillslope sample (JNHs 5) is, on the other hand, finer and more poorly sorted. This is consistent with material in the range 425 mm to 4.75 mm (medium–coarse sand) being eroded and redeposited downslope, while 63–425 mm (fine sand) material leaves the slope to be deposited in the footslope (JNHs 5) or transported into the stream network. The comparatively poor sorting found in the footslope might be explained by the fact that transport conditions at the footslope are completely different to the upslope sites, i.e. this area may store all the material derived from upslope, and possibly some material derived from upstream.

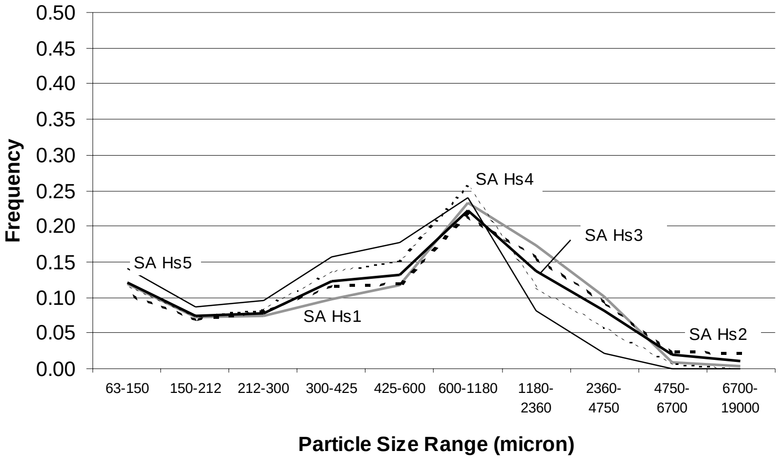


Fig. 5.17. Summary of hillslope particle size histograms, Site SA. Location 1 represents the top of the slope and location 5 is in the footslope

As can be seen from Fig. 5.17 the PSD histograms for hillslope samples taken at site SA are all similar in shape with the peak, or dominant size fraction (0.6–1.18 mm), remaining unchanged at all points down the slope. This could be consistent with the slope being relatively stable and little sediment movement occurring. The only change that appears to occur as one moves down the hillslope is that the relative proportion of coarse material (1.18–19 mm sediment) declines while the relative proportion of medium sand (300–600 mm) increases. One possible explanation for this observation is that medium sand is being mobilised and redeposited down the slope, while some fine sand is lost from the slope.

A comparison of PSD histograms for the hillslope at site DF (see Fig. 5.18) indicates a steady decline in the relative proportion of coarse material (1.18–19 mm) and steady increase in finer material (63 mm – 1.18 mm). Only at the base of the slope (DFHs 6) is there a substantial increase in the relative proportion of some size fractions (i.e. 63–150 mm, i .e. fine sand). These observations are consistent with fine–coarse sand being mobilised on the slope, medium–coarse sand being redeposited on the slope and fine sand being deposited in the footslope area.

Trends between creek sites

A comparison of PSD histograms along Creightons Creek was carried out by first averaging the four samples at each site to produce a single average curve for each site. A visual comparison of the average PSD histograms for each site (Fig. 5.19) appears to indicate three distinct groups of sites. The first group is made up of sites JN, SA, DF and MB. The samples from these four sites are relatively well sorted with about 80% of sediment in the size range 600 mm – 4.75 mm (coarse

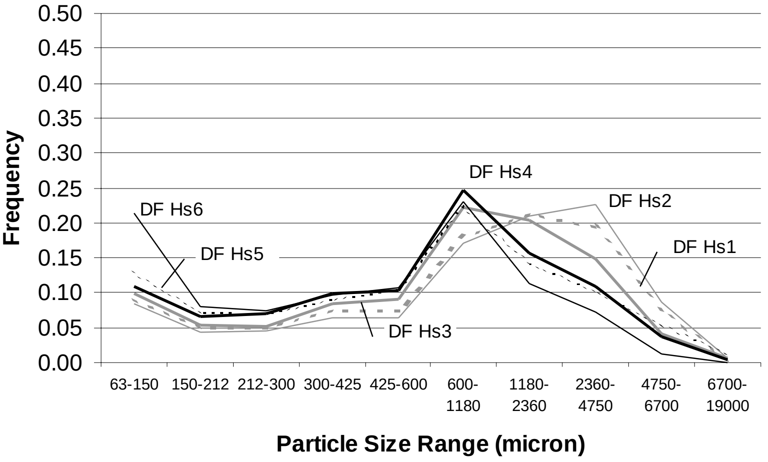


Fig. 5.18. Summary of hillslope particle size histograms — Site DF. Location '1' represents the top of the slope and location '6' is in the footslope.

sand–fine gravel). There is only one site, site SC, in the second group. Group 2 sediments are better sorted than group 1 sediments, with more than 80% of sediment falling into two sieves, the size range being 600 mm – 2.36 mm (coarse sand). The third group also consists of only one site, site LW. In comparison with groups 1 and 2, group 3 sediments are poorly sorted and finer, containing a higher proportion of material in the size range 63–600 mm (fine to medium sand).

A lack of variation in sorting and no trend in mean particle size for the four sites in group 1 is consistent with sediment at the four upstream sites (i.e. JN, SA, DF and MB, which are above the Hume Freeway) being derived predominantly from a local source. On the other hand, sediment at site SC could be derived from upstream because it is better sorted and finer than upstream sediment samples. Sediment at LW is poorly sorted and so could be locally derived.

5.3.3. Coarse fraction method

Results from dry sieving indicated that no samples contained particles with an equivalent diameter greater than 19 mm. However, a number of samples were found to contain particles with an equivalent diameter greater than 6.7 mm. All creek bed samples, except those taken downstream of the Longwood–Pranjip Rd, were found to contain particles greater than 6.7 mm in diameter (i.e. JNck 1–4, SAck 1–4 and DFck 1–4), as did three bank samples (JN Bank, SA Bank A and B) and most of the hillslope samples (JNHs 1–5, SAHs 1–3 and DFHs 1–5).

Several broad conclusions can be drawn from these results.

1. Particles greater than 6.7 mm in diameter may have been transported down to the base of hillslopes at some sites in the catchment (i.e. JN sites) and not at other sites (i.e. SA sites, DF sites).
2. Particles greater than 6.7 mm in diameter may have been derived from bank erosion high up in the catchment (i.e. JN sites and SA sites).
3. Particles greater than 6.7 mm in diameter have not been transported as far downstream as the Longwood–Pranjip Rd.

These conclusions are consistent with the results of the analyses, but assume that the samples analysed are representative of the sites at which they were taken. A method was designed to enable representative samples to be taken, but errors related to sample sizes might have caused this assumption to be violated with respect to coarse sediments in hillslope samples. Where coarse particles were observed in the field, larger samples were taken (as described in the method), but large particles were not observed during sampling on hillslopes and thus the samples taken were smaller than were needed. The effect of this potential source of error is that samples taken at hillslope sites where particles greater than 6.7 mm in diameter are present may not have contained particles greater than 6.7 mm in diameter. Observations made when sampling was carried out

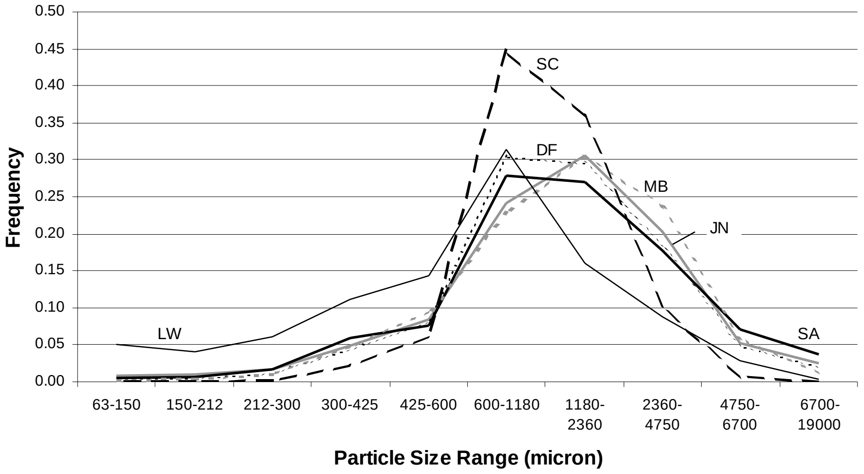


Fig. 5.19. Summary of average creek bed histograms

suggest that although this error could have influenced results at sites SAHs 4–5 it is not likely to have occurred at DFHs 6. Nevertheless, it can be concluded that coarse material in Creightons Creek may have originated from some hillslopes and/or stream banks in the headwaters of the catchment; this material is not, however, transported downstream beyond the Longwood–Pranjip Road.

5.3.4. McLaren technique

The mean, standard deviation and skewness of the particle size distributions of samples taken throughout the Creightons Creek catchment were compared as described in the method, and a matrix was produced (Fig. 5.20). The sites listed across the top of the matrix are possible sources and the sites listed down the side of the matrix are potential sinks. Cells are left blank where a relationship is impossible (e.g. SAck 1 as a source for JNck 1). Where one of the two possible trends is detected, Case 1 or Case 2 is recorded; otherwise a cross (X) is registered.

From the matrix a list of possible source–sink relationships was prepared (Table 5.1).

Table 5.1. Possible source–sink relationships

Hillslope sources	*Store sources*
JNHs1 ⇒ 2 ⇒ 3 ⇒ 4	JN Bk ⇒ SA Bk, JN Dr, JNck1–4
SAHs1 ⇒ 2 ⇒ 4 ⇒ 5	SA PSA ⇒ SAck2–4, DF Dr
DFHs1 ⇒ 2 ⇒ 3 ⇒ 4; DFHs5 ⇒ 6	DF Bk ⇒ DFck1–4, DF Dr
JNHs1–5 ⇒ JNck1–4	DF Dr ⇒ SC Dr
SAHs1–5 ⇒ SAck1–4	MB Bk ⇒ MBck1–4, MB Dr, SC Dr
DFHs1–6 ⇒ DFck2,3; DFHs4–6 ⇒ DFck2	SC Bk ⇒ SCck1,3,4, SC Dr
JNHs1–4, SA1–5 ⇒ SA PSA	
Creek sources	
JNck1–4 ⇒ SAck1–4	
SAck1–4 ⇒ DFck1,2	
DFck1–4 ⇒ MBck1–3	
MBck1–4 ⇒ SCck1_4	

Four main points can be drawn out of the data presented in Table 5.1.

1. Downslope movement of hillslope material is indicated for all three hillslope sites.
2. Hillslope material could have contributed sediment to the nearby creek bed, although another source may be indicated for one of the samples taken at site DF.
3. Local bank sources could have contributed sediment to all creek bed and bank drape samples, although another source may be indicated for one of the samples taken at site SC.
4. With the exception of site LW, upstream creek beds could be the source of sediment for downstream creek bed sites, although another source may be indicated for some of the samples taken at site DF and MB.

As was noted in Section 3.3.3, the presence of aggregates can confound the results of the McLaren analysis, and therefore dispersant was used to break up aggregates. However, it was observed during dry sieving that some aggregates were still present. While the presence of some aggregates can create difficulties with regard to assessing the actual type or size of material sampled (e.g. clay or silt material can appear to be fine sand), it might not necessarily be an error in the application of the McLaren technique for this project. If aggregates do not break down in the laboratory when dispersant is added it seems unlikely that these aggregates would break down in the field during transport. Since we wish to use the McLaren technique to provide information about transport processes it may be appropriate that the aggregates remain aggregated during analysis. Without a

Fig. 5.20. McLaren technique: matrix for comparison of particle size distributions

	Source							
Sink	**JNA**	**JNB**	**JNC**	**JND**	**JNE**	**SA1**	**SA2**	**SA3**
JNA		X	X	X	X			
JNB	X		X	X	X			
JNC	X	X		X	X			
JND	X	X	X		X			
JNE	Case 2	X	X	X				
SA1							Case 2	Case 2
SA2						Case 2		Case 2
SA3						X	X	
SA4						X	X	Case 2
SA5						X	X	X
DF1								
DF2								
DF3								
DF4								
DF5								
DF6								
JN Bank	Case 2	X	X	X	X			
JN Drape u	Case 2	X	X	X	X			
JN Drape d	Case 1	X	X	X	X			
SA Bank A	Case 2	X	X	X	X	X	Case 2	X
SA Bank B	Case 2	Case 2	Case 2	Case 2	Case 2	Case 2	Case 2	Case 2
SA PSA	X	X	X	X	X	X	X	X
DF Bank	X	X	X	X	X	X	X	X
DF Drape	Case 2	X	X	X	X	X	Case 2	X
MB Bank	Case 2	Case 1	Case 1	Case 1	X	Case 2	Case 2	Case 2
MB Drape	X	X	X	X	Case 2	X	X	X
SC Bank	X	Case 1	Case 1	Case 1	X	X	X	X
SC Drape	Case 1	Case 1	Case 1	Case 1	Case 1	Case 1	Case 1	Case 1
JNck1	X	X	Case 1	Case 1	X			
JNck2	Case 2	Case 2	Case 2	X	Case 2			
JNck3	Case 2	Case 2	Case 2	Case 2	Case 2			
JNck4	Case 2	Case 2	Case 2	X	Case 2			
SAck1	Case 2	Case 2	Case 2	Case 2	Case 2	Case 2	Case 2	Case 2
SAck2	Case 2	Case 2	Case 2	X	Case 2	Case 2	Case 2	Case 2
SAck3	Case 2	X	X	X	Case 2	X	Case 2	Case 2
SAck4	Case 2	X	X	X	Case 2	X	Case 2	Case 2
DFck1	Case 2	X	X	X	Case 2	Case 2	Case 2	Case 2
DFck2	Case 2	Case 2	Case 2	X	Case 2	Case 2	Case 2	Case 2
DFck3	Case 2	Case 2	Case 2	Case 2	Case 2	Case 2	Case 2	Case 2
DFck4	X	X	X	X	Case 2	X	X	X
MBck1	Case 2	X	X	X	Case 2	Case 2	Case 2	Case 2
MBck2	Case 2	Case 2	Case 2	X	Case 2	Case 2	Case 2	Case 2
MBck3	Case 2	Case 2	Case 2	X	Case 2	Case 2	Case 2	Case 2
MBck4	Case 2	X	X	X	Case 2	Case 2	Case 2	Case 2
SCck1	Case 2	X	X	X	Case 2	Case 2	Case 2	Case 2
SCck2	X	X	X	X	Case 2	X	X	X
SCck3	Case 2	Case 2	Case 2	X	Case 2	Case 2	Case 2	Case 2
SCck4	X	X	X	X	Case 2	X	X	X
LW1	Case 2	Case 2	X	X	Case 2	Case 2	Case 2	Case 2
LW2	Case 2	Case 2	X	X	Case 2	Case 2	Case 2	Case 2
LW3	Case 2	Case 2	X	X	Case 2	Case 2	Case 2	Case 2

Fig. 5.20. McLaren technique: matrix for comparison of particle size distributions, continued

Sink	Source SA4	SA5	DF1	DF2	DF3	DF4	DF5	DF6
JNA								
JNB								
JNC								
JND								
JND								
SA1	X	X						
SA2	Case 2	X						
SA3	X	X						
SA4		X						
SA5	X							
DF1				Case 1	Case 1	Case 1	Case 1	Case 2
DF2			Case 1		Case 1	Case 1	X	Case 2
DF3			Case 1	Case 1		Case 1	X	X
DF4			X	X	X		Case 2	Case 2
DF5			Case 2	X	X	X		Case 2
DF6			Case 1	Case 1	X	X	Case 2	
JN Bank								
JN Drape u								
JN Drape d								
SA Bank A	X	X						
SA Bank B	Case 2	Case 2						
SA PSA	Case 2	Case 2						
DF Bank	X	X	X	X	X	X	X	X
DF Drape	X	X	Case 1	Case 1	Case 1	X	Case 2	Case 2
MB Bank	Case 2	Case 2	Case 1	Case 1	Case 1	Case 2	Case 2	Case 2
MB Drape	X	X	X	Case 1	X	X	X	X
SC Bank	X	X	Case 1	Case 1	Case 1	Case 1	X	X
SC Drape	Case 1	Case 1	Case 1	Case 1	Case 1	Case 1	Case 1	Case 1
JNck1								
JNck2								
JNck3								
JNck4								
SAck1	Case 2	Case 2						
SAck2	Case 2	Case 2						
SAck3	X	Case 2						
SAck4	Case 2	Case 2						
DFck1	Case 2	Case 2	X	X	X	Case 2	Case 2	Case 2
DFck2	Case 2	Case 2	Case 2	X	Case 2	Case 2	Case 2	Case 2
DFck3	Case 2	Case 2	Case 2	Case 2	Case 2	Case 2	Case 2	Case 2
DFck4	X	X	X	X	X	X	X	X
MBck1	Case 2	Case 2	X	X	X	Case 2	Case 2	Case 2
MBck2	Case 2	Case 2	Case 2	Case 2	Case 2	Case 2	Case 2	Case 2
MBck3	Case 2	Case 2	Case 2	X	Case 2	Case 2	Case 2	Case 2
MBck4	Case 2	Case 2	X	X	X	Case 2	Case 2	Case 2
SCck1	Case 2	Case 2	X	X	X	Case 2	Case 2	Case 2
SCck2	X	X	X	X	X	X	X	X
SCck3	Case 2	Case 2	Case 2	X	Case 2	Case 2	Case 2	Case 2
SCck4	X	X	X	X	X	X	X	Case 2
LW1	Case 2	Case 2	X	X	Case 2	Case 2	Case 2	Case 2
LW2	Case 2	Case 2	X	X	X	Case 2	Case 2	Case 2
LW3	Case 2	Case 2	X	X	Case 2	Case 2	Case 2	Case 2

Fig. 5.20. McLaren technique: matrix for comparison of particle size distributions, continued

	Source							
Sink	**JN Bank**	**JN Drape u**	**JN Drape d**	**SA Bank A**	**SA Bank B**	**SA PSA**	**DF Bank**	**DF Drape**
JNA								
JNB								
JNC								
JND								
JNE								
SA1								
SA2								
SA3								
SA4								
SA5								
DF1								
DF2								
DF3								
DF4								
DF5								
DF6								
JN Bank		X	X					
JN Drape u	X		X					
JN Drape d	X	X						
SA Bank A	X	X	X		X	X		
SA Bank B	Case 1	X	X	X		Case 2		
SA PSA	Case 1	X	X	X	X			
DF Bank	X	X	X	X	X	X		X
DF Drape	Case 1	X	X	Case 1	X	X	X	
MB Bank	Case 1	X	X	Case 1	X	X	X	X
MB Drape	Case 1	X	X	Case 1	X	X	X	X
SC Bank	Case 1	Case 1	X	Case 1	Case 1	Case 1	Case 1	X
SC Drape	Case 1	Case 1	X	Case 1	Case 1	Case 1	Case 1	X
JNck1	Case 1	Case 1	Case 1					
JNck2	Case 1	X	X					
JNck3	Case 2	Case 2	Case 2					
JNck4	Case 1	X	X					
SAck1	Case 2	Case 2	X	Case 2	Case 2	Case 2		
SAck2	Case 1	X	X	Case 1	Case 2	Case 2		
SAck3	Case 1	X	X	Case 1	X	X		
SAck4	Case 1	X	X	X	Case 2	X		
DFck1	X	X	X	X	Case 2	Case 2	Case 2	X
DFck2	Case 1	Case 1	X	Case 1	Case 2	Case 2	Case 2	Case 2
DFck3	Case 1	X	X	X	Case 2	Case 2	Case 2	Case 2
DFck4	Case 1	X	X	X	X	X	Case 2	Case 2
MBck1	Case 1	X	X	X	Case 2	Case 2	Case 2	Case 2
MBck2	Case 1	X	X	X	Case 2	Case 2	Case 2	Case 2
MBck3	Case 1	X	X	X	Case 2	Case 2	Case 2	Case 2
MBck4	Case 1	Case 1	X	Case 1	Case 2	X	Case 2	Case 2
SCck1	Case 1	X	X	X	Case 2	X	Case 2	Case 2
SCck2	Case 1	X	X	X	X	X	Case 2	Case 2
SCck3	Case 1	X	X	X	Case 2	Case 2	Case 2	X
SCck4	Case 1	Case 1	X	Case 1	X	X	Case 2	Case 2
LW1	Case 1	X	X	X	Case 2	Case 2	Case 2	Case 2
LW2	Case 1	X	X	Case 1	Case 2	Case 2	Case 2	Case 2
LW3	Case 1	Case 1	X	Case 1	Case 2	Case 2	Case 2	Case 2

Fig. 5.20. McLaren technique: matrix for comparison of particle size distributions, continued

	Source							
Sink	**MB Bank**	**MB Drape**	**SC Bank**	**SC Drape**	**JNck1**	**JNck2**	**JNck3**	**JNck4**
JNA								
JNB								
JNC								
JND								
JNE								
SA1								
SA2								
SA3								
SA4								
SA5								
DF1								
DF2								
DF3								
DF4								
DF5								
DF6								
JN Bank					X	X	X	X
JN Drape u					X	X	X	X
JN Drape d					X	X	X	X
SA Bank A					X	X	X	X
SA Bank B					X	X	X	Case 2
SA PSA					X	Case 1	X	X
DF Bank					X	X	X	X
DF Drape					X	X	X	X
MB Bank		X			X	X	X	X
MB Drape	X				X	X	X	X
SC Bank	Case 2	X		X	X	X	X	Case 1
SC Drape	X	X	Case 1		X	X	X	Case 1
JNck1						Case 1	Case 1	X
JNck2					X		X	X
JNck3					Case 2	X		Case 2
JNck4					X	X	X	
SAck1					Case 2	X	Case 2	Case 2
SAck2					X	X	X	Case 2
SAck3					X	X	X	X
SAck4					X	X	X	Case 2
DFck1					X	X	X	Case 2
DFck2					X	Case 1	Case 1	X
DFck3					X	Case 1	Case 2	Case 2
DFck4					Case 1	X	X	X
MBck1	Case 2	X			X	Case 1	X	Case 2
MBck2	Case 2	X			X	X	X	Case 2
MBck3	Case 2	X			Case 1	X	X	Case 2
MBck4	Case 2	X			Case 1	X	X	X
SCck1	Case 2	X	X	X	Case 1	X	X	Case 2
SCck2	Case 2	X	X	X	Case 1	Case 1	X	X
SCck3	Case 2	X	X	X	X	X	X	Case 2
SCck4	Case 2	X	Case 1	Case 1	Case 1	Case 1	Case 1	Case 1
LW1	Case 2	Case 2	X	Case 1	Case 1	Case 1	X	Case 2
LW2	Case 2	X	Case 1	Case 1	Case 1	Case 1	X	Case 2
LW3	Case 2	Case 2	Case 1	Case 1	Case 1	Case 1	Case 1	Case 2

Fig. 5.20. McLaren technique: matrix for comparison of particle size distributions, continued

	Source									
Sink	**SAck1**	**SAck2**	**SAck3**	**SAck4**	**DFck1**	**DFck2**	**DFck3**	**DFck4**	**MBck1**	**MBck2**
JNA										
JNB										
JNC										
JND										
JNE										
SA1										
SA2										
SA3										
SA4										
SA5										
DF1										
DF2										
DF3										
DF4										
DF5										
DF6										
JN Bank										
JN Drape u										
JN Drape d										
SA Bank A	X	X	X	X						
SA Bank B	X	X	X	X						
SA PSA	X	X	X	X						
DF Bank	X	X	X	X	X	X	X	X		
DF Drape	X	X	X	X	X	X	X	X		
MB Bank	X	X	X	X	X	X	X	X	X	X
MB Drape	X	X	X	X	X	X	X	X	X	X
SC Bank	Case 1	Case 1	X	X	X	X	X	X	X	X
SC Drape	Case 1	Case 1	X	X	X	X	X	X	X	X
JNck1										
JNck2										
JNck3										
JNck4										
SAck1		X	X	X						
SAck2	X		X	X						
SAck3	X	X		X						
SAck4	X	Case 1	X							
DFck1	X	X	X	X		X	X	X		
DFck2	X	X	X	X	X		Case 1	X		
DFck3	X	X	Case 2	X	X	X		X		
DFck4	Case 1	Case 1	X	X	X	X	X			
MBck1	Case 2	Case 1	X	X	Case 2	X	X	X		Case 2
MBck2	X	X	X	X	Case 2	X	X	Case 2	Case 2	
MBck3	X	X	X	X	X	X	X	X	X	X
MBck4	X	Case 1	X	X	X	X	X	Case 1	X	X
SCck1	X	Case 1	X	X	Case 2	X	Case 1	Case 1	Case 2	X
SCck2	Case 1	Case 1	X	X	X	Case 1	X	X	X	X
SCck3	X	X	X	X	X	X	X	X	X	X
SCck4	Case 1	Case 1	X	Case 1	X	Case 1	Case 1	Case 1	X	Case 1
LW1	X	X	X	X	Case 2	X	X	X	Case 2	Case 2
LW2	X	X	X	Case 1	X	X	Case 1	Case 1	Case 2	X
LW3	X	X	X	Case 1	X	X	Case 1	Case 1	Case 2	X

Fig. 5.20. McLaren technique: matrix for comparison of particle size distributions, continued

	Source								
Sink	**MBck3**	**MBck4**	**SCck1**	**SCck2**	**SCck3**	**SCck4**	**LW1**	**LW2**	**LW3**
JNA									
JNB									
JNC									
JND									
JNE									
SA1									
SA2									
SA3									
SA4									
SA5									
DF1									
DF2									
DF3									
DF4									
DF5									
DF6									
JN Bank									
JN Drape u									
JN Drape d									
SA Bank A									
SA Bank B									
SA PSA									
DF Bank									
DF Drape									
MB Bank	X	X							
MB Drape	X	X							
SC Bank	X	Case 1	X	X	X	X			
SC Drape	X	X	X	X	X	X			
JNck1									
JNck2									
JNck3									
JNck4									
SAck1									
SAck2									
SAck3									
SAck4									
DFck1									
DFck2									
DFck3									
DFck4									
MBck1	X	X							
MBck2	X	X							
MBck3		Case 1							
MBck4	X								
SCck1	X	Case 1		X	X	X			
SCck2	X	X	X		X	X			
SCck3	X	X	X	X		X			
SCck4	X	Case 1	X	Case 1	Case 1				
LW1	X	X	X	X	X	X		Case 2	X
LW2	X	Case 1	X	Case 1	X	X	X		X
LW3	X	Case 1	X	Case 1	X	X	X	Case 2	

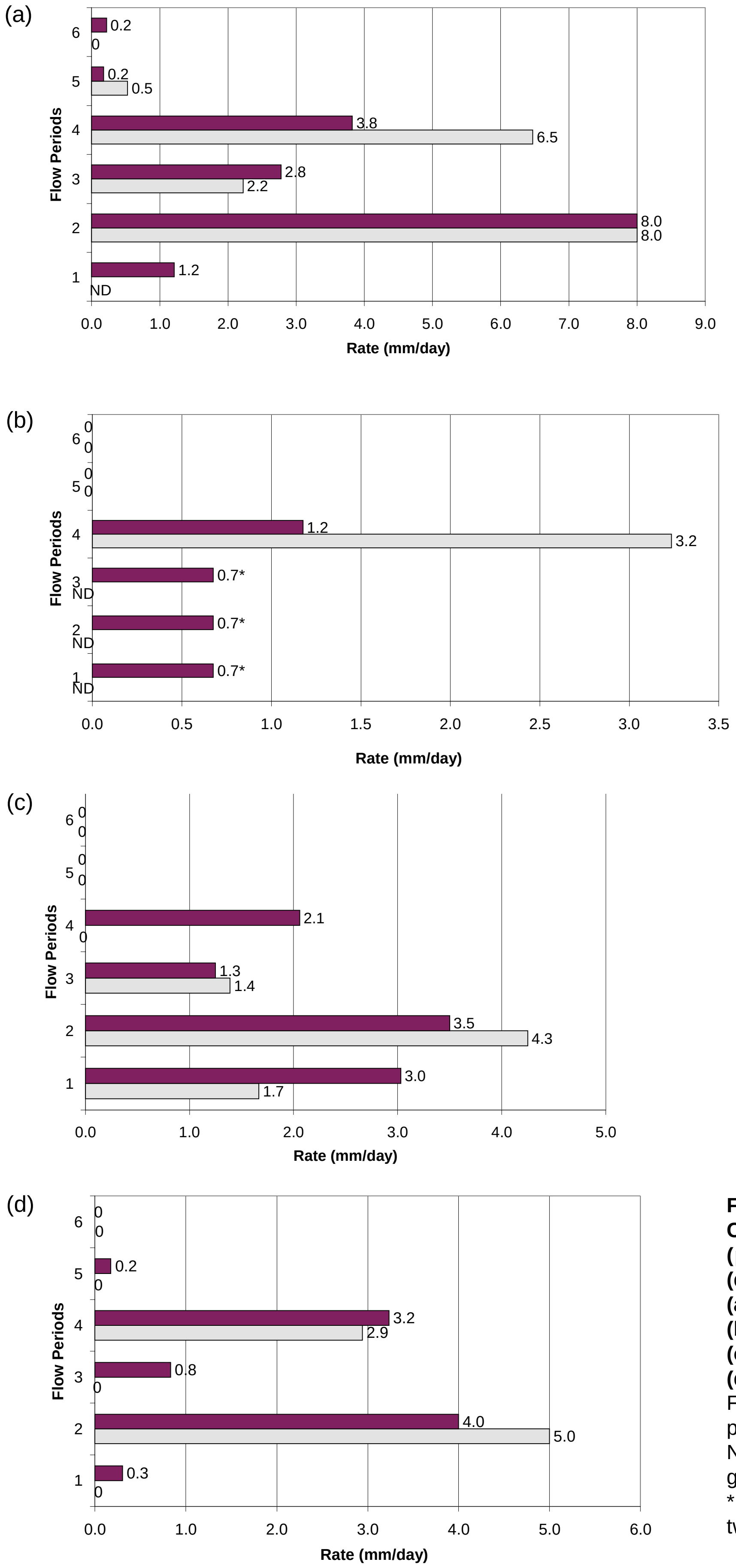


Fig. 5.21. Scour chain data for Castle Creek, showing scour (pale bars) and deposition (dark bars) in mm/day:
(a) Bamford Chain 1;
(b) Bamford Chain 2;
(c) Kubeil Chain 1;
(d) Kubeil Chain 2.
For a description of flow periods 1–6 see Table 5.2.
ND indicates no data for the given period.
* indicates rate averaged over two or more periods.

specific investigation it is difficult to determine the impact aggregates may have had on the outcome of the McLaren analysis, in fact it is only possible to say that the presence of such aggregates may or may not affect the results, and as a consequence the results of the McLaren analysis must be cross-checked with results from other techniques.

5.4. Scour chains

The raw data derived from the monitoring of scour chains placed in the beds of Castle, Creightons and Pranjip–Nine Mile Creeks are presented in Appendix C. The data show change in depth (scour and deposition) for each chain over each monitoring period. To assist with interpretation the data are also presented in Figs 5.21, 5.22 and 5.23 as well as Table 5.3, in a different form. The data presented in Figs 5.21, 5.22 and 5.23 represent the change in depth for each chain (scour and deposition) and each period, averaged over the length of the monitoring period to give a rate of change in mm/day. This removes the influence of monitoring period length and allows the data to be compared more readily. In Table 5.3 the changes in depth for each chain for each period have been added together to give a total change in depth (scour and deposition) for each chain for the entire monitoring period.

The scour chains were inserted in late July (Nine Mile Creek) and early August 1998 (Castle Creek and Creightons Creek) and were checked six times, the last check taking place in mid-May 1999. Thus changes were monitored over six different sets of flow conditions. Official stream gauging data applicable to the three catchments were not available for this period, so other sources of information were used to identify flow conditions during each period. Sources of information included rainfall at the head of Creightons Creek (data collected by a local landholder), flow depths recorded at half-hourly intervals in Creightons Creek at the Carlsson’s property (recorder installed 15/9/98) and observations of flow depths by the authors. These data were then used to roughly identify flow conditions during each of the six monitoring periods (Table 5.2).

Table 5.2. Estimated flow conditions for the six flow periods

Period	Rainfall and flow observations	Description of flow conditions
Period 1 8/98–15/9/98	*Nine Mile Ck:* chains were inserted at the tail end of an event *Castle & Creightons Ck:* low rainfall totals	*Nine Mile Ck:* falling limb of an event and winter baseflow *Castle & Creightons Ck:* winter baseflow
Period 2 15/9/98–5/10/98	During this period there were two significant rainfall events, the first on the 22–23/9 and the second on 3/10, that led to near bankfull flows in some areas	Possibly annual events*
Period 3 5/10/98–10/11/98	No significant rainfall totals during the period, but rainfall from the previous period produced a small event on 6/10	Small event and spring baseflow
Period 4 10/11/98–14/12/98	During this period there was a significant rainfall event on the 11–13/11, that led to bankfull flows in some areas	Possibly an annual event*
Period 5 14/12/98–9/2/99	No significant rainfall totals and baseflow indicated	Summer baseflow
Period 6 9/2/99–11/5/99	Several small rainfall events, but catchment so dry there was no real increase in discharge. Baseflow indicated.	Summer–autumn baseflow

* Description as an annual event is not based on flow data, because there are no gauge data; instead it is based on anecdotal evidence that flows of this size occur at least once a year.

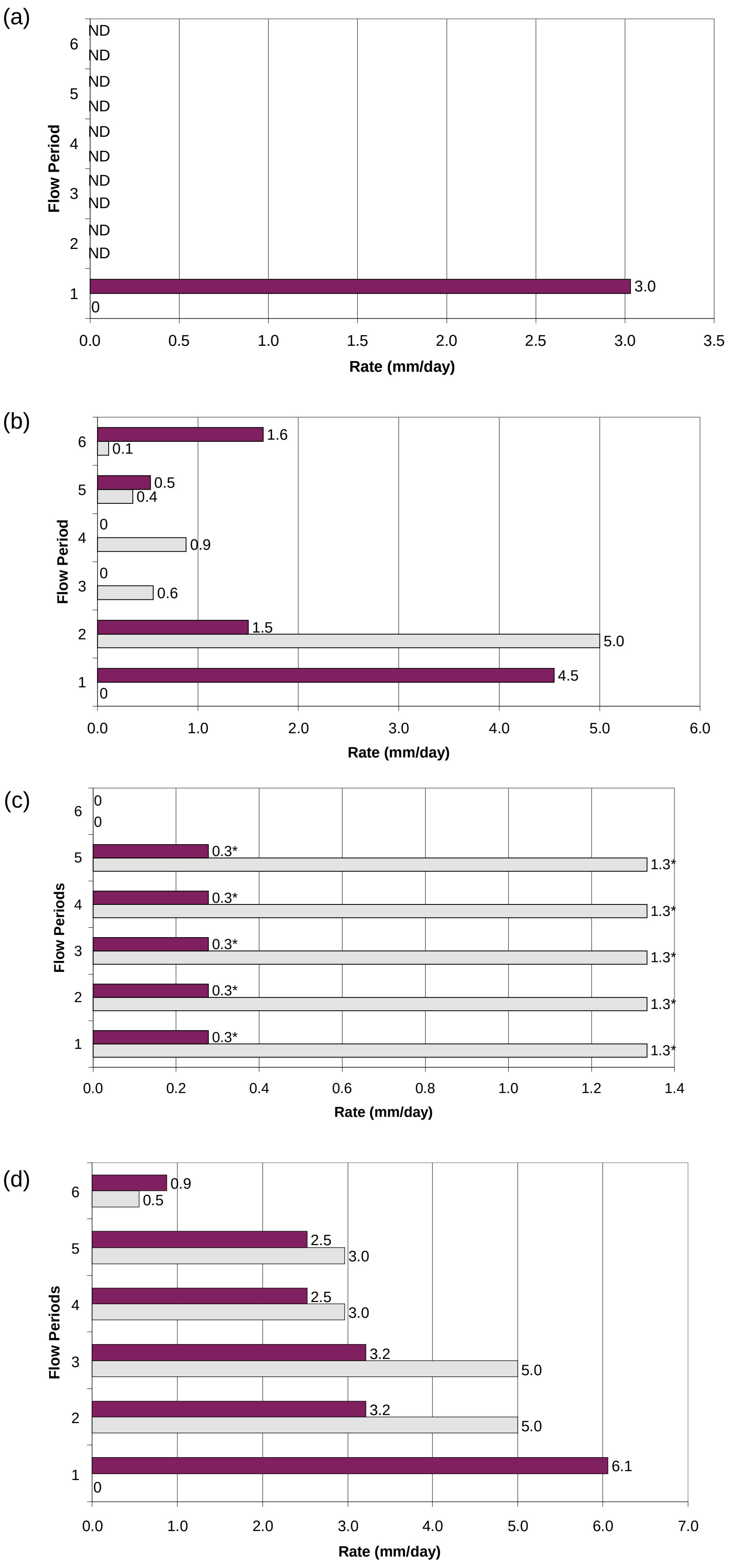


Fig. 5.22. Scour chain data for Creightons Creek, showing scour (pale bars) and deposition (dark bars) in mm/day:
(a) Carlsson Chain 1,
(b) Carlsson Chain 2,
(c) Caldwell Chain 1,
(d) Caldwell Chain 2.
For a description of flow periods 1–6 see Table 5.2.
ND means no data collected for the given period.
* indicates rate averaged over two or more periods.

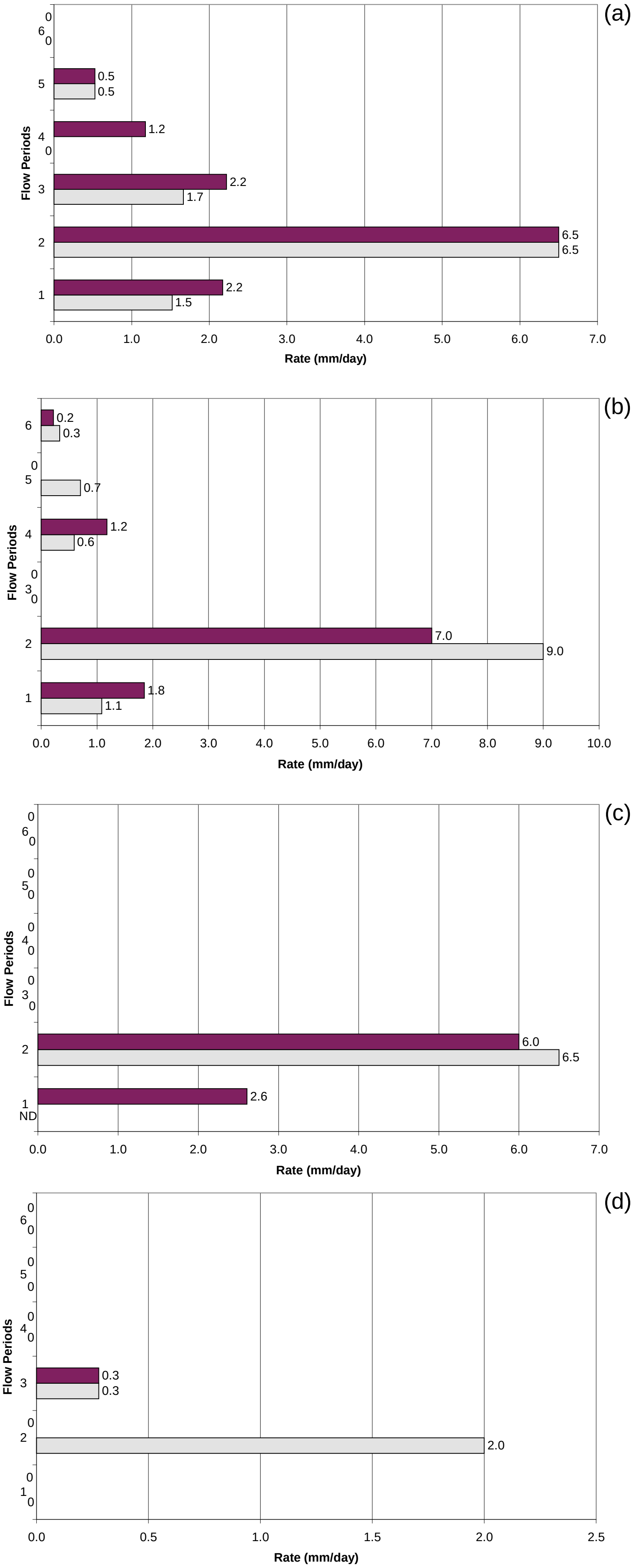


Fig. 5.23. Scour chain data for Nine Mile Creek, showing scour (pale bars) and deposition (dark bars) in mm/day:
(a) Cameron Chain 1,
(b) Cameron Chain 2,
(c) Threlfall Chain 1,
(d) Threlfall Chain 2.
For a description of flow periods 1–6 see Table 5.2. ND means no data collected for the given period. * indicates rate averaged over two or more periods.

Table 5.3. Total change in bed elevation

Creek	Site	Chain 1	Chain 2	Description
Castle Ck	Bamford	–7 cm*	–7 cm*	minor scour
	Kubeil	+9.5 cm	+3cm	minor deposition
Creightons Ck	Carlsson	NL	+18 cm	possibly moderate deposition
	Caldwell	–19 cm	+9cm	minor deposition and moderate scour
Nine Mile Ck	Cameron	+9 cm	–3.5 cm	no change to minor deposition
	Threlfall	–1 cm*	–4 cm	no change

*Totals calculated by ignoring periods where there was an error; NL signifies chain not located.

The information presented in Table 5.2 indicates that scour chain observations made for periods 2 and 4 could be related to flow events, while observations made for period 1 (Castle and Creightons Creek) could be related to winter baseflow and observations for periods 5 and 6 could be related to summer–autumn baseflow.

As expected, all the scour chain graphs for which there are sufficient data (Figs 5.21a,b,c; Figs 5.22b,d; Figs 5.23a,b) suggest that greater scour and deposition occur during flow events than during periods of baseflow. Depending on the creek and the location of the scour chain in the channel, scour of between 10 and 25 cm was observed following flow events (Appendix C), with 0–5 cm of scour observed under winter–spring baseflow and 0–3 cm observed under summer–autumn baseflow. Quite often deposition levels were similar to scour levels (i.e. the ratio of deposition to scour was 100%) over a period, but ratios as low as 0% and as high as 180% were also observed (Appendix C).

As expected, there were substantial variations in the relative amounts of scour and deposition, both within a site and within a creek. One example of intra-site variation comes from Castle Creek (Appendix C) where, following period 4, scour of 0 cm and 10 cm with deposition of 7 cm and 11 cm was observed at one site (Kubeil). A second example comes from Nine Mile Creek (Appendix C) where, following period 3, scour of 6 cm and 0 cm with deposition of 8 cm and 0 cm was observed at the one site (Cameron). There was no clear pattern of major or minor scour and deposition in the channel. In some instances scour and deposition were largest in or adjacent to the low flow channel; at other sites and at other times scour and deposition were higher away from the low flow channel.

Intra-creek variation is illustrated by the depth of total change over the measurement period given in Table 5.3. The table shows that scour and deposition and consequent changes in bed elevations can vary from site to site along a creek, at least in the short term.

Table 5.3 also shows that while scour of 25–30 cm and deposition of 20–30 cm may occur as a result of flow events, over the short term at least there is relatively little impact on bed elevations. Nevertheless these results may be indicating that during flow events the top 20–30 cm of the streambed is being mobilised and significant sand transport taking place. While the depth of sand mobilised during winter–spring baseflow is not as great as during flow events (i.e. ~5 cm, cf. 20–30 cm) the length of time over which winter–spring baseflow persists is such that it may transport substantial volumes of sand and thus be of similar significance, with regard to sand transport volumes, as flow events.

5.5. Bedload sampling

Bedload sampling was carried out at two sites on Creightons Creek. Sampling was conducted on Stan Artridge’s property (SA) six times between September 1998 and February 1999 and four times on Maurie Brodie’s property (MB, shown as MB1 on Fig. 2.1) between October 1998 and February 1999. At each sampling time, discharge was measured and the total volume of bedload

Table 5.4. Bedload data for Creightons Creek

Date	Site	Discharge (L/s)	Bedload trans. rate (kg/hr)	Flow description
14/09/98	SA	106	41	spring baseflow
05/10/98	SA	172	72–84	spring baseflow
19/10/98	MB	432	130–320	spring baseflow
19/10/98	SA	126	30–137	spring baseflow
13/11/98	MB	1140	390–490	falling limb of an event
13/11/98	SA	170	90–135	falling limb of an event
14/12/98	MB	91	55–63	early summer baseflow
14/12/98	SA	43	5	early summer baseflow
13/02/99	MB	est. 15	0	late summer baseflow
13/02/99	SA	est. 5	0	late summer baseflow

movement was determined. Some of the bedload samples were dry sieved. These results and observations of dune movement are discussed at the end of this section.

5.5.1. Bedload transport rates

The data collected during bedload sampling at Creightons Creek are presented in Table 5.4; they include approximate flow conditions at the time, based on rainfall data, flow depth records measured on the Carlsson's property and observations made by the authors in the field. As was the case for analysing the scour chain data it was considered useful to know qualitatively what the relative flow conditions were in Creightons Creek at the time of bedload sampling, e.g. baseflow condition, rising limb of a flow hydrograph. Such information enables a better understanding of the relevance of the bedload data measured on a particular day.

The bedload transport rate data for both sites are plotted against discharge in Fig. 5.24. Where a maximum and minimum bedload was measured at a site, both values are plotted. The data presented in Fig. 5.24 indicate that within the range of events sampled (baseflow and the falling limb of a small event) the bedload transport rate appears to increase linearly with discharge. Bedload transport rates are also controlled by bed slope. At site SA the relationship is steeper, indicating bedload transport rates increase at a faster rate with discharge, compared with site MB where the bed slope is lower.

A relationship showing that bedload transport rates increase with discharge is not surprising and in fact would probably have been predicted. Bedload samples were not, however, taken during the

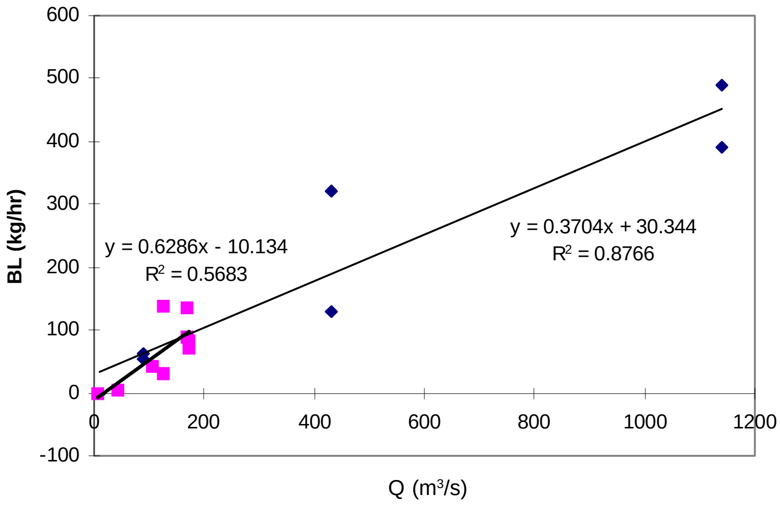
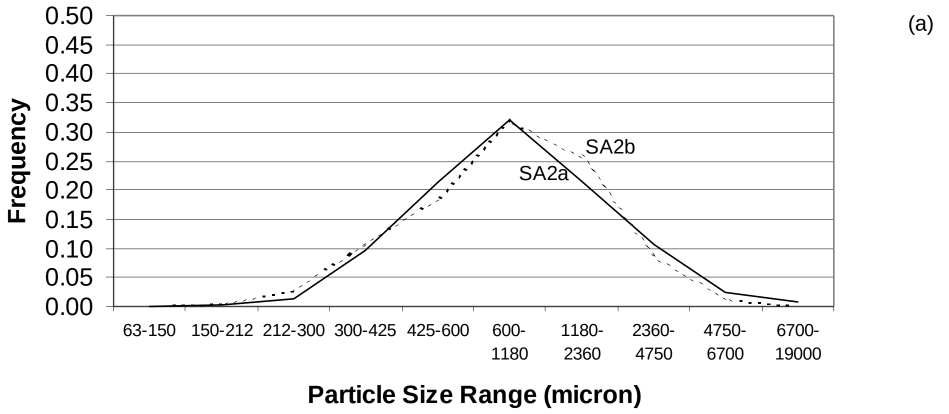


Fig. 5.24. Bedload (BL) transport rates vs. discharge (Q):
■ = SA, ◆ = MB
▬ = line of best fit (SA)
— = line of best fit (MB)



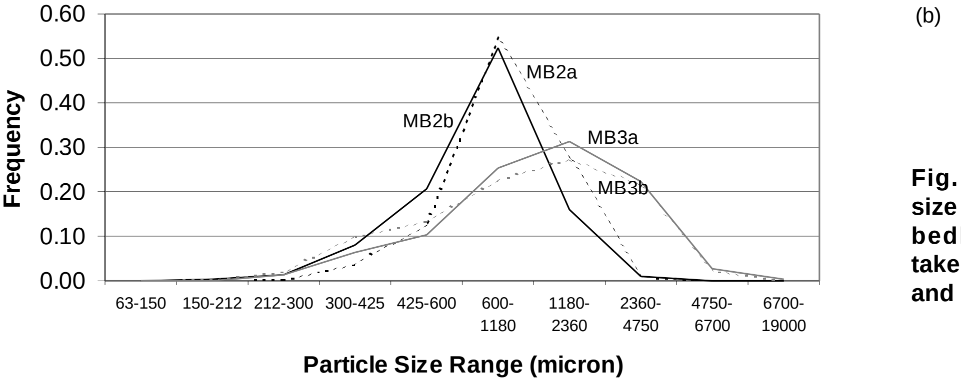


Fig. 5.25. Particle size distributions of bedload samples taken at (a) site SA and (b) site MB

rising limb or peak of a flow hydrograph, nor was a large event sampled and consequently it is not possible to say anything about bedload transport rates during periods when transport rates would be expected to be at their peak. The collected data, nonetheless, provide us with important information about bedload transport during low flows. Bedload transport rates during baseflows in late summer were negligible, but bedload transport rates were quite high during spring (30–140 kg/hr at site SA and 130–320 kg/hr at site MB). Because of a lack of bedload event data and discharge data, as well as the errors associated with bedload measurement, it is neither possible nor appropriate to estimate the relative contribution made by baseflow to overall bedload transport. However, the data collected in Creightons Creek suggest that baseflow, particularly in winter and spring may make a substantial contribution to bedload transport.

5.5.2. Particle size distributions

Bedload samples taken at sites SA and MB (site MB1 on Fig. 2.1) on the 19/10/98 were dry sieved and the particle size distributions (PSDs) were compared. The results of the dry sieve analysis are presented graphically in Figs 5.25a, b. The numbering of the bedload samples relates to the sampling location along the cross-section. When bedload sampling was conducted an appropriate cross-section was selected and split into several segments which were numbered consecutively across the section. The cross-sections sampled at SA and MB were both split into four segments. The samples taken at segments 1 and 4 at site MB were very small (<10 g) and were not dry sieved. The samples taken at segments 2 and 3 at site MB, on the other hand, were large (>0.5 kg) and so the segments were sampled twice, to give samples MB2a, MB2b, MB3a and MB3b. At site SA samples taken at segments 1, 3 and 4 were small, consequently only two samples (SA2a and SA2b) were sieved.

Despite large variations in the mass of material collected at a given site on a cross-section the particle size distributions of the bedload samples are distinctly similar (Figs 5.25a, b). This

Fig. 5.26. An example of dune formation observed on Castle, Creightons and Pranjip–Nine Mile Creeks at various times

observation suggests that at a given site on a cross-section, under a steady discharge, particle size distributions are consistent regardless of variations in the rate of bedload transport. However, a comparison of particle size distributions taken at different sites on a cross-section under the same discharge indicates that particle size distributions can vary significantly across the bed (Fig 5.25b).

5.5.3. Dune movement

Dune formation was observed on many occasions in the sanded sections of Castle, Creightons and Pranjip–Nine Mile Creek, in both high and baseflow conditions (e.g. Fig. 5.26). Dune movement was monitored on one occasion at site MB following a bedload sampling run. The dunes observed on this occasion had an amplitude of 10 cm, a wavelength of 140 cm and a period of 5 minutes. The dune sequence was also observed to cover approximately one quarter of the channel width. The implications of these observations are that during spring baseflow up to 25% of the bed scours to a depth of 10 cm and refills every 5–6 hours.

5.6. Synthesis

Combining the results of the analyses undertaken to assess current condition for the Creightons Creek catchment it is possible to arrive at a number of preliminary conclusions.

Sediment sources

The results from the particle size distribution analysis suggest that downslope movement of sediment is occurring on the hillslopes, although the patterns vary over the three hillslopes sampled. At site JN, medium to coarse sand is being mobilised and redistributed on the slope, while fine sand, silt and clay are being transported to the footslope; parts of these fractions are being moved into the stream network. At site SA the hillslope appears to be relatively stable, although some redistribution of fine–medium sand may be occurring. At site DF medium to coarse sand is being mobilised and redistributed on the slope, while fine sand, silt and clay are being transported to the footslope. The differences between the three slopes could be explained by variations in slope steepness and land management, but these results still indicate that while fine sands, silts and clay might be transported off some hillslopes in the catchment, other slopes are relatively stable. Consequently while the McLaren technique and the coarse fraction analysis both suggest that the hillslopes could be sources of material for the creek bed it seems unlikely that sufficient coarse material is being mobilised under current conditions for the hillslopes to be a significant source.

The results from the four analysis techniques for particle size distribution for the creek bed samples taken above the Longwood–Pranjip Rd suggest that these creek bed sediments have been derived from local streambanks and in-stream sources higher up in the catchment, which is consistent with the results of the sediment budget and field observations. Below the Longwood–Pranjip Rd, creek bed sediments appear to have two distinctly different sources. At site SC, creek bed sediments appear to be derived predominantly from sources upstream, whereas at site LW creek bed sediments appear to be derived from local sources. This final observation is consistent with the explanation for the pink sand found at site LW but not at other sites on Creightons Creek (see Section 5.1.2).

Field observations suggest that the main sources of sediment in the Granite Creeks systems today are bed and bank erosion, with some minor gullying. The results of the sediment budget suggest that erosion of drainage lines via stream incision and gullying, has been the main source of sediment to the Granite Creeks over the last 150 years and not just recently.

It is important to be aware that the relationships between sediment sources and sinks discussed above refer only to the present period (i.e. the last 150 years). Ultimately (i.e. on a geological time scale) all material has been derived from the hillslopes, but relationships at such a time scale are not relevant for management of the Granite Creeks today.

Movement of the sand slug

The results from the scour chains indicate that in the short term there are no clear trends in scour or deposition at any of the sites or creeks. However, the results suggest that in small annual events, scour of 25–30 cm and deposition of 20–30 cm is not unusual, while scour of up to 5 cm can occur under winter–spring baseflow. Observations of dune movement suggest that up to 25% of the streambed can be scoured to a depth of 10 cm and refilled 3–4 times a day under spring baseflow conditions.

Field observations indicate that the sand front on Creightons Creek has not moved a substantial distance over at least the last decade.

Bedload sampling did not extend to cover the rising limb or event peaks, but the results suggest that relatively high rates of sediment transport occur during the falling limb of an event as well as during spring baseflow (30–140 kg/hr in the upper reaches of the catchment and 130–320 kg/hr in the lower reaches of the catchment). These data suggest that while high flow events can transport high volumes of sediment and scour streambeds, spring baseflow can also be significant because it persists for a far longer time than an event. Therefore, in terms of volume of sediment transported and streambed stability for in-stream biota, it could be as important as, or more important than, high flow events. The incongruity of apparent high bedload transport rates and the seemingly slow migration rate of the snout of the sand slug are discussed in Chapter 6.

6. DISCUSSION OF RESULTS

6.1. Introduction

This chapter discusses the results presented in Chapters 4 and 5. This discussion specifically relates to: (i) the original objective and hypotheses, as outlined in Chapter 1; and (ii) the implications the results have for the rehabilitation of the Granite Creeks.

6.2. Objective and hypotheses

The objective being addressed by this component of the Granite Creeks project is:

> to determine the levels of sediment input into selected streams from the catchments of the Strathbogie Ranges, and the movements of such sediments within the streams.

The objective was investigated via the development of two key hypotheses:

1. that increased inputs of sediment (sand) to Strathbogie Range streams have resulted from post-settlement catchment land-use;
2. that downstream sedimentation associated with accelerated erosion, post-settlement, in the catchments is mitigated through sediment storage in the catchment slopes and tributary valleys.

Hypothesis 1

Activities associated with European settlement have caused stream incision and gullying in the catchments of the Granite Creeks which has led to severe aggradation of the middle and lower reaches of these systems. While there is evidence to suggest that incision and gullying had occurred prior to European settlement it seems likely that these were isolated episodes in response to disturbances such as bushfires. The incision and gullying that has occurred since European settlement has been widespread and synchronised across the Granite Creeks catchments.

The conclusions drawn from this project have been based on the results of analyses and assessment conducted on only a few of the Granite Creeks. However, other information (e.g. see Appendix A) and the distinctive physical characteristics (and history) of the Granite Creeks suggests that what has occurred on Castle, Creightons and Pranjip–Nine Mile Creek has probably been repeated on the other Granite Creeks.

Hypothesis 2

Storage plays an important role in mitigating sediment pulses released by accelerated erosion. Sediment can be stored at a number of locations throughout a catchment for varying periods of time before it is remobilised (e.g. from one day to hundreds of thousands of years). The effect of this storage is that pulses of sediment released by erosion can be attenuated, so that the peak of the sediment load is much lower, but the period over which levels above background levels persist is increased. Such behaviour has implications for management, particularly if sediment stores can be identified and appropriate management techniques can be applied for minimising remobilisation.

In Section 2.3 of this report the hillslope channel connectivity (HCC) values for the three Granite Creeks being studied were calculated. The HCC is effectively a measure of a catchment’s ability to store sediment and the HCC values for all three catchments indicate that, in general, sediment mobilised on hillslopes would be stored in the catchment in footslope areas. However, the sediment released in the Granite Creeks catchments over the last 150 years has been derived from drainage lines (i.e. creek beds and banks, as well as gullying) and this has tended to affect the capacity of the catchments to store and attenuate the sediment pulse.

There are two reasons for this. First, the sediment released by erosion of drainage lines is pumped directly into the stream network, by-passing important footslope stores. Second, substantial segments of the Granite Creeks have incised (particularly in the upper reaches of the catchments), so the creeks are subject to overbank flows relatively infrequently. Because overbank flows are the mechanism by which sediment is stored on floodplains, a number of floodplain stores would also have been by-passed. Consequently, the type of erosion that has occurred in the Granite Creeks catchments has reduced the accessibility of sediment stores in the upper catchment, and thus the capacity of the upper catchment to attenuate the sediment pulse.

This is not to say that there has been no storage in the catchments. In fact the majority of sediment released has been stored in the catchment, in floodplain stores that were still accessible, on the Riverine Plain, and in in-channel stores, i.e. the sand slugs (see Section 5.2). However, more sediment may have been delivered to these stores, including the sand slug, than would have occurred had the upstream erosion stores not been by-passed.

These observations imply that management needs to prevent or minimise further erosion to stop other stores being by-passed; and to protect the existing sediment stores. The storage delay times associated with stores on the riverine plain would range from thousands to hundreds of thousands of years, and so such stores are not vulnerable on a management time frame. Storage delay times associated with floodplain storage are also reasonably high and are again not likely to be vulnerable in a management time frame. Sand stored in the sand slugs is at greatest risk of mobilisation. Consequently efforts should be made to prevent mobilisation of in-stream stores by appropriate management of the riparian zone, particularly in relation to revegetation and stock access.

6.3. Implications for rehabilitation

6.3.1. Introduction

When considering the implications of the findings reported here, for the rehabilitation of the Granite Creeks, three issues require discussion: (i) control of further sand delivery to the sand slugs; (ii) the rate of migration of the sand slug; and (iii) how to improve in-stream habitat on a sand slug. Each of these issues is discussed below.

6.3.2. Minimising further sediment input

Results presented in Chapter 5 indicate that drainage lines in the Granite Creeks catchments are the main source of the sediment now forming sand slugs in the creeks. Thus any project which is developed to rehabilitate the Granite Creeks must also address the issue of minimising further sediment inputs from the drainage lines.

The analysis of historical information (Chapter 4) revealed that a number of activities or incidents appear to have contributed to the initiation of erosion heads in the past, including clearing, agriculture, channelisation, channel dredging and clearing, bushfires and droughts. Today, erosion heads are still being initiated by activities such as channel dredging and clearing, and by uncontrolled stock access to drainage lines. Thus to minimise further sediment input to the Granite Creeks, in the first instance, unauthorised activities in local streams must cease and stock access to drainage lines must be controlled. These controls require landholder cooperation, which generally can only be achieved by education. The landholders need to understand why their current activities might be detrimental and the benefits that could result (both on and off farm) if cooperation is achieved. The cost of fencing and off-stream water supplies for stock may also be a deterrent to fencing-out drainage lines, but it does not appear to be the primary obstacle.

Secondly, best practice land management techniques need to be applied throughout the Granite Creeks catchments. This approach is needed because droughts and bushfires have triggered erosion in the past; it is clearly important to maintain adequate vegetative ground cover under all conditions.

The evidence presented in Chapter 4 indicates that the upper catchment of Creightons Creek (i.e. above the Hume Freeway) may be more sensitive to disturbance than the lower catchment. This has implications for the sequence in which activities are undertaken to mitigate erosion. A surprising outcome of the discussion of possible sources of erosion heads was that one of the most significant disturbances for all the Granite Creeks, i.e. the construction of the North-Eastern Railway, appears to have produced little response in the creeks. The upper catchment, on the other hand, appears to have responded to a range of disturbances — from bushfires and droughts to clearing and stock access to streams. This variation in response can be explained by variations both in soil type and in channel slope. There is a tendency for the soils downstream of the Hume Freeway to contain a higher proportion of fines, particularly clay; so stream banks below the Freeway are probably more cohesive and therefore more resistant to erosion. Similarly, the channel slope below the Hume Freeway is low, leading to reduced stream power and hence a decreased propensity for channel erosion.

While this observation suggests that activities in the upper catchment should take priority, it is important to remember that erosion heads initiated in the lower catchment can migrate upstream some distance, so certain activities in the lower catchment may also need to be prioritised.

6.3.3. Sand slug movement

Migration of the snout

The migration of the sand slug front (or snout) downstream is threatening reaches of stream that appear, geomorphologically at least, to be in good condition. It is important to have some understanding of what is influencing the sand slug's rate of migration.

As indicated in Section 5.1.2, there is evidence to suggest that the front of the sand slug in Creightons Creek has not moved a significant distance downstream in the last decade. Yet the bedload transport rates measured in the creek suggest that even at low flow (winter–spring) there is substantial sand migration, and these rates would be expected to be substantially higher in high flow events. To reconcile these two apparently conflicting pieces of evidence, the potential of Creightons Creek to mobilise and transport sand was investigated.

Stream power (w) is the amount of work done by a stream per unit time at a given point in the stream. Thus stream power is a useful way of determining how much energy might be available in the stream for activities such as mobilising sand. Madej & Ozaki (1996) found that the transit rate of a sand slug in Redwood Creek in the USA varied directly with stream power.

Stream power is a function of discharge and the stream's energy slope:

$$w = \mathrm{rg}Qs\ ,$$

where r = density of water (1000 kg/m^3),

g = acceleration due to gravity (9.81 m/s^2),

Q = discharge (m^3/s),

s = slope of the energy line.

For the purposes of examining how stream power varies along Creightons Creek, only relative measures of stream power are required. Neither discharge nor energy slope data are available, so surrogates were used for each: catchment area was used as a surrogate for discharge, and stream-bed slope was used as a surrogate for energy slope. Catchment area can be used as a surrogate for discharge because discharge is a function of rainfall characteristics, runoff coefficient and catchment area, and if it is assumed that rainfall characteristics and runoff coefficient are the same for the entire catchment, then discharge varies directly with catchment area. Stream-bed slope can be used as a surrogate for energy slope when streamflow is uniform (Gordon *et al*. 1992), which is an acceptable assumption for the purposes of this investigation.

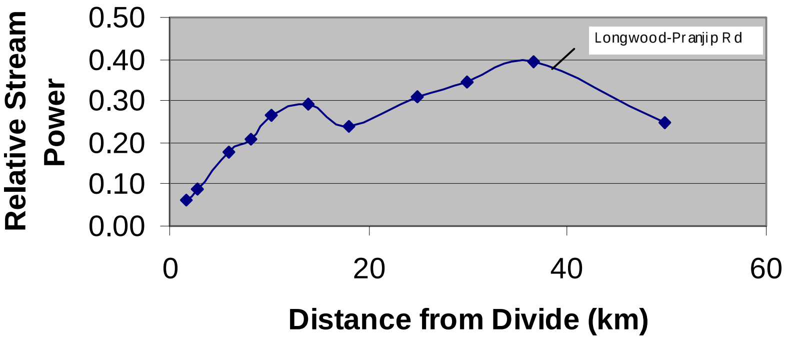


Fig. 6.1. Relative stream power vs stream length

A relative value of stream power was calculated for 11 points along Creightons Creek, starting in the headwaters, by multiplying catchment area by stream-bed slope (both catchment area and stream-bed slope were obtained from 1:25 000 topographic maps). The relative stream power against stream length is plotted in Fig. 6.1.

Figure 6.1 suggests that stream power generally increases downstream, although it appears to decline downstream of the Longwood–Pranjip Rd. The decline in stream power downstream of the Longwood–Pranjip Rd would account for the migration rate of the sand slug declining near this point, but it would not account for migration stopping altogether. It is interesting to note that before flow was diverted to Branjee Creek (below Nelsons Rd) the sand slug in the old Creightons Creek channel had also migrated as far as the Longwood–Pranjip Rd. This observation could be coincidental, or it could indicate that a decline in stream power at this point also stalled sand transport in the old channel.

This analysis assumes that the flow or combination of flows that are primarily responsible for the migration of the sand slug are contained in the channel. If the relevant flows are low flows then this assumption would be valid, but if they are high flows then this assumption may be violated. Due to channel enlargement via erosion of Creightons Creek particularly through the foothills and downstream as far as Drysdale Rd, high flows can be retained in the channel. Below Drysdale Rd, however, the channel is not enlarged and less flow can be retained in the channel; and at high flows this can result in a lower than expected stream power. The reduced flow retained in the channel during high flow events downstream of Drysdale Rd is further lessened by flow losses to anabranches. Hence the lower reaches of Creightons Creek, during high-flow events, cannot contain the discharge predicted using catchment area as a surrogate for discharge; and so stream power in these reaches could be even lower than predicted in Fig. 6.1. This analysis then indicates that the bedload transport rates in Creightons Creek declines downstream of the Longwood–Pranjip Rd. Given that bedload transport rates are relatively high upstream of the Longwood–Pranjip Rd, it must be assumed that sand is accumulating in the bed in this area, as well as moving into anabranches.

The anabranching may also have another effect on sand slug migration in the Granite Creeks. As was noted in Section 3.3.5 in relation to the development of a suspended sediment sampler, it is probable that sand is carried high up in the water column during high flow events. Under these conditions, some proportion of the sand in transport would be carried into the anabranches (e.g. the old Creightons Creek channel) where it would be deposited, effectively removing sand from the sand slug. It was not possible to collect the data required to test this hypothesis during this project (see Section 3.3.5), but it can be speculated that such losses not only occur but may be significant enough to affect the migration rate of the sand slug.

The migration rate of the sand slug in Creightons Creek appears to be insufficient to account for the rate of bedload movement measured and observed during the fieldwork undertaken for this report. The apparently low migration rate may, however, be due to two factors. First, there is reduced stream power (due to a relatively low gradient and discharge) in the reach where the snout of the sand slug is located. Second, the flows diverted into anabranches during high flows may be carrying substantial amounts of sand, effectively removing sand from the slug.

These results have some implications for rehabilitation, the most important of which is that any rehabilitation works carried out in the lowland reaches of the Granite Creeks (i.e. on the flats) should not lead to channel enlargement which might increase stream power and reduce the volume of sand being stored in the anabranches. Similarly every effort should be made to maintain anabranch connections with the main channel to ensure sand can still be delivered to the anabranches for storage.

Evacuation of the sand slug

Slugs do not remain in a stream system forever. It should be expected that the sand slugs in the Granite Creeks will leave these streams eventually. However, given the apparent effect of low stream power and anabranching on the slug migration rate in the lower reaches of Creightons Creek, it appears unlikely that the sand slugs will leave these systems quickly or in the foreseeable future. This is not to say that the slugs will not evacuate from the upper and middle reaches of the Granite Creeks in the coming years. For example, it is possible that the tail section of the Creightons Creek sand slug may have evacuated the middle reaches of Creightons Creek, i.e. between Kellys Bridge and Bartons Lane (see Section 4.8).

It should not be assumed that a reach will immediately return to pre-slug conditions once a sand slug has passed through it. Nicholas *et al*. (1995) noted that ‘the zone of disequilibrium generated by the slug passes downstream at a variable rate, eventually exiting the system, although not necessarily leaving it in a condition similar to that prior to the introduction of the slug’ (Nicholas *et al*. 1995, p. 507). Rutherfurd & Budahazy (1996) noted, where sand slugs had evacuated from some streams in the Glenelg River system, that stream incision had followed. Several factors may have contributed to this response, including commercial sand extraction and the fact that stream incision had been active prior channel aggradation. Madej & Ozaki (1996) have reported pools returning to stream segments previously affected by sand slugs in Redwood Creek. It can be hypothesised, however, that for pools to return to Creightons Creek, conditions conducive to pool formation must exist and one of the most important elements for pool formation in the Granite Creeks appears to be large woody debris (see Section 6.3.4). If, as suspected, large woody debris is vital to the re-establishment of pools in the Granite Creeks following slug evacuation, efforts will need to be made to effectively manage large woody debris in these reaches.

Fig. 6.2. Pranjip–Nine Mile Creek on the ‘flats’. The trunk of a large tree lying across the creek has created a large scour pool.

6.3.4. Improving the in-stream environment on the sand slug

Incidental observations made by the authors during fieldwork suggest that even where sand aggradation is severe some variability of bedform can develop with the introduction of large woody debris (LWD) (e.g. Fig. 6.2). It is probable that LWD would have been an important feature of the Granite Creeks (both physically and biologically) before European settlement, but it has disappeared as a result of removal by authorities and landholders (in the belief that removal would reduce flooding and erosion), and by being buried under sand slugs. In all instances, where LWD is still present it would have been derived from the local riparian zone which is in at least a moderate condition. So, clearly, stream fencing and landholder education would help preserve and regenerate riparian zones which would in turn aid stream rehabilitation. In areas where the riparian zone is so impacted that supply of LWD to the stream is negligible, LWD may need to be sought from elsewhere and placed in the stream. The process by which LWD is reintroduced to streams, particularly those affected by sand slugs, is an emerging area of research, and an experimental study may need to be set up in the Granite Creeks catchments to guide the use of LWD in stream rehabilitation.

7. CONCLUSION

7.1. The Granite Creeks

Activities associated with European settlement in the Granite Creeks catchments, such as clearing of vegetation, agriculture, channelisation and channel dredging and clearing, have initiated erosion heads in the Granite Creeks which have caused extensive channel incision and gullying. While other forms of erosion have also occurred in the Granite Creeks catchments, it is erosion of gullies and streambeds and banks that has produced most of the sediment that now forms sand slugs in the three Granite Creeks studied here. Incision and gullying occurred in the Granite Creeks catchments before European settlement, but it is probable that such incidents were either related to some external stimulus (such as climate change) or, more commonly, to specific local conditions. Erosion in the Granite Creeks catchments over the last 150 years appears to have been synchronised over a wide area and this synchronisation can be attributed to European settlement. The effects of settlement, in terms of the geomorphic effect on the channels, can be likened to a substantial climate change.

The sand slug observed in Creightons Creek is typical of those found elsewhere in the Granite Creeks. The snout of the slug is indistinct, with the completely sanded and unsanded stream segments separated by a transition zone. Stream incision in the middle of Creightons Creek may be indicative of the passing of the sand slug downstream. Sanding along the main body of the sand slug has buried pools and large woody debris, producing a flat sand bed in most reaches.

Because of the nature of erosion and sediment storage in the Granite Creeks catchments there are two main issues that need to be addressed in any rehabilitation program that is developed for the Granite Creeks:

1. minimisation of further sediment inputs. While the main sources of sediment for the sand slugs are no longer active, some erosion is still continuing. Activities responsible for initiating erosion heads today are channel dredging and clearing and uncontrolled stock access. These problems will be best dealt with via landholder education and cooperation. Best practice land management techniques will also be important to minimise gullying that has resulted in the past from the combination of high rainfall totals and low levels of vegetative cover. While the upper catchment would appear to be more fragile and in need of priority action, prevention of erosion head initiation in the lower reaches of the creeks will also be important.
2. management of existing sand slugs. The most important aspect of managing the existing sand slugs is to minimise the migration rate of the snout of the sand slug to protect unaffected downstream reaches. It would appear that natural features of the Granite Creeks (e.g. anabranching, low gradients and discharge) help to slow the snout migration rate at the lower end of these systems. Any management strategies should recognise this and seek to prevent channel enlargement and the restriction of flow to anabranches.

Rehabilitation activities on those sections of the Granite Creeks already affected by sand deposition should focus on the creation of better habitat conditions through the re-establishment of bed features such as pools. Observations made during this study suggest that the reintroduction of large woody debris will assist the development of such bedforms, but further research is required in this area.

7.2 Beyond the Granite Creeks

7.2.1. Methodological outcomes

In the introduction it was suggested that the methods employed during this study might be useful as a template upon which similar investigations in the future could be based. The methods employed here fell into two parts. The first part comprised the historical analysis and the second part consisted of the assessment of current condition. The activities conducted as part of the historical analysis, i.e. deriving evidence of historical stream condition from Land Selection Files, Local Government records, explorers' diaries, etc., could be readily undertaken by someone from the community without previous experience. The only prerequisite for such a person would be the ability to ignore all preconceived ideas and objectively assess the available evidence. As has been demonstrated in this report, archives can be extremely useful sources of information about historical stream condition, with Land Selection Files, explorers' diaries and historical maps proving to be the most valuable resources for this study.

However, assessment of current condition is not a task that could or should be undertaken without technical input. While the techniques applied in the current stream condition assessment (e.g. observation, sediment budget, sediment tracing, scour chains) provided limited information individually, when the information generated by all the techniques was combined and considered with the benefit of technical understanding, a number of useful conclusions were reached.

7.2.2. Final outcomes

The conclusions derived from this investigation have implications for small granitic catchments elsewhere in south-eastern Australia, and for anabranching streams affected by sand slugs. The evidence available for the three streams studied here suggests that a range of activities associated with European settlement have initiated erosion heads that have led to channel incision and gullying, and while this is not new, the fact that activities in the riparian zones of these streams are still initiating erosion heads, is unusual. It is commonly accepted that many streams in south-eastern Australia are now recovering from disturbances initiated by European settlement (Rutherfurd 2000) and it is not widely acknowledged that some activities are still causing stream degradation today, particularly in relatively sensitive environments such as small granitic catchments. While the erosion being caused by recently initiated erosion heads is minor compared to that which occurred historically, it still threatens areas where recovery has commenced, as well as potential rehabilitation sites. Clearly small granitic catchments require careful management from the top to the bottom of the catchment, which in turn requires managers to be aware of threatening activities and to educate land owners accordingly.

While a good deal of research has been carried out on sand slug migration in single-thread channels (e.g. Gilbert 1917; Knighton 1989; Erskine 1994; Rutherfurd & Budahazy 1996), little if any work has focused on migration through multiple channel systems. The anabranching nature of the Granite Creeks, and the stream systems' subsequent response to sand slugs, suggest that anabranching streams may have the same effect on sand as they do on water moving through the systems, i.e. during flood events they distribute material out onto the floodplain via the anabranches. While water distributed on the floodplain will evaporate, find its way back into the main channel further downstream, or enter groundwater stores, sand enters long-term storage on the floodplain. Not only is sand lost to the floodplain but the rate of migration of the sand that remains in the main channel is slowed, due to both reduced discharge and declining stream gradients. These observations are based on the Granite Creeks but the evidence suggests that, in general, anabranching streams play an extremely important role in removing and storing both fine and coarse sediment from streams and rivers, and as such must be preserved from modification, to protect downstream reaches from sedimentation.

Observations of the changes in stream condition brought about by sand slug development in the Granite Creeks indicate that all aspects of the stream environment are affected, from stream hydrology and hydraulics to stream chemistry and ultimately in-stream habitat. The sanding of the stream bed has filled deep pools and removed all bed variability, leaving a shallow rectangular channel. The change in channel shape and substrate has altered the stream hydrology and hydraulics. Low flows now sink into the deep sand bed, reducing the frequency of surface flows during the summer months. The change in channel shape has reduced channel resistance (with both bedforms and large woody debris being largely submerged by the sand) and thus has probably resulted in increased in-stream velocities. The loss of deep pools has reduced the areas of low velocities in the creeks to a minimum.

Stream chemistry has been affected in several ways. The sand bed acts as a filter producing a clear water stream where previously turbid water would be found. This is compounded by the loss of pools which would provide an environment in which tannins would leach out of vegetable material and stain the water. Clear, shallow water has two effects: it makes fish and other stream inhabitatants more vulnerable to predation, and it facilitates water temperature changes.

Finally, the sand slugs have submerged two important habitat elements: large woody debris and the original stable substrate. The habitat that remains is an unstable sand bed that is mobile, either by saltation or by dune migration at all flows except summer–autumn baseflows. The complete change in the stream environment brought about by the development of sand slugs in the Granite Creeks is likely to have dramatically changed the ecology of these streams also. This hypothesis is partially supported by work conducted in Creightons Creek in the late 1980s. O’Connor (1991) found that the sanded sections of Creightons Creek were species-poor during high discharges, compared with low-flow periods. Further investigation of the ecological impact of the sand slugs on the Granite Creeks is now underway.

The Granite Creeks Project is a case study which also has implications for catchment management activities more generally. It shows the importance of a rigorous analysis of the history of a catchment in laying the foundation for rehabilitation. All too frequently, unsubstantiated anecdotes and casual observations are accepted uncritically as an accurate representation of the history of an area. The history must be researched with the same rigour as is used in any branch of science.

In the management of river channels, individual sections cannot be treated in isolation from the whole. In the Granite Creeks, individual landholders have intervened in the stream channel to solve their local problems and have unwittingly set in train problems both for their downstream and their upstream neighbours. Effective rehabilitation of these systems requires that individual riparian landholders subjugate their own local interests in favour of the integrity of the whole channel system. To achieve this coordination along the length of the channel is a challenge for catchment managers.

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DNRE Files:

85/22219 — Castle Creek

2020 WW (62/19071) — Castle Creek (RWC Watercourse File)

Goulburn-Murray Water Files:

2020 WW — Creightons Creek (RWC Watercourse File)

Land Selection Files

The following files are held by the Public Records Office of Victoria. The notation used is VPRS/unit/file. e.g. PROV VPRS 626/603/16871 refers to PROV, VPRS 626, unit 603, file 16871.

Creightons Creek, the Flats:

PROV VPRS: 626/603/16871, 16872; 626/605/16966, 16968, 16972, 16982; 626/614/17419 (Branjee); 626/640/19003; 626/2119/4694; 626/2068/2725; 626/2097/3867, 3866; 626/2064/2576; 626/2121/4747 (Longwood); 626/2047/1871; 626/2123/4823; 626/2015/152; 626/2084/3346; 626/2071/2820; 626/2080/3170, 3171; 626/2029/987; 629/62/11338, 11339 (Molka); 626/2056/2140; 626/2141/5567; 626/2055/2134; 626/2096/3793, 3798, 3801; 626/2093/3713; 626/2145/5728; 626/2144/5689; 626/2093/3708; 626/2054/2081; 626/2119/4671, 4673, 4692; 626/2137/5435; 626/2121/4740; 626/2142/5601, 5606; 626/2129/5116, 5120; 626/2132/5232, 5233; 626/2134/5308; 626/2140/5540; 626/2139/5528; 440/1878/284; 5357/5502/2477; 5714/364/458; 5714/344/288; 5714/501/1050 (Pranjip).

Creightons Creek, the Hill Country:

PROV VPRS: 626/21/1315; 626/43/3019; 626/44/3079; 626/23/1486; 626/54/3752; 626/61/4280, 4281; 440/20/2946; 5357/583/296; 5357/587/337 (Garratanbunell); 626/2097/3839; 626/2026/815; 626/2069/2731, 2760; 626/2146/5751; 626/2071/2815, 2816; 626/2095/3774; 626/2043/1697; 625/595/48050; 626/2044/1743; 626/2056/2152; 626/2014/113; 626/2022/636; 626/2086/3494; 626/2039/1495; 626/2066/2640; 625/365/25452; 626/2021/589; 626/2035/1271; 626/2082/3259; 626/2061/2476; 626/2020/539; 626/2017/315; 626/2021/610; 626/2025/782; 625/397/28381; 626/2022/620; 625/194/11996; 626/2058/2287; 626/2110/4368; 439/274/305; 5714/305/101; 5714/1674/1008; 5714/351/281 (Longwood); 626/2025/787; 626/2026/814; 626/2092/3665; 440/1877/261; 5357/5428/2786; 5357/5435/0230; 5357/5483/2035; 5357/5528/2258 (Ruffy).

PTC Bridge Files:

Somerton to Wodonga Line, Index: 143, 150, 160 & 186.

Local Government Records:

Strathbogie Shire Council Bridge Plans: 002, 018, 019, 022, 038, 054, 076, 099, 129, 135, 168, 182, 294, 331, 518, 529, 554 & 554-3.

APPENDIXES

Appendix A: Recollections of Streams in North East Victoria
By Mr Robert (Bert) McKenzie

The following letter was written by Bert McKenzie, who resided on the Strathbogie Ranges for most of the 20th century. The original letter was handwritten and difficult to read. Question marks indicate that a word or phrase could not be deciphered. Italics indicate words added by the translator.

Recollections of Streams in the North East Victoria. By Mr Robert (Bert) McKenzie

Years 1906 to 1913

All the creeks of the Tableland (i.e. Terip, Ruffy, Dropmore, Caveat, Tarcombe and Kobyboyn) were packed with Black fish and Silver minnows. All were crystal clear and it was possible to see to the bottom , down to six or eight feet at midday and (as a cousin and I used to do), it was possible to grind up a few worms with sand and drop them in the pool. We would fish for the bigger ones. Fourteen inches was our best. Most of our haul would be round 13 inches down to 9 inches. However, someone caught one 15 inches.

In 1912 or 1911, Mr Jimmy Hobart acquired, from Ballarat, 2000 brown trout and, from somewhere, 6 tench which were all released at the Boathole, Hughes Creek, Ruffy. They spread and bred rapidly down stream and were being taken up to seven pounds by 1914.

In 1912, 2000 rainbow(trout) were released.

In the spring of 1914, I landed my best some twenty yards behind me and about the same *height..???* and by the autumn was handling fish up to four and a half pounds.

Prior to this, in 1903, my father had taken me down twice to the Dropmore on the lower Hughes Creek, just a mile above the Homestead, and using worms and caught small cod (Trout Cod) up twelve inches and saw my father take several of two and three pounds.

On a later trip with a party of four, everybody caught cod up to six pounds and every hole had six to ten inch fish galore if worms were used.

Our next trip in 1913 was a disaster. A cousin was killed and virtually ended our Cod trips.

The Hughes Creek for two miles above Dropmore up until 1916 was a slow running stream with a series of very deep holes mostly edged with Capungi (*Phragmites?)* reeds. In 1916, a flash flood ripped through and tore the creek bed down to bedrock and left a long channel of sand and in my opinion swept away the Trout Cod breeding grounds in those Capungi edged pools for the whole of the Hughes Creek.

Whether or not that flood carried the whole of the Cod population down into the Goulburn and the Nagambie Lake area, I do not know. But around 1918 to 1924, Nagambie was the Mecca for Cod fishermen from all over and in that period and was probably the supply area for all the Trout Cod that inhabited the National Channel which filled Waranga Basin and the Wilson Channel feeding Shepparton, Tatura, etc. Even the smaller channels carried small Cod and an occasional four pound Catfish. I had Cod to Four and a half pounds from both the National and Wilson. Old Nagambie residents could probably supply the exact dates of this era when suddenly the whole catfish population were wiped out in the Goulburn River system. The same thing happened in the Murray River system, I think after the second stage of the Hume Weir or when???

Anyhow that flash flood was the end of the Trout Cod in the Hughes Creek in the Dropmore area. I certainly caught a few while fishing for trout in 1919 to 1934 or 1924. These were mainly around the four to five and a half pound weight and an odd two pounder, suggesting that there may have been some fluke breeding.

In 1920/21 we had one hundred acres rented around the Dhuringile Homestead, Toolamba, hence the fishing in the channels. At the same time the home base was one farm on the Sevens Creek followed by one on the Castle Creek in the Branjee area.

The Castle Creek had quite a lot of Macquaries and Blackfish and the Seven Creeks, from the farm, five miles from Euroa was loaded with small Trout Cod, Macquaries and Blackfish. The Seven Creeks in drought years often stopped running from Euroa down, concentrating the fish in the deeper pools and for a few weeks the fishing was fast and furious. Fish in the main were Trout Cod and Macquaries to two pounds. In those days there were miles of those waters, all heavily stocked with trout cod (small) and Macquaries likewise.

In those days it seemed impossible that mere fishing would overtake supply in the Goulburn River which I fished at Molesworth, Cathkin, Alexandra and Thornton. In these stretches of the Goulburn in those days at Christmas and Easter, it was estimated that the campers numbered 500 to the mile of river. They came from Melbourne by train and the local farmers carted their camping gear to the river and I have no doubt profited considerably by doing just that. It would seem at the time that it would be utterly impossible to eliminate the Trout Cod and the Macquaries from the waters they inhabited. But around 1922 or 1923, the old Eildon Weir was built and acted, I believe, as a settling dam and the water became crystal clear and I believe the smaller fish became easy prey for the large Trout Cod and Redfin then inhabiting the river.

In the Eildon itself, various stretches were teaming (Big River) with small Macquaries and in the UT Creek area, I landed at least 20 small cod proclaiming at least two breeding grounds for Trout Cod and Macquaries.

The Cod fishing deteriorated in the Goulburn and the Macquaries to a lesser extent, but after the greater Eildon Weir was built in the late Forties, both fish have been practically wiped out, at least as a fishing proposition.

In so far as the Macquaries are concerned, the breeding grounds have been destroyed by the colder water or siltation. I believe that where the main streams enter our reservoirs, new breeding grounds will have to be established not by releasing fry but establishing natural breeding places by the use of spawn or eggs in a natural setting in the river beds to which mature fish will return when their turn comes to drop their spawn. From what some of the older residents have told me in the Riverina, streams completely dried up in severe droughts (before Samuel McCackie *spelling* built dams on them) but the small cod and big appeared back in the streams as soon as those streams began to flow again. Their breeding grounds would be headwater streams that did not stop flowing.

Appendix B: Plots of Stream Cross-sections Measured at the Hume Freeway and the North-Eastern Railway Line

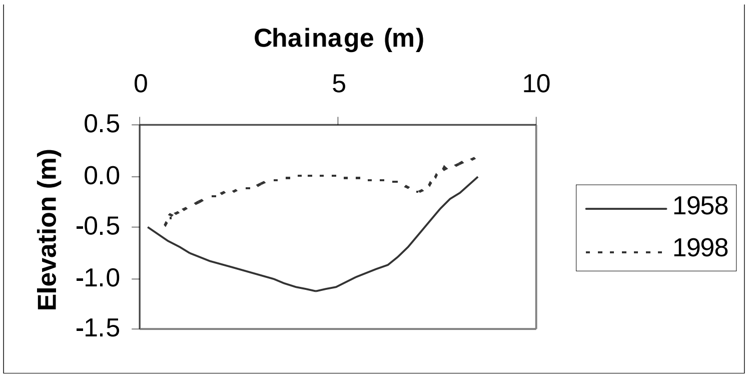


Fig. B1. Bed elevations for Pranjip Creek at the Hume Freeway for 1958 and 1998

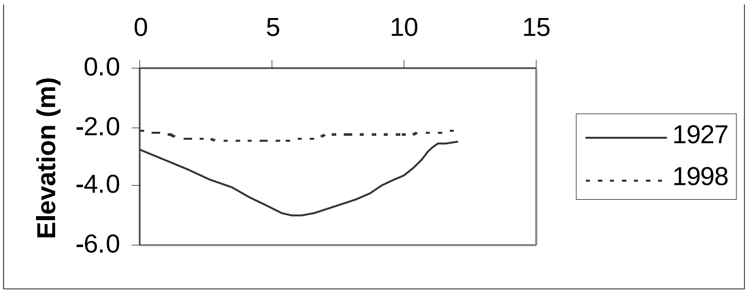


Fig. B2a. Bed elevations for Nine Mile Creek Span A at the Hume Freeway for 1927 and 1998

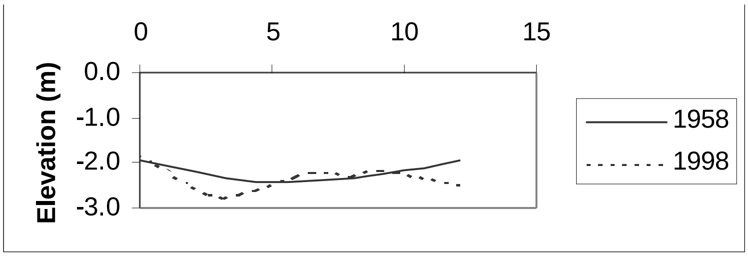


Fig. B2b. Bed elevations for Nine Mile Creek Span B at the Hume Freeway for 1958 and 1998

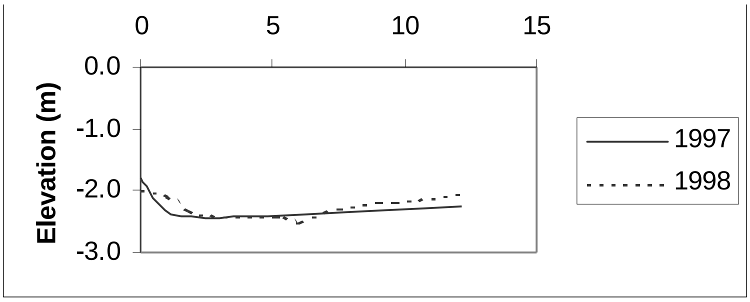


Fig. B2c. Bed elevations for Nine Mile Creek Span C at the Hume Freeway for 1997 and 1998

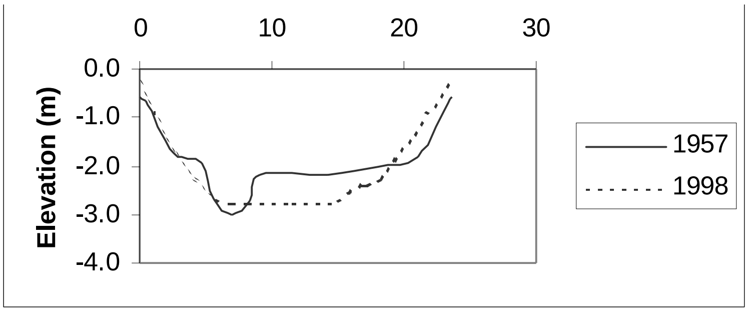


Fig. B3. Bed elevations for Creightons Creek at the Hume Freeway for 1957 and 1998

Fig. B4. Bed elevations for Castle Creek at the Old Hume Highway for 1938 and 1998 (upstream and downstream)

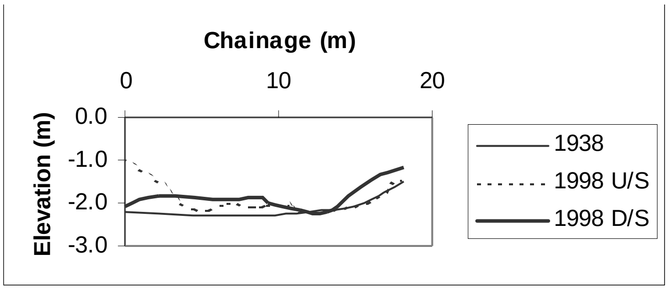


Fig. B5. Bed elevations for Pranjip West bridge over Pranjip Creek at the railway line for 1871, 1922, 1947, 1995 and 1998

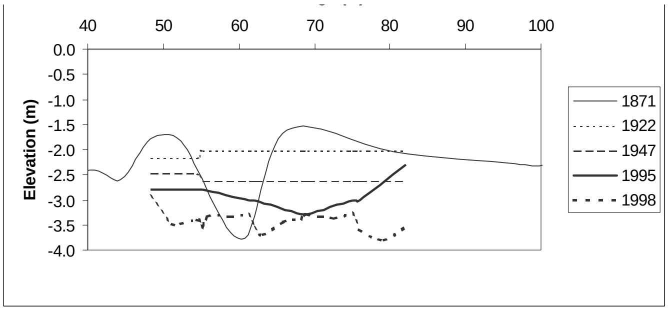


Fig. B6. Bed elevations for Pranjip West Bridge over Nine Mile Creek at the railway line for 1871, 1926, 1995 and 1998

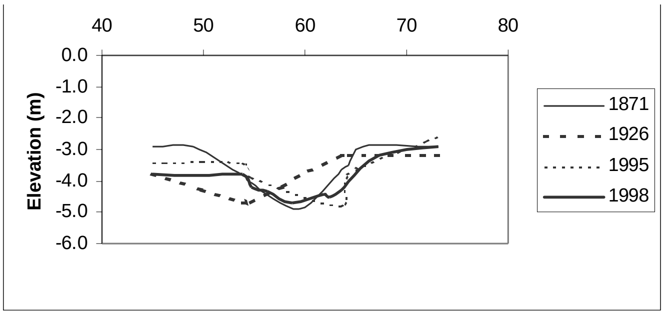


Fig. B7. Bed elevations for Creightons Creek at the railway line for 1871, 1872, 1922, 1995 and 1998

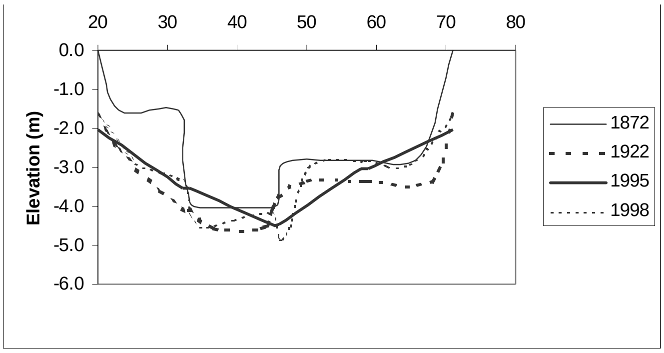
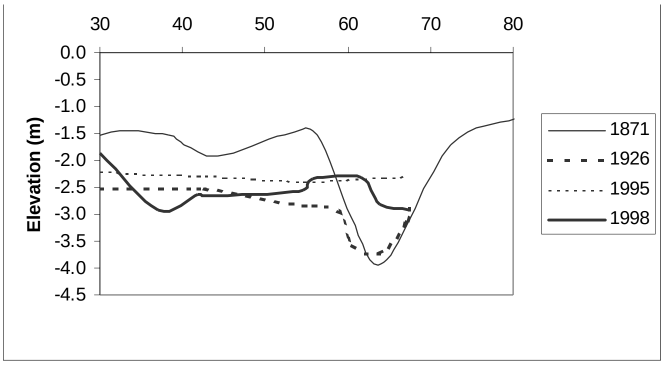


Fig. B8. Bed elevations for Castle Creek at the railway line for 1871, 1926, 1995 and 1998



APPENDIX C

Table of results from scour chain monitoring

	Date checked					
	15/9/98	5/10/98	10/11/98	14/12/98	9/2/99	11/5/99
Castle Ck						
Bamford						
Scour 1	E	16 cm	8 cm	22 cm	3 cm	0 cm
Deposit 1	4 cm	16 cm	10 cm	13 cm	1 cm	2 cm
Scour 2	NL	NL	E	11 cm	0 cm	0 cm
Deposit 2	NL	NL	6 cm	4 cm	0 cm	0 cm
Kubeil						
Scour 1	5.5 cm	8.5 cm	5 cm	0 cm	0 cm	0 cm
Deposit 1	10 cm	7 cm	4.5 cm	7 cm	0 cm	0 cm
Scour 2	0 cm	10 cm	0 cm	10 cm	0 cm	1 cm
Deposit 2	0 cm	8 cm	3 cm	11 cm	1 cm	0 cm
Creightons Ck						
Carlsson						
Scour 1	0 cm	NL	NL	NL	NL	NL
Deposit 1	10 cm	NL	NL	NL	NL	NL
Scour 2	0 cm	10 cm	2 cm	3 cm	2 cm	1 cm
Deposit 2	15 cm	3 cm	0 cm	0 cm	3 cm	15 cm
Caldwell						
Scour 1	NL	NL	NL	NL	24 cm	0 cm
Deposit 1	NL	NL	NL	NL	5 cm	0 cm
Scour 2	0 cm	NL	28 cm	NL	27 cm	5 cm
Deposit 2	20 cm	NL	18 cm	NL	23 cm	8 cm
Nine Mile Ck						
Cameron						
Scour 1	7 cm	13 cm	6 cm	0 cm	3 cm	0 cm
Deposit 1	10 cm	13 cm	8 cm	4 cm	3 cm	0 cm
Scour 2	5 cm	18 cm	0 cm	2 cm	4 cm	3 cm
Deposit 2	8.5 cm	14 cm	0 cm	4 cm	0 cm	2 cm
Threlfall						
Scour 1	E	13 cm	0 cm	0 cm	0 cm	0 cm
Deposit 1	12 cm	12 cm	0 cm	0 cm	0 cm	0 cm
Scour 2	0 cm	4 cm	1 cm	0 cm	0 cm	0 cm
Deposit 2	0 cm	0 cm	1 cm	0 cm	0 cm	0 cm

E: Error, chain indicated change that was physically impossible or highly improbable (assumed to be caused by error in placement or reading). NL: Not Located, chain could not be found.

OTHER PUBLICATIONS OF

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The Cooperative Research Centre for Freshwater Ecology publishes a range of books, guidelines, newsletters, technical reports and brochures. These publications can be ordered from the Cooperative Research Centre for Freshwater Ecology at its Albury centre, by phoning 02 6058 2310, or by email to enquiries@mdfrc.canberra.edu.au.

Many reports are also available on our web site at http://freshwater.canberra.edu.au

Books

CRC for Freshwater Ecology. 1997. *Living on Floodplains*. Limited copies available.

Brochures

- Billabongs, floodplains and river health
- Chaffey Dam project
- Effects of a drying phase on the ecology of Menindee Lakes
- Environmental flows for the Campaspe River
- Lowland rivers
- Providing an ecological basis for the sustainable management of Menindee Lakes
- Rivers and fish in stress
- Sustainable rivers: the Cap and environmental flows

Guidelines

Lawrence, I. & Breen, P. 1998. *Design Guidelines: Stormwater Pollution Control Ponds and Wetlands*.

Identification Guides

The CRC for Freshwater Ecology sells 31 different Identification Guides to the Invertebrates of Australian Inland waters, including Hawking, J. & Smith, F. 1997. *Colour Guide to Invertebrates of Australian Inland Waters*. ID Guide no. 8. ($24.00)

Technical reports

Cottingham, P. 1999. *Scientific Forum on River Condition and Flow Management of the Moonie, Warrego, Paroo, Bulloo and Nebine River Basins*.

Cottingham P., Whittington J. & Hillman, T. 1999. *Riverine Management and Rehabilitation Scoping Study*.

Cottingham, P. & Hart, B. 2000. *Nutrient Loads from the Macalister Irrigation District*. Technical report no. 5/2000.

(continued overleaf)

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Cullen, P., Whittington, J. & Fraser, G. 2000. *Likely Ecological Outcomes of the COAG Water Reforms*. Also on the Web at http://freshwater.canberra.edu.au (then click Publications; then clickTechnical Reports)

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Whittington, J. 2000. *Technical Review of Elements of the WAMP Process of the Queensland DNR.*