NATIONAL EUTROPHICATION MANAGEMENT PROGRAM

Physical and nutrient factors controlling algal succession and biomass in Burrinjuck Reservoir

Technical Report
January 2000

Ian Lawrence[1], Dr Myriam Bormans[2], Dr Rod Oliver[2],
Gail Ransom[1], Dr Brad Sherman[2], Dr Phillip Ford[2], Dr Bob Wasson[3]

1. CRC for Freshwater Ecology
2. CSIRO Division of Land and Water
3. Centre for Resources and Environmental Studies

Cooperative Research Centre for Freshwater Ecology
Ph: +61 02 6201 5168
Fax: +61 02 6201 5038
e-mail: pa@lake.canberra.edu.au
http://freshwater.canberra.edu.au

ISBN: 0967704844

Burrinjuck

Bare trees must forever shiver
In this inundated land,
Where the moonlight-fashioned shadows
Interlaced with silver bands
Steal across the silent water,
Light and darkness hand in hand.
Here the red hills old, untroubled,
Curtained by the wispy fogs,
Hear the boo-boo chime the hours
Oer the throbbing song of frogs,
Whilst sister rivers, sold to bondage,
Victims of the master race,
Chained to concrete walls forever,
Are bloated and defaced.

Stuart Hamilton Hume

From *He Heard the River Calling, The Life and Times of Stuart Hamilton Hume*, Compiled and edited by Jennifer Hume Macdougall 1996, Published by Jennifer Hume Macdougall

Permission of the Publisher to incorporate the poem is gratefully acknowledged.

Acknowledgments

This research is part of the National Eutrophication Management Program (NEMP) which aims to develop an understanding of the causes of excessive algal activity in Australian fresh and estuarine waters, and to help managers use that understanding to reduce algal blooms. The project is jointly funded by the Land and Water Resources Research and Development Corporation (LWRRDC) and the Murray Darling Basin Commission (MDBC).

This research was supported by the Australian Government's Cooperative Research Centre Program through the Cooperative Research Centre for Freshwater Ecology (CRCFE) and the CSIRO Division of Land and Water.

The CRCFE exists to improve the condition of Australia's inland waters. It provides ecological understanding to improve inland waters through collaborative research, education and resource management.

It is a collaborative venture between:

ACTEW Corporation
CSIRO Land and Water
Dept. of Land and Water Conservation, NSW
Dept. of Natural Resources, Qld
Dept. of Natural Resources and Environment, Vic
Environment ACT
Environment Protection Authority, NSW
Environment Protection Authority, Vic
Goulburn-Murray Rural Water Authority
Griffith University
La Trobe University
Lower Murray Water
Melbourne Water
Monash University
Murray-Darling Basin Commission
Murray-Darling Freshwater Research Centre
University of Canberra
Sunraysia Rural Water Authority
Sydney Catchment Authority

The contribution to this research by the CSIRO Division of Land and Water, and by Dr Bob Wasson, Director of the Centre for Resources & Environmental Studies, ANU is gratefully acknowledged.

The research was substantially based on data collected by Commonwealth, ACT and NSW State agencies over the period 1976 to 1998. The support of ACT Electricity & Water, the NSW Department of Land & Water, and Environment ACT in providing streamflow and water quality data, and in assisting in resolution of archival and quality control aspects of the data, is gratefully acknowledged.

Management implications of the research findings were developed in association with reservoir managers from around Australia, through a series of Reservoir Managers Workshops. The contribution of the managers, and the support provided by LWRRDC, Goulburn-Murray Rural Water Authority and CSIRO Division of Land & Water in facilitating the Workshops is gratefully acknowledged.

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Background

The National Eutrophication Management Program was established in 1995 by the Land and Water Resources Research Corporation and the Murray-Darling Basin Commission, to provide the scientific underpinning necessary for the effective management of algal blooms.

The Burrinjuck algal succession research project was one of a large number of projects funded in a multi-pronged approach to research. The primary focus of the project has been analysis to better describe the factors driving algal growth in reservoirs and determining algal composition in reservoirs.

Algal blooms are now a widespread and recurrent reservoir management problem, having the potential for severe environmental, social and economic impacts. An important component of the Burrinjuck project has been the development, in collaboration with managers, of guidelines that enable better management of reservoirs in limiting the incidence and severity of algal blooms.

Factors determining algal growth and composition in reservoirs

The availability of nutrient, light and mixing conditions, the water residence time and temperature are the major determinants of algal growth and composition. Both biomass levels and composition may be further modified by grazing by zooplankton. The interplay of these factors are complex and variable, even within a single reservoir, reflecting latitude; catchment land uses and management; reservoir depth, shape and drawdown conditions; and seasonal climatic variability.

Physical conditions prevailing within Burrinjuck Reservoir

A range of important vertical and longitudinal physical partitioning conditions have an impact on nutrient pathways and on algal biomass and composition. During early summer, the surface waters of lakes are heated by adsorption of solar radiation, progressively becoming warmer than the deeper waters. The Burrinjuck analysis indicated that there is a strong pattern of vertical thermal gradients over summer periods, partitioning the Reservoir into a surface epilimnion zone (or surface mixed layer) and a deep hypolimnion zone (or bottom waters), separated by a thermocline.

With cooling of the mixed surface layer during autumn, the depth of the surface mixed layer increases, progressively entraining the cool bottom waters, until the full Reservoir depth is mixed (reaches a uniform temperature). This transition from a stratified to a fully mixed condition is sometimes referred to as reservoir turnover.

There is also a strong pattern of longitudinal partitioning of water, with well mixed inlet zones in the upper shallow reaches, and stable stratified zones across the deeper middle and downstream reaches during summer months, but fully mixed waters over the late autumn to spring months.

The attenuation of light (by absorption and scattering) through water with depth, limits the zone in which algal growth is possible to the surface layer (defined as the euphotic depth). The extent of light penetration may be further reduced as a result of elevated turbidity. The ionic composition of Burrinjuck waters is predominantly sodium. As a result, the Reservoir is characterised by sustained high levels of fine suspended clay and organic particles which limit light penetration into the water column, thereby limiting light availability for algae other than those able to maintain a position close to the surface.

There is a seasonal pattern of light conditions, with low euphotic depth and deep mixed layer depth in winter, and higher euphotic depth and shallower mixed layer depth in summer.

Nutrient availability within Burrinjuck Reservoir

In addition to sufficient light the algae also require nutrients. Although a wide range of nutrients are required it is the availability of nitrogen and phosphorus that usually regulate algal growth when light conditions are sufficient.

The Burrinjuck research identified seven possible pathways for nutrient transfer to the surface mixed layers, with several pathways potentially contributing at any one time, and with switching between pathways over time dependant on physical mixing conditions, reservoir outlet arrangements and reservoir drawdown. The research indicates that in Burrinjuck:

1. the ’direct pathway’ (algal up-take of nutrients directly discharged into reservoirs) is the least likely nutrient pathway for many Australian reservoirs;
2. the ’internal loading related pathways’ (release of nutrients from the sediments as a result of elevated organic loading) are the most likely nutrient pathways.

The algal growth stimulus provided by the transfer of nutrients may be further modified by the nutrient bio-availability. Some forms of nutrients are not bio-available, others are not directly bio-available, while inorganic forms are assumed to be directly bio-available. The level of bio-availability of organic carbon is a critical factor in determining the microbial growth rates potentially resulting in reducing conditions in sediments. Organic carbon also exhibits a range of bio-availability levels from low rates of bio-availability (refractory) to high rates of bio-availability (labile) forms.

The research identified that reservoir sediments are the major pool of nutrients, which largely mediate (via internal loading) the availability of nutrients for algal growth. Consequently, an understanding of sediment redox processes is critical to an understanding of the conditions and rates of release of nutrients to overlying waters. The rate of supply and deposition of organic carbon (from external loads) is the major driver of reducing conditions. Thermal stratification significantly exacerbates the reducing potential due to the barrier to oxygen transfer from the atmosphere, through the water column to the sediments.

It appears that it is the availability of nutrients which largely determines algal biomass in Burrinjuck Reservoir, so it appears likely that neither light limitation nor grazing have a significant impact on biomass levels.

Algal composition and succession within Burrinjuck Reservoir

Algae which are dependent on mixing currents for circulation through the euphotic zone are disadvantaged under the low mixing conditions which commonly prevail over summer periods across Australian temperate regions. Consequently, mixing conditions are an important factor influencing algal composition and succession.

Algal composition and succession patterns in Burrinjuck reflected seasonal flow, temperature, mixing and nutrient factors, as follows:

1. elevated levels of inflow and associated mixing, and silica concentrations in Spring, with dominance of Diatoms under these conditions;

2. reduced inflow and thermal stratification (reduced levels of mixing and nutrients) over summer, with a shift in dominant algae to greens in early Summer;

3. potential nutrient limitation and depressed mixing regimes in late summer, with a shift in dominant algae to non-N-fixing blue-green algae (under high ammonia or reducing conditions) or motile forms of green algae (under low ammonia—high nitrate conditions), or N-fixing blue-green algae in situations where nitrogen becomes limiting over the summer period.

While a substantial amount of zooplankton data had been collected, the level of speciation was insufficient to assess the potential impact of grazing on algal biomass and composition.

Response to reduction in nutrients discharged in Canberra sewage effluent

In 1978, the ACT authorities commissioned a new sewage treatment plant, incorporating provision for removal of both phosphorus (97%) and nitrogen (95%). The plant phosphorus removal facility was commissioned over the period 1978 to 1980, with operation of the nitrogen removal facility for limited periods during 1980 to 1983.

As noted above, the research identified a complex range of factors determining Reservoir algal responses and processes, such that it is difficult to disassociate one factor from the cumulative and interactive range of factors. Never the less, as a result of the analysis, it is now possible to make a number of observations with reasonable confidence. In the period post 1983, there was:

1. a significant reduction in phosphorus concentration and change in nutrient forms;
2. a substantial diminution of redox conditions in bottom waters during the non nitrogen removal periods;
3. a substantial reduction in algal biomass, except for periods of low Reservoir levels;
4. a shift in algal composition, from dominance of blue-greens over summer periods to greens and flagellated algae.

The research highlighted the importance of substantial reduction in phosphorus and BOD, and the provision of a well nitrified effluent, in contributing to these changes. The re-occurrence of blue-green algal blooms under conditions of Reservoir drawdown point to the continued significant levels of organic carbon loading from the catchment. The provision of an effluent high in nitrate (NO_3) appears to buffer the affect of the organic carbon under conditions other than low Reservoir operating levels. As noted below, the management objective needs to be one further reducing the organic loading from the catchment in the future.

Reservoir management

As part of the Burrinjuck algal research project, Reservoir Managers' Workshops were undertaken with a view to:

1. transferring the new understanding of the major factors driving algal growth and composition in reservoirs;
2. identifying the major implications and operational issues for reservoir managers;
3. identifying the range of possible reservoir algal management options;
4. developing management guidelines and identifying related information needs.

Implications of findings for management

Management of algal blooms is strongly related to other water quality management considerations: thermal pollution; DO; metals; organics; pathogens. Consequently, there is a need to consider algal management in association with other in-reservoir water quality and water supply objectives, and information guiding reservoir management responding to all of these objectives.

Reservoirs are just one line of defence in the management of algae, taste and odour, pathogens, etc. There is a need for an integrated strategy together with catchment management, stream management, water supply treatment, and consumer awareness and management responsibilities.

The new understanding of pathways and processes points to the adoption of different management options requiring new supporting information and guidelines, for example, sources and management of organic carbon, inlet zone management, criteria regarding potential for drawdown impacts, and guidelines on selection of outlet level.

The research highlights the complexity of different and changing pathways and processes, and the need to provide the reservoir manager with information necessary to determine prevailing processes and appropriate management responses. How is this information to be packaged such that it is accessible and relevant and covers a diverse range of conditions?

Management options

In the light of the information on processes, a wide range of options for better managing algal blooms was identified. They included:

1. Improved information related strategies, including raising awareness of community (living with blue-green algae), and managers (pressure-state pathways and processes and management options).
2. adoption of catchment management strategies, including at-source management, interception and in-stream management strategies, to address loading on the Reservoir.
3. reservoir management strategies:
    - inlet zone management strategies;
    - control of draw-down rates and minimum reservoir levels;
    - selection of off-take level;
    - sediment redox management;
    - mechanical aeration and oxygenation of bottom waters;
    - bio-manipulation;
    - turbidity: sediment re-suspension management;

- chemical coagulation of suspended soil particles or precipitation of nutrients;
- use of algacides.

Management information needs

In order to select options appropriate to local conditions, and to apply the options in operational terms, the Reservoir Managers Workshops identified the need for a range of information, including:

1. better definition of management objectives, particularly in the case of multi-purpose reservoir operation;
2. guidance on techniques for assessment of risk of algal bloom occurrence for local reservoirs and changing seasonal conditions;
3. simple tools for determining the dominant pathway/process for local reservoirs;
4. information on the range of possible options, including guidelines on the selection of options and decision support tools guiding reservoir operations;
5. guidance on techniques for assessment of performance of options.

Management guidelines

The preliminary development of management guideline frameworks has been undertaken as part of the Burrinjuck project. They include an outline of Reservoir and Catchment Management Guidelines, and are included in the Reservoir Managers' Workshops Report (Lawrence et al. 2000).

Monitoring needs

In order to respond to the information needs and reservoir operation decision guidelines, a range of monitoring programs are required. Monitoring covers operations related monitoring, performance assessment related monitoring, and system understanding (research) related monitoring. In addition, the research pointed to a number of limitations of current programs that need to be addressed. The monitoring needs are listed in Chapter 7 of this Report.

Research needs

The new understandings regarding algal processes require further elaboration and testing, particularly related to their translation into reservoir management decision support tools. Research needs include:

1. Further description of the form and pattern of delivery of nutrient and organic material to reservoirs, and sedimentation patterns in the the inlet and shallow depositional zones, including the impact of rapid drawdown.
2. Development of onditions and processes associated with nutrient transfer from bottom waters to surface waters during periods of stratification, including spatial and temporal scale aspects.
3. Development of improved models for estimating general mixing and light conditions, including consideration of temperature stratification, wind mixing, particle aggregation, and photosynthetic pigments of natural waters.
4. Examine the role of different forms of nitrogen, and critical light requirements of Cyanobacteria and microalgae, to develop a more reliable basis for predicting the influence of mixing and turbidity on their growth.
5. Examine the environmental conditions influencing the growth of benthic algae and their impact on nutrient and carbon dynamics.
6. The development of a reservoir classification system as the basis for translation of broadly based management option guidelines to local condition.
7. The development of simple dynamic models enabling managers to link reservoir algal responses with catchment runoff and stream flow and nutrient delivery processes, and reservoir drawdown and discharge level factors.

Chapter 1

Background and purpose of research

1.1 National Eutrophication Management Program

The National Eutrophication Management Program (NEMP) was established in 1995 by the Land and Water Resources Research Corporation and the Murray-Darling Basin Commission to provide the scientific underpinning necessary for the effective management of algal blooms.

Burrinjuck Reservoir was selected as one of a large number of NEMP projects, in view of the extensive streamflow, water quality and algal data base available for the Reservoir, covering the period 1976 to 1998; and in view of the significant reduction (90%) in phosphorus loading on the Reservoir in 1978, resulting from the commissioning of a nutrient removal wastewater treatment plant in Canberra. The Project was undertaken by the Cooperative Research Centre for Freshwater Ecology, in association with the CSIRO Division of Land & Water. Dr Bob Wasson, initially from CSIRO and later from the Australian National University, was also a contributor to the Project.

1.2 Research objectives

Objectives of the Project comprised:

1. To provide an enhanced understanding of the relationship between reservoir inflow, nutrient loading, mixing and drawdown and algal biomass and composition, for the period 1976 to 1996. In view of the re-emergence of algal blooms in the period 1997/1998, the study was later extended to include this period.
2. To collate a valuable and long term reservoir physical, chemical and biological water quality data set.
3. To develop, in association with reservoir managers, guidelines on reservoir management practices.

1.3 Outline of the Report

Chapter 2 summarises:

1. the Reservoir details and history in respect to volume, surface area, and external water, nutrient and organic loads;
2. the in-reservoir water quality;
3. the catchment details and history in respect to area, land use, population growth, wastewater management.

Chapter 3 describes the physical mixing and light conditions prevailing in the reservoir for the period 1976 to 1998, and examines the factors determining these responses, including inflow temperature and discharge arrangement.

Chapter 4 examines the pathways and processes determining the availability of nutrient to algae in surface waters, the bio-availability of nutrients, the role of sediments, and the role of external loads in modifying nutrient pathways and supply rates.

Chapters 5 and 6 examine the factors determining algal biomass and composition, including mixing, light availability, and nutrient availability.

Chapter 7 considers the implications of the findings for reservoir and catchment management.

Management options and guidelines are addressed in a separate report, *Factors controlling algal growth and composition in reservoirs* (Lawrence et al. 2000).

Chapter 2

Reservoir and catchment description

2.1 Description of Burrinjuck Reservoir

Construction of Burrinjuck Dam (originally Barren Jack) commenced in 1907, with commencement of storage in 1913. The Reservoir was designed as an irrigation storage servicing the Murrumbidgee Irrigation Area. The uses of water from the Murrumbidgee River downstream of the Dam were later extended to include the South Western Tablelands Water Supply Scheme.

Rapid growth in the Murrumbidgee and Colleambally Irrigation Areas through the 1960s resulted in greater annual abstraction of water from Burrinjuck for irrigation water supply purposes than pre 1960. Diversion of part of the Snowy River to the Murrumbidgee River at Gundagai (via Blowering Dam and the Tumut River) also contributes water supply for these irrigation areas.

The Reservoir has a dendritic shape, with long and narrow reaches for each of the three rivers discharging to the Reservoir. This is shown in Figure 2.1, a plan of Burrinjuck Reservoir.

Figure 2.1 also identifies the location of the major water quality sampling stations. While longitudinal comparisons have been made through the Reservoir, the bulk of the analysis has focussed on Station 104 as typical of other stations, and having the most extensive and intensive data set. Where analysis is performed on a reach basis (for example, internal Reservoir nutrient loading) the area defined as the 'reach' extends from the listed station in both an up and down-stream direction, to a point that is half way to the next station. For example, Station 101 reach starts mid-way between Station 201 and 101, and ends midway between Station 101 and 102.

Figures 2.2 and 2.3, hypsometric curves for Burrinjuck Reservoir, illustrate the change in volume and surface area as a function of depth at the Dam wall. Separate curves were computed for each of the Murrumbidgee arm reaches, in order to undertake the mass balances of pollutants over time.

Table 2.1: Details of Reservoir

Volume	1026 GL
Surface area	6000 ha
Full supply level	AHD 363.6 m
Mean depth	17.1 m
Length (Murrumbidgee Arm)	55 km
Mean annual inflow	1400 GL
Mean annual water load	23 m
Mean annual TP load:	
Pre Canberra sewage nutrient removal	3.6 g/m^2
Post Canberra sewage nutrient removal	0.7 g/m^2
Outlet structure:	
Bottom penstocks power station	AHD 322.4 m
Bottom needle valves	AHD 322.4 m & 314.2 m
Sluice gate	AHD 349.9 m (high inflow release)
Stratfication pattern	Monomictic
Operation	Irrigation water supply release November to February

Figure 2.4, cross sections Murrumbidgee River arm, indicate the significant variation in the Reservoir cross section longitudinally.

2.2 Description of catchment

The catchment draining to Burrinjuck Reservoir comprises predominantly low intensity grazing and national park land uses. The Canberra and Queanbeyan urban areas constitute the major population centre within the catchment, and up until 1978, the most significant source of nutrients discharging in the catchment. Details are given in Tables 2.2 to 2.4.

2.2.1 Wastewater management

Over the last 15 years, there has been development of feed lots and aquaculture facilities within the catchment. Environmental controls have been put in place to limit the discharge of nutrients from these sites. There has also been progressive upgrading of wastewater treatment plants at Queanbeyan (phosphorus removal), Yass (land disposal) and Cooma (phosphorus removal) over the last 15 years.

During the 1970s and early 1980s, nuisance algal blooms emerged over the spring, summer and early autumn periods, in the Murrumbidgee and Yass arms of the Reservoir, and along the Murrumbidgee River downstream of Canberra. Both the recreational amenity of the Reservoir and downstream water supply were impacted as a result of the blooms.

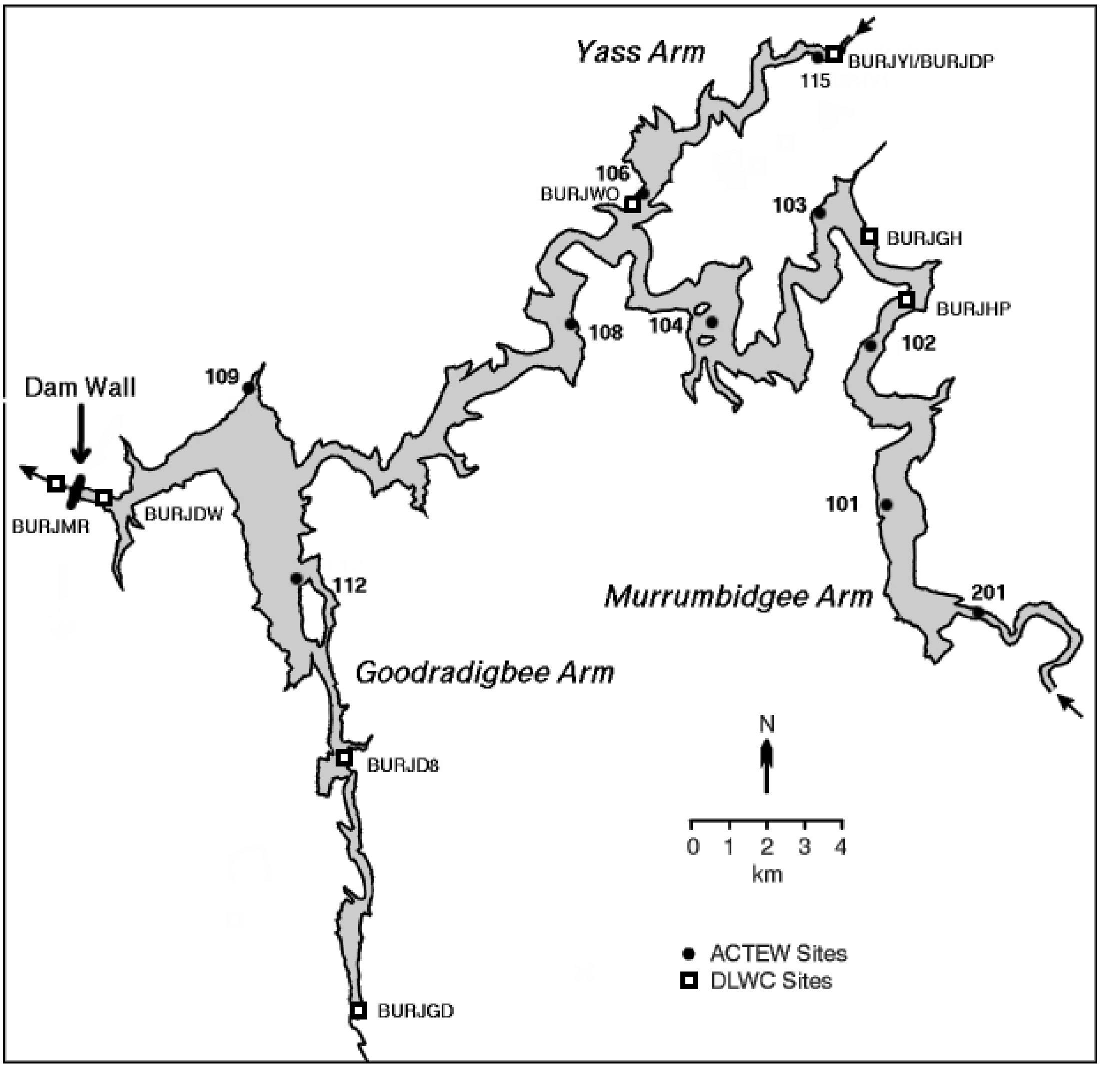

Figure 2.1: Burrinjuck Reservoir site map

Table 2.2: Details of catchment

Area	13,000 km^2
Land use	47% rural (grazing), 50% national park & forest, 1% rural residential (4 ha to 16 ha lots), and 2% urban.
Climate	Sub-alpine mountain ranges to semi-arid plains.
Geology	Granites, odivician & silurian sedimentary shales, limestone.
Soils	Alpine humus soils in alpine areas, lithosols on upper slopes, podsolics on the intermediate slopes, solodic soils on foot slopes and plains, and alluvium on floodplains.
Rainfall	Over 1000 mm/yr (sub-alpine areas) to 500 mm/yr (semi-arid areas).
Catchment runoff	1400 GL/yr as measured at Burrinjuck Dam.
Water chemistry	$Na^+ > Mg^{2+} + Ca^{2+}$ :: $HCO_3{}^- > Cl^- > SO_4{}^{2-}$

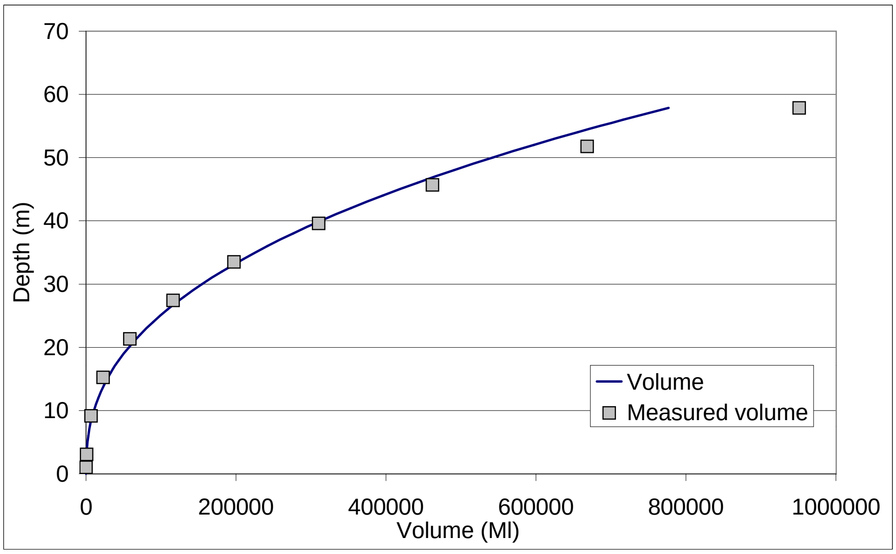

Figure 2.2: Hypsometric curve for volume, Burrinjuck Reservoir

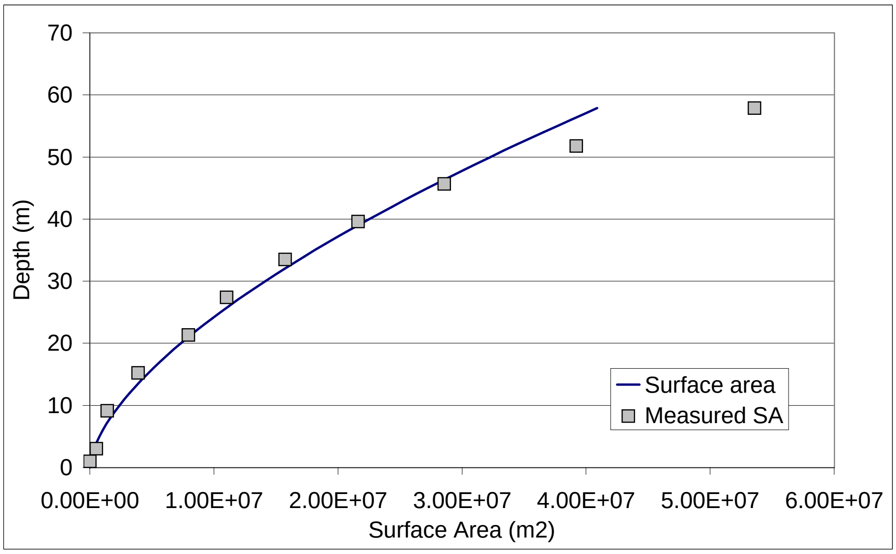

Figure 2.3: Hypsometric curves for surface area, Burrinjuck Reservoir

In 1973, the Commonwealth authorities commenced the construction of a tertiary wastewater treatment plant, designed to treat all of Canberra's domestic wastewater. Design of the plant, the Lower Molonglo Water Quality Control Centre (LMWQCC), included

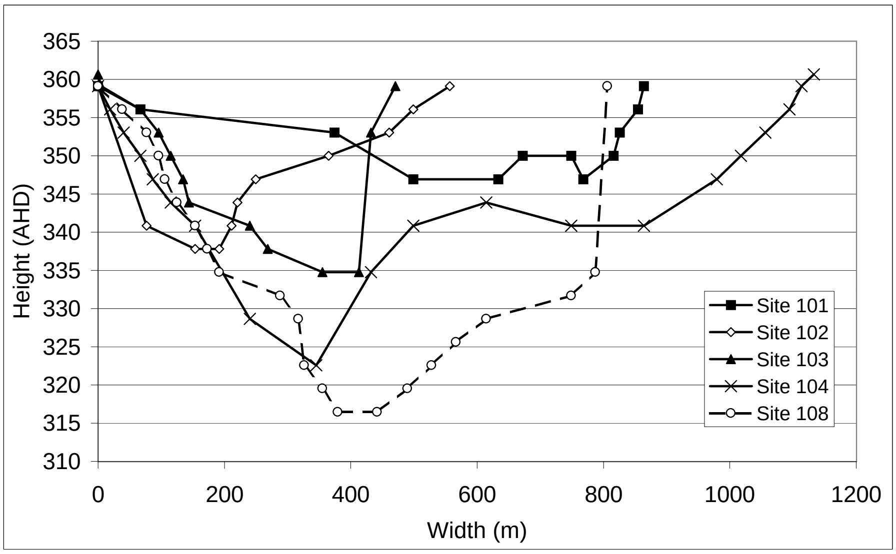

Figure 2.4: Channel cross sections, Murrumbidgee River arm.

Table 2.3: Summary of sub-catchments and land use

Sub-catchment	Land use area (km^2)						Mean annual flow	
	Native vegetation & grazing	Forest plantation	Horticulture	Rural residential	Urban	Total	Flow (GL/ year)	Percent of total
Murrumbidgee	9075	203	36	128	225	9667	1010	73
Yass	1495	1	23	75	4	1598	83	6
Goodradigbee	1110					1110	290	21
Burrinjuck	331					331		
Total	12011	204	59	202	229	12704	1383	
Percent	94.5	1.6	0.5	1.6	1.8	100		100

provision for 97% removal of phosphorus, 95% removal of nitrogen, and 98% removal of BOD. Commissioning of the new plant occurred in May 1978, with application of P removal over the period 1979 to 1980, and P and N removal for the period 1981 to 1983.

The nitrogen removal component of the plant was closed in April 1983, and has not been operated since. The decision to close the nitrogen removal component was based on the absence of any measured reduction in algal blooms over the 1981 to 1983 period, difficulties incurred in operating the component, and the high cost (methanol based denitrification process) of operating the component. Assessment of the performance of the plant in reducing algal blooms over this period was complicated by significant

Table 2.4: Canberra and Queanbeyan population growth

Year	Population	Average annual stormwater discharge (ML/yr)
1950	50,000	10,000
1960	90,000	18,000
1970	170,000	34,000
1980	260,000	52,000
1990	330,000	66,000
1995	360,000	72,000

drawdown (to 5% of storage volume) of the Reservoir over the 1980 to 1983 drought.

Following the refilling of the Reservoir in May 1983, and continued operation of the plant with phosphorus removal only, the Reservoir was free of algal blooms until 1997.

A summary of the major wastewater treatment plants across the Burrinjuck catchment is given in Table 2.5.

Table 2.5: Summary of major wastewater treatment plants across the catchment

Facility	Description of treatment process	Year	SS/BOD/TP Effluent (mg/L)
Weston Ck STW	Sedimentation, trickling filter.	1927 to 1978	40/50/8
Belconnen WPCC	Activated sludge, aeration ponds.	1970 to 1980	15/15/8
Fyshwick STW	Sedimentation, trickling filter, aeration ponds.	1963 onwards	Diverted to Weston Ck/LM
Queanbeyan STW	Activated sludge, trickling filter, aeration ponds.	1940 to 1980 1980 onwards	30/30/8 15/15/0.5
Yass STW	Pasaveer ditch, aeration ponds.	1960 to 1980 1980 onwards	40/50/8 Land disposal
Cooma STW	Sedimentation tanks, trickling filter, aeration ponds.	1950 to 1995 1995 onwards	30/30/8 30/30/1
Lower Molonglo WQCC	Lime dosage, sedimentation, nitrification, clarification, filtration, chlorination/de-chlorination.	1978 onwards	5/5/0.03

During the period 1986 to 1995, LMWQCC experienced a number of operation difficulties, resulting in by-passing of the Tertiary (filtration) treatment stage, and on three occasions, loss of biological media from the nitrification tank.

Based on information provided by Environment ACT, the additional TP load in the by-pass was estimated as shown in Table 2.6.

Table 2.6: Summary of LMWQCC Tertiary treatment by-passes

Year	TP bypassed (kg)	Proportion of annual load (%)
1986	210	3.3
1987	nil	nil
1988	929	9
1989	2953	27
1990	497	5
1991	3753	36
1992	3	0.2
1993	42	1.6
1994	1	<0.1
1995	389	12

These estimates have been included in the estimates of total load on Burrinjuck Reservoir, for purposes of algal response analysis.

In 1995, the construction of a by-pass dam, designed to intercept all potential by-passes up to a 1 in 6 year wet weather by-pass situation, was constructed.

2.3 Reservoir water quality

2.3.1 Data source

As part of the eutrophication abatement program, the Commonwealth authorities (until 1989) and ACTEW and Environment ACT post 1989, together with the NSW Department of Land & Water Resources, have maintained a comprehensive streamflow, reservoir level, and physical, chemical and biological water quality monitoring program to assess Reservoir response to management actions across the catchment.

Commencing in 1976, monitoring comprised fortnightly sampling of surface and bottom waters across 10 sites through the Reservoir. In 1980 the program was reduced to approximately monthly sampling, and this has been maintained to the present time.

Through the collaboration of ACTEW, DLWC and Environment ACT, an extensive period of Reservoir water quality and algal data and stream flow and nutrient loading data has been made available, as the basis for the research Project. A major component of the Project has been the acquisition and compilation of the data into a single data set for the period 1976 to 1998, including quality validation of the data. Meteorological data for the Dam site (DLWC) and Yass and Canberra Airport (Bureau of Meteorology) have been added to the data set. This data, together with Burrinjuck Reservoir sediment cores taken and analysed by CSIRO Division of Land & Water, have been the sole basis of the research. Refer to Appendix A for details on the data set.

In the interests of clarity and conciseness, the chemical compounds are described throughout this Report by their chemical symbols. The following list, Table 2.7 summarises the major nutrient groups addressed in the Report. Further information is available in the glossary in Appendix C.

Table 2.7: Summary of chemical symbols

P — Phosphorus
TP — Total Phosphorus
FRP — Filterable Reactive Phosphorus

N — Nitrogen
TN — Total Nitrogen
TKN — Total Kjeldahl Nitrogen
NO_x — Nitrate + Nitrite Nitrogen
NH_3 — Ammonia Nitrogen

C — Carbon
TOC — Total Organic Carbon
BOD — Biological Oxygen Demand

Si — Silica

2.3.2 Water quality

Previous studies

The Commonwealth authorities (Australian Department of Construction et al. 1978) undertook a study of Burrinjuck water quality and algal processes in 1978, based on data collected over the November 1976 to August 1977 period (referred to hereafter as the *ACT Region Water Quality Study* (1978)). The monitoring was preceded by significant floods in August 1974 and October 1976.

The Study found that waters downstream of Canberra and Queanbeyan were heavily polluted by nitrogen, phosphorus, bacteria, and after floods, by suspended material. Over a normal (streamflow) year, about three quarters of the nitrogen and phosphorus stem from sewage effluents and the remainded from runoff from rural and urban land.

The Study found that algal growth in the Murrumbidgee River downstream of Canberra has been substantial and has given rise to unsightly floating mats during summer. It concluded these excessive growths are attributable to the release of nitrogen and phosphorus from Canberra.

The Study concluded that the quality of the waters of Burrinjuck Reservoir is determined by that of the entering rivers. Major growth of algae in the Reservoir has been stimulated by nutrients entering from the Murrumbidgee River.

FRP values monitored for surface waters were in the range of 50 to 400 μg/L in the inlet zone, but 10 μg/L or less for the middle and lower reaches of the Reservoir.

Analysis of data from 1976 to 1998

Water quality data for the period 1976 to 1998 is summarised in the time series plots (Figures 2.5 to 2.10) of in-Reservoir water quality.

Both Figures 2.5 and 2.6 (TP and FRP respectively) indicate a significant reduction in surface and bottom concentrations of phosphorus post 1983.

Measurement of TKN, or direct measurement of TN, is only available for the period 1993 onwards. Estimates of TN prior to this period were based on the sum of inorganic N forms and Chlorophyll 'a' measurements. The estimation of TN is described in further detail in Appendix B.4.

The time series plots of TN, NO_x and NH_3 (Figures 2.7, 2.8 and 2.9 respectively) indicate a signficant reduction in nitrogen during the LMWQCC denitrification treatment operation periods (Sept 1979 to April 1981 and Sept 1981 to May 1983), but a significant increase in NO_x after the May 1983 period as compared to conditions prior to that time.

Figure 2.9 indicates a significant reduction in NH_3 levels post 1983 in the bottom waters, whereas there is a marked increase in NO_x in both top and bottom waters post 1983 (Figure 2.8).

Figure 2.10 indicates Silica levels for Station 104. Low Silica levels in 1978/1979 are associated with low flows during this period, while high Silica levels in 1992/1993 are associated with high inflow conditions.

2.3.3 Algal biomass

Previous studies

A survey of algal composition in Burrinjuck over the period 1972 to 1975 (May V., 1978) identified a total of 31 species of algae. Toxic species included *Anacystis (Microcystis) cyanea* and *Anabaena circinalis.* Typically, the summer bloom commenced as *Anabaena*

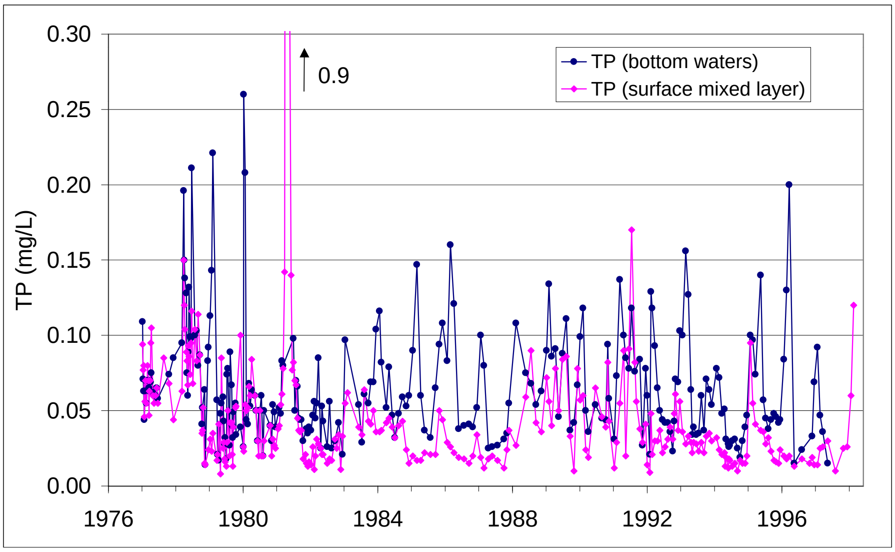

Figure 2.5: TP concentration, Site 104 Burrinjuck Reservoir.

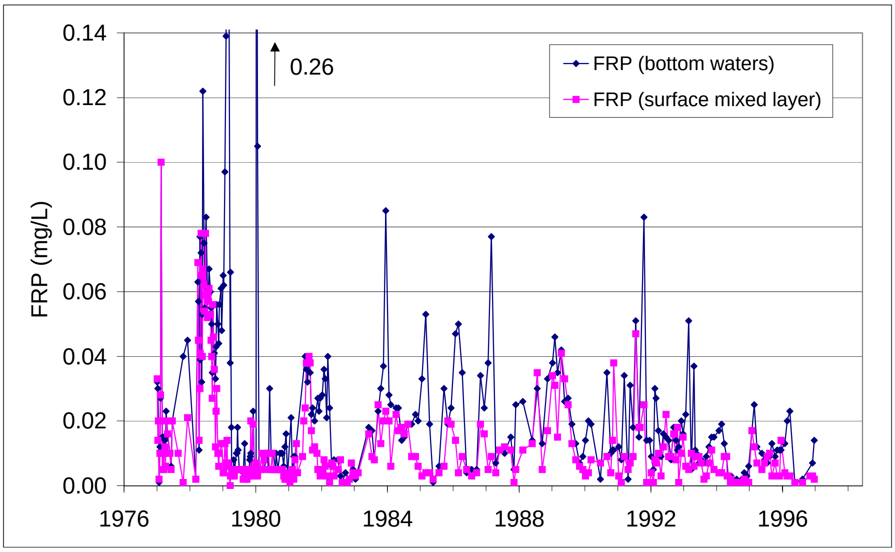

Figure 2.6: FRP concentration, Site 104 Burrinjuck Reservoir.

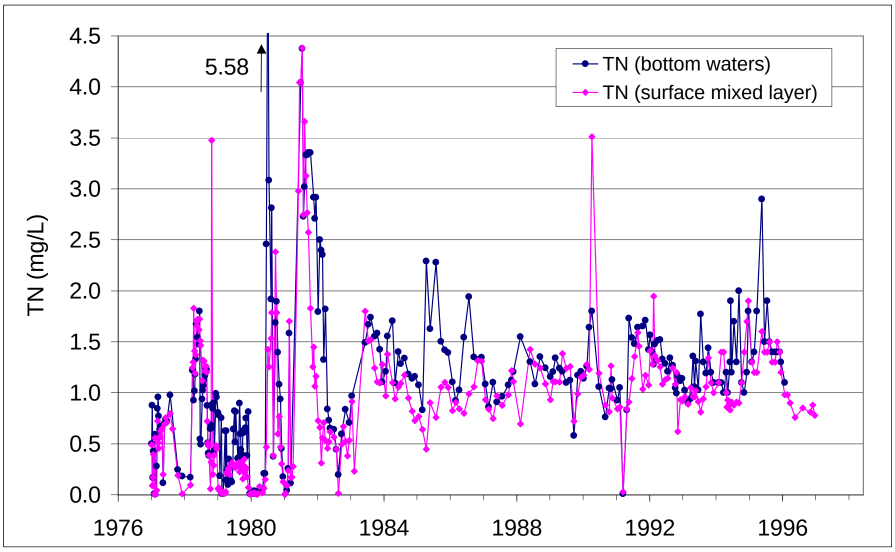

Figure 2.7: TN concentration (calculated), Site 104 Burrinjuck Reservoir.

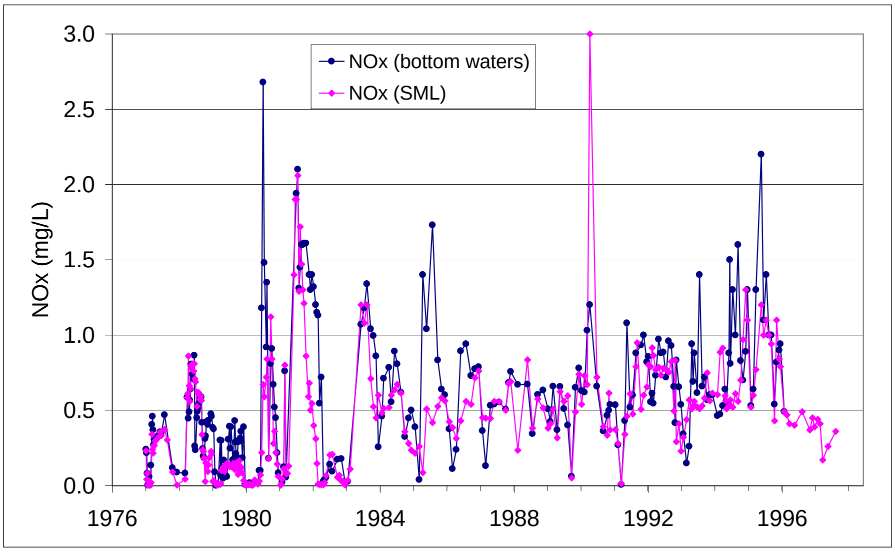

Figure 2.8: NO_x concentration, Site 104 Burrinjuck Reservoir.

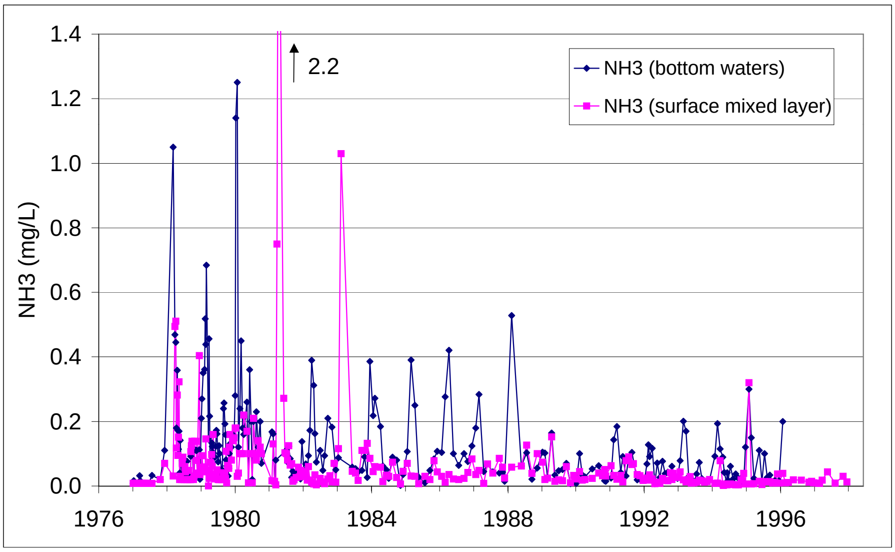

Figure 2.9: NH_3 concentration, Site 104 Burrinjuck Reservoir.

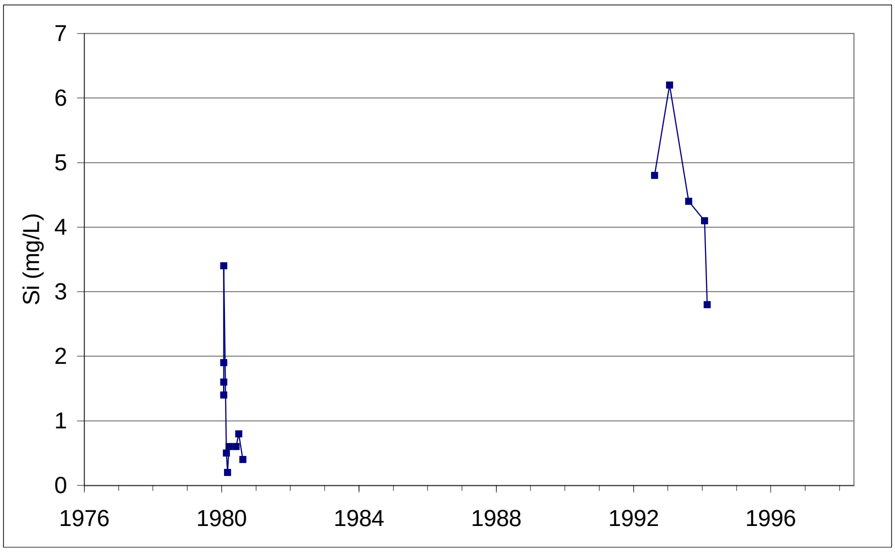

Figure 2.10: Si concentration, Site 104 Burrinjuck Reservoir.

from July to February, and Anacystis from November to August.

During the 1973-1974 summer, *Anabaena* was plentiful throughout the Reservoir, occurring from July 1973 to February 1974, with bloom levels from November to February. *Anacystis* occurred from November 1973 to August 1974, with a dense bloom from November to February.

A major flood in August 1974 appeared to have flushed much of the algae from the Reservoir, with growth in 1974/1975 much more sparse.

The *ACT Region Water Quality Study* (1978) identified algal biomass levels (Chlorophyll 'a') in the range of 40 to 80 μg/L in the inlet zone of the Murrumbidgee arm of the Reservoir, with rapid reduction to levels of 10 μg/L through the middle and lower reaches of the Reservoir.

Algal monitoring undertaken by the Department of Housing and Construction identified *Anabaena* at Station 104 in February 1981 to 1983 (*ACTEW Field Notes* 1980-1983).

Analysis of data from 1976 to 1998

Algal biomass data for the period 1976 to 1998 is summarised in Figure 2.11, a time series plot of Chlorophyll 'a' and algal cell numbers (by major groups) for Station 104. The Figure indicates a significant decrease in average annual algal biomass from 20 μg/L Chlorophyll 'a' pre 1983 to 5 μg/L Chlorophyll 'a' post 1983.

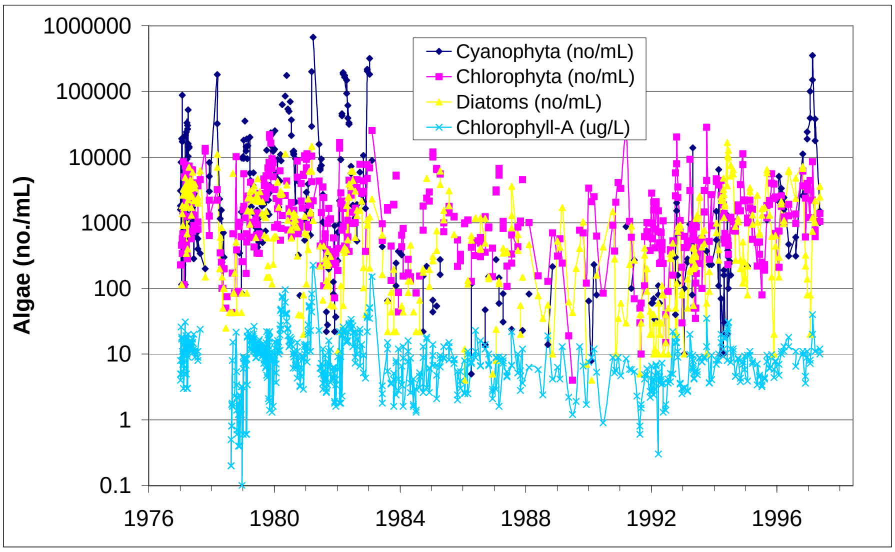

Figure 2.11: Chlorophyll 'a' and algal cell numbers (by major groups), Station 104 Burrinjuck Reservoir.

Average annual values increase again, to an average 9 μg/L Chlorophyll 'a', for the Reservoir drawdown periods 1994 to 1995 and 1997 to 1998.

2.3.4 Algal composition

Previous studies

The *ACT Region Water Quality Study* (1978) noted that the succession pattern for 1976/1977 comprised Diatoms following the flood event, followed by Chlorophyta in late Spring, and Cyanobacteria in late December to March. There was a return of Chlorophyta through the middle and lower reaches of the Reservoir post March, but sustained high levels of *Microcystis* in the upstream reaches.

Analysis of data from 1976 to 1998

Figure 2.11 provides a time series plot of algal composition (by major groups) for the period 1976 to 1998 for Station 104. The figure indicates dominance of Cyanobacteria for the period 1976 to 1983, and Chlorophyta for the period 1983 to 1996. Cyanobacteria is largely absent over the period 1983 to 1996, but re-appears in 1997/1998.

2.4 Reservoir sediments

The available data on both the sediments and the sediment nutrient release rates in Burrinjuck Dam is quite limited. Several cores were taken from the deepest part of the dam in 1985 and dated using ^{137}Cs supplemented by charcoal and pollen variations. Phosphorus, iron and other major element concentrations in the solid material were measured by XRF and a detailed stratigraphy developed (Olley et al. 1995, Wasson et al. 1987). The results of this analysis are described below. Since this core is now approximately 12 years old, a more recent core (1997) was analysed also, and the results incorporated into this report. More recent work (Wasson et al., in press) used a range of algal pigments preserved in the sediments to infer the changes in species over time. In addition a detailed history of sediment deposition in different regions of the dam was developed. The sediment core data has a coarse time resolution and reflects flow events and changes in algal abundance on a yearly basis.

2.4.1 Analysis of cores

The longer core collected from the deepest part of the reservoir has been dated using ^{137}Cs and the chemical composition determined by XRF. The most significant finding is a significant change in the atomic P:Fe ratio from approximately 0.03 to 0.05 at a depth corresponding to 1965 to 1970. The P:Fe ratio remained at this higher level throughout the 1970s before starting to decline in the 1980s. While the decline has been attributed to the operation of the LMWQCC, the explanation of the increase in the late 1960s remains uncertain, though it coincides with an abrupt increase in the Canberra population and a significant shift from a prolonged dry to a wet period. It has yet to be shown whether the Canberra increase in nutrient loading caused a major increase of the catchment non point source load in that period. The effects of a major inflow event in 1983 also needs to be considered, as this event, together with other flood events, delivered a large fraction of the total P delivered to the reservoir during its existence.

The Chlorophyll 'a' content of the sediments increases at the same point in the core with the increase in the P:Fe ratio, suggesting that the total biomass reflects the abundance of phosphorus i.e. it is a phosphorus limited system.

The pigments most characteristic of blue green algae also show a sudden increase in relative abundance from 1967/1968. The second core was taken opportunistically from the mud banks of the river during low water in the dam. The Fe:P ratio is intermediate between the high and low values observed in the deeper core suggesting we have either fortuitously sampled sediment from the intermediate transition zone from the late 1960s or, more likely, that it is reworked material which combines sediments of different ages. The C:N ratio of this material is about 15:1, which is higher than the norm for sediments dominated by algal debris of 8:1, but considerably less than the ratio for terrestrially derived organic materials (C:N of greater than 20). The simplest interpretation is that this material is a mixture of both the algal and terrestrial sources. Investigation of the C and N isotopic values of this material which may clarify this point is yet to be done.

2.5 External loading characteristics

2.5.1 Meteorological conditions

Figures 2.12 to 2.15 provide time series plots of daily meteorological conditions (precipitation, wind speed and air temperature) for the Meteorological Station at Yass. Figure 2.16 summarises the estimates of seasonal solar radiation conditions for the Canberra region, based on sunshine hours at the Reservoir itself.

Analysis of data from 1976 to 1998

With the exception of rainfall, analysis of meteorological conditions indicates that wind speeds, temperature, humidity and solar radiation are predominantly seasonally based.

The wind data at Yass was compared with wind data measured at the Reservoir (Dam) for a limited period 29 November 1995 to 5 September 1996. The correlation of both wind speed and direction is very poor, suggesting that meteorological conditions away from the Reservoir are not representative of the factors influencing mixing conditions on the water. For example, for the period of comparison the average wind speed at

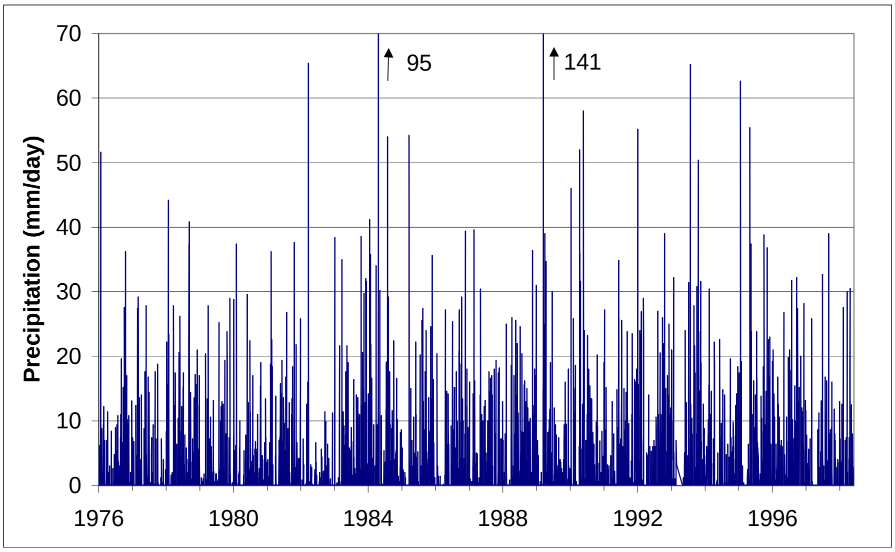

Figure 2.12: Precipitation for Yass meterological station.

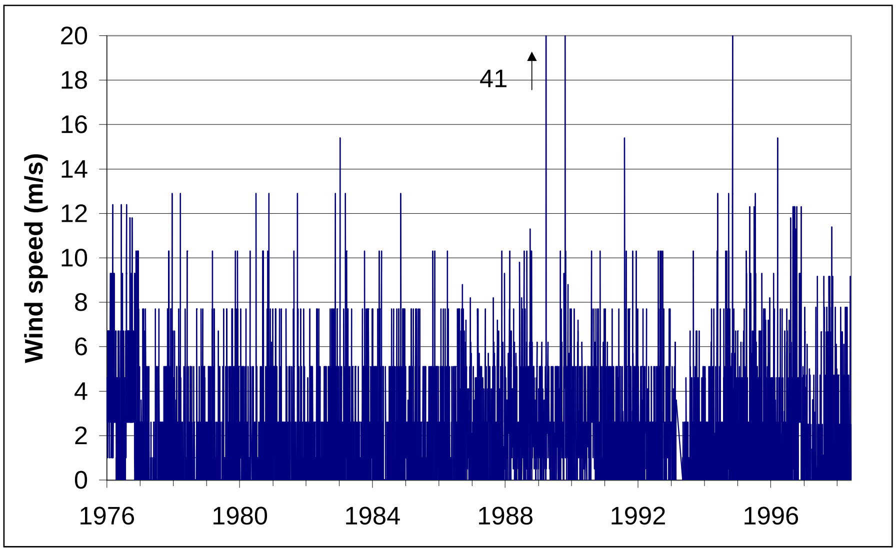

Figure 2.13: Wind speed at 9:00 am for Yass meterological station.

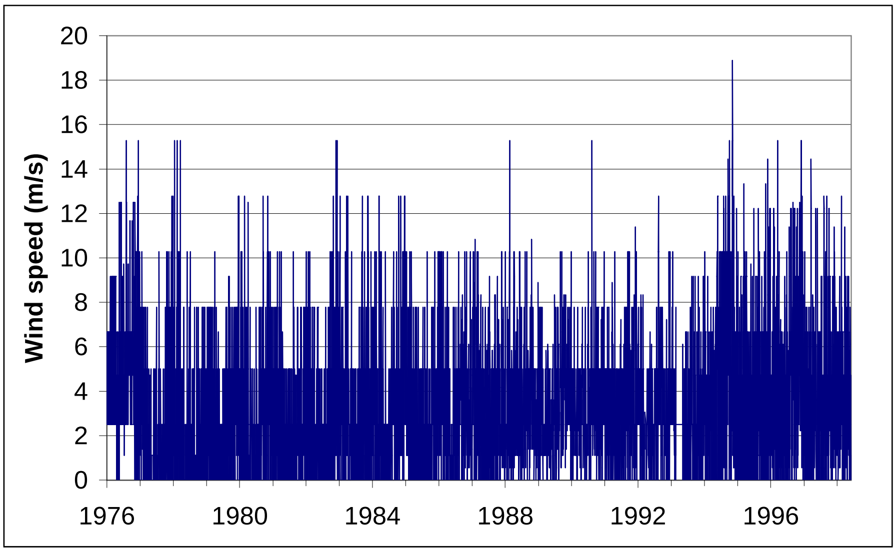

Figure 2.14: Wind speed at 3:00 pm for Yass meterological station.

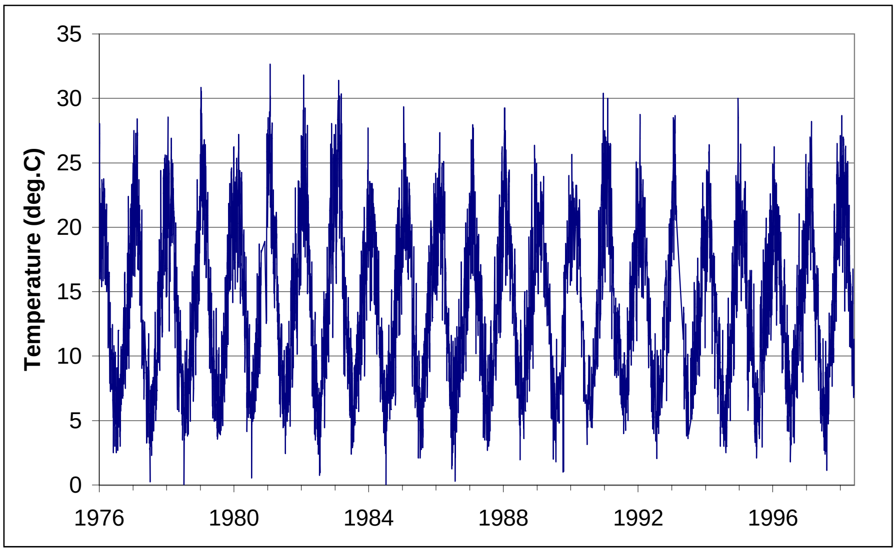

Figure 2.15: Daily mid-range air temperature for Yass meterological station.

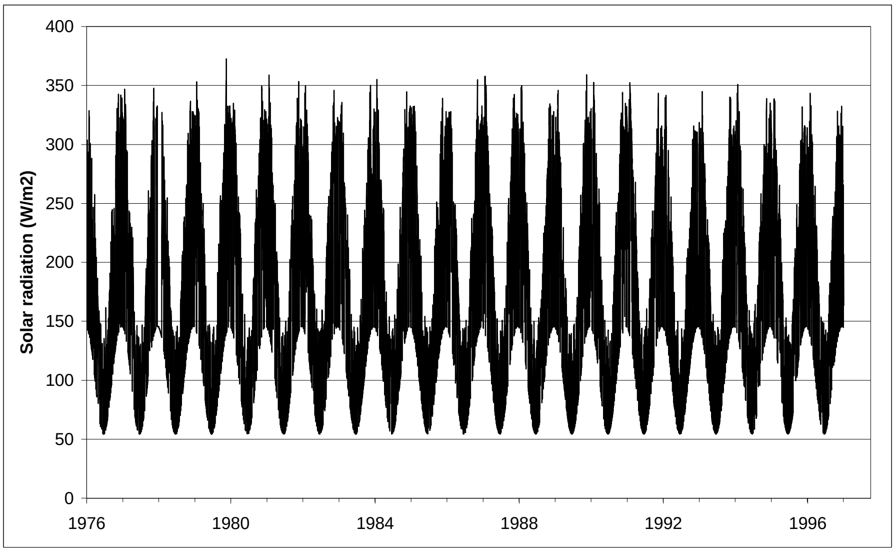

Figure 2.16: Average daily solar radiation, Canberra.

Burrinjuck Reservoir is 3.4 m/s compared to an average wind speed at Yass of 3.0 m/s.

2.5.2 Inflow and nutrient loading on Reservoir

Previous studies

A study on the Lake Burley Griffin nutrient budget (Cullen & Rosich 1978) indicated that flood events contributed 69% of the TP loading on the lake for the 18 month period monitored, but these floods occupied only 9% of the time. A point source, Queanbeyan sewage effluent, was the major source of TP during normal and drought flow periods, where it contributed 72% and 90% of TP load respectivly.

Catchment nutrient exports under high flow conditions were dominated by agricultural and forested areas of catchments. The form of P from these areas was 67% to 93% particulate P and 7% to 33% FRP. Phosphorus discharged in sewage effluent comprised 9% to 17% particulate P and 83% to 91% FRP under normal to low flow conditions. Consequently, flow conditions impacted on both the level of export and the composition of phosphorus.

Flow conditions also influenced the proportion of TP retained in the lake, with 91% retained under low flow conditions, 65% under normal flow conditions, and 12% to 32% under flood flow conditions.

The *ACT Region Water Quality Study* (1978) notes that waters downstream of Canberra and Queanbeyan are heavily polluted by nitrogen, phosphorus, bacteria, and after floods, by suspended material. Over a normal (streamflow) year, about three quarters of the nitrogen and phosphorus stem from sewage effluents and the remainder from runoff from rural and urban land.

The Study also noted that less than one third of the FRP and one tenth of the ammonia passing the Molonglo-Murrumbidgee Rivers confluence, reach the Reservoir (under the median to low flow conditions monitored).

Analysis of data from 1976 to 1998

Figures 2.17 to 2.21 provide time series plots of daily loading of water, TP, TN, Si and TOC on the Reservoir respectively. Figure 2.22 provides a breakdown of daily TP loading in terms of point and non-point derived sources. Figure 2.23 provides a cumulative loading plot for the period 1976 to 1998 for TP, TN, NO_x and NH_3.

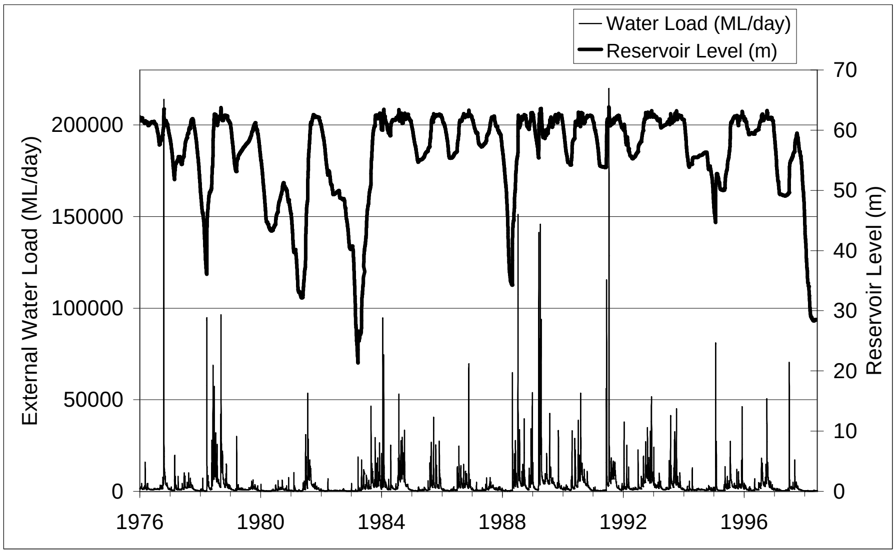

Figure 2.17: External water load and water level, Burrinjuck Reservoir.

Figure 2.17 indicates that streamflow is extremely varied, from cessation of flow (other than point source effluent discharges) to extreme flood flows, equalling the whole Reservoir volume in just a few days. The figure also indicates the pattern of water level drawdown during October to March irrigation water release period.

The Reservoir level in general is inversely related to annual inflow, with substantial drawdown over the 1977, 1980 to 1983, 1988 and 1994 to 1998 drought periods. In the case of the extended drought periods, the Reservoir was drawn down to less than 5%

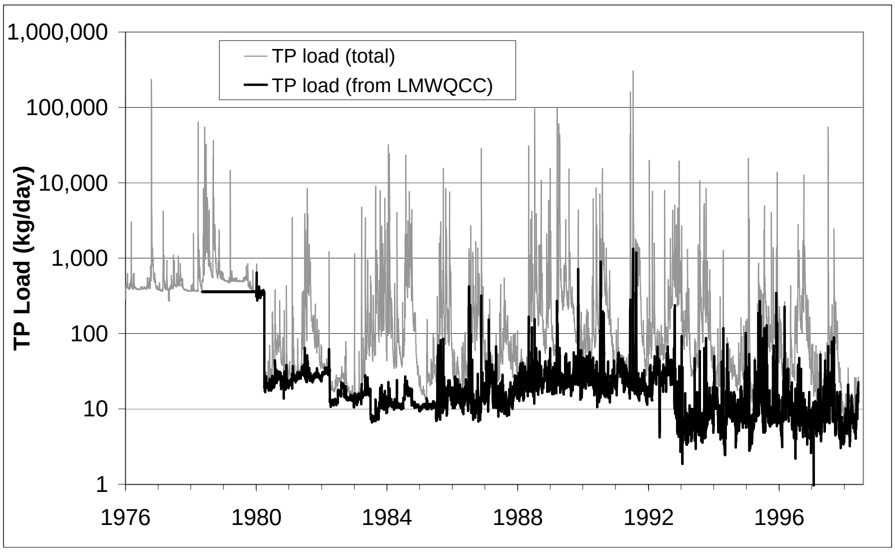

Figure 2.18: External TP load, Burrinjuck Reservoir.

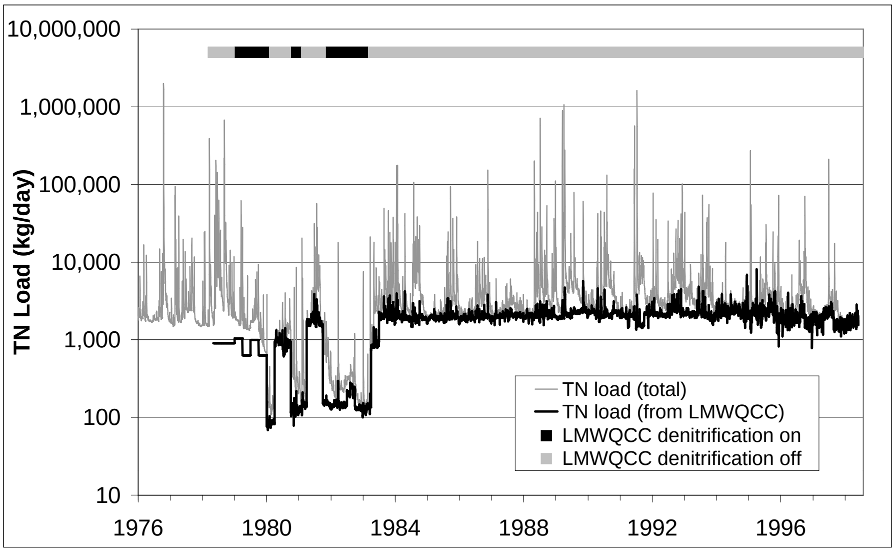

Figure 2.19: External TN load, Burrinjuck Reservoir.

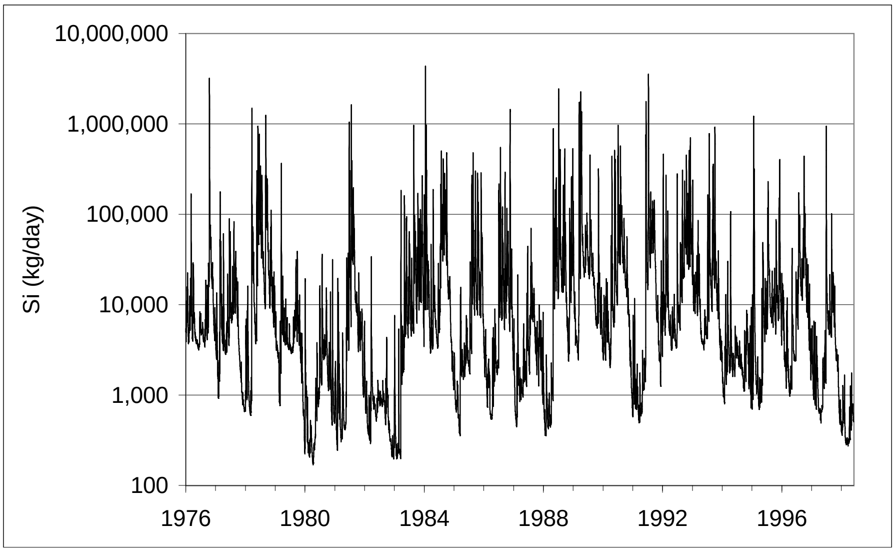

Figure 2.20: External Si load, Burrinjuck Reservoir.

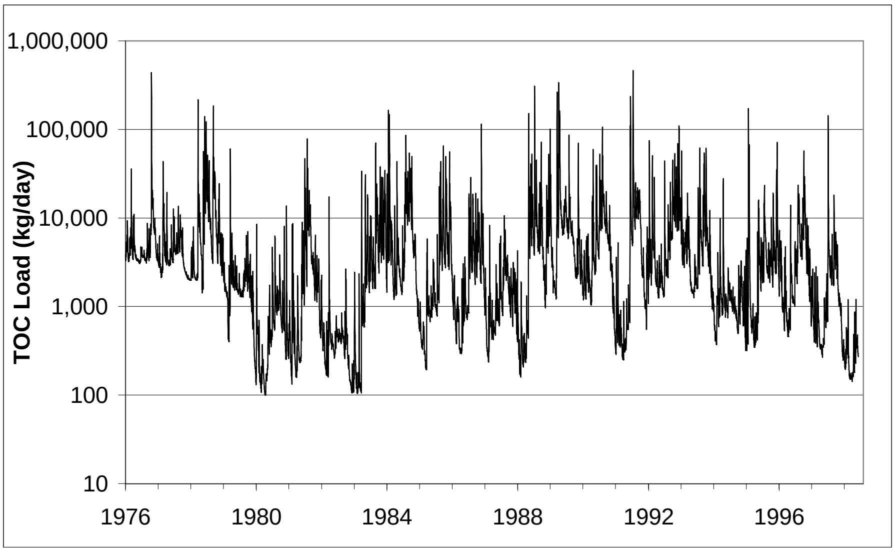

Figure 2.21: External TOC load, Burrinjuck Reservoir.

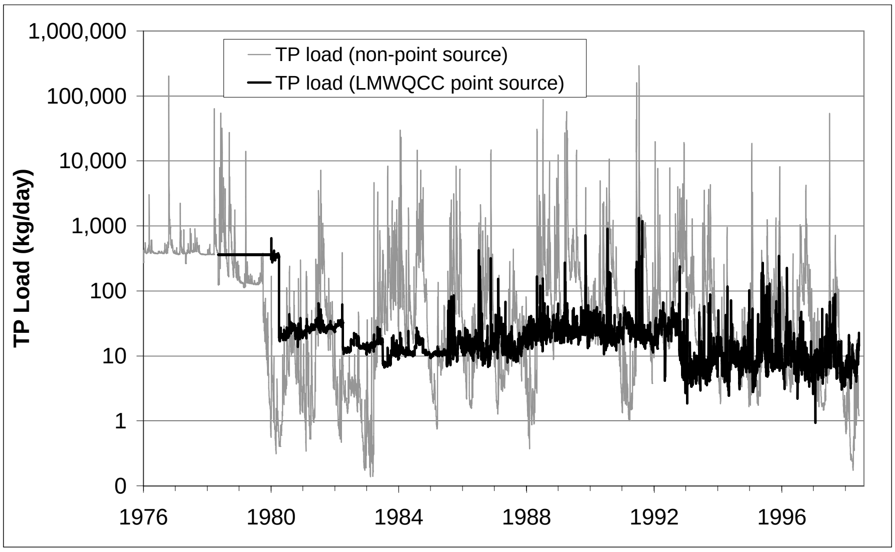

Figure 2.22: External TP point and non point source load, Murrumbidgee arm of Burrinjuck Reservoir.

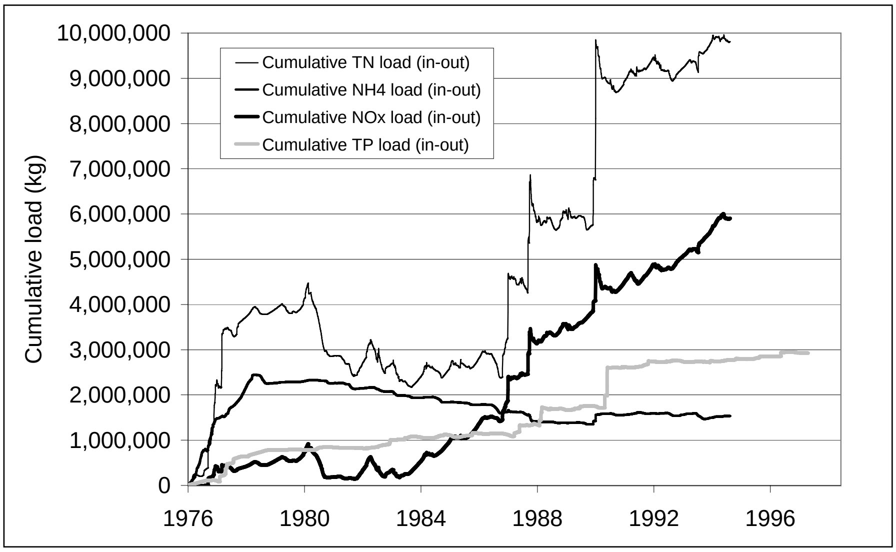

Figure 2.23: Cumulative external loads, Burrinjuck Reservoir.

of its capacity. Figure 2.17 also indicates the rapid rate of drawdown, with up to 30 m drawdown in the 12 week irrigation water release period (drawdown rates of the order of 3 m per week).

For the period 1976 to 1998, the Murrumbidgee River catchment contributed 66% of the total water load, Goodradigbee River 31% of the load and the Yass River just 3% of the load.

Figures 2.18 and 2.21 indicate the substantial reduction in TP and TOC loads associated with the improvement in P and TOC removal operation in the new LMWQCC in 1980. The Figures also illustrate periods of extreme loads of all nutrients associated with elevated runoff from the catchment area.

Figure 2.22 breaks down the TP loading into point and non-point sources. Prior to 1980, the point sources (municipal wastewater) represented the major proportion of TP loading. Post 1980, the point-source represented less than 10% of the total TP loading. However, under low flow conditions (less than 1000 ML/day) typical of summer, it is 75% of total loading.

Figure 2.19 presents the time series plot of TN loading on the Reservoir. Except for the brief periods of de-nitrification treatment at LMWQCC in 1980 and 1981 to 1983, there has been little change in the total TN loading. As noted previously (see Section 2.3.2), there has however been significant change in the form of the nitrogen, from high NH_3 and organic forms pre 1980 to substantially NO_x forms of N post 1980.

The time series plot of cumulative loads on Burrinjuck Reservoir (Figure 2.23) indicates that the Reservoir retained some 3000 tonnes of TP over the period 1976 to 1998. This value is of the same order as the estimate of TP in sediments derived from the sediment core analysis undertaken by CSIRO Division of Land & Water (Wasson 1999, pers. comm.).

Chapter 3

Reservoir physical processes

3.1 Background

The availability of nutrient, light and mixing conditions, the water residence time and temperature, are the major determinants of algal growth and composition. Both biomass levels and composition may be further modified by grazing by zooplankton. The interplay of these factors are complex and variable, even within a single reservoir, reflecting latitude, catchment conditions and land uses and management, and reservoir depth, shape and drawdown conditions.

The following sections seek to explain the components of each of these factors, and the manner in which they collectively determine algal biomass and composition.

3.2 Stratification

Stratification has significant implications for lake water quality and biological processes. The thermocline creates a barrier to the transfer of oxygen adsorbed by surface waters into deeper waters, and the transfer of nutrient rich bottom waters into the surface mixed layer (SML). The level of mixing within the SML is a function of wind strength and travel distance over the water surface. Burrinjuck, as is the case for most deep Australian temperate region reservoirs, is monomictic in that it experiences a single annual stratification and turnover cycle.

3.2.1 Previous studies

The *ACT Region Water Quality Study* (1978) notes that the Reservoir stratified over the period November 1976 to March 1977.

A study based on the application of DYRESM to Burrinjuck (Humphries & Imberger

1981) noted an annual pattern of thermal stratification with depth, commencing in September and mixing in April. The study concluded that the stratification reflected:

1. heating and cooling of the water surface;
2. river inflows;
3. outlet depth and discharge volume.

Analysis of the mixing depth in summer noted mixing depths of 2—8 m, usually less than 5 m at night less than 2 m during the daytime.

3.2.2 Analysis of data from 1976 to 1998

During early summer, the surface waters of lakes are heated by adsorption of solar radiation, progressively becoming warmer than the deeper waters. Given that the density of water decreases as the temperature rises, the warming of the surface layers relative to the deeper layers creates a physical separation of the surface and bottom layers in terms of density resistance to mixing. The depth of the surface mixed layer is a function of the solar radiation, differences in air and water temperatures, evaporation rates and wind driven eddy currents.

This pattern was assessed for Burrinjuck using the temperature profiles measurements available from monitoring (Figure 3.1 Monthly Average temperature profile at Station 108). The Figure indicates thermal stratification over summer months for Burrinjuck Reservoir, with deepening of the surface mixed layer in the autumn period until the whole depth is isothermal (mixed).

With cooling during autumn, the depth of the surface mixed layer increases, progressively entraining the cool bottom waters, until the full Reservoir depth is mixed (uniform temperature).

Figures 3.2 and 3.3 indicate the pattern of longitudinal temperature profiles for the Murrumbidgee River arm of Burrinjuck Reservoir. The plot for the stratified conditions (Figure 3.2) indicates a mixed zone at the upstream end of the Reservoir, followed by rapid establishment of stratified conditions downstream. Drawing on the inferred solar radiation, evaporation rates, and wind strength (refer to Chapter 2.5.1), the surface heat flux was calculated and plotted versus the mixed layer depth at Site 104. The inverse relationship found indicated that the mixed depth was mainly determined by solar radiation and evaporative fluxes at the surface, and that wind was not a significant factor in modifying mixed depth.

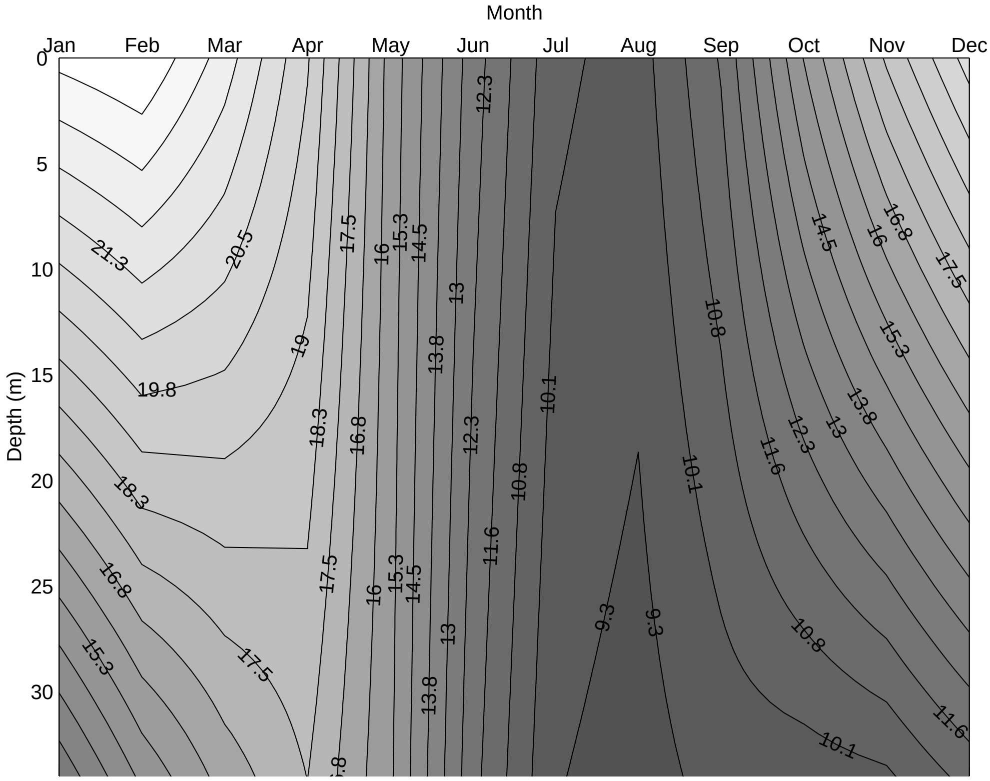

Figure 3.1: Average temperature profile (1976 to 1996), Station 108 Burrinjuck Reservoir.

3.3 Mixing and inflow pathways

3.3.1 Previous studies

The *ACT Region Water Quality Study* notes that the Reservoir stratified over the period November 1976 to March 1977, and that Murrumbidgee River water reaching Burrinjuck Reservoir under low flow summer conditions was relatively warm and therefore spread over the surface water layer.

As an inland irrigation storage within the temperate region of SE Australia with a large rural catchment, Chaffey Reservoir has a number of similarities with Burrinjuck Reservoir, and provides some useful pointers in relation to Burrinjuck processes.

The Chaffey Reservoir monitoring dramatically illustrated the nature of event inflow incursions into the Reservoir water body. Conductivity profile measurements following a major inflow event during February 1997 indicated that the inflow formed an intrusion just below the surface mixing layer. The level of the intrusion was determined by the temperature of the inflow relative to thermal stratification within the reservoir (Figure 3.4).

In Chaffey Reservoir, nutrients that accumulated in the hypolimnion were a significant determinant of the following year's average annual algal biomass. Artificial destratifica-

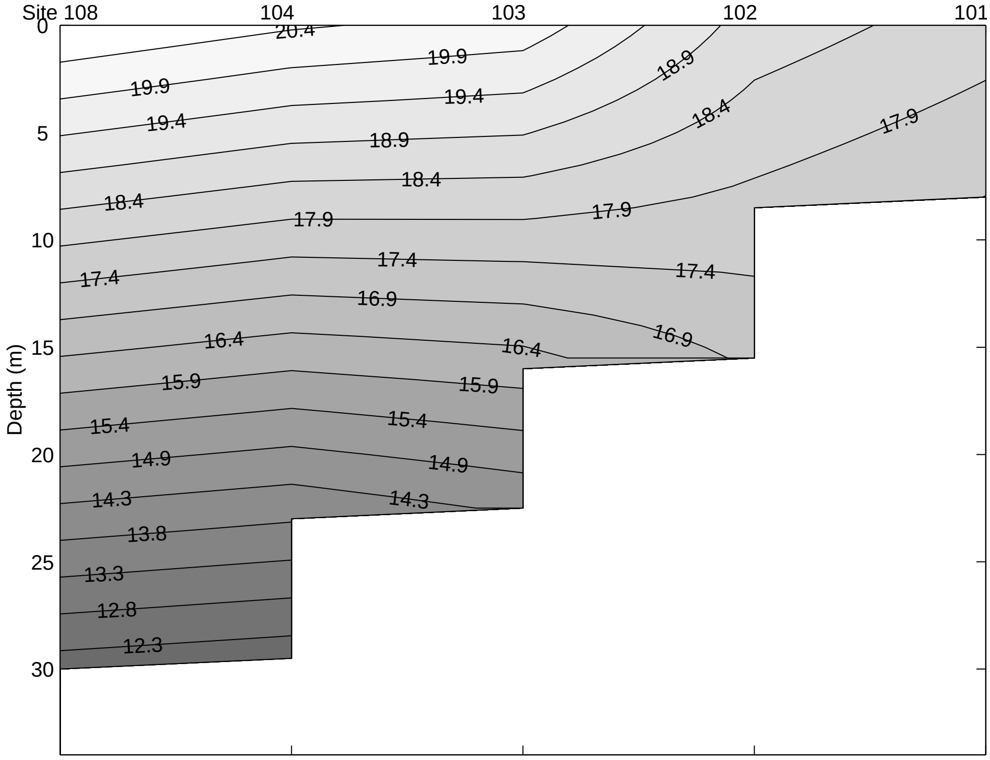

Figure 3.2: Longitudonal temperature profile (Site 101 to 108), Summer 1984-1985.

tion was observed to reduce the internal nutrient load by about 85% and algal biomass was much lower during the years following artificial destratification. However, artificial destratification did not eliminate blue-green algae from the phytoplankton population.

Another common observation at Chaffey Reservoir was that of low algal biomass during late summer due to the depletion of epilimnetic nutrients. The biomass would remain low until the surface mixed layer deepened as a result of wind stirring and autumnal cooling sufficiently to entrain nutrients that had accumulated below the SML. Algal biomass increased rapidly following the entrainment of nutrients and then eventually diminished when the SML deepened enough that light availability limited algal growth.

3.3.2 Analysis of data from 1976 to 1998

Inlet zones, with their shallow depth and more elevated flows (smaller cross section) are normally mixed, but may be prone to thermal stratification for short periods under low flow and elevated solar radiation conditions during summer, particularly where surface water turbidity is elevated following a storm event inflow.

Figures 3.2 and 3.3 (Temperature profiles of the Murrumbidgee arm during Summer and Winter) show stratification over the summer/autumn period for the deeper downstream Sites 103 to 108, but substantially isothermal conditions within the shallow inlet reaches 101 and 102.

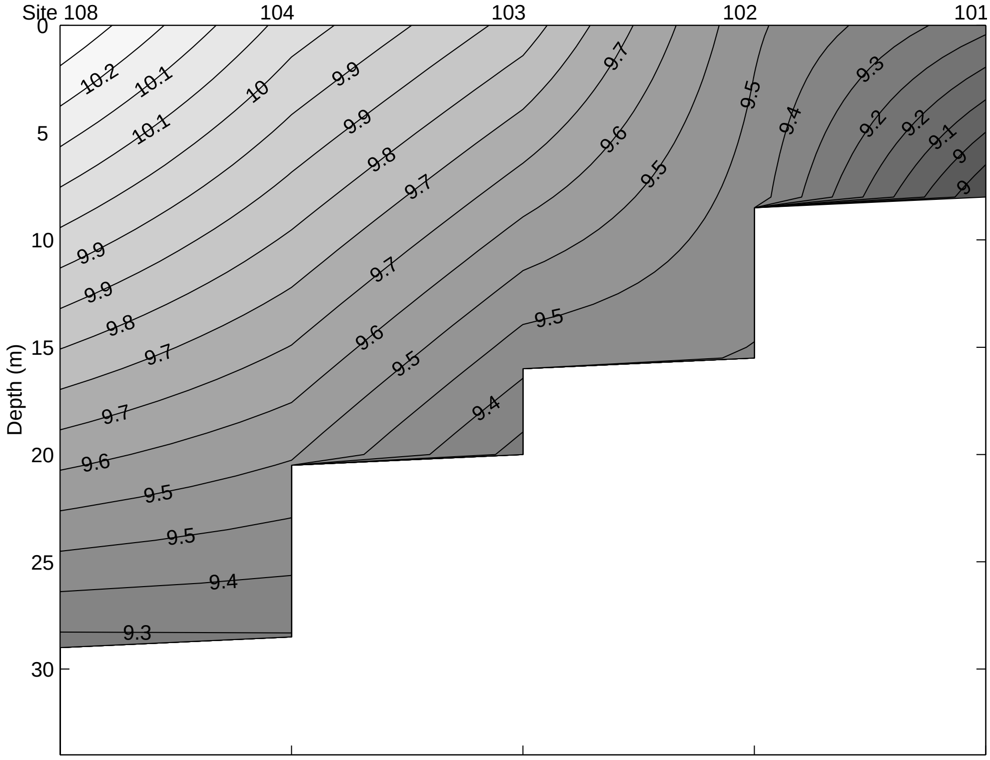

Figure 3.3: Longitudonal temperature profile (Site 101 to 108), Winter 1984.

The pathway followed by water discharged from streams feeding reservoirs will depend on the temperature of inflow relative to the temperature of the surface mixed layer. Analysis of monitored Murrumbidgee River temperature (Uriarra Crossing) indicates a significant correlation with flow, with flows greater than median flows having temperatures less than that of the surface mixed layer, and consequently diving to the bottom waters. Conversely, the temperature of flows less than median levels were warm relative to the surface mixed layer temperature, and consequently, occurred as surface water flows. This is illustrated in Figure 3.5 for the Murrumbidgee arm of Burrinjuck Reservoir. In summer, an inflow of up to 1000 ML/day has on average a higher temperature than that of the SML. In winter however, inflow generally has a lower temperature than that of the Reservoir SML and so will plunge to the bottom waters.

This pattern of surface or bottom water inflows has significant implications for the availability of nutrients to surface water algae over summer periods (refer to Chapter 4).

Several aspects of these findings are addressed for Burrinjuck in the following material.

The location of the reservoir outlet relative to surface waters or bottom waters has an important bearing on water and associated nutrients pathways through reservoirs.

Under conditions of bottom water release over summer months, when inflow is low or to the bottom waters, there will be drawdown of bottom waters when the release exceeds inflow. The surface waters may remain isolated from high nutrient bottom waters or,

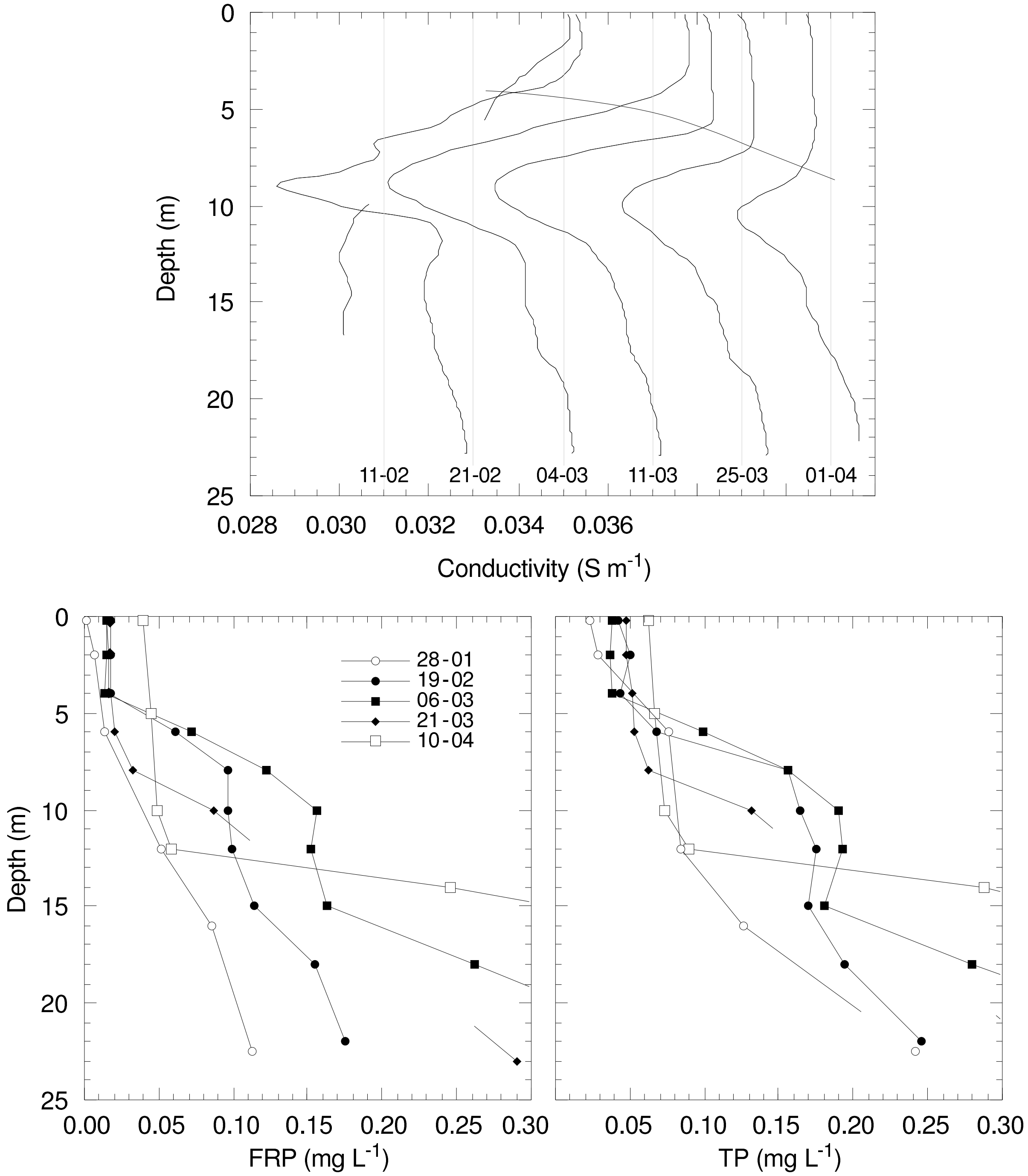

Figure 3.4: Conductivity (top) and FRP and TP (bottom) profiles measured at Chaffey Reservoir before and after the Feb 97 inflow. Conductivity profiles are offset by 0.002 S m^{-1}; grey vertical lines are located at 0.031 S m^{-1} for each profile. The trajectory of the maximum surface mixed layer depth between profile is shown by the heavy line in the upper figure. Reprinted from Sherman et al. (in press).

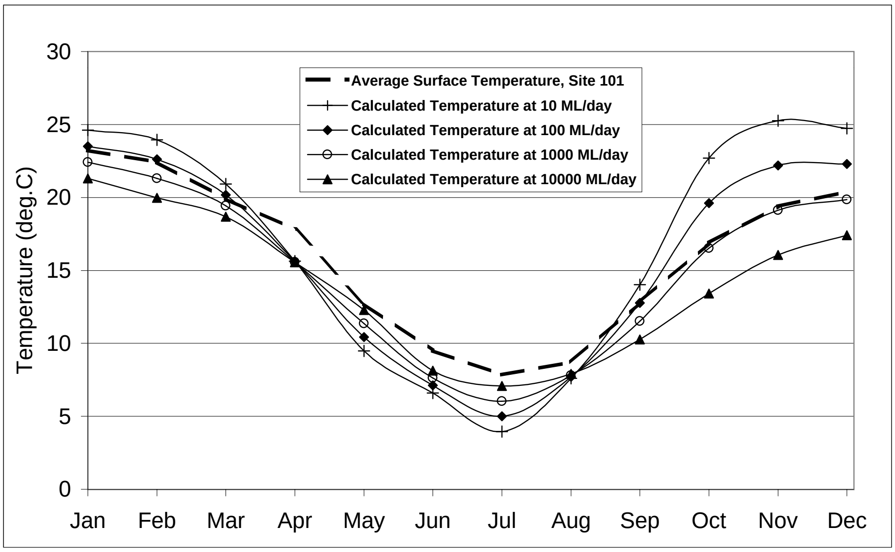

Figure 3.5: Surface temperature at Site 101 and inflow temperature at Uriarra Crossing showing an average decrease in temperature with increasing flow. When the temperature of the inflow drops below that of the reservoir the flow will be to the bottom waters.

when inflow is to the surface water and release from the bottom water, may be entrained into the bottom waters.

Under conditions of surface water release over summer months, when inflow is low or to the bottom waters, there will be drawdown of the surface waters where the release exceeds inflow. However, as the mixed depth (z_{mix}) is a function of solar radiation and wind mixing, the z_{mix} will remain relatively constant relative to the surface of the Reservoir. Consequently, under these conditions, nutrient rich bottom water is progressively entrained into the surface mixed layer.

Figure 3.6, Reservoir dominant flow pathways, illustrates the longitudinal and vertical transfers between surface and bottom waters for a range of outlet arrangements, and for the 'reservoir turnover' condition.

Except for during periods of spillway overflow, the release from Burrinjuck Reservoir is via bottom outlet penstock and valves. Consequently, upwelling or entrainment of bottom waters into the SML in the lower reaches of the Reservoir would not be expected.

Analysis of internal loading indicates a net loss from the SML to the bottom waters and sediments for the middle reaches of the Reservoir.

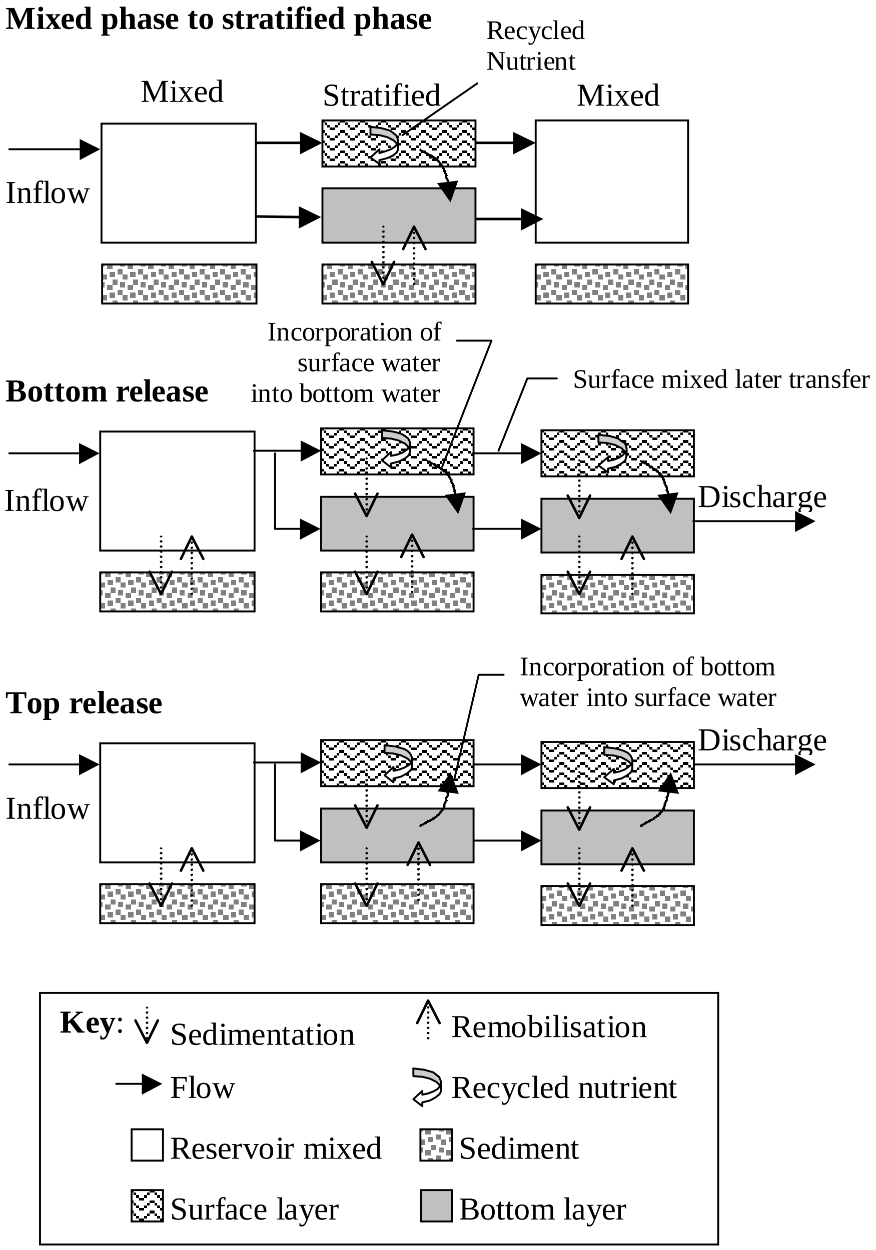

Figure 3.6: Reservoir dominant flow pathways

3.4 Light conditions

The microalgae that grow suspended in the water column are referred to as phytoplankton. Unlike land plants that are fixed in position, phytoplankton are moved vertically and horizontally through the water column by mixing processes and by their own intrinsic bouyancy or flagella. As a result the light that they encounter is not simply a function of the daily incident sunlight but also the extent to which mixing moves the cells through the area of water where light penetrates.

In all aquatic systems, even those with very clear water, the light intensity diminishes with depth due to absorption and scattering by dissolved compounds and particles within the water column. The depth at which light is 1% of its surface value is called the euphotic depth (z_{eu}) and below this level the algal cells have very little light to support algal photosynthesis and must rely on using stored energy to maintain their growth.

However, stored reserves of energy are limited and will only last for a relatively short period of time. Consequently if the phytoplankton spend too much time below the euphotic zone then growth will not continue. If the depth of water mixing (z_{mix}) is greater than the euphotic depth then the motion will carry cells in and out of the light zone. The proportion of time that the cells spend in the light is then determined by the ratio of the euphotic depth to the mixing depth (z_{eu}:z_{mix}). This is illustrated in Figure 3.7. If the mixing depth is large then the cells will spend a relatively short period of time in the light and growth will be restricted. To assess the impact of light climate on algal growth it is necessary to know the depths of the euphotic zone and of the mixing layer.

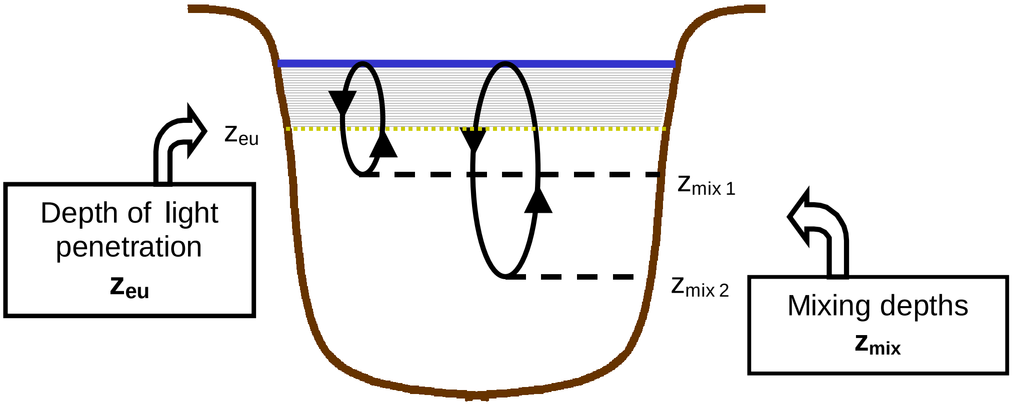

Figure 3.7: The effect of light availability on algal growth. The fraction of time that phytoplankton spend in light is given by the ratio of light penetration depth to mixing depth, z_{eu}:z_{mix}.

The optical characteristics of the water that determine the extent of light penetration do not usually change very rapidly and so light measurements can be made at intervals of one or two weeks and sometimes longer. In contrast, mixing in reservoirs is driven largely be meteorological conditions including wind speed, differences in air and water temperatures, and evaporation rates. These conditions can change rapidly and consequently so can the mixing environment. Changes in mixing are usually tracked from detailed temperature changes in the water column. This requires a series of temperature sensors suspended at different depths (a thermistor chain) to gather data at frequent intervals, sometimes every few minutes, in order to characterise the mixing conditions. These changes can be related to meteorological conditions if a weather station is situated on the reservoir surface. Detailed information on water mixing acquired from temperature measurements provides a basis for tracing water movement, but if the algae are not fully captured in the water motion then they will not be mixed to the extent that the temperature measurements indicate. The rate of water movement can be estimated from the meteorological data in conjunction with the temperature data and if this is compared with the floating or sinking rate of algae then the extent to which the algae are entrained in the movement can be estimated. This can be particularly important when bloom forming blue-green algae are a problem because these organisms are able to float up into the well illuminated layers when mixing is sufficiently weak.

3.4.1 Previous studies

Kirk (1993) has compiled characteristics of the underwater light regime for an extensive range of water bodies, including Burrinjuck Reservoir. The measurements on Burrinjuck show the vertical attenuation coefficient for the photosynthetically active wavelengths (400—700 nm) ranging between 0.71 and 3.71 m^{-1}. These are high values compared to North American and European standards but typical of australian inland lakes (Kirk 1993, p.68, 103, 141). Analysis of the adsorption of photosynthetically active radiation by particulate and dissolved components indicated that 46% of adsorption was by colour, 26% by suspended particles including phytoplankton and 28% by the water. Burrinjuck was classified as a 'dissolved colour, rather low turbidity and plentiful phytoplankton' optical type water body (Kirk 1994).

Photosynthesis achieved by a phytoplankton cell depends on the rate of capture of quanta of light field. This is a function of the light adsorption properties of the photosynthetic biomass, and the intensity and spectral quality of the light field. Major differences exist between the main taxonomic groups of aquatic plants with respect to the kinds of photosynthetic pigment present and associated differences in the absorption spectra.

Given the variation in intensity and spectral quality of the light field in the aquatic environment, it is likely that photosynthetic pigment composition could be a major factor determining which species of aquatic plant grow in relation to variation in light climate with depth, seasonal changes and between reservoirs.

3.4.2 Analysis of the 1976 to 1998 data

Figure 3.8 presents a time series plot of turbidity at Station 104. This figure indicates elevated turbidity levels associated with high inflows (floods in 1977, 1978 and 1991 Figure 2.17) and with periods of intermediate Reservoir drawdown (1982/1983 and 1995). Under conditions of extreme Reservoir drawdown, Station 104 is dry.

Figure 3.9 presents plots of Secchi disk depth for Stations 101 to 108. The Figure indicates a strong inverse relationship between turbidity and euphotic depth. Sources of turbidity are the abiotic particulate material discharged from the catchment during storm events, and biotic particulate material (phytoplankton) over spring to autumn periods. Generally, there is a pattern of increasing Secchi depth over the late Spring period associated with decreased inflows and sedimentation of abiotic particulates, followed by decreasing depth over the summer periods, associated with increased algal cell numbers.

The Figure also indicates a pattern of increasing Secchi depth with distance downstream of the inlet zone, reflecting both the reduction in abiotic particles as a result of upstream sedimentation, and the reduced algal levels.

Analysis of the mixed layer depth indicated that the depth was determined predominantly by solar radiation, temperature and evaporation factors, with wind having limited discernible impact. The seasonal pattern of mixed layer depth is shown in Figure 3.10 for Site 104 at the Reservoir.

Figure 3.11 shows a time series plot of euphotic depth for Stations 101, 104 and 108. The figure shows the horizontal variability in $\mathrm{z_{eu}}$ from the shallow upstream reaches down to the deeper parts of the Reservoir. The station 101 to 108 reach was selected to assess the transition from the 'mixed' condition for the relatively shallow water upstream zones of Station 101 to the stratified conditions for the deeper water zones of Station 108. Station 108 is a distance of 37 km downstream of the entry point of the Murrumbidgee River to the Reservoir and just 18 km upstream of the Dam wall. Figure 3.12 presents a time series plot of $\mathrm{z_{eu}:z_{mix}}$ ratio for Station 104. The euphotic to mixed depth ratio ranges from 0.1 to 1, with a strong seasonal pattern evident both in mixed depth and in the $\mathrm{z_{eu}:z_{mix}}$ ratio. This has important implications for algal composition discussed later in the Report (see Chapter 6). $\mathrm{Z_{eu}}$ is calculated from measurement of Secchi depth using the relationship

$$z_{eu} = 2.7 \times z_{secchi}. \tag{3.1}$$

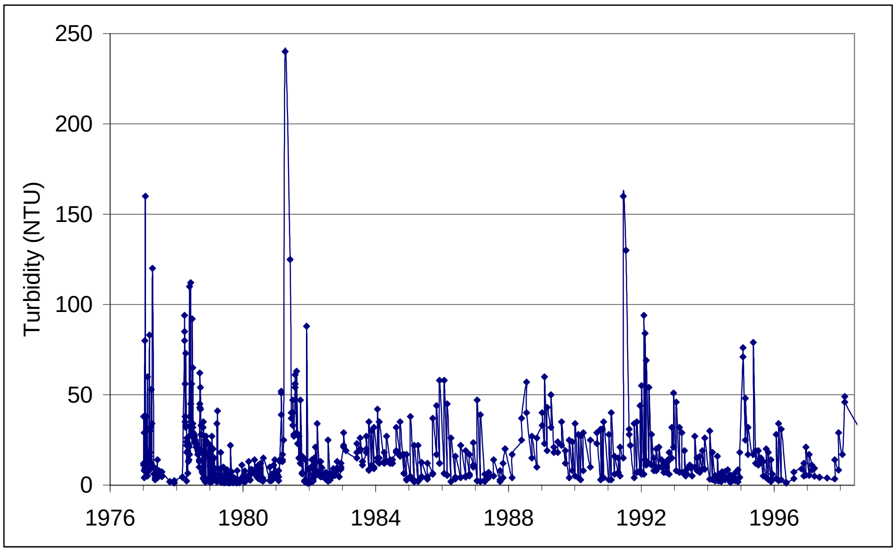

Figure 3.8: Turbidity, Site 104 Burrinjuck Reservoir.

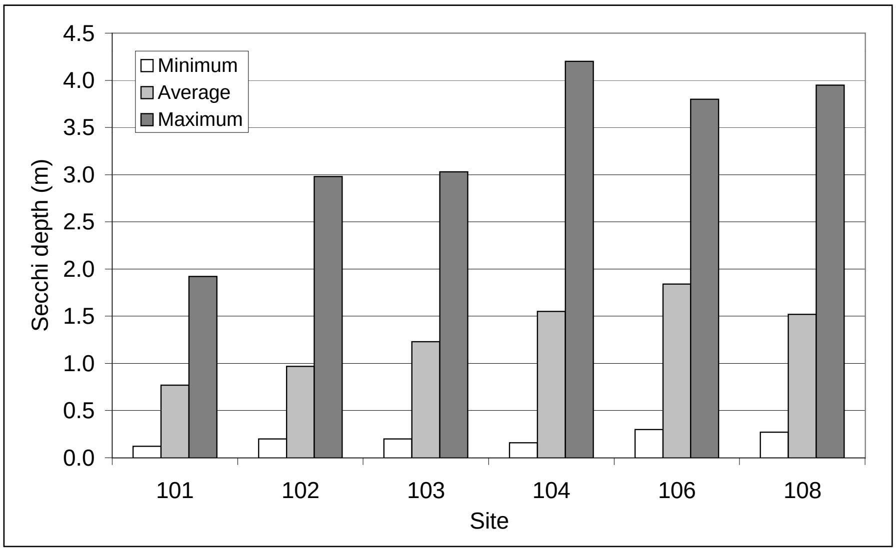

Figure 3.9: Secchi depth (1977 to 1998), Sites 101 to 108 Burrinjuck Reservoir.

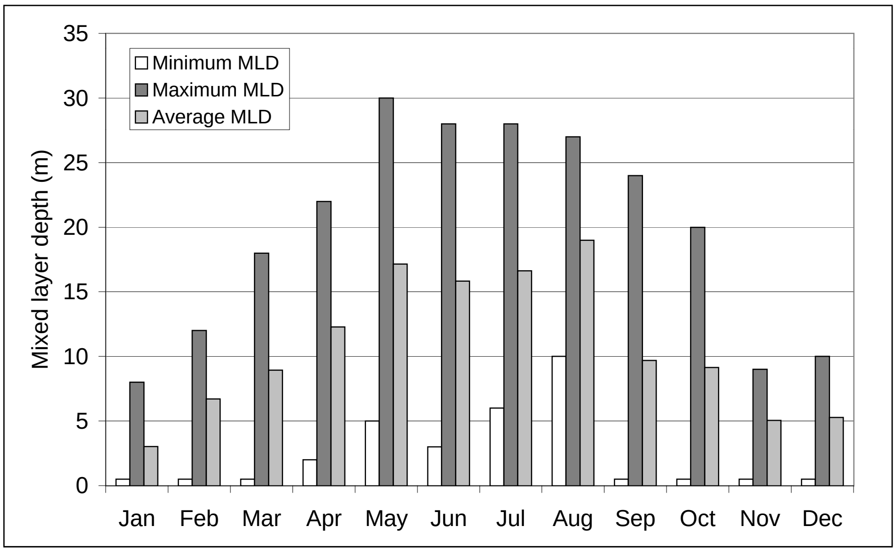

Figure 3.10: Seasonal pattern of surface mixed layer depth, Site 104 Burrinjuck Reservoir.

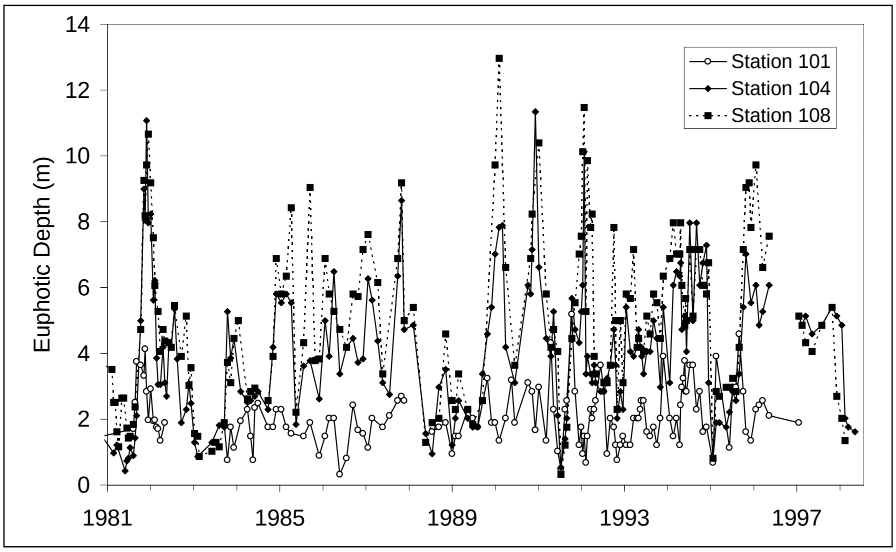

Figure 3.11: Euphotic depth, Sites 101, 104 & 108 Burrinjuck Reservoir.

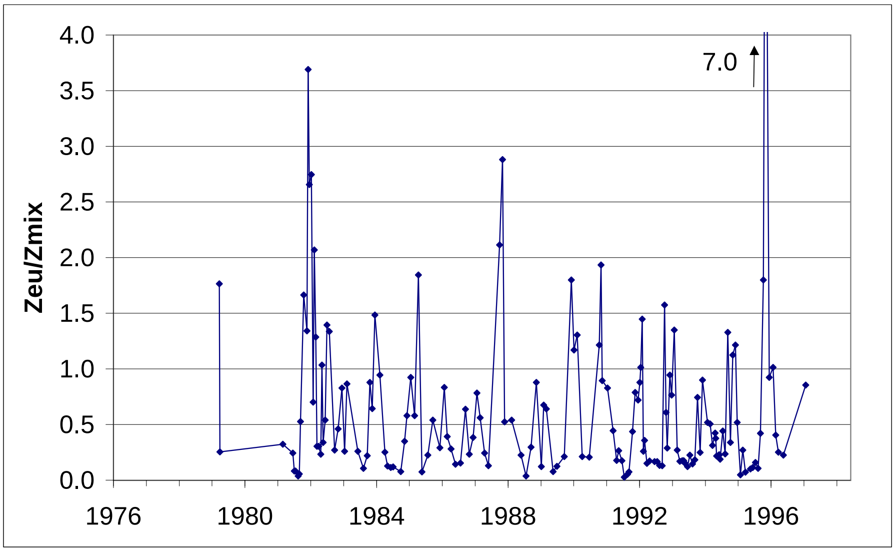

Figure 3.12: Mixed layer depth and euphotic depth, Site 104 Burrinjuck Reservoir.

Chapter 4

Reservoir nutrient pathways

4.1 Range of possible nutrient pathways

In addition to sufficient light algae also require nutrients for growth. Although a wide range of nutrients are required it is the availability of nitrogen and phosphorus that usually regulate algal growth when light conditions are sufficient. This section examines the range of possible nutrient pathways in relation to availability for algal growth. The issue of bio-availability of nutrients is also discussed.

Harris notes that in a dynamic approach to lake and reservoir management, we must focus on rates of transfers between pools, on loads and fluxes and not simply on concentrations (Harris 1996). The questions then become: What is the relative magnitude of external and internal loads? How do microbial interactions influence the fluxes and the cycling of elements? What is the role of the detrital pathways in these systems?

Harris also stresses the importance of addressing inputs and outputs of elements at a variety of scales if we are to understand and manage these highly complex and variable systems. Time scales and the magnitude of extreme events are of great importance in Australian systems. Australian rivers are pulsed systems; irregular flow events dominate system function at a range of scales.

4.1.1 Previous studies

The *ACT Region Water Quality Study* (1978) noted that during floods, most of the phosphorus in the rivers is in the unavailable (particulate) form associated with soil particles, and settles to the bottom of Burrinjuck reservoir. A large proportion of the nitrogen, on the other hand, can be in a bio-available form.

During dry periods, available nitrogen and phosphorus, derived largely from sewage effluent and often in high concentrations, can stimulate growth of algae, especially the attached algae in the River. The available nutrients are thus substantially depleted in concentration by the time the water reaches Burrinjuck Reservoir.

Water reaching Burrinjuck Reservoir under low flow summer conditions is relatively warm and spreads over the surface water layer. Depending on the concentrations of nutrients remaining after uptake by attached algae upstream, nutrients in this discharge may stimulate algal growth in surface waters of Burrinjuck Reservoir.

Following turnover (mixing) of the reservoir, considerable amounts of available nutrients which are present in the bottom waters during stratified conditions are mixed into surface waters, stimulating growth throughout the Reservoir.

Harris notes that in addition to loadings determining the overall trophic state of water bodies for time scales up to a decade after the event, the timing of the event loadings will have significant downstream ecological consequences on the seasonal succession of species (Harris 1996). This can be seen in the weekly data from North Pine storage in Brisbane (Harris & Baxter 1996) where individual storm events had consequences for years afterwards.

4.1.2 Analysis of the 1976 to 1998 data

Chapter 3 describes the flow pathways, and the manner in which they are modified by stratification (physical separation of the warmer surface water layer from the cooler bottom water layer), inflow temperature relative to the surface water layer, and the impact of the discharge arrangement on flow pathways within the reservoir. These flow patterns are one of the primary determinants of nutrient movement within reservoirs, and availability to surface water algae.

This research has identified seven potential nutrient pathways in reservoirs. They comprise:

1. direct uptake of bio-available nutrients flowing in to the surface mixed layer (both deep and shallow reservoirs);
2. mixing of nutrient rich bottom waters at times of reservoir turnover (deep reservoirs);
3. development of anoxic sediments in shallow lakes;
4. re-mobilisation of nutrients from sediments in inlet depositional zones (both deep and shallow reservoirs);
5. mixing, drainage and re-suspension of anoxic sediment pore water, which is high in nutrients, with the surface mixed layer under conditions of rapid drawdown (deep reservoirs);
6. entrainment of nutrient rich bottom waters in the surface mixed layer under conditions of surface water discharge from the reservoir (deep reservoirs);
7. direct recycling of nutrients between algae by microbial processes (both deep and shallow reservoirs).

These pathways are described in more detail in the following text.

Direct uptake of bio-available nutrients flowing in to the surface mixed layer

Under conditions of direct discharge of wastewater effluent or irrigation discharge to reservoir surface waters experiencing low, non-point source inflow (low suspended solids), the elevated phosphate and inorganic nitrogen in discharges becomes readily available to algae.

Where the discharge occurs to a feeder river some distance upstream from the reservoir, the level of bio-available nutrients will be gradually reduced as a result of instream uptake by attached algae, biofilm and benthic Diatoms, dependant on the stream morphology, substrate and light conditions. This pattern occurs within the Murrumbidgee River upstream of Burrinjuck Reservoir both for the pre and post LMWQCC nutrient removal periods.

This pattern is evident in Figures 4.1 and 4.2, Instream modification to loads, Murrumbidgee River 1976–1980. During periods of low flow, there is uptake of some 90% of the FRP monitored over the 40 km of River from the Molonglo River confluence to Taemas Bridge. A similar pattern occurred during 1983–1998. Analysis of FRP contribution to surface waters for Burrinjuck Reservoir indicates that only a small proportion of the observed algae can be explained by this pathway. Estimates of relative contribution of FRP to the Surface Mixed Layer are shown in Table 4.1. Here, the hypolimnion estimate is based on an average hypolimnion volume of 330,000 ML multiplied by the average FRP at turnover for the period. Direct inflow FRP estimates are based on average FRP at Station 201 for low inflows (less than 1000 ML/day) for the period, multiplied by the sum of low inflows.

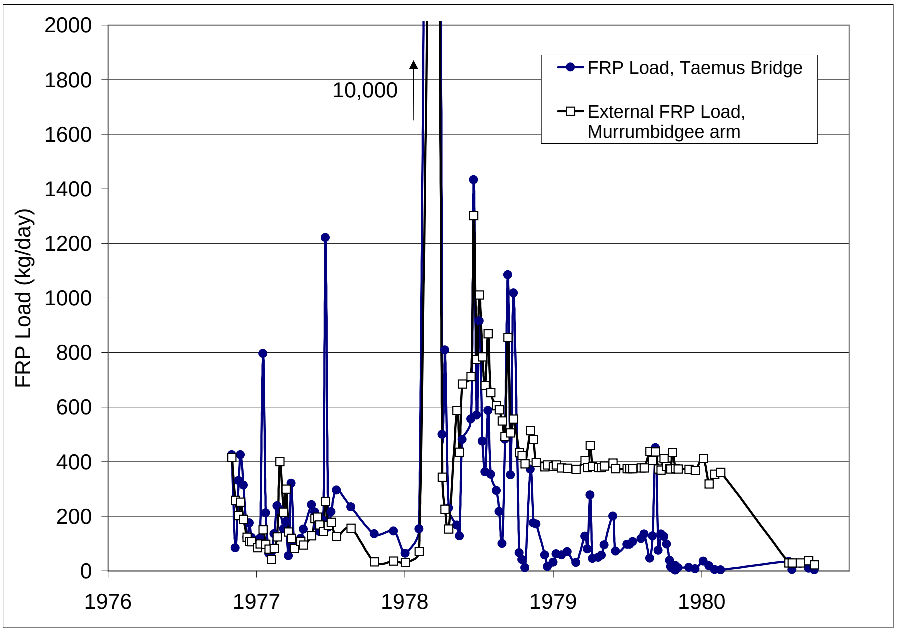

Figure 4.1: Burrinjuck Reservoir FRP Load, Taemus Bridge and External (Murrumbidgee Arm)

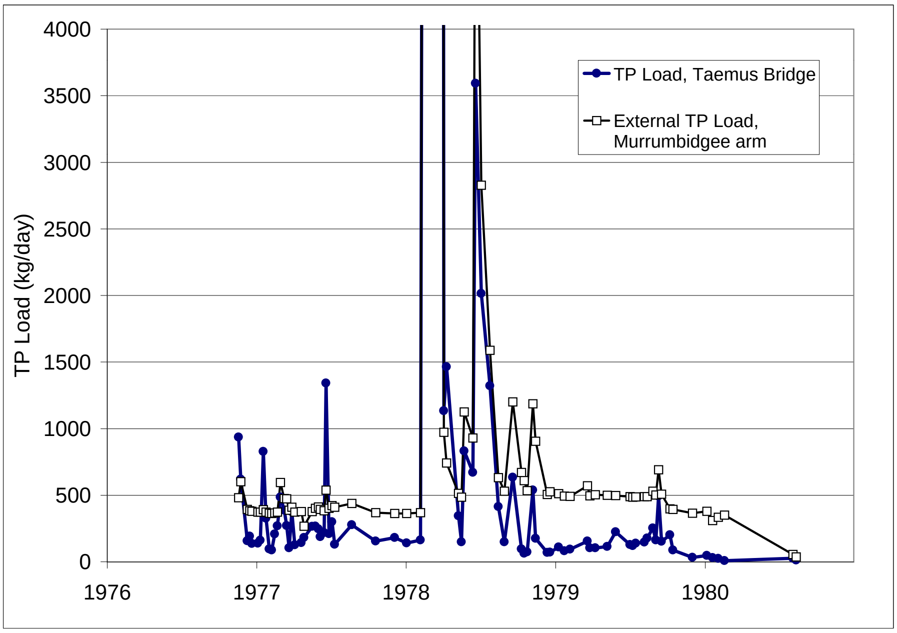

Figure 4.2: Burrinjuck Reservoir TP Load, Taemus Bridge and External (Murrumbidgee Arm)

This represents a significant departure from the reported major nutrient pathway for northern hemisphere lakes and reservoirs. The Ca^{2+} dominant and low abiotic suspended solids nature of many northern hemisphere waters, and the sustained flows and deep streams, limit the instream adsorption and biological uptake prior to discharge to lakes and reservoirs. In addition, the large size of lakes is often such that there are direct discharges of municipal wastewater to the lakes.

Table 4.1 further illustrates the minor role of direct inflow of nutrients as compared to bottom water sources.

Table 4.1: Estimate of relative contribution of FRP to Surface Mixed Layer

Period	FRP Source	Annual load (kg)
Pre 1980	Hypolimnion	20,000
	Direct inflow	15
Post 1983	Hypolimnion	3,300
	Direct inflow	0.6

Mixing of nutrient rich bottom waters at time of reservoir turnover

During periods of reservoir stratification, nutrients may be released from sediments to the bottom waters as a result of the decomposition of sedimented organic material under anoxic conditions. Over late autumn, the surface mixed layer cools until they are at the same temperature as the bottom waters. At this point full mixing of waters of the reservoir occurs, and the nutrient rich bottom waters are mixed throughout the surface waters. Subject to inflow conditions over the following winter and early spring period, these nutrients may be available in the surface mixed layer for algal growth in the following spring and summer growth periods.

Analysis undertaken on Chaffey Reservoir indicated that the amount of algae that develops in the growth season is often reliant on the amount of phosphorus released from the sediments into the anoxic deeper waters during the preceding year (Figure 4.3). This phosphorus is mixed into the surface layers when the lake is fully mixed and determines the concentration in the surface layer when temperature stratification re-develops. It is this phosphorus that supports algal growth in the next growing season.

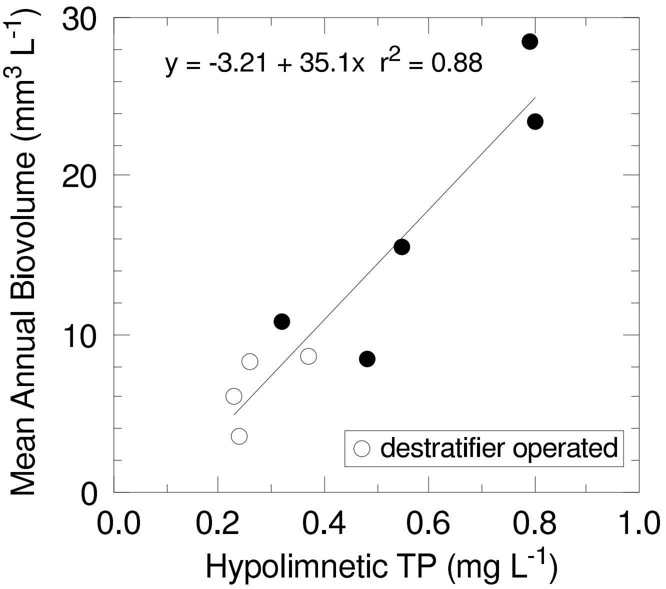

Figure 4.3: Maximum hypolimnetic phosphorus and mean annual algal volume just prior to turnover at the start of the algal growing year at Chaffey Reservoir. Open circles denote that the destratifier was operating

An analysis was undertaken of Burrinjuck algal biomass versus hypolimnetic FRP at turnover for the previous autumn. The estimate of FRP in surface waters is based on the mass of hypolimnetic water FRP at turnover in the previous autumn period. The analysis is presented at Figure 4.4. The Figure indicates that:

1. during the pre LMWQCC nutrient removal period (1976 to 1980), the measured Chlorophyll 'a' to estimated FRP levels in surface waters are close to a 1:1 ratio, with a correlation coefficient of 0.87;
2. during the post LMWQCC phosphorus removal period (1984 to 1998), the measured Chlorophyll 'a' to estimated FRP ratio was 1:3, with a correlation coefficient of −0.3.

The high Chlorophyll 'a' to estimated FRP ratio in the case of the pre-sewage nutrient removal period indicates that hypolimnetic P is the major source of nutrient during this period. The lower ratio in the post-sewage nutrient removal period indicates that the hypolimnetic FRP was a less significant source for this period.

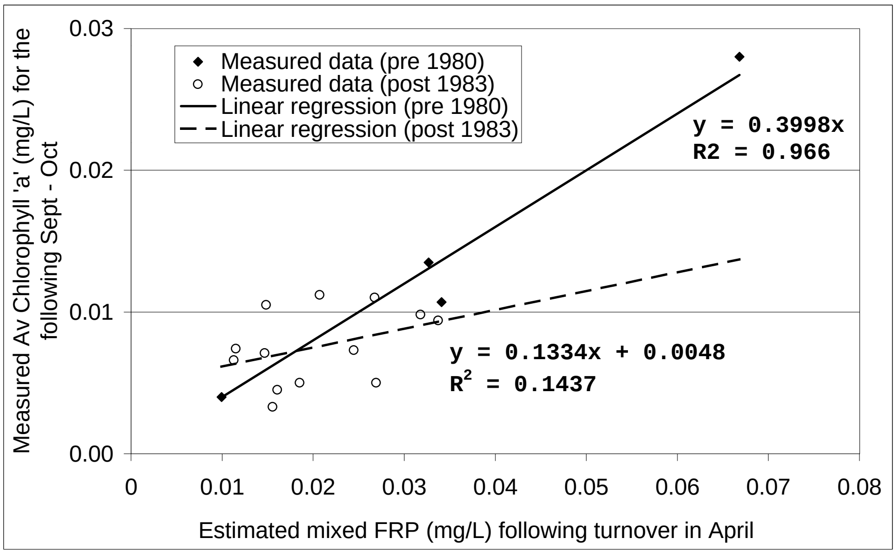

Figure 4.4: Algal biomass vs. hypolimnetic FRP at turnover, Burrinjuck Reservoir.

The high correlation coefficient in the case of the pre-sewage nutrient removal period is indicative of the high organic loading on the Reservoir sustained by Canberra sewage discharges. This has masked the effect of other factors such as drawdown, washout and non-point source contributions, on the actual mass of hypolimnetic P mixed into and retained in the surface mixed layer. Conversely, for the post-sewage nutrient removal period, the sewage derived nutrients and organic material is no longer dominant, with a range of factors influencing the transfer of hypolimnion P to the surface mixed layer.

Development of anoxic sediments in shallow waters

Shallow lakes (less than 1 m in depth) may have a high level of internal productivity, given their generally mixed condition and high light availability.

Periodic calm (low wind) conditions may lead to development of anoxic sediments in shallow waters and high productivity lakes. The anoxic sediment may result when:

1. there are short periods of reduced wind and high solar radiation, such that steep thermal gradients develop in the water column, limiting dissolved oxygen transfer to the sediments;
2. there is elevated organic material decomposition resulting from high macrophyte and attached algal growth associated with shallow lakes or deposition of organic material from a storm inflow just prior to period of low winds.

This is understood to be more a feature of open shallow lakes and reservoirs, rather than deep reservoirs. In view of the depth of Burrinjuck, it is unlikely to be a significant pathway in this case.

For this pathway, wind is the major factor determining nutrient availability and algal growth dynamics.

Re-mobilisation of nutrients from sediments in inlet depositional zones

Suspended solids and organic material, discharged to reservoirs under storm inflow conditions, settle rapidly upon entering the relatively calm flow conditions within reservoirs. Typically, a large proportion of organic material settles out in a zone close to the inlet point. Consequently, the loading of organic material per square metre of sediment within these zones is significantly greater than for sediments further within the reservoir.

The significantly greater transfer of oxygen through these shallow and mixed inlet zone waters than for the deeper downstream (stratified) waters is normally sufficient to offset the oxygen depletion associated with decomposition of the organic material. However, where there is a rapid reduction in flow following the storm event, the elevated turbidity and high summer solar radiation in association with low wind conditions may lead to the development of a steep temperature gradient vertically through the water column. This may occur for waters as shallow as 1 m. Under these conditions, there will be substantial reduction of oxygen transfer through the water column, with a high potential for the development of reducing conditions in the sediments and the release of nutrients in a highly bio-available form.

These nutrients will be available to algae either as a result of sporadic limited mixing as a result of thermal cooling in the evening or light winds, or as a result of alga varying their depth in response to light conditions (via buoyancy control). Algae will be washed through downstream surface waters under the low (warm water) inflow conditions, or in association with reservoir drawdown.

The potential for re-mobilisation of nutrients via this pathway will be significantly exacerbated by dendritic shaped reservoirs, with narrow and contained inlet zones and reduced wind exposure.

Burrinjuck Reservoir receives a continuous flow of water even during the dry summer as a result of the discharge from a large sewage treatment plant and stormwater discharges from urban areas. In this system the interaction of flow, nutrient content in the discharge, and the delivery of organic carbon to the narrow and relatively shallow receiving arms of the Reservoir, regulates algal growth. When nutrients are high during the growing season then algal concentration is high. Historically nutrients were high because the sewage treatment works discharged large quantities of nutrients. Micro- and macro-algae growing in the river upstream of the Reservoir initially captured the nutrients, but during high flows this plant material was transported to the Reservoir and sedimented in the shallow receiving arms. The breakdown of the organic material in the shallow arms released nutrients that stimulated micro-algal growth.

For this pathway, the pattern of event or 'pulsed' inflow of catchment drainage, nutrients and organic material, and the shape of the inflow hydrograph, are important factors determining nutrient availability and algal growth dynamics.

When nutrient release from the sewage treatment works was decreased around 1980 the peak algal biomass in the Reservoir also declined. However, recently increased algal growth has again occurred within the Reservoir and is associated with increased nutrient concentrations in the water column. However, this increase in nutrient concentrations does not seem to be due to increased nutrient release from the sewage treatment plants.

The recent increase in algal biomass appears to be strongly associated low Reservoir levels. In this case inflow is to a much reduced and restricted volume in the shallow receiving arms of the Reservoir. As a result the same river nutrient load has a larger impact on nutrient concentrations in the receiving water, particularly if the transported material is sedimented to the bottom prior to metabolism and release of nutrients. The increased nutrient concentrations stimulate algal growth. This is supported by increased concentrations of other nutrients (Figures 2.6 and 2.9) that also come from the sediments, including ammonia, and by analysis of sediment redox conditions for the inlet depositional zone.

Figure 4.5 presents the results of model analysis of inflow, washout, sedimentation, sediment redox and P release, and algal uptake of released P for the inlet reach Station 101 to 102. The model estimates a high FRP release as a result of severely reduced sediments following a storm event (deposition of organic material) in early August 1978, and the uptake of the released FRP by algae. The pattern of estimated Chlorophyll 'a' closely reflects the monitored Chlorophyll 'a' values for the period.

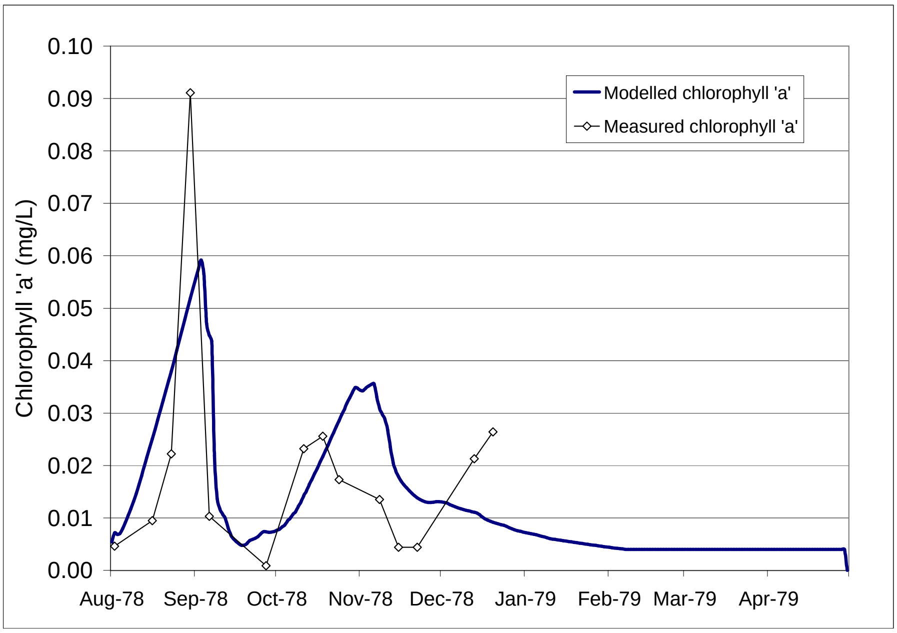

Figure 4.5: Lake redox model estimates of Chlorophyll 'a', Burrinjuck Reservoir inlet depositional zone

Figure 4.6 presents a time series plot of daily inflow, TP sedimentation and FRP release from sediments for the inlet depositional zone. The estimate of FRP has been drawn from the model analysis outlined above. The figure indicates the limitation of mass balance based analysis, with both sedimentation of particulate P and release of FRP occurring simultaneously. A simple mass balance based solely on TP analysis would conclude that there is a net loss of P to the sediments for this period, but when the different forms of P are considered, a net release of FRP is apparent.

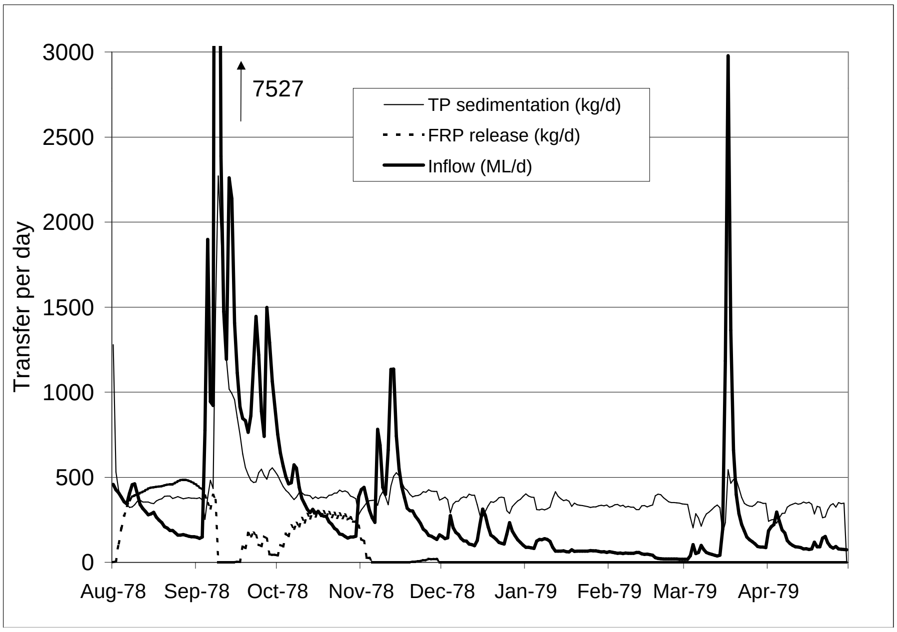

Figure 4.6: Nutrient sedimentation and remobilisation, Burrinjuck Reservoir inlet depositional zone

It is concluded that for low Reservoir level conditions, Reservoir algal growth is the result of a complex interplay of nutrient release from sediments as a result of deposition of storm event organic material, followed by low inflow (mixing) and wind driven mixing conditions.

Nutrients released into the water column will be washed through (either as dissolved nutrients or algae) into surface waters of downstream reaches under the low flow conditions, with algal cycling of nutrients sustaining algal biomass through subsequent reaches. With each cycle of nutrients there is some loss, reflected in declining algal biomass with distance downstream.

Mixing, drainage and re-suspension of anoxic sediment pore water with the surface mixed layer

Under conditions of rapid drawdown, some areas of anoxic sediments previously existing within the anoxic bottom water zone, will be entrained in the surface mixed layer, or even emerge from the receding reservoir water surface. Under these conditions the nutrient rich pore water is mixed with the surface waters, or where the sediments are left above the receding reservoir water level, the pore water drains to the receding surface waters. The analysis of the inlet depositional zones indicated increases in algal levels associated with continued drawdown and low water depths (refer to Figure 4.5). The algal biomass exceeded levels which could be explained by the sediment redox modelling and inflow. The analysis suggests that there is another significant source of nutrients under these conditions. Drainage of pore water from the exposed sediments and increases in algal levels over and above that explained by remobilisation of nutrients for the sediment in the inlet depositional zone was put forward as a hypotheses explaining this anomoly.

Drawing on hypsometric curves for Station 102 reach, a surface mixed layer depth of 3 m, a porosity of 30% and a sediment exchangeable pore water depth of 50 mm, an analysis of internal loading associated with drawdown for this reach was undertaken. The results of the analysis are summarised in Figure 4.7. The figure indicates that as the reach pool approaches substantially reduced volumes, and drainage is invoked from the lower flatter valley slopes, the contribution from sediment pore water drainage becomes significant (refer to methods at Appendix B).

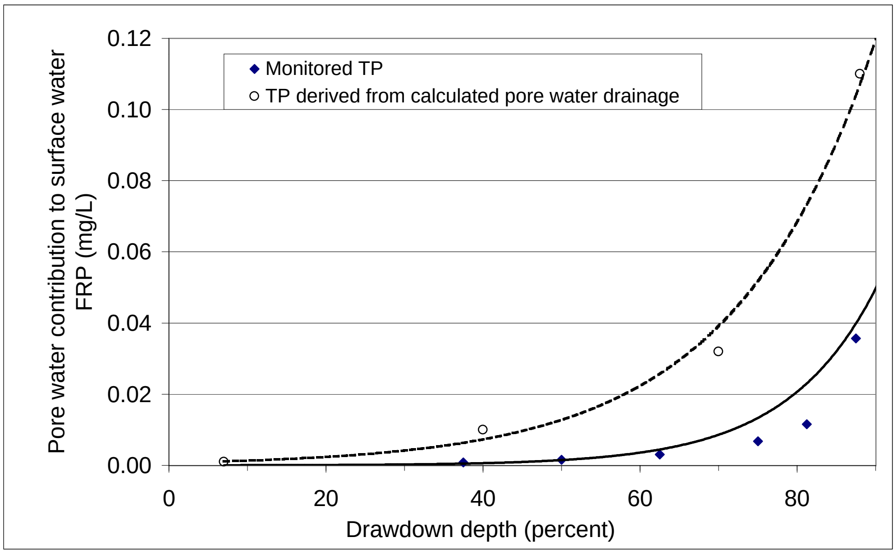

Figure 4.7: FRP contributed by sediment pore water as a function of Reservoir drawdown, Station 102 reach.

The analysis suggests that while this pathway is not significant relative to other pathways for normal reservoir levels, as the reservoir reaches shallow (reduced volume) conditions in association with substantial drawdown, the pathway become significant. Where reservoirs are interconnected with substantial groundwater systems, this pathway would be significantly exacerbated.

Entrainment of nutrient rich bottom waters in surface mixed layer.

Where the discharge of water from the reservoir is via a top outlet, under low surface inflow conditions and high surface water release (typical summer water supply situation), the surface mixed layer would normally be depleted. However, as the mixed depth is largely determined by solar radiation and air temperature, and consequently remains relatively constant, nutrient rich bottom waters are progressively entrained in the SML.

As Burrinjuck Reservoir is currently a bottom release based system, this potential pathway does not apply.

Recycling of nutrients between algae by microbial processes.

Under conditions of limited dissolved nutrients algae have an ability to recover nutrients from dead cells by way of biological processes. In this way, algal biomass may be sustained, even where there are no new sources of nutrient transferred to the surface mixed layer.

This pathway is seen as the explanation of sustained algal biomass through the Reservoir surface waters during periods where fresh sources of nutrients via the pathways outlined above, are not evident.

4.2 Bio-availability of nutrients

As the nutrient pathways involve transformations in the form of nutrients, it is important to understand the relationship between the form of the nutrients and their bio-availability.

The primary form of P used by phytoplankton is inorganic phosphate (PO_4 — P) although some organic forms of P may be used, particularly when ortho-phosphate is scarce in oligotrophic lakes (Harris 1994). Clearly, if the majority of P loading is in a form which is readily available for algal growth then the resulting biomass will be greater than if much of the P is in particulate or organic forms which are not readily available to the algae.

Harris also notes that the question of P availability in Australian waters is complicated by terminology and deciding what is the “limiting” nutrient. Because of the wide variety of processes in operation in natural waters (growth, grazing, microbial metabolism, sedimentation) and the rapid turnover of some P pools, it is possible to argue that over sufficient time, all the P in the system will be available for the accumulation of phytoplankton biomass. What will determine the biomass produced will be the exchange coefficients between all the chemical and biological forms of P in the system and the final distribution of pool sizes. What controls the rate of growth of the phytoplankton is the flux of P which links the uptake of P by the algae to the turnover and depletion of the other pools.

4.2.1 Previous studies

The *ACT Region Region Water Quality Study* (1978) noted that during floods, most of the phosphorus in the rivers is in the unavailable (particulate) form associated with soil particles, and settles to the bottom of Burrinjuck reservoir. A large proportion of the nitrogen, on the other hand, can be in an available form.

4.2.2 Analysis of the 1976 to 1998 data

Some portion of total phosphorus may be present in crystalline form, and not be bio-available.

Some portion of total phosphorus may be present as iron phosphate, a highly bound condition in which the P is not bio-available unless separated by a process of reduction of the iron (III) to iron (II) and release of the phosphate.

Iron is typically associated with surface coating of fine suspended particles, or may be chelated with natural organic compounds. Rivers discharging into Burrinjuck have relatively high iron levels at 0.1 to 0.3 mg/L.

Some ortho-phosphate may be adsorbed, together with iron, onto the surfaces of abiotic particles. Fine suspended particles may also be coated with a bio-film, incorporating phosphorus and nitrogen. While not as readily bio-available to algae as dissolved phosphate or inorganic forms of nitrogen, algae may be able to access this form by biological breakdown processes. However, where the suspended solids settle out of the surface waters to the bottom sediments, the adsorbed ortho-phosphate and the bio-film coated particulate potential sources outlined above may removed too quickly to be available to the algae.

Phosphorus that has been synthesised into organic material may become bio-available by processes of mineralisation (oxidation) of the organic material, or by way of a biological breakdown process whereby the algae can access this source directly.

Un-adsorbed forms of phosphate are highly bio-available for algal uptake. The bio-available (soluble) component of total phosphorus is best measured by filtering the TP sample through a 0.003 μm filter. The Standard Methods determination of FRP is based on a 0.45 μm filter, and is the basis of all FRP determinations in the Burrinjuck data sets.

In the case of nitrogen, the inorganic forms are highly mobile and bio-available. Organic forms require mineralisation (oxidation) before becoming available to algae.

Organic carbon also exhibits a range of bio-availability levels which is critical in respect to the sediment microbial decomposition processes. Organic material deriving from native vegetation is typically low in labile (rapidly assimilable portion) carbon and high in refractory (slowly assimilable portion) carbon. Organic material derived from fertilisers, municipal or agricultural wastewater, grass and algae, have a high labile carbon content, and are much more likely to result in anoxic and reducing conditions than for the native vegetation derived material.

BOD analysis of a range of organic materials within the Murrumbidgee River catchment indicate that wastewater organic material and algae have $\mathrm{BOD}_{\mathrm{5day}}$ rates an order higher than for local native vegetation derived organic material.

4.3 Role of the sediments

Mention has been made in Chapter 3 of nutrient release from sediments to bottom waters and inlet zone waters, as a result of reducing conditions in sediments. The relative importance of these internal releases (loads) vis-a-vis the external loading depends on a number of factors including stratification of the dam, organic material loading, extent of drawdown over summer and the magnitude of episodic inflows.

Nutrients are released from the sediments as a result of the reducing conditions created by bacterial breakdown of organic matter delivered during inflows or dead algae produced within the reservoir itself. The coarse (inflow derived) organic matter is concentrated at the upstream end of the reservoir. The algal detritus and slowly settling fine particles are distributed throughout the reservoir sediments.

The bacteria use oxygen in breaking down the organic matter leading to anoxic bottom waters and reducing conditions in persistently stratified reservoirs. The nutrient concentrations in the pore waters and bottom waters build up to high concentrations especially of ammonia and FRP under reducing conditions. Dissolved iron and manganese concentrations rise significantly in the pore waters and bottom waters and any nitrate in the anoxic water column is consumed by bacteria (denitrified). Under oxic conditions the ammonia released from sediments is directly transformed into nitrate (nitrification) while the dissolved phosphate is not released due to the iron present in the sediments.

4.3.1 Previous studies

A study on the Lake Burley Griffin nutrient budget (Cullen & Rosich 1978) concluded that sedimentation was the major process for removal of P from lake water, but bioassay studies showed that sediment P is potentially available to promote algal and plant growth.

Rosich (1983) noted that the P, N and C content of the sediments of Lake Burley Griffin and Lake Ginninderra were comparable, even though Lake Burley Griffin received a sewage effluent discharge and Lake Ginninderra did not. Laboratory experiments were undertaken, placing equal amounts of sediments from each Lake in the bottom of glass jars, and filling the columns with water. The columns were then capped and subjected to anaerobic conditions. The Lake Burley Griffin sediments released phosphorus levels 40 times that released from the Lake Ginninderra sediments.

It was concluded that there was a vast difference between Lake Burley Griffin and Lake Ginninderra sediments which was not explained by differences in gross parameters (TOC). It was hypothesised that given direct discharge (ex sewage) of bio-available P in the case of Lake Burley Griffin, there was accumulation of bio-available carbon in the sediments, whereas, in the case of Lake Ginninderra, the sediment bio-available carbon was extensively worked over.

4.3.2 Analysis of the 1976 to 1998 data

Figures 4.8 to 4.10 present the results of internal loading analysis for TP, TN and SS respectively. For each reach, input load comes from the upstream reach, and output goes to the next reach downstream. Within each reach, transfer of material occurs vertically between the atmosphere, the surface mixed layer, the bottom waters, and the sediments. Analysis was undertaken on a reach by reach basis (refer to Appendix B for method). The results of the analysis of each reach are presented in terms of a set of bars, showing the net loss from the surface mixed layer, the net loss from the bottom waters, and the net gain in the sediments. A bar below the axis in the case of the sediments indicates a net release from the sediments back into the bottom waters.

The Figures indicate high interannual variability, and a pattern of high net loss of TP, TN and SS to the sediments, particularly during the elevated inflow spring period, and particularly in the inlet depositional zone (Station 201 to 101 or 102). The Figures also demonstrates the high net sediment release of P and N back into the bottom waters for the deeper downstream reaches (Stations 102, 103 and 104). Figure 4.9 indicates a net release of N from the sediments within the inlet (mixed) depositional zone for the 1988 and 1993 Spring periods. Given the high rate of TP adsorption onto surfaces of SS and removal to the sediments by settling, periods of remobilisation are masked by the periods of high deposition of particulate P during inflow events.

Figure 4.6 presented the results of the inlet depositional zone redox analysis modelling, including daily inflows and washout, analysis of organic material deposition rates, rate of decomposition and oxygen depletion, and sediment redox levels, using a daily time step. Figure 4.6 indicates the significant FRP release from the sediments under the severe reducing conditions following inflow events, where the inflow events are followed by low flow conditions. The modelled algal biomass (Figure 4.5) correlates closely with monitored values for the inlet depositional zone and downstream reaches. This was a significant source of nutrients driving algal growth in the pre 1980 period, and possibly the dominant source of nutrients in the post 1983 period, particularly where the Reservoir is at a low level.

In the case of event inflow plunging into the bottom waters, some organic material will be transported through and settle out onto the sediments of these downstream reaches.

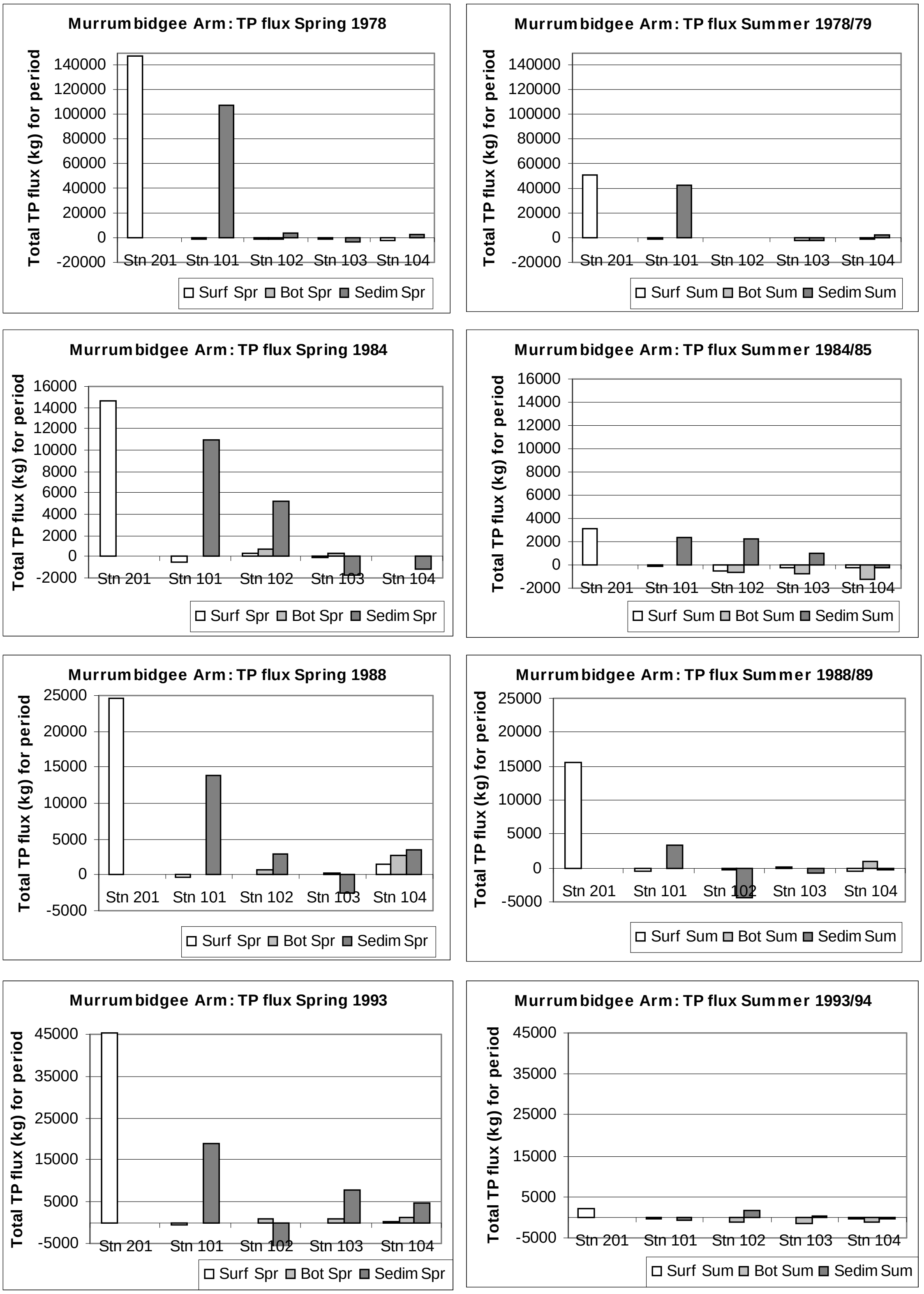

Figure 4.8: Reach based internal TP loading, Murrumbidgee arm of Burrinjuck Reservoir

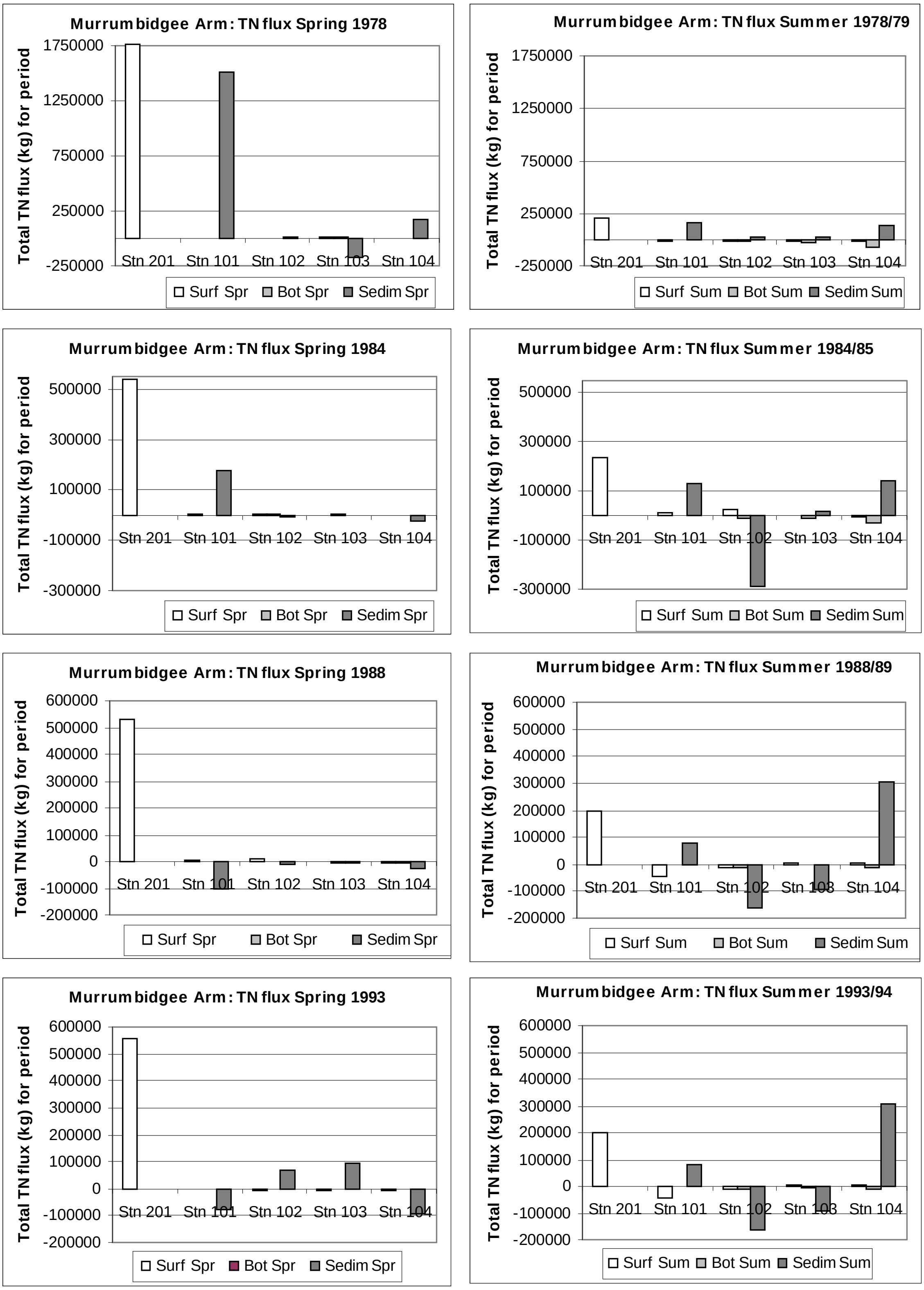

Figure 4.9: Reach based internal TN loading, Murrumbidgee arm of Burrinjuck Reservoir

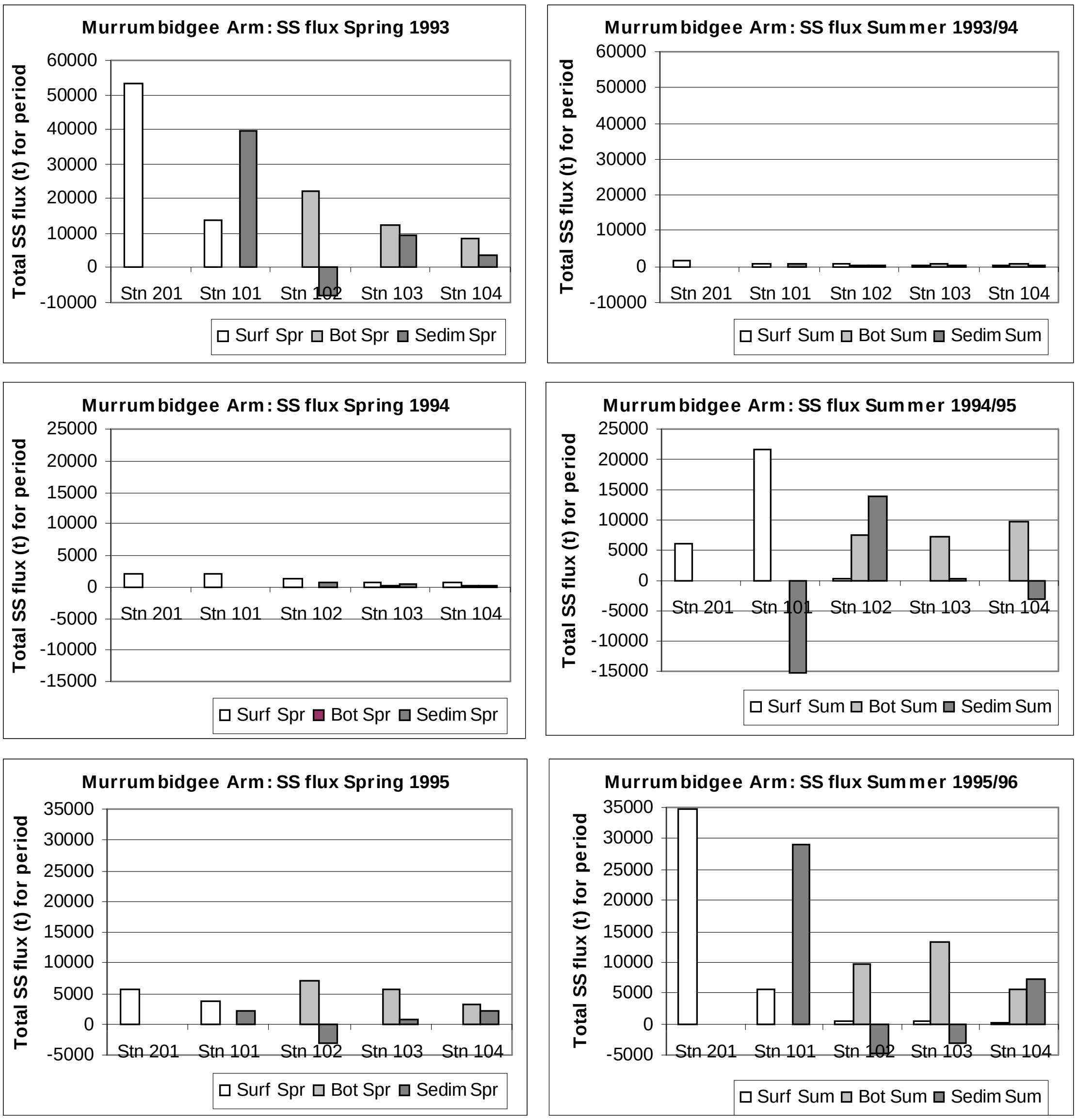

Figure 4.10: Reach based internal SS loading, Murrumbidgee arm of Burrinjuck Reservoir

4.3.3 Modifiers of sediment redox processes

There are a number of potential modifiers of these sediment redox processes, as outlined in the following notes.

Previous studies

Surveys of algal composition over the period 1973 to 1975 (May 1978) indicated that the 1974 flood significantly modified algal biomass and composition, with significant depletion of algae during 1975, and removal of the species *Anabaena circinalis*.

Analysis of the 1976 to 1998 data

There is evidence indicating that extreme floods are an important modifier of sediment redox conditions. Several processes are associated with these modifications:

1. elevated inflows causing re-suspension of previous sedimented material and transfer to downstream deeper zones of the Reservoir, or discharge from the Dam outlets;
2. inflow of extreme suspended solids loads, high in abiotic material, with significant blanketing of organic sediments.

The effect of these changes is to significantly reduce for a period the redox conditions of the sediments (SOD) as a result of the depletion of previously stored organic material, and by blanketing of organic material under a layer of abiotic particles, having a high adsorption capacity.

As noted in Section 2.4, the results from sediment core dating analysis for the second core indicated significant discontinuities in the layer sequence, with presumably removal of layers under extreme flow conditions (Wasson et al., in press).

Discharges high in NO_3 act as a significant buffer to reducing conditions in bottom waters (internal loading). In situations where there is a high residue of organic material in the sediments as a result of earlier wastewater discharges (SOD), or there remains elevated levels of organic material (BOD) in discharges, there may be a case for the use of wastewater effluent high in NO_3 as a means of redox manipulation.

Conversely, effluent high in BOD or COD (such as nht) will exacerbate the redox conditions in the reservoir.

Analysis of bottom water DO, nox, NH_3 and P concentrations for summer (stratified) conditions for Burrinjuck indicate depletion of DO and high NH_4 and P levels in the pre sewage nutrient removal period, but low NH_3 (high NO_x) and low P levels for the post sewage P removal period.

It is concluded that while there is sufficient sediment BOD to deplete DO in the bottom waters over the post 1983 periods of stratification, the NO_x buffers further reduction such that denitrification occurs as N_2 gas rather than NH_3, and reducing levels are limited such that the release of P is substantially diminished. As a result, the major nutrient pathway for the pre-sewage nutrient removal period is now substantially diminished, with other pathways becoming more important. Increases in pH will generally increase the redox energy required to transform iron to soluble forms.

Sulphate in reservoir waters will act as an oxidant of organic matter. However, the transformed HS- will then act as a reducer in respect to ferric iron, releasing PO_4 to the water column.

The modifiers of sediment redox processes are shown in Figure 4.11. The chemical composition of sediments is an important determinant of their transformation responses to reducing conditions. Sediments high in iron will reduce to dissolved forms at moderate redox levels, releasing PO_4 to the water column. Sediments high in aluminium will require much higher energy to release the bonded PO_4.

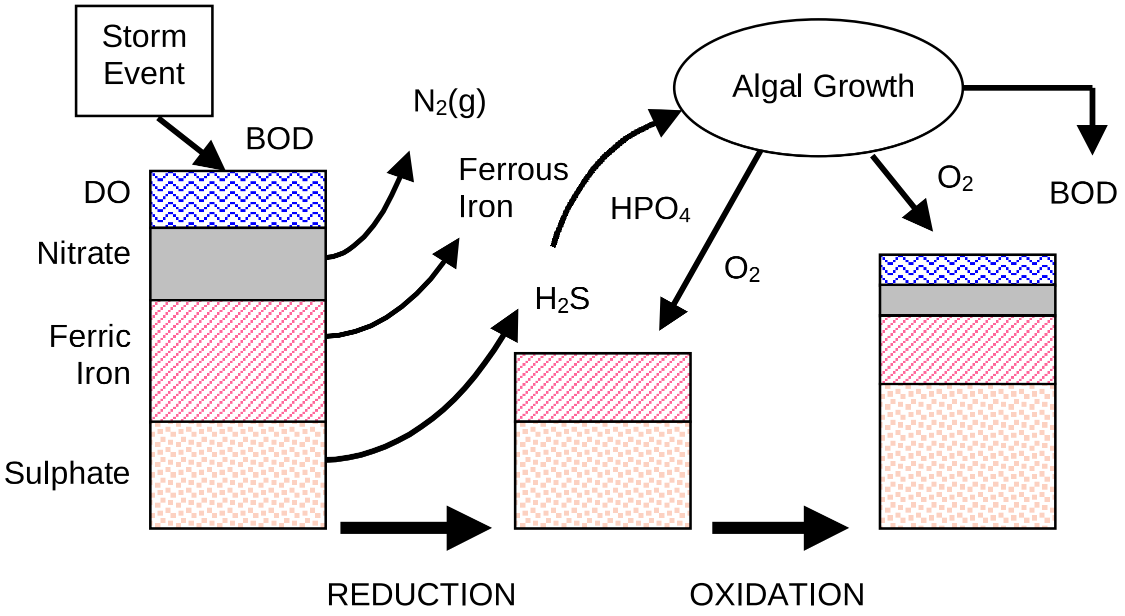

Figure 4.11: Sequence of sediment redox processes

As noted previously, high levels of residual organic material in sediments may create a significant benthic oxygen demand. Organic material deposited from external loading may significantly exacerbate the level of sediment oxygen demand.

Consequently, sediments represent a major store (usually 90% to 98%) of phosphorus in reservoir systems. Nutrients and organic material accumulate under the reduced water temperatures over the autumn and spring periods. Organic carbon is consumed more rapidly under the increased water temperatures over the late spring and summer periods, potentially leading to severe reducing conditions in the sediment, and release of P and N into the water column.

It could be argued that as the P and N stored in the sediments have originally come from external loading, they are the drivers of algal growth. This view fails to recognise that the normal geomorphological process is one of deposition and burial of organic material and P and their re-integration into the earth's geology. The management issue is the excess level of disassociated nutrients available at any one time in surface waters. Secondly, at the time of deposition, much of this material is bound or in a non-bioavailable form. As a result of excessive loading of sediments with labile C, the N and P are transformed into highly bio-available forms and released back into the water column.

4.4 Role of external loads

There is a need to examine the role of external supply of organic carbon and nutrients, and the manner in which they modify the nutrient pathways and supply rates outlined in Section 4.1.

The external loading (nutrients and organic material discharged from the catchment) are linked to reservoir water quality and ecological impacts on the basis of our understanding of:

1. in-stream transport, interception, re-suspension and transformation processes and pathways and their implications for spatial and temporal pattern of delivery to the reservoir, and for their composition;
2. the manner in which the discharges influence in-reservoir nutrient pathways.

Normally base flows are low in suspended solids (SS). In situations where a point source discharge with elevated nutrient levels is superimposed on non-point source flows, the nutrients are subject to uptake by attached algae and biofilm within the river channel upstream of the reservoir. Inflows to reservoir surface waters are low in nutrients under these conditions.

Elevated or event flows are typically high in SS. Under these conditions, there is rapid adsorption of P onto surfaces of SS and re-suspension of attached algae and biofilm that had accumulated in the river channel under periods of low flow prior to the event flow. Inflow to the reservoir is characterised by high levels of abiotic SS and biotic particulate material and its rapid sedimentation in upstream shallow pools. Some SS and organic material are transported through into bottom waters, depending on the magnitude and duration of the flow event.

Consequently, the total nutrient and organic material load (point or non-point sources) across the catchment and the phosphorus bio-availability and labile carbon content composition of discharges, are important determinants of the in-reservoir nutrient pathways, and of the ultimate availability of nutrients for algal growth in reservoirs.

Where a catchment comprises predominantly low intensity grazing free of point source discharges, levels of bio-available nutrients during periods of low flow will normally be limited, limiting algal biomass under the direct discharge low flow conditions. Under high discharge conditions from non-point sources across the catchment, high loads of SS and limited organic material loading on inlet depositional zones and on bottom water sediments will again limit the potential for remobilisation of nutrients from either the mixed inlet zone waters or the bottom water sediments.

Where a catchment comprises intensive agriculture or wastewater or irrigation drainage water discharges, high levels of bio-available nutrients during periods of low flow may increase algal biomass under direct discharge low flow conditions. Under high discharge conditions from non-point sources across the catchment, high loads of SS and organic material on inlet depositional zones and on bottom water sediments will occur, leading to remobilisation of nutrients from both the inlet zone and bottom water sediments.

The analysis of algal biomass and composition in Burrinjuck as a function of nutrient and organic material loading pre and post-sewage nutrient removal phases, illustrates both the rural catchments with high point source nutrient discharges, and rural catchments with low point source nutrient discharge conditions.

Analysis of internal C loading and external C loading indicates that the external loading is some 40 times the internal loading pre sewage nutrient removal (98 vs 2.3 $g/m^2/a$), and some 10 times the internal loading post sewage nutrient removal (9.8 vs 0.8 $g/m^2/a$). For further detail on these calculations, refer to Section B.7

4.4.1 In-stream modification to pattern and composition of nutrient discharge to the reservoir

The in-stream modification to nutrient composition and temporal pattern of delivery outlined above are a function of catchment types and flow conditions. They are summarised in Table 4.2.

Figures 4.2 and 4.1 summarise the analysis of TP and FRP daily loads at the confluence of the Molonglo and Murrumbidgee Rivers 40 km upstream of the discharge to Burrinjuck Reservoir (Taemus Bridge), and the monitored daily load at Taemas Bridge.

The substantial loss of nutrients under low flow conditions indicates the in-stream (biological) uptake of FRP between the Molonglo River confluence and Taemus Bridge. The substantial delivery during elevated flow conditions of the Molonglo River confluence load, or delivery of loads in excess of the confluence load, indicate the scouring and re-suspension of nutrients lost during the low flow periods.

4.4.2 Morphology of reservoir

The shape and depth of the reservoir has important implications for processes such as wind mixing depth, stratification patterns, and the distribution of organic material deposited per unit area across the reservoir sediments.

Table 4.2: In-stream modification to nutrient composition

Catchment type	**Low flow conditions**	**Elevated flow conditions**
Lowland rural stream	Low SS, low nutrient and organic material. Warm stream relative to reservoir in summer enters surface mixed layer.	Elevated SS, elevated nutrients and organic material. Cold stream relative to reservoir in summer plunges below surface mixed layer.
Lowland rural stream + WWTP discharge	As above plus in-stream uptake of nutrients by attached algae and biofilm (riffles, sand beds).	As above plus re-suspension of organic material accumulated during low flow periods.
Lowland rural stream + WWTP and urban catchment discharges	As above plus reduced low flow duration due to urban stormwater runoff.	As above plus increased frequency of elevated flow events, with sharp hydrographs and reduced event flow duration.
Direct discharge of WWTP effluent to reservoir	Direct uptake of dissolved nutrients. Elevated BOD, remobilisation of sedimented nutrients.	

An open reservoir shape will experience higher wind velocities and increased surface mixing than a dendritic shaped reservoir such as Burrinjuck. The reservoir depth relative to the mixed depth will determine the potential extent of anoxic bottom waters (internal loading) over the summer period.

A broad delta arrangement at inflow points to the reservoir will maximise the distribution of sedimented organic material, thereby limiting the deposition per unit area per day and consequently the redox potential, as compared to a constrained linear shape such as Burrinjuck.

Chapter 5

Factors determining algal biomass

5.1 Background

Like all plants, algae require nutrients, light and an adequate temperature to grow (Figure 5.1). The mass of cells that results when these environmental conditions are satisfactory is also influenced by cell losses resulting from animal grazing, sedimentation from the water column, wash-out by high flows and cell death due to disease. Despite these complicating factors, the initial development of algal populations is largely dependent on the physical and chemical conditions supportive of growth. Because responses can vary between reservoirs, the modelling of algal growth requires information on the specific characteristics of a site and in particular the availability of light and nutrients and the degree of water mixing and hydraulic retention time. The purpose here is to describe some of these characteristics and their importance in an assessment of reservoir function.

5.1.1 Availability of light

The microalgae that grow suspended in the water column are referred to as phytoplankton. Unlike land plants that are fixed in position, phytoplankton are moved vertically and horizontally through the water column by mixing processes. As a result, the light that they encounter is not simply a function of the daily incident sunlight but also the extent to which mixing moves the cells away from the illuminated surface layers.

A description of the light characteristics through the water column, with reduction with depth, to a point where light is insufficient to support algal photosynthesis ($\mathrm{z_{eu}}$ or euphotic depth) is provided in Chapter 3. A description of factors driving mixed depth is also provided in Chapter 3. The material highlights the importance of the $\mathrm{z_{eu}}$:$\mathrm{z_{mix}}$ratio as an indicator of availability of light. At ratios of less than 0.3, algae dependant on mixing will be disadvantaged in relation to other alga having other strategies for maintaining their position in the euphotic zone (blue-green alga having bouyancy vacules, dino-flagellates having swimming flagella). Conversely, the green alga require some vertical mixing to

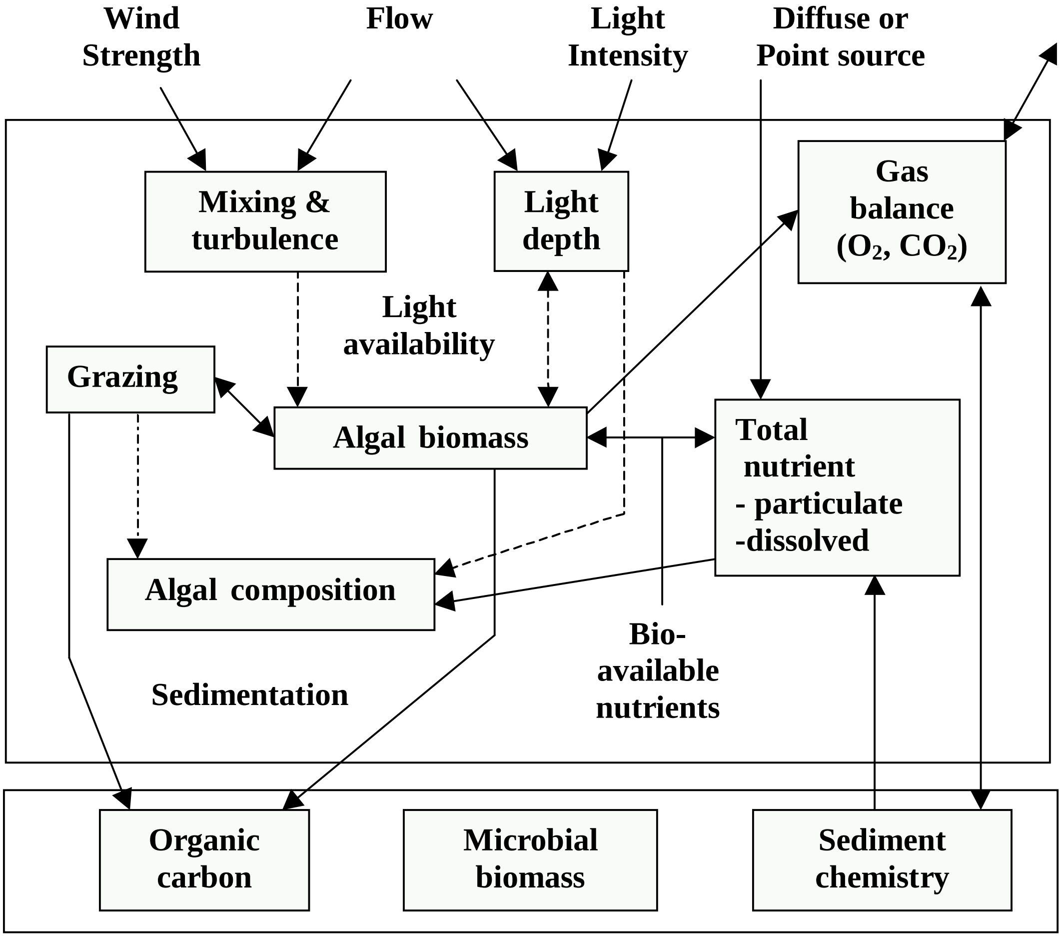

Figure 5.1: Factors influencing algal growth and composition

cycle them through the euphotic zone. Under calm (low mixing) conditions typical of mid to late summer, green alga will be further disadvantaged in relation to other alga which have strategies for maintaining their position in the euphotic zone.

5.1.2 Availability of nutrients

In addition to sufficient light the algae also require nutrients. Although a wide range of nutrients are required it is the availability of nitrogen and phosphorus that usually regulate algal growth when light conditions are sufficient. In freshwater ecosystems phosphorus is often in shortest supply and runs out first as the algae grow. As a result, the quantity of phosphorus that is available to the algae will determine the maximum algal concentration that can form.

This dependency has been used in many lakes to try and predict the amount of algae that will develop in the growth season from the amount of phosphorus present in the water preceding the growth period. Although this has been very successful for specific reservoirs, the relationships differ significantly between reservoirs. As a result there is not a simple, single relationship that can be used in all situations. One reason for this variability is that the techniques generally used to measure phosphorus are not specific to the form of the nutrient that is available to algae. In some cases the cells cannot access a large amount of the measured phosphorus and so the maximum population shows no relationship to the phosphorus concentration. Recently techniques have been improved to directly measure the forms of phosphorus available to the algal cells and this appears to improve the models relating phosphorus to cell development.

In eight reservoirs across southern Australia a single relationship was developed to predict the summer algal growth (Oliver, R. 1999, pers comm). This is illustrated in Figure 5.2. In these systems thermal stratification was persistent through the summer period. Consequently, available nutrients were largely limited to those within the surface mixed layer.

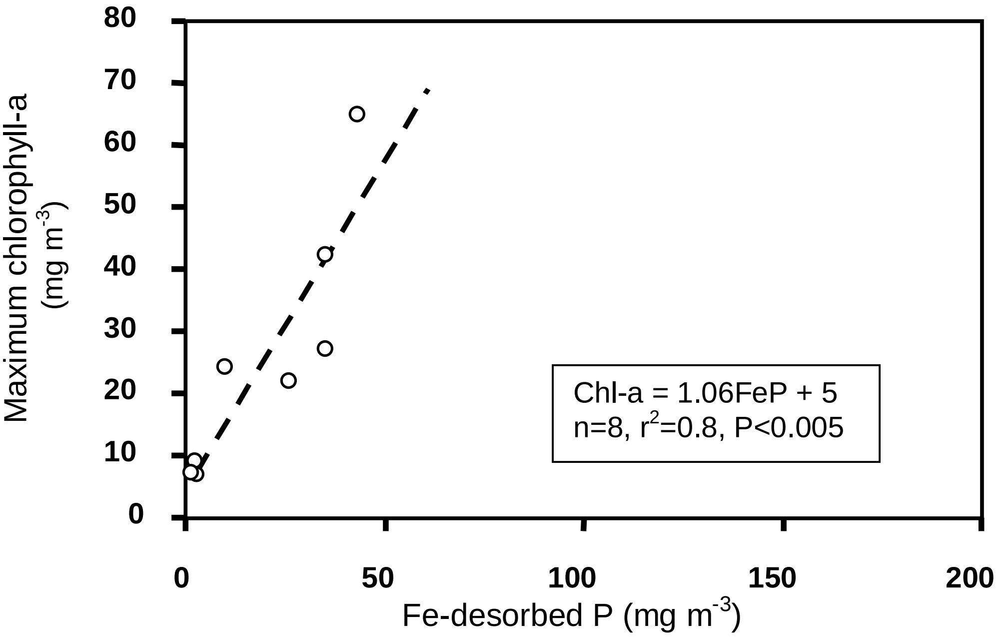

Figure 5.2: Maximum summer Chlorophyll 'a' concentration as a function of bioavailable phosphorus for eight reservoirs in SE-Australia.

Harris notes the relationship between the total P concentration in natural waters and the biomass of algae in water. Chlorophyll 'a':TP ratios decline from about 1.0 for oligotrophic lakes to 0.2 to 0.3 for eutrophic lakes (Harris 1986).

It appears from these reservoir studies that the availability of phosphorus regularly controls the final biomass of algae that develops and this is consistent with findings from many lakes around the world. However this does not mean that nitrogen, the other major nutrient required for cell growth, is always abundant and has no influence on algal growth. There are important interactions resulting from the relative availabilities of nitrogen and phosphorus that are particularly relevant to the management of algal blooms.

In weir pools on the Darling River and Murrumbidgee River it has been shown that nitrogen can initially be the nutrient in shortest supply and the first to run out as algae grow (Webster et al. 1996). In these systems an initial nitrogen limitation was observed to occur just as often as an initial phosphorus limitation, and at times nitrogen limitation regulated the algal biomass. The influence of nitrogen limitation on algal growth continued in these systems so long as mixing of the water column was maintained, disadvantaging the growth of buoyant blue-green algae. However, as soon as flows declined and intense temperature stratification occurred, problematic blooms appeared. These conditions are particularly suitable for buoyant blue-green algae that are not reliant on water motion to sustain their suspension in the water.

Certain species of blue-green algae can capture nitrogen gas that has dissolved into the water from the atmosphere and are able to use this as a source of nitrogen. For example blue-greens blooms of the group *Anabaena* commonly occur. Because these organisms can overcome the nitrogen limitation in the water they are advantaged over competing algae. The supply of nitrogen from the atmosphere is effectively inexhaustible and consequently the nitrogen fixing blue-green algae continue to grow until a secondary limitation occurs. In many cases it is the availability of phosphorus that determines the potential final biomass of the population. In these situations nitrogen limitation provided a growth advantage to an undesirable species that causes considerable water quality problems. A reduction in the phosphorus load to such systems can reduce the final biomass of nitrogen fixers that will develop. It can also reduce the likelihood of nitrogen limitation and so reduces the probability that nitrogen fixing blue-greens will appear.

Loss factors such as grazing and sedimentation modify the species composition of algal communities and can decouple relationships between nutrients and biomass. Much more information is required on these complex interactions. The complexity can be demonstrated by a decision support tree (Oliver & Ganf 1999) that was devised in an effort to explain the major factors influencing the appearance of particular genera of blue-green algae (Figure 5.3). This highlights especially the interplay of light, mixing and forms of nitrogen in determining the success of particular Cyanobacteria. It provides a series of hypotheses about physical, chemical and biological interactions that need further research.

5.2 Previous Burrinjuck studies

A dimensional analysis performed to evaluate factors governing algal and nutrient distributions (Humphries & Imberger 1981) concluded that:

1. under elevated flow conditions, flow driven advection mixing is important;

2. horizontal mixing considered was not important;

3. phosphorus is the most likely the limiting nutrient.

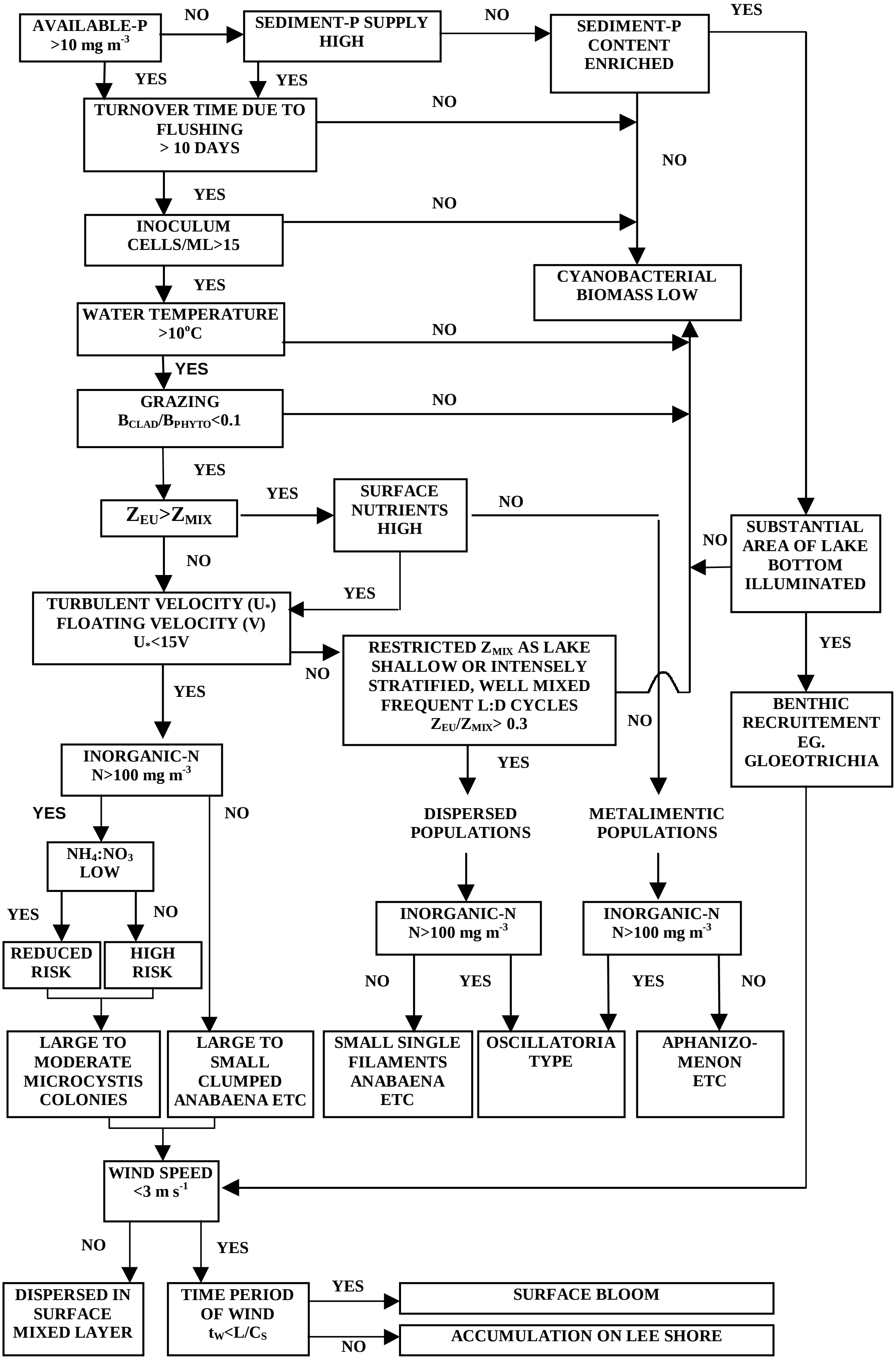

Figure 5.3: Flow chart summarising prominent environmental characteristics supporting the development of Cyanobacteria blooms and selecting for particular genera.

Monitoring undertaken in the period 1981 to 1986 (Office of ACT Administration 1987) indicated that in the case of Lake Burley Griffin, algal biomass correlated with nutrient levels in the Molonglo River (Sewage treatment plant discharge 3 km upstream), whereas in the case of Lake Ginninderra (urban and rural non-point source (event) discharges), there was no correlation between in-lake nutrient levels and algal biomass.

Concentrations of in-lake TP and FRP were 3 to 6 times higher in Lake Burley Griffin than in Lake Ginninderra. The TN:TP ratio was 5–10 for Lake Burley Griffin and 20–30 for Lake Ginninderra. The NH_3:NO_xratio (gravimetric) was 0.33 for Lake Burley Griffin and 0.28 for Lake Ginninderra. The Chlorophyll 'a':TP ratio ranges from 0.43 to 0.63 for the two lakes.

The middle reach sediments of Lake Burley Griffin had similar median TP composition (0.43 mg P/g) to Lake Ginninderra sediments (0.35 mg P/g). However, the sediments in the upstream basin of Lake Burley Griffin had a median TP value of 0.7 mg P/g sediment.

Redox analysis (column based analysis) indicated mean release rates of 17 g P/m2/day for Lake Burley Griffin upstream basin versus 0.4 mg P/m2/day for Lake Ginninderra at the same DO level (1 mg/L). Helium gas was used to strip DO. There was no addition of organic material to the columns, with sole reliance on SOD to drive redox levels down.

5.3 1976 to 1998 data: Algal biomass conditions

Figures 5.4 to 5.9 summarise the average TP, FRP, NH_3, NO_x, NH_3:NO_xratio and Chlorophyll 'a' for the summer periods 1976 to 1998 longitudinally through the Reservoir.

The contours illustrate a general pattern of elevated TP, FRP, NH_3 levels and NH_3:NO_xratio for the period 1976 to 1981, followed (with the exception of 1996/1997) by substantially reduced values thereafter. The NH_3:NO_xratio shifts from ranges of 0.4 to 1.0 (gravimetric) pre 1981, to 0.2 to 0.1 post 1985. An exception occurs in 1996/1997 when NH_3:NO_xratios again increase to the order of 0.4 to 0.8.

The contours also illustrate the significantly higher levels of TP, FRP,NH_3,NH_3:NO_xratio in the inlet zone to the Reservoir, with gradual decay in values with distance downstream of the inlet zone towards the Dam wall.

Figure 5.9, average Chlorophyll 'a' values illustrates the elevated levels (20 to 80 μg/L) pre 1981, and substantially reduced levels (20 to <1 μg/L) for the post 1985 period, but with elevated levels for the period 1996/1997. Again, the Figure illustrates a pattern of higher levels of Chlorophyll 'a' in the inlet zone as compared to downstream reaches.

The inlet zone ('hot spots' on the contour graph) moves downstream during periods of significant Reservoir drawdown, such that the shallow inlet depositional zones may occupy a lower reach previously considered a deep and stratified middle reach.

Figure 5.10, Chlorophyll 'a':TP ratios for surface waters, indicates Chlorophyll 'a' to

TP ratios of 0.1 to 1.5, with a mean of the order of 0.4. High ratios appear to be associated with periods of severe drawdown (pore water high in FRP), while low ratios are associated with periods of high inflow (high abiotic particulates, adsorption of P).

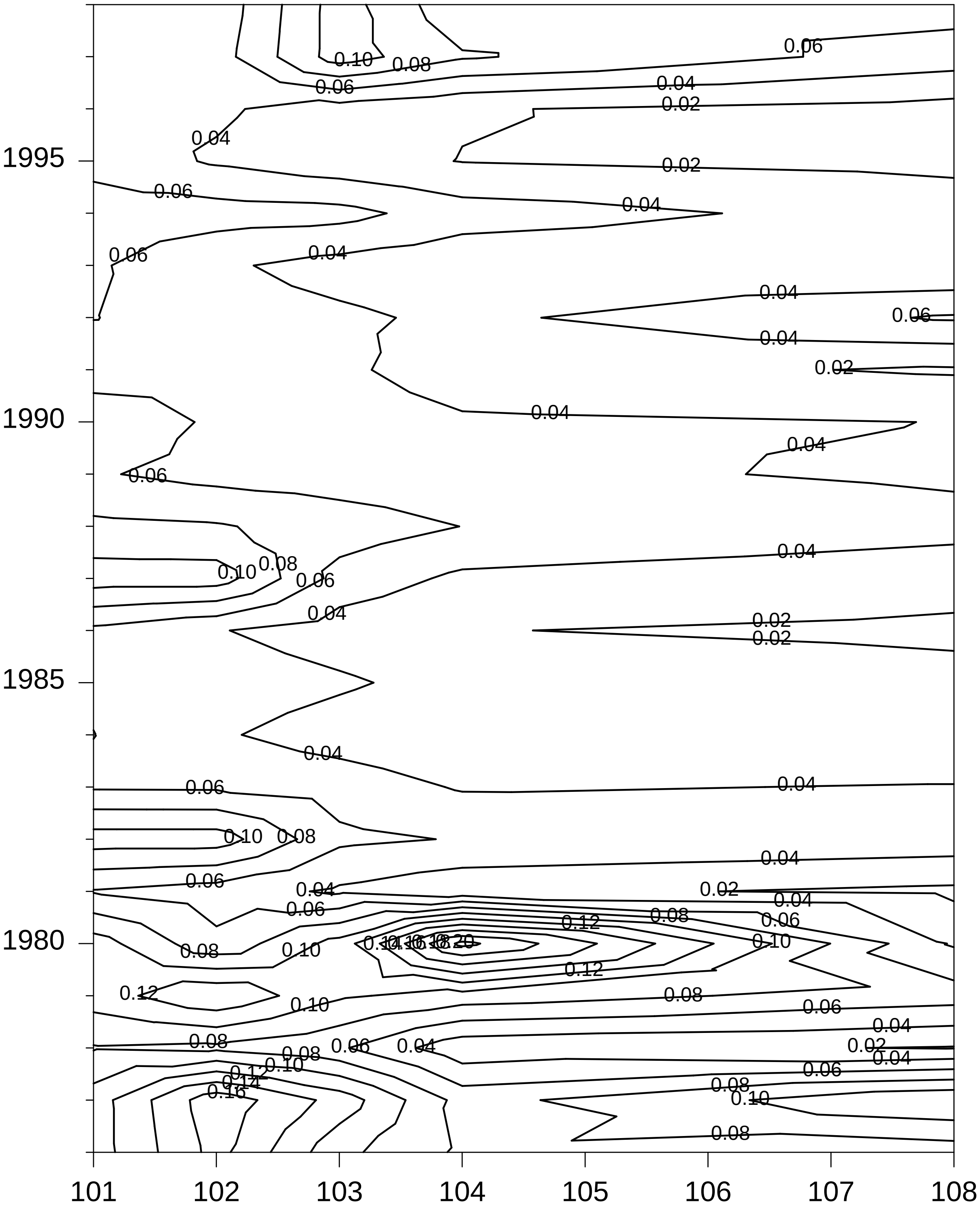

Figure 5.4: Reservoir average TP (mg/L) as a function of time and station.

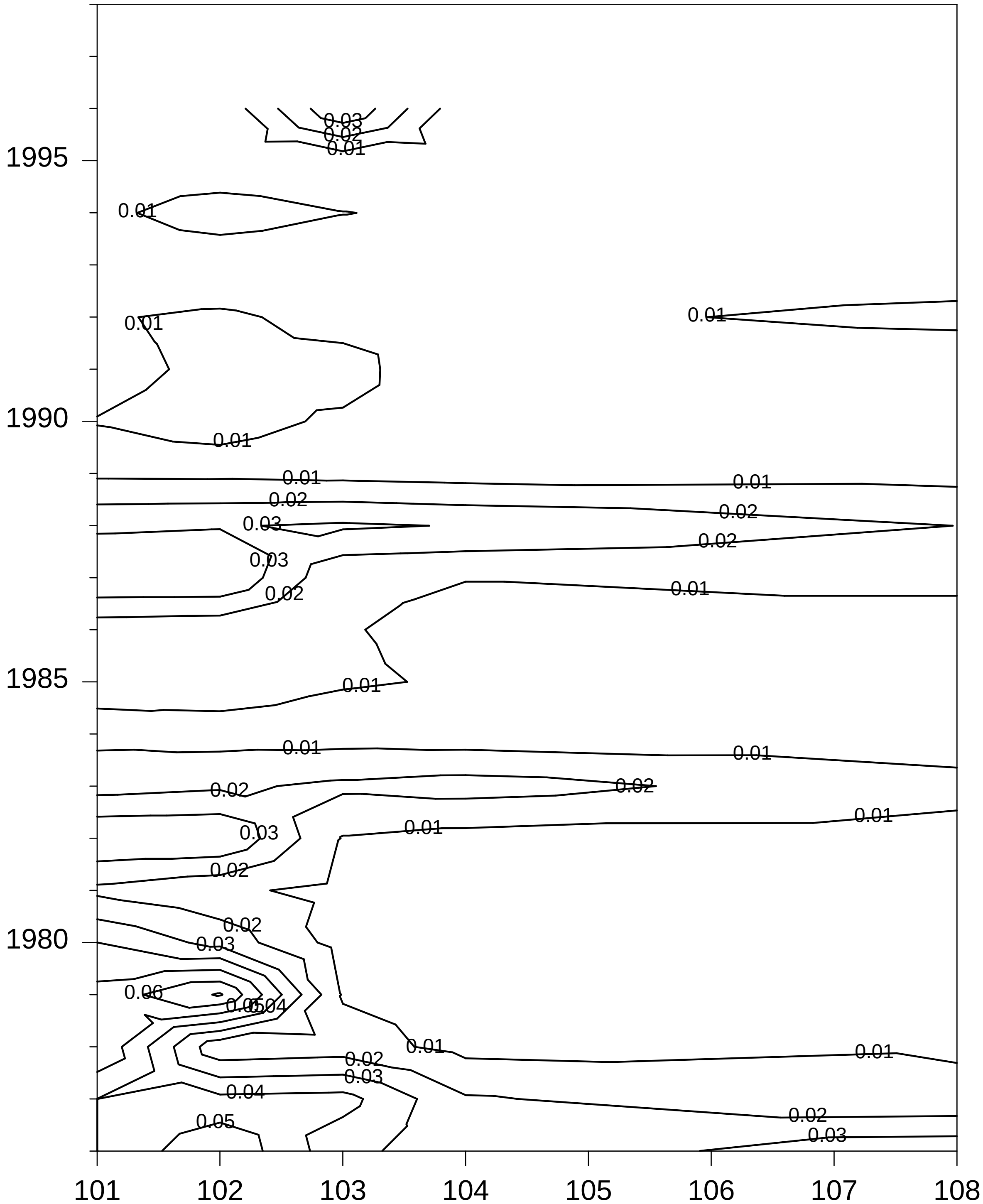

Figure 5.5: Reservoir average FRP (mg/L) as a function of time and station.

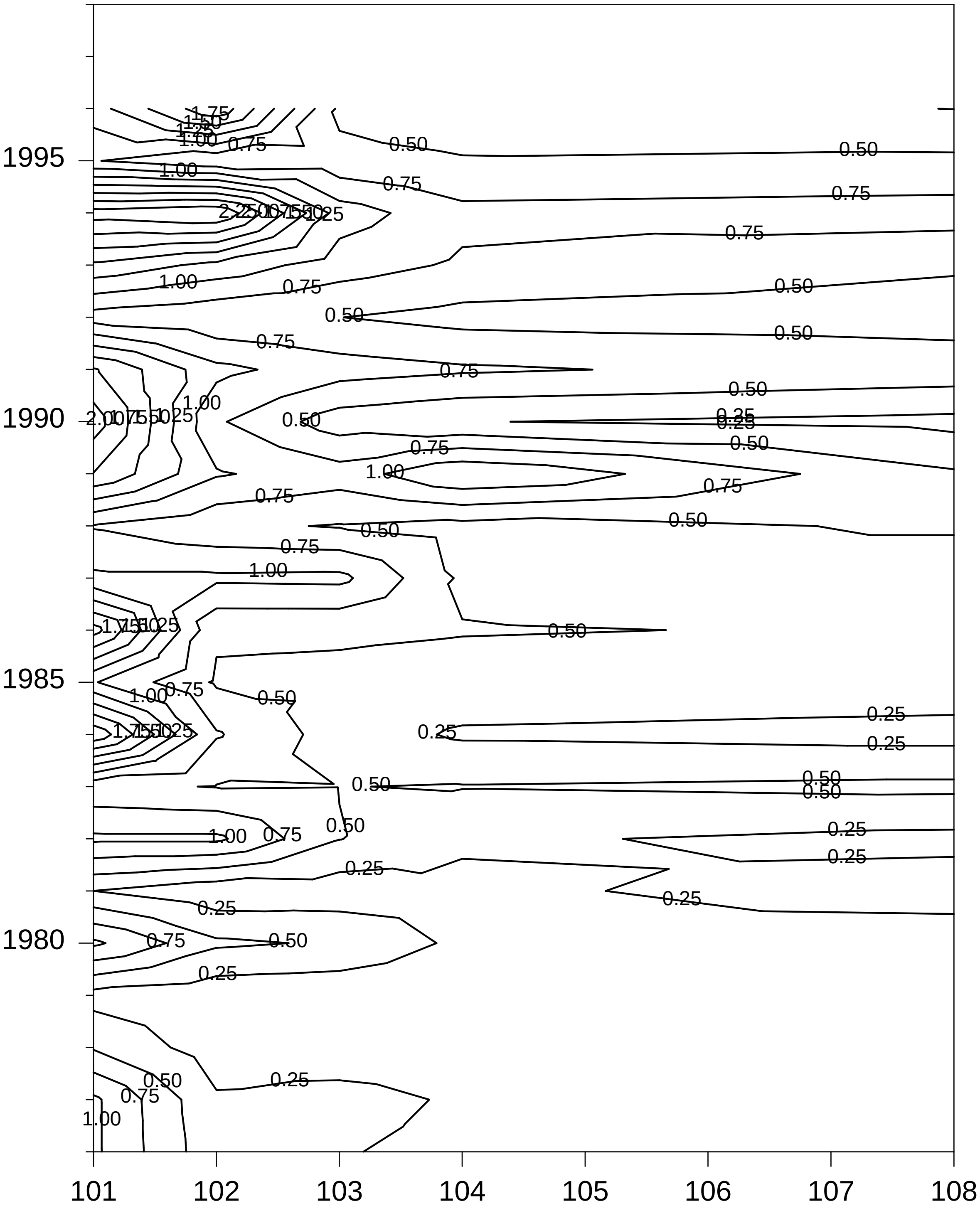

Figure 5.6: Reservoir average NO_x (mg/L) as a function of time and station.

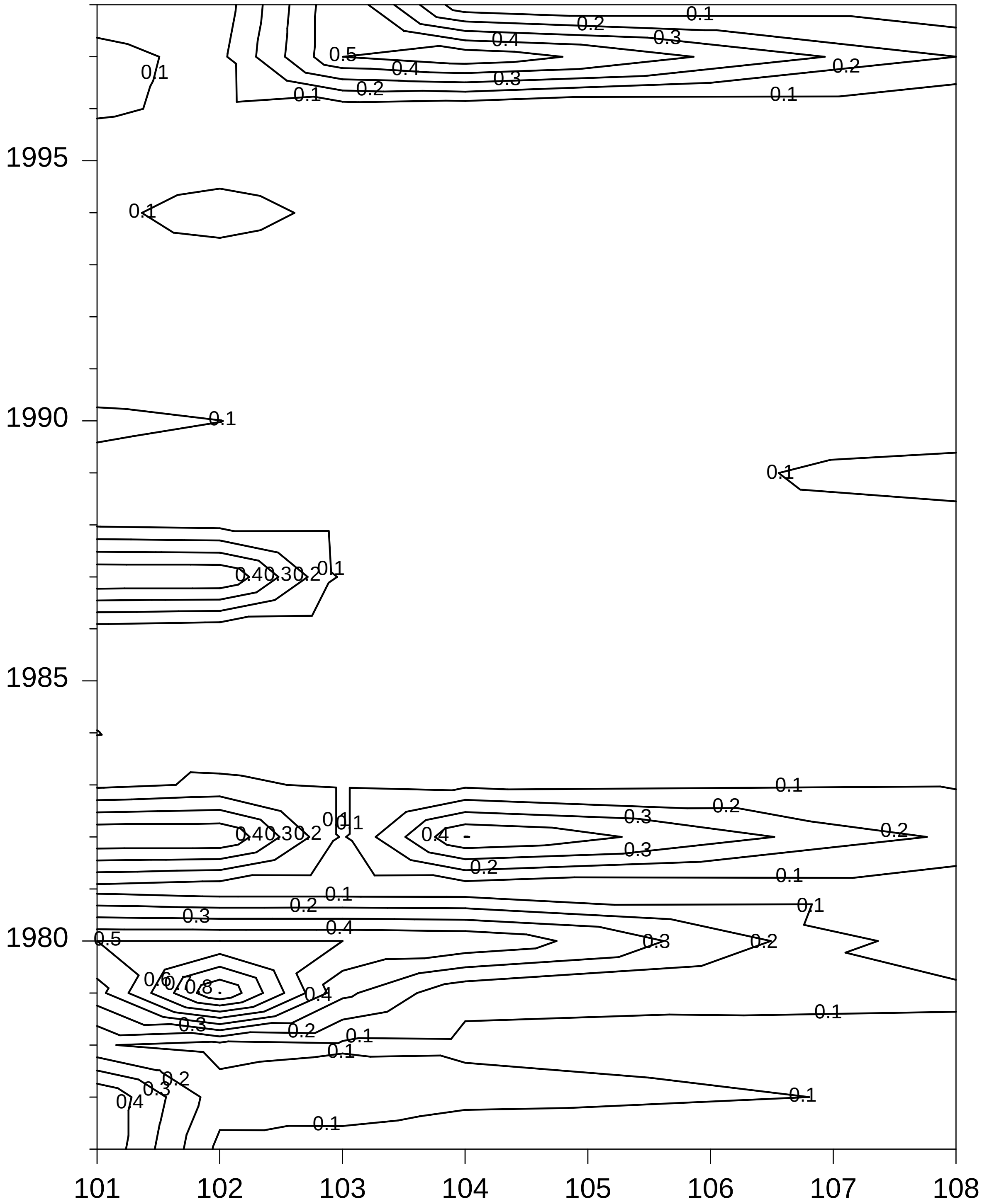

Figure 5.7: Reservoir average NH_3 (mg/L) as a function of time and station.

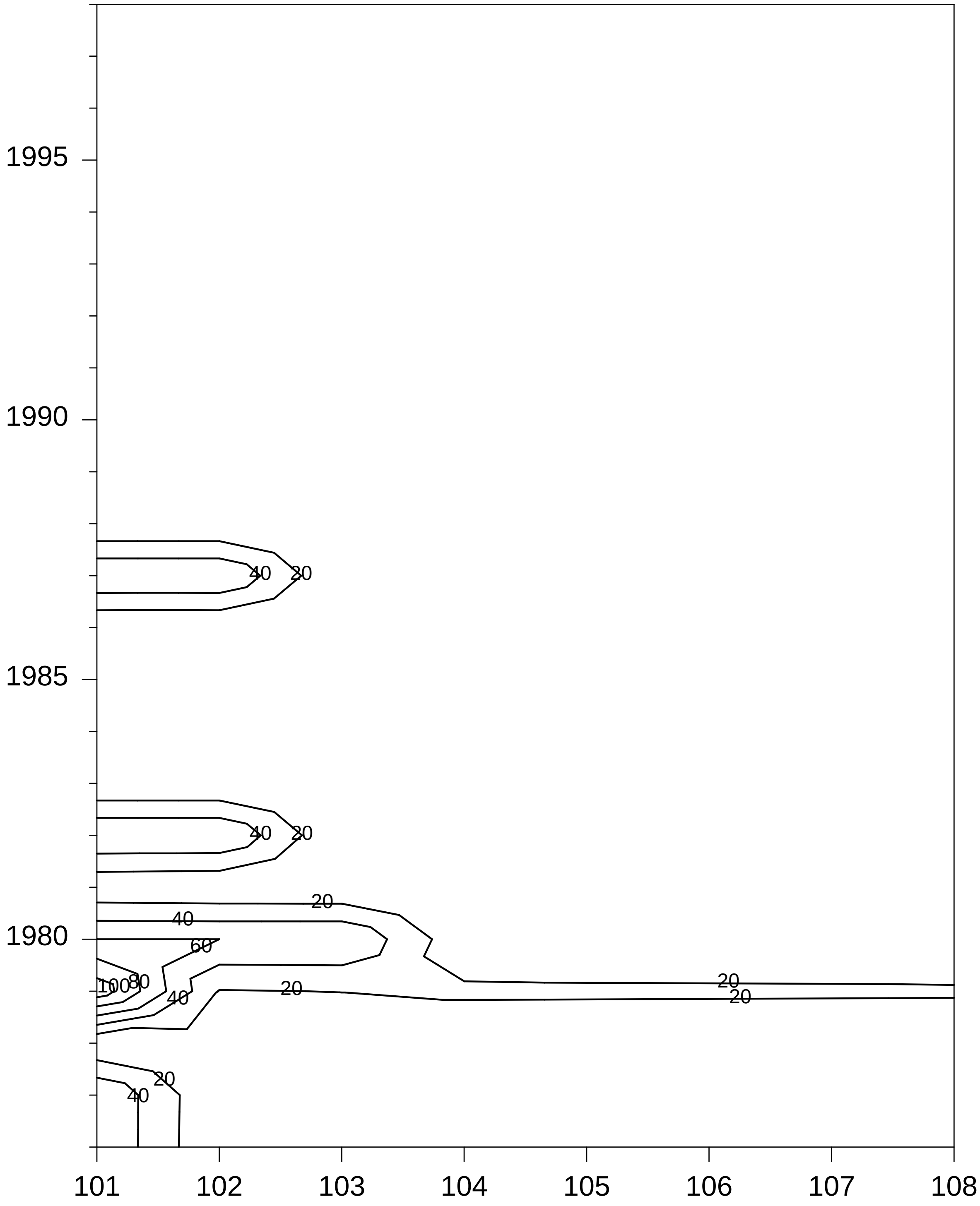

Figure 5.8: Reservoir average NH_3:NO_x ratio (molar) as a function of time and station.

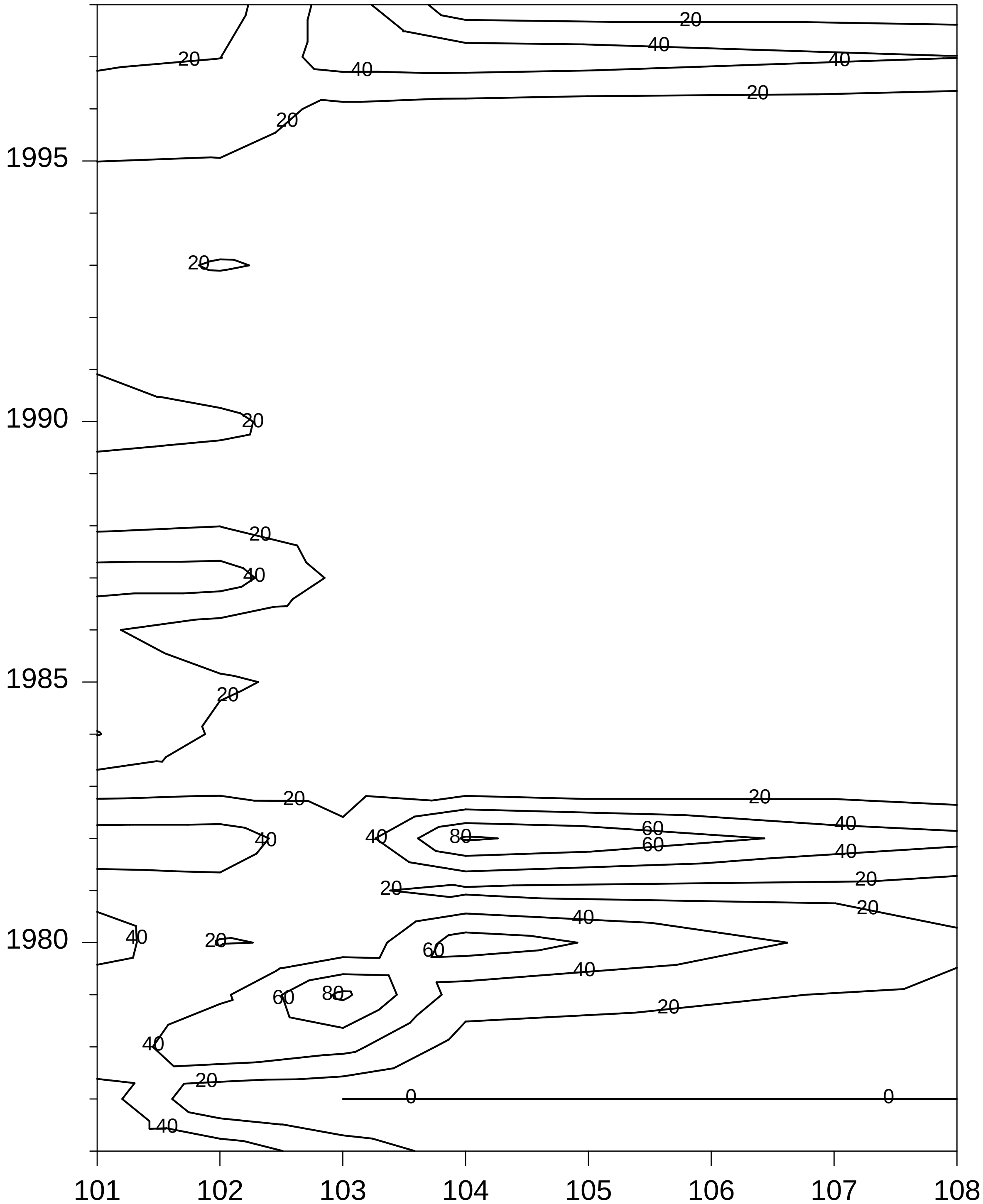

Figure 5.9: Reservoir average Chlorophyll 'a' (μg/L) as a function of time and station.

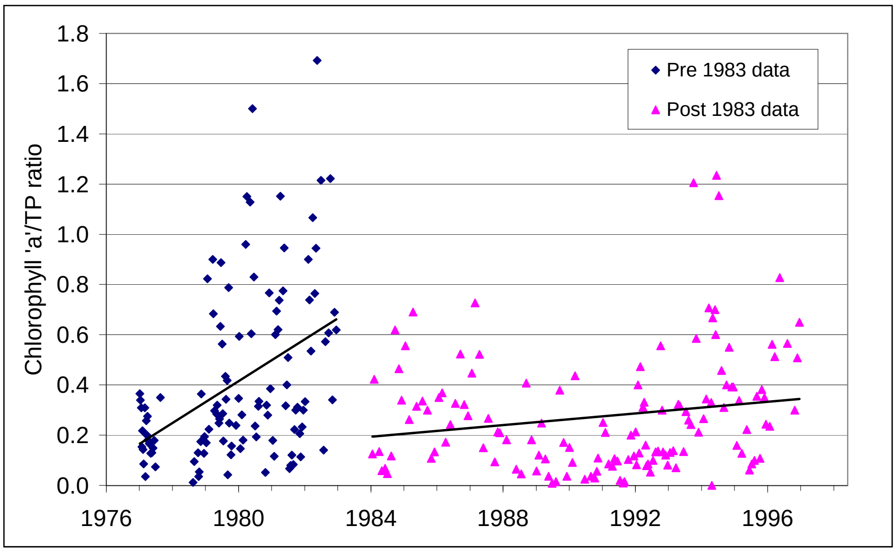

Figure 5.10: Chlorophyll 'a' to TP ratio, Station 108 Burrinjuck Reservoir.

5.4 1976 to 1998 data: Explanatory analysis

The analysis identified the following key processes and pathways:

5.4.1 Pre sewage phosphorus removal period: 1976 to 1978

During this period, Canberra sewage effluent discharges were high in nutrients, ammonia, suspended solids and BOD. A high rate of uptake of nutrients is evident in the data for the Murrumbidgee River downstream of the wastewater effluent discharges, with the attached algae (*Hydrodictyon*, *Cladophora*) forming kilometres of algal mats across the River water surface. Periodic sloughing of material occurred as a result of urban storm discharges or wider catchment discharges.

Under these conditions, there was significant sedimentation of organic matter discharged during inflow events in inlet depositional zones of the Reservoir, or across several reaches under high and sustained inflow conditions. The deposition of organic material lead to reduction of sediments and remobilisation of FRP in a bio-available form. Bottom waters exhibited depletion of DO and high levels of NH_3 and FRP, indicative of severe reducing conditions in these waters. The mixing of nutrient rich bottom waters with surface waters at the time of Reservoir turnover appears to be the major source of nutrients driving algal growth for this period. There were high levels of algal biomass as a result.

5.4.2 Sewage phosphorus and nitrogen removal period: 1978 to 1983

The de-nitrification unit of the LMWQCC was operated during:

December 1978 to April 1979 (limited de-nitrification achieved);
September 1979 to April 1980;
August 1980 to April 1981;
September 1981 to May 1983.

This operation is evident on the time series plot of TN loading on the Reservoir (Figure 2.19).

The algal response (increase in Cyanobacteria cell numbers) to operation of the de-nitrification unit was complicated by the significant Reservoir drawdown over this period. The NH_3:NO_xratio (refer to Figure 5.11, Bottom NH3:NOx ratio, Site 104) increased significantly (ratio 1.0) during periods of de-nitrification as compared to levels for similar stratification periods of P removal but no de-nitrification (ratio of 0.1) from 1984 onwards.

The inference is that the reducing conditions within sediments of the Reservoir were exacerbated by de-nitrification.

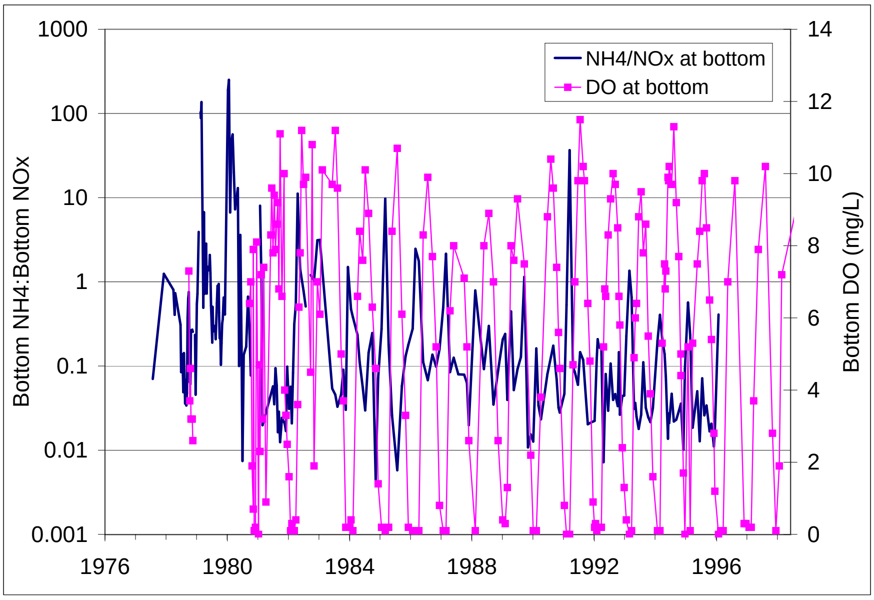

Figure 5.11: Bottom DO and NH_3 to NO_x ratio, Station 104 Burrinjuck Reservoir

5.4.3 Post sewage phosphorus removal period: 1984 to 1998

Medium to high Reservoir storage levels

While there was continued high rate of sedimentation of SS discharged during inflow events in upstream (mixed) reaches of the reservoir, the substantial reduction in organic material discharged limited the potential for reduction of sediments and therefore remobilisation of P. This is reflected in the low nht:$\mathrm{NO_x}$ ratios within the water column, and substantial reduction in algal biomass.

While bottom waters generally exhibit low to zero DO, they continue to maintain high levels of $\mathrm{NO_x}$, indicating limited redox conditions even in the bottom waters. Under these conditions, the bottom waters ceased to be a major source of nutrients to the surface waters at the time of Reservoir turnover. As a consequence, there was substantial reduction in algal biomass to oligotrophic levels.

The application of inflows having high $\mathrm{NO_x}$ is analogous to the injection of $\mathrm{NO_x}$ into sediments of lakes applied in the northern hemisphere, as a means of oxidising organic material in the sediments to restore lake water quality.

For medium to high Reservoir storage level conditions, the substantial area of the inlet depositional zone ensured low levels of organic carbon loading per area, thereby limiting the potential for remobilisation of nutrients within the inlet zones.

Periods of significant Reservoir drawdown

Under conditions of significant Reservoir drawdown the volume and the surface area of upstream reaches are significantly reduced (to 10% to 20% of their Reservoir full levels). As a result, the deposition of organic material per square metre of sediment area is significantly increased, leading to the development of severe redox conditions and the remobilisation of P.

A *lake model* analysis indicates good fit between predicted and observed TP and algal growth data, except for the close to empty conditions, when observed TP and algal levels are in excess of model estimates. Significant drainage of P rich pore waters from sediments exposed by Reservoir drawdown is postulated as a possible explanation of this anomaly.

The release of significant P to surface waters led to significant increase in algal biomass under these conditions.

5.5 Conclusions

It is concluded that the availability of phosphorus in the surface mixed layer appears to be the major determinant of algal biomass. Major phosphorus sources or pathways comprise:

1. hypolimnetic P during the period of high nutrient and organic carbon loading on the Reservoir (1976 to 1980);
2. remobilisation of sediment P in inlet depositional zones following inflow events in spring and summer, particularly under low Reservoir level conditions;
3. drainage of P rich pore waters and re-suspension of particulates from sediments (exposed by rapid drawdown of Reservoir) to receding Reservoir surface water.

Chapter 6

Factors determining algal composition

6.1 Background

The composition of the algal community is influenced by a range of physical, nutrient availability and composition (forms), and grazing processes. As a result, algal composition reflects in large measure:

1. the seasonal changes that occur in mixing conditions:
    - turbulent conditions with elevated inflows in early spring;
    - thermal stratification over late spring through summer;
2. potential reduction in available light as a result of self-shading of algal growth;
3. potential depletion in one or other nutrients to limiting levels;
4. build-up (grazing) of zooplankton populations.

Frequently the first algal types to increase in concentration in early spring are the Diatoms, followed by green algae, then blue-green algae and finally dinoflagellates. As temperature stratification breaks down in autumn there can be a resurgence of some of these populations before the algal numbers fall away to low levels through winter.

Harris notes that a knowledge of the factors underlying seasonal species successions may make it possible to predict the occurrence of particular species (Harris 1994). Droughts and floods tend to switch Australian water bodies between Cyanobacteria blooms (which either regulate their buoyancy or float) and Diatoms (which sink rapidly) so the climate variability has a major impact on the biota and the biogeochemistry of the ecosystem (Heaney et al. 1995).

Diatoms are favoured by short residence times, vertical mixing, optically deep water columns and strongly pulsed external sources of silica (Harris & Baxter 1996). They have relatively high sedimentation rates and are physiologically suited to growth under deeply mixed, low light conditions (Harris 1978) when silica is available. Diatoms therefore respond to increased flows.

Cyanobacteria are favoured by long residence times, quiescent (stratified) states, low dissolved inorganic nitrogen (DIN) in surface waters, and in monomictic systems, strong hypolimnial anoxia. Many Australian storages have anoxic hypolimnia with a strong build-up of ammonia, phosphate and sulphides in bottom waters. Cyanobacteria which show buoyancy faculty are able to regulate their depth through a mechanism of gas vacuoles and ballast accumulation which is linked to photosynthesis and the underwater light climate (Reynolds et al. 1987). This buoyancy regulation mechanism is necessarily rather slow so rapid fluctuation in turbulence and the underwater light climate do not favour this growth strategy.

Sediment fluxes of N, which regulate the form and concentration of N in surface waters (especially ammonia from anoxic sediments), are important in determining both the biomass and species composition (Harris 1996). A recent paper (Blomquist et al. 1994) has shown that the species composition of dominant Cyanobacteria in freshwater may be manipulated by changing the dominant form of DIN in the system. Small-celled, non N-fixing Cyanobacteria (*Microcystis*) appear to be favoured by the presence of high levels of ammonia in the water, whereas N-fixing Cyanobacteria (*Anabaena*, *Aphanizomenon*) are favoured by low concentrations of nitrate.

Table 6.1 shows a summary of factors determining algal composition. *Mixing conditions* refers to vertical circulation as a result of wind or inflow forces:

High mixing	$z_{eu}:z_{mix} < 0.2$
Moderate mixing	$z_{eu}:z_{mix}$ 0.2–0.4
Low mixing	$z_{eu}:z_{mix} > 0.4$

Table 6.1: Summary of factors determining algal composition

Nutrient environment	**Mixing conditions in the surface mixed layer**		
	High	**Moderate**	**Low**
High Si, High P, High N	Diatoms (high biomass)	Greens (high biomass)	Blue-Greens
Low Si, Low P, Limiting N	Diatoms (low biomass)	Greens (low biomass)	Blue-Greens

6.2 Previous Burrinjuck studies

The *ACT Region Water Quality Study* (1978) noted that the succession pattern for 1976/1977 comprised Diatoms following the flood event in October 1976, followed by greens in late Spring, and blue-greens in late December to March. There was a return of the greens through the middle and lower reaches of the Reservoir post March, but sustained high levels of *Microcystis* in the upstream reaches.

A study based on the application of DYRESM to Burrinjuck (Humphries & Imberger 1981) concluded that the shallow mixing layer depth conditions prevailing in Burrinjuck Reservoir advantaged the floating species (Cyanobacteria) over the mixing dependent (sinking) species

6.3 1976 to 1998 data: Algal composition conditions

Figures 6.1 to 6.4 summarise the algal cell numbers for the major algal Divisions, for the period 1976 to 1998, longitudinally through the Reservoir. Figure 6.1 illustrates the strong seasonal succession pattern with Diatoms generally dominant over the autumn to early spring period, greens over mid spring to early summer, and blue-greens through summer to early autumn. Figure 6.2 illustrates relatively constant Diatom numbers throughout the 1976 to 1998 period, except for a few periods of high and prolonged inflow to the Reservoir (1978, 1984 and 1994).

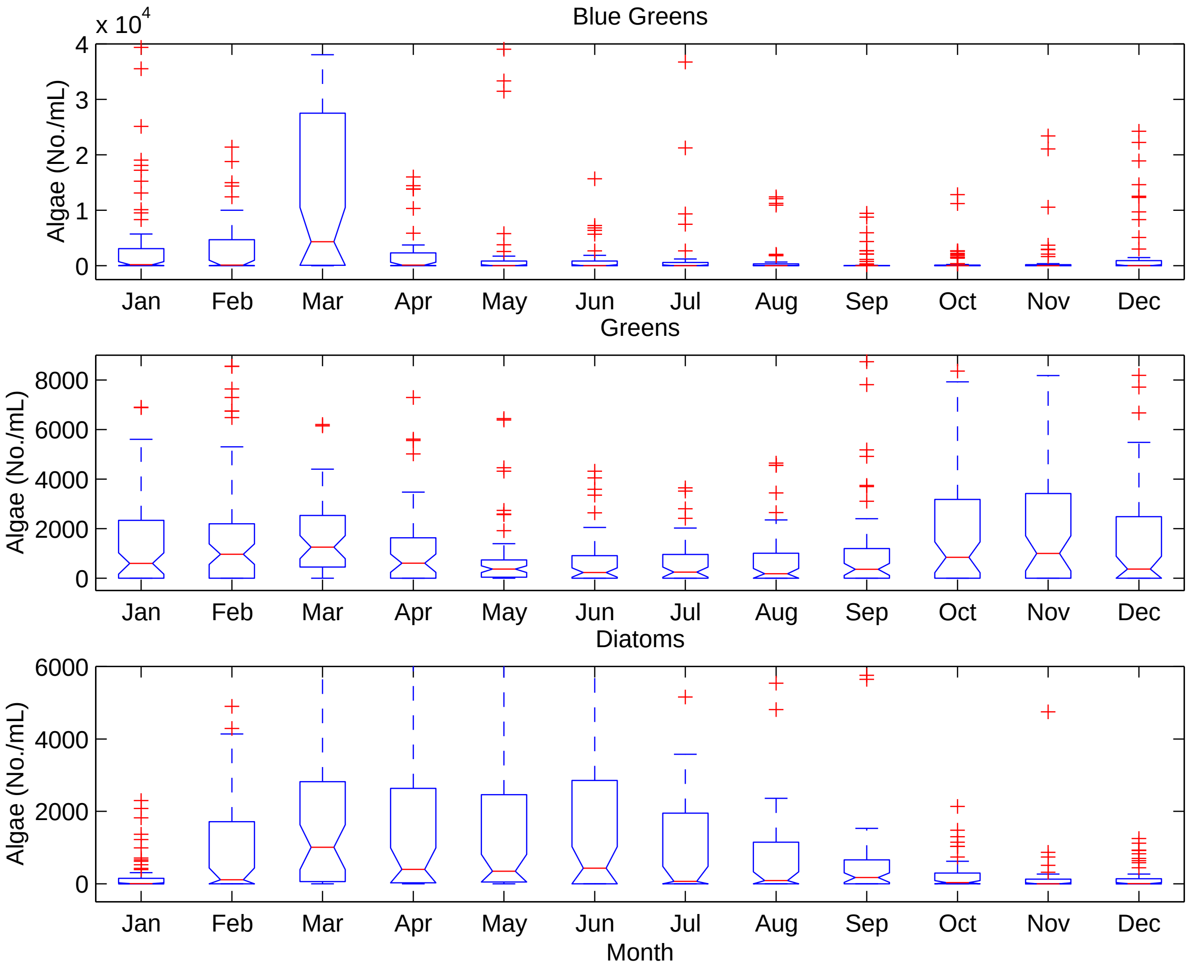

Figure 6.1: Succession of Cyanobacteria, Chlorophyta and Diatoms.

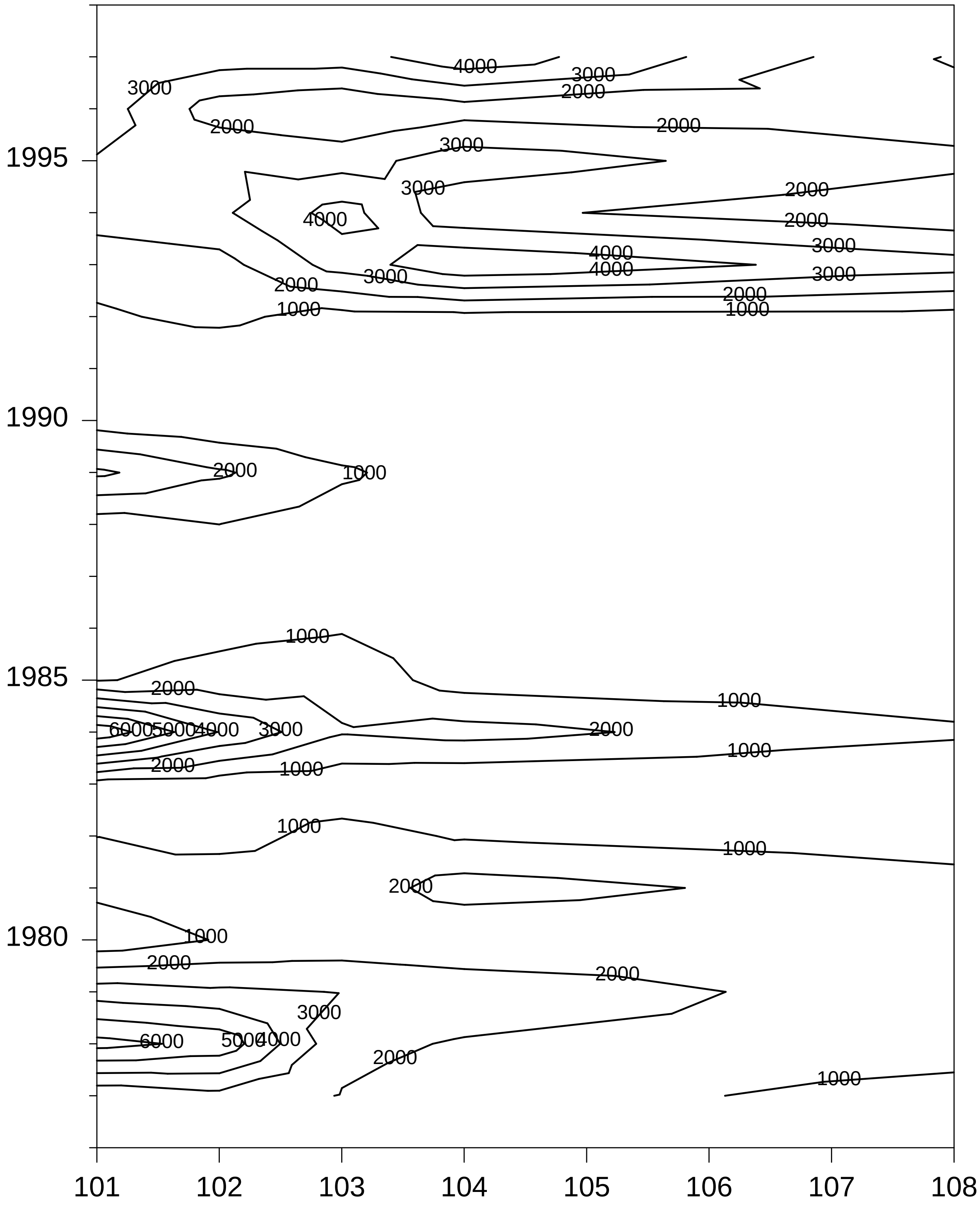

Figure 6.2: Reservoir average Diatoms as a function of time and station.

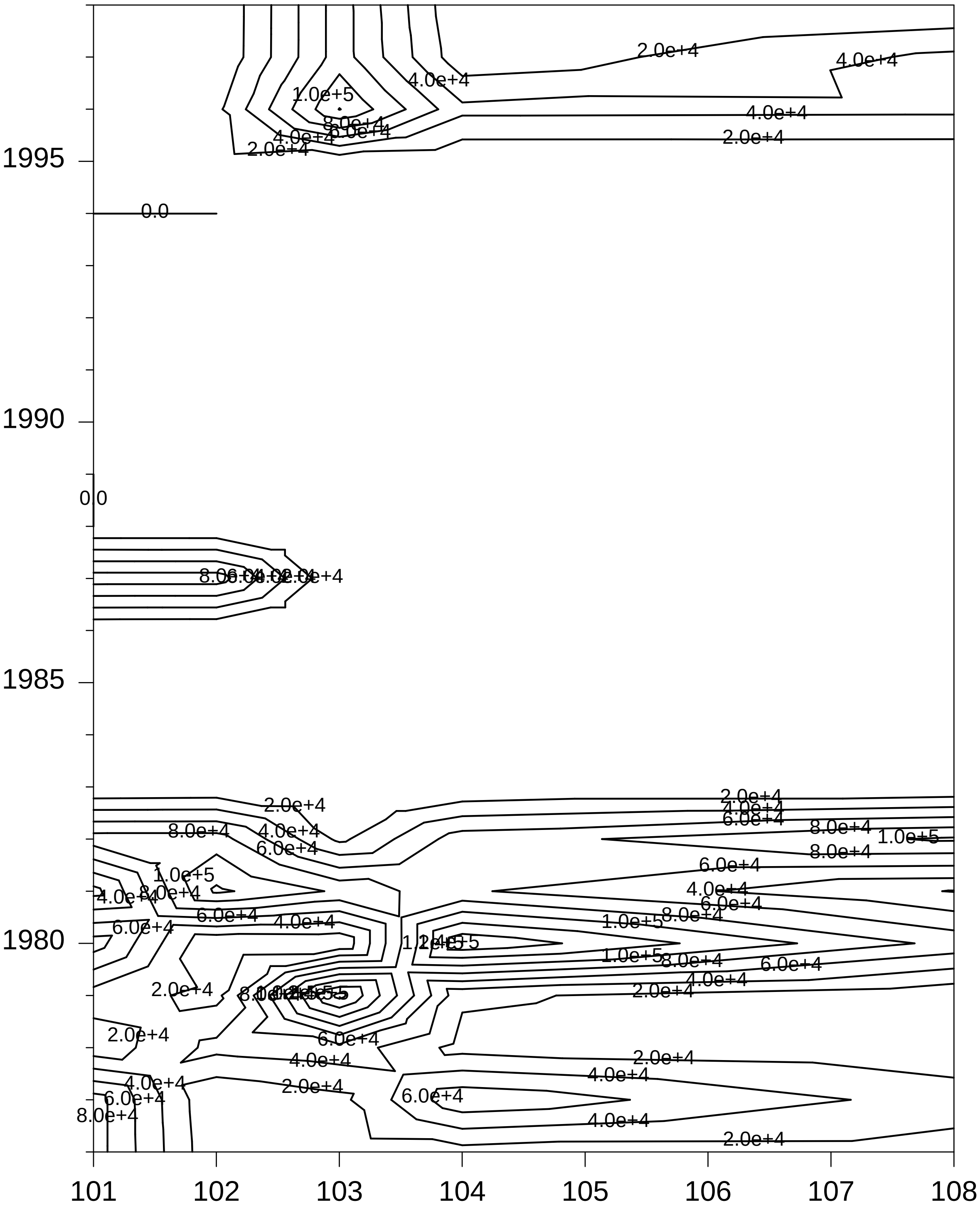

Figure 6.3: Reservoir average Cyanobacteria as a function of time and station.

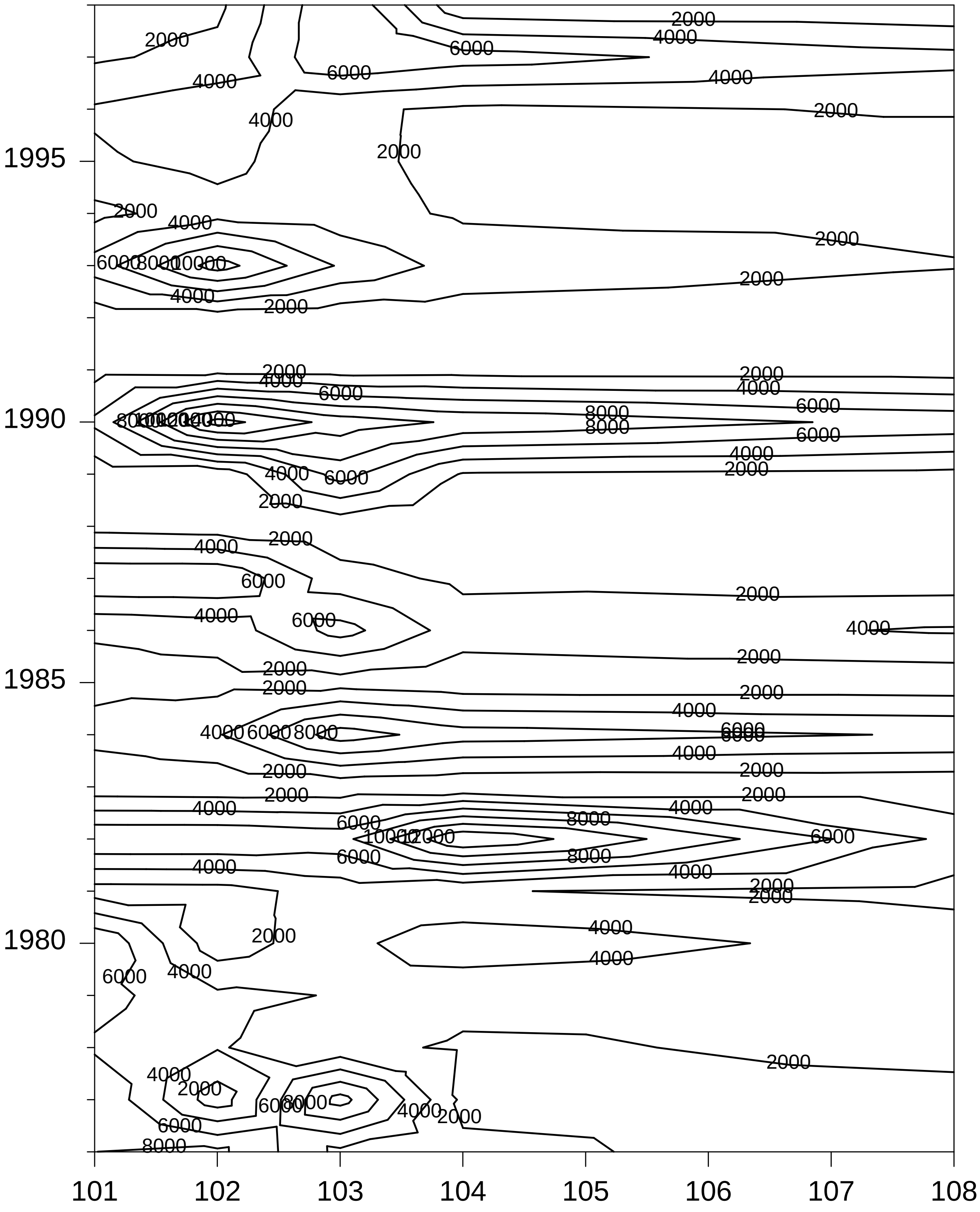

Figure 6.4: Reservoir average Chlorophyta as a function of time and station.

Figure 6.3 illustrates the high numbers of Cyanobacteria for the period 1976 to 1983, and virtual absence thereafter until 1995. Figure 6.4 illustrates the relatively constant Chlorophyta numbers throughout the 1976 to 1998 period. Higher numbers are evident at the inlet zones, particularly during periods of high drawdown.

The inlet zone (*hot spots* on the contour graph) moves significantly downstream during periods of low Reservoir levels associated with low inflows and high water abstraction.

6.4 1976 to 1998 data: Explanatory analysis

In general, Burrinjuck Reservoir exhibits the succession of Diatoms, Cyanobacteria and Chlorophyta (Figure 2.11) . As temperature stratification breaks down in autumn there can be a resurgence of Diatoms before populations fall away to low levels over winter. Although this general pattern is often observed, it can be significantly modified depending on the flow conditions and Reservoir levels prevailing each year.

A number of shifts in the seasonal pattern of algal composition were observed for Burrinjuck for the period 1976 to 1998.

Table 6.2: Association of algal composition with physical and chemical factors for the October to April growth period, Murrumbidgee arm Burrinjuck Reservoir

Year	Spring diatoms	Summer dominance		Spring inflows	Reservoir level	$z_{eu}:z_{mix}$	Wastewater nutrient discharge	Summer TN:TP in SML
		Cyano	Chloro					
1976/77	D	D	F	VH	H		High P and NH_3	3–30
1977/78	D	D	F	L	H–E		High P and NH_3	3–40
1978/79	D	D	F	VH	H	0.5–0.2	Low P, High NO_x	4–30
1979/80	D	D	F	L	H–E		Low P, Low N	9–40
1980/81	D	D	F	L	L–E	0.3	Low P, Low N	1–60
1981/82	F	D	F	M	H–M	0.3	Low P, Low N	2–20
1982/83	F	D	F	VL	M–E	0.5–0.3	Low P, Low N	4–100
1983/84	F	A	D	H	H	1.0–0.1	Low P, High NO_x	20–30
1984/85	D	A	D	M	H–M	0.4	Low P, High NO_x	30–40
1985/86	D	A	D	M	H–M	0.5–0.3	Low P, High NO_x	20–100
1986/87	D	A	D	H	H–M	0.5–0.3	Low P, High NO_x	30–100
1987/88	F	A	D	L	H–E	0.5–0.3	Low P, High NO_x	30–100
1988/89	F	A	D	H	H	0.5–0.1	Low P, High NO_x	15–30
1989/90	F	A	D	M	H–M	0.5–0.1	Low P, High NO_x	100
1990/91	F	A	D	M–L	H–M	0.5–0.2	Low P, High NO_x	4–80
1991/92	D	A	D	M–L	H–M	0.5–0.2	Low P, High NO_x	20–100
1992/93	M	D	F	M	H	0.5–0.1	Low P, High NO_x	20–80
1993/94	M	A	D	M	H–M	0.4–0.2	Low P, High NO_x	80
1994/95	F	A	D	VL	M–L	0.3–0.1	Low P, High NO_x	100
1995/96	D*	D	F	M	H	0.5–0.3	Low P, High NO_x	100
1996/97	D	D	F	M	H– L	0.5–0.3	Low P, High NO_x	30–80
1997/98	D	D	F	L	H–E		Low P, High NO_x	

Key for Table 6.2

D	Dominant	F	Few	M	Medium
A	Absent	VH	Very High	H	High
L	Low	VL	Very Low	E	Empty
*	late summer dominance				

6.4.1 Mixing conditions

Elevated spring inflows appear important in terms of supply of silica, together with well mixed Reservoir conditions (elevated wind over spring period and elevated inflows), in determining Diatom dominance over the spring period.

While the summer z_{eu}:z_{mix} ratio is low throughout the 22 year period of data, Cyanobacteria is the dominant group only for the high wastewater nutrient discharge period (1976 to 1983), and for periods of low Reservoir levels. At other times, Chlorophyta is the dominant algal group. The Chlorophyta group adapts to the low z_{eu}:z_{mix} ratio by shifting to dominance by the flagellated genera in late summer.

6.4.2 Limiting nutrient

Discharges to the reservoir that are low in nitrogen relative to phosphorus, or losses of nitrogen from the reservoir as a result of de-nitrification, may reduce inorganic nitrogen to limiting values, providing a competitive advantage for the N-fixing blue-green alga over the green alga.

Under elevated suspended solids, elevated iron and low bio-available P discharges to the reservoir (catchments free of point source discharges), there may be limitation of bio-available P for microbial growth in the sediments, with accumulation of TP and organic material in the sediments resulting.

The ratios of total nitrogen to total phosphorus concentration are commonly used to assess the relative availability of nitrogen and phosphorus for algal growth. Unfortunately this can be very misleading as the nutrient forms included in the analyses of total amounts are not all available to algae.

The (NO_x+NH_3):PO_4–P ratio for surface waters for Station 104 is presented at Figure 6.5. The graph indicates that limiting N conditions (N:P less than 16 molar, or less than 7 gravimetric), with ratios as low as 1 gravimetric, occurred over the period 1976 to 1980. During periods of de-nitrification at LMWQCC, low ratios (less than 1) again occurred over the period 1980 to 1983. The growth of *Anabaena circinalis* was reported over this period, in association with *Microcystis*. Under N limiting conditions, alga having N-fixing capabilities such as *Anabaena circinalis*, will have a competitive advantage over other alga.

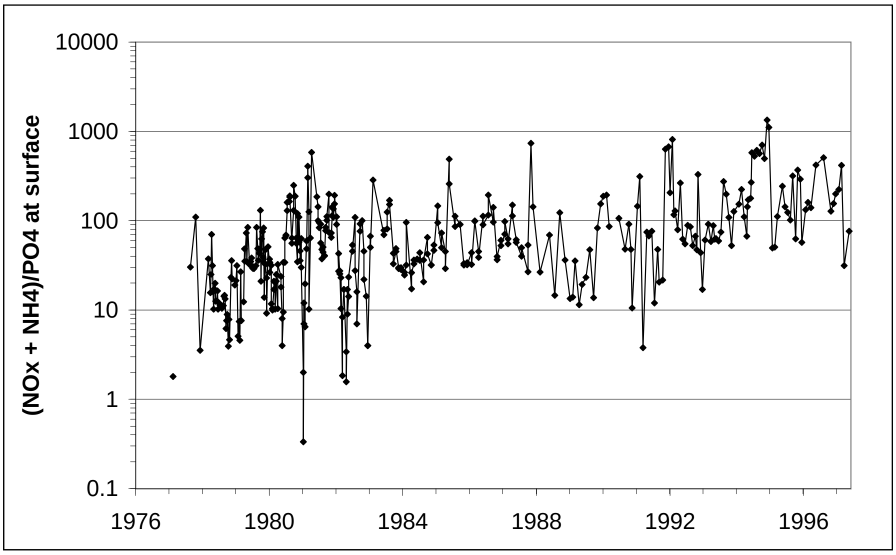

Figure 6.5: (NO_x+ NH_3):FRP ratio (gravimetric) in the surface mixed layer, Station 104 Burrinjuck Reservoir).

6.4.3 Form of nutrient

Different forms of the same nutrient can also have substantial impacts on the composition of algal communities. When the physical environment is stable and suitable for the growth of large buoyant Cyanobacteria, their occurrence is influenced by the forms of nitrogen that are available. As discussed in the preceding section, nitrogen fixing genera are advantaged when nitrogen limitation occurs. When nitrogen is in limiting concentrations but present as nitrate then green algae seem to have an advantage. However, when nitrogen is limiting in the surface waters but present as ammonia in the deeper anoxic layers then the colonial blue-green algae like *Microcystis* often dominate. These subtle effects on algal species composition of relative nutrient concentrations and the relative concentrations of different forms of the same nutrient are still not well understood.

Figures 2.8 and 2.9, Surface NO_x and NH_3 for Station 104, presents data for the period 1976 to 1998. The Figures indicate the high proportion (30% to 70%) of NH_3 for the period 1976 to 1983 and, excepting for periods of low Reservoir level, the dominance (80% to 90%) of NO_x thereafter. This is one possible explanation for the dominance by Cyanobacteria in the 1976 to 1983 period.

The elements C, N, O, S, Fe and Mn are predominant participants in the aquatic redox process. Photosynthesis ($C_{106}H_{263}O_{110}N_{16}P$) and externally derived organic matter are the major causes of disequilibrium redox conditions in natural waters, producing local centres of highly negative redox.

While the generation of N compounds such as NH_3 are biologically mediated, the amount of NH_3 maintained in the water column is a function of redox equilibria. Consequently, the composition of N forms is very much a reflection of the redox and pH environment of the water body.

Iron (III), often present in natural waters in significant amounts, will bond with P to form insoluble Fe_3PO_4. However, under low redox levels, the Fe(III) is transformed to Fe(II), a soluble form of iron, with release (bio-availability) of P into the water column.

The redox diagram in Figure 6.6 provides some important insights into algal management, namely the need to limit organic carbon loading (both direct and indirect pathways) on waters to levels maintaining pε values:

- above +4 to limit amounts of $NH_4{}^-$ maintained in the water column and enhancing Microcystis formation;
- above 0 to minimise the net release of Fe(II) from the sediments and associated release of $PO_4{}^{3-}_{-}$.

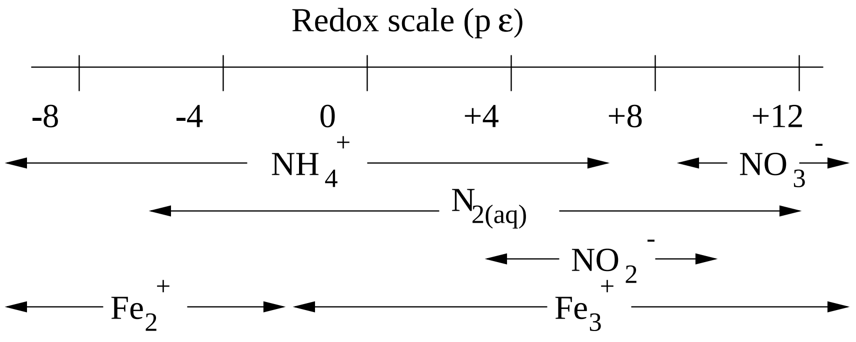

Figure 6.6: Redox scale and equilibrium phases for selected nutrients and metals (Adapted from Stumm and Morgan 1970)

6.4.4 Prevailing wind speeds and openness of water

An open reservoir shape and/or strong prevailing winds, will normally deepen the mixed surface layer depth, through greater travel across the water surface, and greater shear forces. While it is difficult to assess the wind induced mixing in Burrinjuck given the sparsity of wind data over the Reservoir itself, it is noted that the dendritic shape of Burrinjuck would further mitigate the mixing power of wind. The Reservoir depth relative to the mixed depth will determine the potential extent of anoxic bottom waters (internal loading) over the summer period.

6.5 Conclusions

The key processed determining algal composition are summarised in the following text.

6.5.1 Entire analysis period: 1976 to 1998

Diatoms appear the dominant algal group throughout the early Spring growth periods. This is a reflection of the availability of Si and the well mixed — turbulent conditions typical of this season.

6.5.2 Pre sewage nutrient removal period: 1976 to 1978

Cyanobacteria is the dominant group only for the high wastewater nutrient discharge period (1976 to 1978).

Cyanobacteria develops from low numbers in December to increased numbers through January, February and March. There appear to be a number of factors contributing to the dominance of Cyanobacteria under these conditions, including:

1. the low wind and hence low mixing energy resulting in dominance of Cyanobacteria as a result of its buoyancy faculty;
2. the high level of P availability through this period;
3. the low z_{eu}:z_{mix} ratios throughout the summer period;
4. the potential direct involvement of *Microcystis* in the redox process (as an electron acceptor);
5. the high NH_3 composition of inorganic N.

Elevated turbidity as a result of high inflow events over this period, together with high algal biomass, further reduced the z_{eu}:z_{mix} ratio over summer periods.

While (NO_x + NH_3): PO_4–P ratios during this period are frequently less than the gravimetric ratio (7) below which N may become limiting, NH_3 levels are generally above the 100 μg/L threshold level below which N-fixing Cyanobacteria become dominant.

The low N:P ratio, along with elevated NH_3:NO_x ratios typical of much of this period indicate the elevated redox conditions prevailing in the Reservoir under these conditions.

6.5.3 Sewage phosphorus and nitrogen removal period 1978 to 1983

The algal response (increase in Cyanobacteria (*Microcystis*) cell number, and occurrence of *Anabaena circinalis*) to operation of the de-nitrification unit was complicated by the significant Reservoir drawdown over this period. The NH_3:NO_x ratio increased significantly (to a ratio of 1.0) during periods of de-nitrification as compared to levels for similar stratification periods of P removal but no de-nitrification (ratio of 0.1) from 1984 onwards. The level of inorganic N was frequently depressed to 0.1 mg/L or less during this period. As noted previously, alga having N-fixing capabilities such as *Anabaena circinalis*, will have a competitive advantage over other alga under N limiting conditions.

The inference is that the reducing conditions within sediments of the Reservoir were exacerbated by de-nitrification.

6.5.4 Post sewage phosphorus removal period

Normal Reservoir operating levels

The reduction in direct and indirect (in-stream transformation of bio-available nutrients) discharge of organic material as a result of substantial reduction in P and BOD in sewage effluent, significantly eased the potential for reduction of Reservoir sediments and associated remobilisation of P, and production of NH_3. As a consequence, there was shift from Cyanobacteria dominance to dominance by Chlorophyta.

The reduced turbidity levels associated with reduced algal biomass resulted in an increase in the z_{eu}:z_{mix} ratio, further enhancing the competitive advantage of Chlorophyta over Cyanobacteria. Under the calm (low mixing) conditions of mid to late summer, motile forms of alga of the Chrysophyta and Euglena Divisions became dominant.

Periods of significant Reservoir drawdown

The increased deposition of organic material per area of sediments resulting from the reduced area of inlet depositional zones exacerbated the reducing conditions to the point where P and NH_3 were released. The release of significant mass of P to surface waters led to significant increase in algal biomass under these conditions.

The rapid drawdown conditions resulted in local re-suspension of fine colloids, which, together with the increased algal biomass, significantly reduced euphotic depth. Under the reduced z_{eu}:z_{mix} ratio conditions and the elevated NH_3 levels, the Cynaophyta were advantaged over the Chlorophyta. There is also the possibility that as a result of direct involvement of Microcystis in the redox process (as an electron acceptor), growth of the Cyanobacteria was favoured over that of Chlorophyta.

Chapter 7

Management Implications

7.1 What new understanding does the research provide?

The research highlighted the importance of establishing water and nutrient pathways and transformation patterns, in order to understand algal responses. In addition, the research identified a number of key processes determining algal biomass and composition responses, including:

1. the rapid transition from fully mixed to stratified and poorly mixed within 2 to 3 weeks, and sustained stratification over the late spring to early autumn period;
2. the importance of event frequency and event duration as drivers of organic material delivery to the Reservoir, of distribution through the Reservoir, and of the extent of mixing post peak of event;
3. the indirect pathways (internal loading) as the major nutrient source for the surface water layer (driven by organic carbon rather than by N or P);
4. the significant role of in-river processes in modifying the pattern (timing) and form of delivery of nutrients and organic material to the Reservoir;
5. non-point discharges from catchments having soils in which P is normally limiting in respect to biological growth;
6. the role of wastewater discharges in providing P and organic material sources necessary to generate redox conditions (the remobilisation of sediment P);
7. the significance of NH_3 vs NO_3 in determining redox conditions (release of P) and a potential for blue-green algae.
8. the important role of NO_x as a redox buffer for deep stratified reservoirs having high rates of organic loading;
9. the major driver of algal biomass is the amount of bio-available phosphorus transferred to the surface mixed layer;

10. the major drivers of algal composition are the availability of light (z_{eu}/z_{mix} ratio — function of abiotic particulates and algal biomass) and mixing conditions.

The primary implications of this new understanding for algal management comprise:

1. the substantial storage of P accumulated in the sediments, as a potential source of P supporting algal growth;
2. the need to minimise both direct and indirect sources of organic loading on reservoirs;
3. where it is not possible to substantially reduce organic loading (sediment BOD, external sources), the important role of NO_x as a redox buffer, limiting the level of nutrient remobilisation and algal biomass and blue-green algal dominance;
4. the need to ensure well nitrified wastewater effluent, low in BOD and P (indirect source of organic matter);
5. the wide range of possible reservoir water and nutrient pathways, and implications for the selection of outlet valves (drawoff depth relative to surface or bottom waters);
6. the increased risk of algal blooms under conditions of low reservoir levels and high rates of drawdown;
7. the role of in-stream interception, transformation and re-suspension of organic matter and nutrients, and implications of land use change on catchment hydrology.

7.2 What are the Reservoir management issues?

A series of Reservoir Managers' Workshops were conducted to enable the identification of management concerns, management options and information needs related to algal and wider reservoir management issues.

The concerns identified included:

Risk assessment and better management

In view of the serious impacts of algal blooms on treatability of water, and of treatment costs, recreational values, aesthetic values and ecology, how can the risk of algal blooms and severity be better assessed, and how can reservoirs be better managed to limit the incidence of algal blooms and/or algal entrainment in water abstracted for water supply?

Management in terms of a range of (conflicting) issues

Algal management is just one of a range of issues reservoir managers have to balance in their operation of reservoirs. Other issues include thermal pollution associated with the discharge of colder bottom waters, and the formation of odours, taste, colour, organics and toxicants in anoxic bottom waters under stratified and high organic loading conditions. What are the means of determining the trade-offs between in-reservoir environmental values and the downstream ecological and water use values?

There is a need for predictive tools and decision support tools which enable integrated consideration of the full range of issues. The research, with its strong process focus, indicated that the physical, chemical and biological factors contributing to nuisance algal growth are also critical in relation to a range of other water quality management issues.

Fragmentation of water cycle management

Previously, catchment management, reservoir management and treatment were considered integrally. The fragmentation of some agencies, separation of purchaser and provider functions, and out-sourcing of some functions (treatment provision) are a few of the factors leading to separate management consideration of each component, with boundary conditions prescribed in contractual arrangements (including penalties). How can managers respond to these reservoir specific requirements?

The research indicated a strong nexus between inflow characteristics (catchment management) and reservoir processes and responses. How is this critical link to be managed in a fragmented reservoir and catchment based approach?

The role of water supply reservoirs as one line of defence in management of pathogens. What are the water abstraction level policies related to minimising risk of abstraction of waters high in pathogens, and what are the monitoring requirements necessary to implement these policies?

Implications of complexity for delivery of information

There is a significant increase in information needs related to responding to an environment of increased social demands (multi-purpose operation), technical complexity and accountability (audits, liability). How can information be packaged in a form that is adequate and accessible to managers to respond to this new environment?

How can management related information be packaged in a way capable of addressing the diversity of structures, catchment and water use values?

7.3 What are the Reservoir management options?

At the series of Reservoir Managers' Workshops (Lawrence et al. 2000), the reservoir managers in association with the research scientists, identified a range of management options available to better manage algae in reservoirs, as follows.

Reservoir based algal management options:

1. design and selection of outlet structures;
2. pre-impoundment treatment;
3. destratification, oxygenation and hypolimnetic aeration;
4. use of well nitrified effluent as a redox buffer;
5. storage levels — limit drawdown rate, limit minimum depths;
6. establish pre-treatment forebays or swales ;
7. use of bio-manipulation (macrophytes, fish) techniques;
8. littoral zone management;
9. use of chemical flocculants and/or algacides as contingency measure.

Catchment based algal management options:

1. the development, implementation and review of catchment management plans;
2. management of point source discharges — ensure well nitrified wastewater effluent, low in BOD and P;
3. management of non-point source discharges, in terms of land use and location, management practices, set backs, buffer zones, wetlands, vegetated waterways, erosion and sediment control;
4. riparian zone management of streams.

Some preliminary guidelines for the selection of management options have been provided as part of the Reservoir Managers' Workshops Report (Lawrence et al. 2000).

7.4 What are the management information needs?

Drawing on the list of Management concerns, the range of possible management options, and the enhanced understanding of the factors and processes determining reservoir algal biomass and composition, the Reservoir Managers' Workshops identified the following information needs. The research team's responses to each of the identified needs are provided (material in brackets). Also refer to Figure 7.1, a diagram of the relationship between reservoir algal processes and catchment land use and management.

1. Better definition of management objectives, particularly in the case of multi- purpose reservoirs. (This is seen as a matter for reservoir management agencies.)
2. Better information on the major determinants of algal biomass and composition. (This report, together with the Reservoir Managers' Workshops Report, provides a substantial enhancement of information regarding processes and determinants of algal biomass and composition, and the range of options for their management. Gaps in knowledge are addressed in Section 7.7.)
3. Better predictive tools and techniques for assessment of the risk of bloom conditions. (This important need is addressed under Section 7.5 below.)
4. Better information on the range of management available options, and guidelines on the selection of options appropriate to local conditions. (The Reservoir Managers' Workshops Report includes preliminary guidelines on the selection of reservoir and catchment management options. Two approaches are recommended to the expansion of this framework into specific criteria; the development of reservoir classification system, and the application of decision support tools which deal with the complex range of processes in an integrated and dynamic manner. Further details of each are provided in Section 7.7.)
5. Development of a reservoir classification system to aid managers in identifying algal response processes, management and monitoring protocols. (It is proposed that the Classification system build on our evolving understanding of the major determinants of reservoir algal response processes, including:
    - reservoir depth, shape, outlet arrangements and drawdown conditions;
    - catchment description: hydrology; point and non-point source loads and nutrient composition; catchment soils and land use;
    - reservoir lattitude and elevation and light environment (light and temperature depth profiles, mixing depth);
    - the range of in-reservoir and downstream environmental and water use values or objectives.)
6. Provide profiles and watching briefs on emerging issues, such as new monitoring devices, analytical methods, destratification or hypolimnetic aeration techniques, decision support tools, monitoring design, data analysis, etc. (A range of government agencies and water research centres such as LWRRDC, MDBC, CRC for Freshwater Ecology, CRC for Water Quality, CRC for Catchment Hydrology and CSIRO Division of Land & Water are emerging as centres for information of this type.)

7.5 What decision support tools are needed?

The Reservoir Managers' Workshops identified the need for a range of decision support tools, including monitoring guidelines, data analysis techniques, criteria guiding

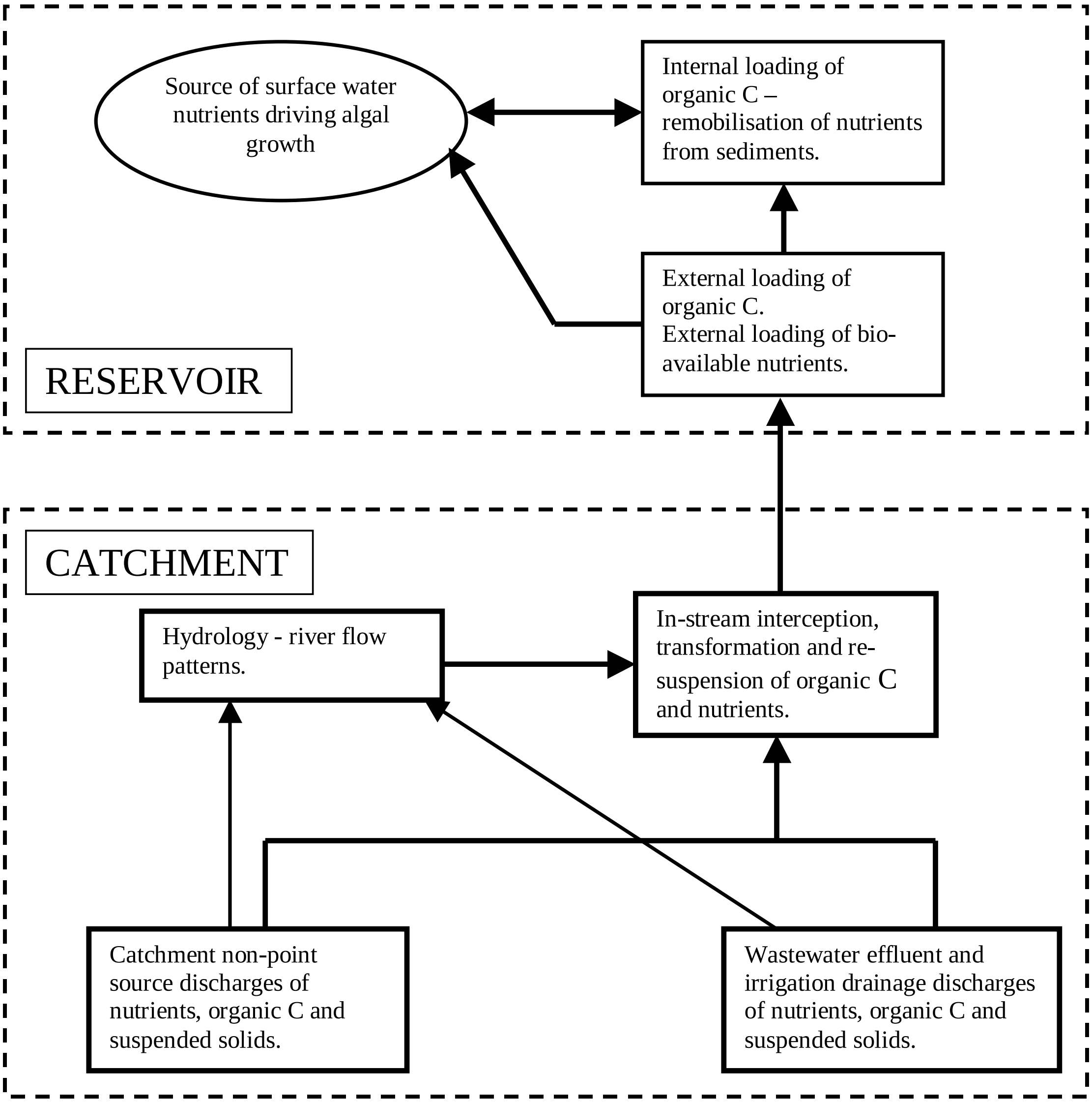

Figure 7.1: Relationship between reservoir algal processes and catchment land use and management.

the selection of outlet levels, criteria guiding the selection and design of management options. The reservoir managers stressed the importance of limiting the complexity and parameterisation requirements of tools, while ensuring that the tools are scientifically based.

Harris questions the relevance of 'average annual load — steady state' based models to Australian catchment, characterised by pulsed (event driven) exports of nutrients, extreme variability in sedimentation losses, and nutrient composition comprising a high particulate nutrient component (Harris 1994).

Vollenweider's models of the impact of nutrient loading on phytoplankton biomass in lakes assume equilibrium at scales of a year. They therefore cannot, strictly speaking, be used for highly perturbed systems which are subject to periods of high flow. A new generation of dynamic based models is required which incorporates more terms and processes (Harris 1996). The Burrinjuck analysis suggests that this argument may not hold in the case of the hypolimnetic P dominant pathway.

Harris notes that Australian aquatic ecosystems are characterised by highly dynamic, non-steady state behaviour, at a range of scales. In these systems, fluxes of elements are strongly dependent on catchment processes, sediment exchanges and biological processes at a range of scales. Flow regulation has a major impact on in-water processes in rivers, storages and estuaries. In particular, flow regulation alters the balance of external vs internal loads and diffuse vs point sources of nutrients.

There now exists a range of appropriate process based catchment, river and lake models which can provide guidelines for land use change, point-source loads and management options. These should be used in preference to standard guidelines based on concentration and nutrient ratios. These new models provide a means of working backwards from ecosystem impacts and desired ecosystem values to the calculation of critical loads ad the means of achieving them. They can be applied at regional scales to solve large scale resource management problems (Harris 1996).

The Burrinjuck research has highlighted the dynamic nature of nutrient pathways, with inflow patterns and load composition as major determinants of the dominant pathways at any one time. Modelling approaches need to be capable of representing the dominant systems and their switching factors, if they are to provide a reliable decision support tool to managers.

7.6 What are the monitoring needs?

In responding to the management issues, management options and information needs, a number of monitoring implications were identified.

The research team observed that the value of the monitored data provided by agencies could be substantially enhanced by reducing the emphasis on the routine monthly monitoring program and instead incorporating occasional *intensive monitoring of responses to selected events* based programs. The installation of solid state probes capable of continuous monitoring of pH, DO, temperature and light would also substantially enhance the data.

Special note was made of the importance of placing the design of monitoring program in the context of:

1. the purpose/issues to be addressed by monitoring data;
2. the understanding of dominant pollutant transport and transformation pathways and processes.

The managers also stressed the importance of being clear on the separation of research/descriptive studies related monitoring needs from operation related monitoring needs.

The specific monitoring needs identified by the workshop comprised:

1. effective monitoring of external loads and discharges (flow, nutrients);
2. improved information on mixing conditions — establishment of thermistor chains and vertical profiles of DO and light;
3. algal characterisation/monitoring — Chlorophyll 'a', major genera cell numbers, production/respiration (diurnal DO, pH);
4. zooplankton — determine species dominance and populations by size (grazing pressure);
5. provision of guidelines on techniques for the interpretation of data;
6. integration of quality assurance processes into sampling, analysis and archiving processes;
7. monitoring wind speed and direction and solar radiation on reservoir surfaces.

7.7 What are the research needs?

A number of research needs were identified during the Reservoir Managers Workshops. They included:

1. field investigation of the impact of rapid drawdown and shallow depths in remobilising and re-suspending sediment nutrients;
2. further description of the form and pattern of nutrient and organic material discharge, and of the pattern of organic material deposition in inlet depositional zones and bottom waters within middle reaches, and sediment redox responses;
3. identification of the conditions and processes associated with nutrient transfer between the bottom waters and the surface mixed layer, including spatial and temporal scale effects;
4. the development of improved models for estimating general mixing and light conditions, including consideration of temperature stratification, wind mixing, particle aggregation and photosynthetic pigments of natural waters;
5. examination of the role of different forms of nitrogen and the critical light requirements of Cyanobacteria and micro-algae, to develop a more reliable basis for predicting the influence of mixing and turbidity on growth;
6. examination of the environmental conditions influencing the growth of benthic algae and their impact on nutrient and carbon dynamics;
7. the development of a reservoir classification system to aid managers in determining appropriate management and monitoring protocols for local reservoirs;

8. the development of simple dynamic models to enable managers to link reservoir algal responses with catchment runoff and stream flow and nutrient delivery processes, and reservoir drawdown and discharge level factors.

The Burrinjuck project has built on data provided by DLWC, ACTEW, Environment ACT and the Bureau of Meteorology. The integrated nature of the data set and the validation of data associated with the project has resulted in the consolidation of an extremely valuable data set from a research perspective. There is an opportunity for further substantial benefits to be derived from further analysis of this data.

There is a strong case to make this data available more widely to research institutions, in the interest of promoting ongoing reservoir water quality and algal management related research. Consultation is proceeding with the data providers to explore opportunities for placing the data set on the Web.

Chapter 8

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Data sources

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ACTEW Reservoir Water Quality Data Archive 1976–1998, ACT Electricity & Water

ACTEW Stream Gauging Data Archive 1976–1998, ACT Electricity & Water

Australian Climate Computer Archive (database), Commonwealth Bureau of Meterology Australia

Environment ACT Stream Water Quality Data Base 1976–1998, Environment ACT.

DLWC Water Quality Database 1991–1998, Department of Land and Water Conservation

DLWC Stream Gauging Database 1976–1998, Department of Land and Water Conservation

Appendix A

Description of the data base

The initial stage of this project involved the consolidation of over 20 years of measured data for both Burrinjuck Reservoir and its catchment area. The data was compiled from various sources, primarily ACT Electricity and Water, the Department of Land and Water Conservation, Environment ACT and the Bureau of Meterology. The data collected spans a period of over 20 years, from 1 January 1976 to 31 March 1998, though many of the variables were sampled sporadically during this time and some do not span the entire period.

The meterological data comprises evaporation, air temperature, rainfall, wind direction and speed recorded at daily or twice daily intervals for the entire study period.

The water quality data comprises data collected at six Reservoir stations for the period 1976 to 1998 and data from another five stations for the period 1992 to 1998. Sampling frequency is irregular, generally ranging from weekly to monthly with occasional gaps of several months to several years at some sites. At each sampling event, samples were usually taken at varying depth profiles, ranging from water surface to the reservoir bottom.

The hydrographic data comprises streamflow data for inflows to and discharge from the Reservoir for the period 1976 to 1998, including daily reservoir levels. A summary of the compiled data is given below in Table A.1

A.1 Quality assurance

Quality control of data was undertaken at the source agencies. After compilation of the data this was followed by further validation using simple techniques such as visual examination for expected data magnitude and temporal alignment. Many anomalies were discovered during this validation in both the raw data and subsequent interpretation of the data, so the process of reconstructing a correct data set became a time consuming but necessary task. Difficulties involved factors such as varying data formats (eg. units of data, format of dates) and meanings over the 20 year period. For example in one data

Table A.1: Summary of the Burrinjuck Reservoir Data set

Raw Data		Location
Algae	Cyanophyta, Chlorophyta, Diatoms, Chrysophyta, Xanthophyceae, Euglenophyta, Chrysophyceae, Chlorophyll-A	Burrinjuck Dam sites
Zooplankton	Cladocera, Copepoda Calanoida, Copepoda Cyclopoida, Copepoda Harpacticoi, Rotifera, Nymphs, Ciliophora	Burrinjuck Dam sites.
Physical Characteristics	True colour, Secchi depth, Turbidity, Specific conductance, pH, Suspended solids, Temperature, Dissolved Oxygen.	Burrinjuck Dam and sites on inflows to the dam.
Chemistry	Calcium, Chloride, Total Iron, Magnesium, Manganese, Potassium, Silicon, Sodium, Sulphate	Burrinjuck Dam and sites on inflows to the dam.
Nutrients	Total Nitrogen, NH3, NOx, TKN, Total Phosphorus, FRP	Burrinjuck Dam and sites on inflows to the dam.
Stream Flow		Inflows from the Murrumbidgee R., Yass R. and Goodradigbee R.
Meterological data	Evaporation	Burrinjuck Dam
	Air Temperature (min and max), Precipitation, Wind Direction, Wind Speed	Yass
	Relative Humidity, Sunshine	Canberra city and airport
Reservoir height		Burrinjuck dam wall

set the same field entry signified either *surface water*, a *tube sample* or *unknown depth* depending on the time period. Difficulties or time delays in finding archival information on older data formats and meanings of fields were also encountered.

A.2 Data storage structure and protocols

Data is currently stored in Microsoft Excel's proprietory format, with individual variables combined into logical groups with a common abscissa (date). The editing or updating of these files is centrally administered to ensure data integrity.

Most of the processing and analysis of data was done using Matlab (Mathworks 1996) and Microsoft Excel so derived data and results are also stored in both delimited text and Microsoft's proprietory file format.

A web site was established to allow all project members access to the data and to provide information on the project. The site is divided into areas for the data base, for general information and for analysis. For the duration of the project, the entire site was restricted by password protection to members of the project team

A.3 Future of the data set

A proposal has been forwarded to the providers of data suggesting that the integrated data set be placed on the Web as a resource for further research. The proposal notes the enormous value of the integrated data set from a research perspective, and that there remains considerable opportunities to secure further new knowledge from further analysis of the data set.

A.4 Statistical summaries

This appendix contains basic statistical information for the Burrinjuck data set (Tables A.2 to A.4). Shown is a mean, or median where appropriate, the range of the data and the number of data (n). The information given is for the key sites 103, 104, 108, 109/BURJDW and BURJMR. Results are presented in tabular form and grouped according to type of data, eg Algal, Physical etc. For each group, the parameters considered most relevant to this report are given.

Also in this section are tables of nutrient loads for each of three influent sources; the Murrumbidgee, Goodradigbee and Yass arms (Tables A.5 and A.6). This information is split into daily and yearly loads, and a range of data given for each.

Table A.2: Burrinjuck Reservoir algal data.

Burrinjuck Reservoir algal data 01 Jan 1976 to 31 Dec 1996				
Site		Cyanobacteria (cells/mL)	Chlorophyta (cells/mL)	Diatoms (cells/mL)
103	Range	0–3357900	0–50544	0–32368
(n=700)	Median	0	600	182
104	Range	0–669600	0–28405	0–16670
(n=705)	Median	0	522	85
108	Range	0–1426800	0–60460	0–12410
(n=716)	Median	0	444	60
109/BURJDW	Range	0–78811	0–12320	0–4560
(n=206)	Median	191	288	156
BURJMR	Range	0–794	0–2214	28–702
(n=9)	Median	28	23	116

Table A.3: Burrinjuck Reservoir physical data.

Burrinjuck Reservoir Physical Data 01 Jan 1976 to 31 Dec 1996			
Site		Turbidity (NTU)	Specific Conductance (μS)
103	n	766	768
	Range	0.7–152	69–479
	Mean	17.62	176.27
104	n	790	830
	Range	0.91–240	75–458
	Mean	16.04	174.91
108	n	789	830
	Range	0.45–230	84–481
	Mean	14.25	175.99
109/ BURJDW	n	273	365
	Range	0.5–160	94–256
	Mean	11.94	168.53
BURJMR	n	66	78
	Range	2–37	121–245
	Mean	11.20	170.68

Table A.4: Burrinjuck Reservoir nutrient data.

Burrinjuck Reservoir Nutrient Data 01 Jan 1976 to 31 Dec 1996							
Site		N (mg/L)	NH_3 (mg/L)	NO_x (mg/L)	FRP (mg/L)	TP (mg/L)	Si (mg/L)
103	n	82	787	787	772	679	22
	Range	0.66–3	0–1.92	0–3.28	0–0.31	0–0.612	0.5–11.5
	Mean	1.49	0.10	0.50	0.02	0.07	4.98
104	n	91	806	806	795	712	15
	Range	0.39–6.4	0–2.2	0–3	0–0.26	0–1.16	0.2–6.2
	Mean	1.25	0.09	0.47	0.02	0.06	2.25
108	n	89	807	807	790	713	16
	Range	0.43–2.7	0–1.7	0–2.43	0–0.235	0–0.42	0.2–5.9
	Mean	1.10	0.08	0.44	0.02	0.05	2.42
109/ BURJDW	n	10	219	230	220	225	42
	Range	0.46–1.0	0.003–0.73	0.001–1.78	0.001–0.4	0.007–0.362	0.2–15.4
	Mean	0.81	0.047	0.31	0.01	0.044	7.29
BURJMR	n	2	30	37	37	54	19
	Range	1.0–1.0	0.01–0.22	0.124–0.85	0.002–0.04	0.007–0.14	1.8–11.6
	Mean	1.00	0.04	0.58	0.01	0.04	8.05

Table A.5: Burrinjuck Reservoir Inflows — Yearly Water and Nutrient Loads.

<table>
<tr><th colspan="6">Burrinjuck Reservoir Inflows — Yearly Water and Nutrient Loads
01 Jan 1976 to 31 Dec 1996</th></tr>
<tr><th></th><th>Water load (ML/yr)</th><th>TP load (kg/yr)</th><th>TN load (kg/yr)</th><th>Si load (kg/yr)</th><th>TOC load (kg/yr)</th></tr>
<tr><td colspan="6">Murrumbidgee Arm</td></tr>
<tr><td>Minimum</td><td>83984</td><td>8879</td><td>86530</td><td>338653</td><td>174590</td></tr>
<tr><td>Maximum</td><td>2064985</td><td>503553</td><td>2990621</td><td>20561473</td><td>4749335</td></tr>
<tr><td colspan="6">Yass Arm</td></tr>
<tr><td>Minimum</td><td>4611</td><td>194</td><td>6279</td><td>12981</td><td>-</td></tr>
<tr><td>Maximum</td><td>245450</td><td>10309</td><td>18396502</td><td>2540858</td><td>-</td></tr>
<tr><td colspan="6">Goodradigbee Arm</td></tr>
<tr><td>Minimum</td><td>46447</td><td>853</td><td>11926</td><td>329765</td><td>-</td></tr>
<tr><td>Maximum</td><td>481883</td><td>12047</td><td>171735</td><td>9485053</td><td>-</td></tr>
</table>

Table A.6: Burrinjuck Reservoir Inflows — Daily Water and Nutrient Loads.

<table>
<tr><th colspan="6">Burrinjuck Reservoir Inflows — Daily Water and Nutrient Loads
01 Jan 1976 to 31 Dec 1996</th></tr>
<tr><th></th><th>Water load (ML/day)</th><th>TP load (kg/day)</th><th>TN load (kg/day)</th><th>Si load (kg/day)</th><th>TOC load (kg/day)</th></tr>
<tr><td colspan="6">Murrumbidgee Arm</td></tr>
<tr><td>Minimum</td><td>56</td><td>7</td><td>88</td><td>165</td><td>102</td></tr>
<tr><td>Maxmum</td><td>178973</td><td>129546</td><td>598798</td><td>3745836</td><td>428117</td></tr>
<tr><td colspan="6">Yass Arm</td></tr>
<tr><td>Minimum</td><td>0</td><td>0</td><td>0</td><td>0</td><td>-</td></tr>
<tr><td>Maxmum</td><td>35423</td><td>1488</td><td>8814690</td><td>599228</td><td>-</td></tr>
<tr><td colspan="6">Goodradigbee Arm</td></tr>
<tr><td>Minimum</td><td>17.49</td><td>0.25</td><td>4.39</td><td>53.40</td><td>-</td></tr>
<tr><td>Maxmum</td><td>16892</td><td>554</td><td>15637</td><td>752448</td><td>-</td></tr>
</table>

Appendix A. Description of the data base

Appendix B

Outline of analysis methods

B.1 Water temperature

At each station the water temperature was obtained from the profiles done on at least a monthly basis. Seasonal variations in temperature were plotted for each year as well as an average over the 20 years. A similar pattern was obtained each year. Stratification building up from September to February, convective cooling from March to August mixing the reservoir to complete overturning in winter.

B.2 Mixing depth

From the temperature profiles, the depth of the surface mixed layer was calculated as the maximum depth where the temperature gradient was less than 0.2°C per meter. The temperature profiles are taken around mid-day and, particularly during Summer, the surface layer is strongly stratified at this time. During the night however the mixing is much deeper. So to try to gauge the maximum surface mixed layer in a 24 hour period, as an indication of how deep the algae would have been mixed down overnight, only the water below 3m depth was used. This is a crude way of assessing the surface mixed layer depth but in our view the only possible way given a single profile per day.

B.3 Euphotic depth

The euphotic depth, $\mathrm{z_{eu}}$, is the depth at which 1% of the surface radiation penetrates into the water column. It is used as a measure of the depth below which photosynthesis is limited. In this study it was calculated from secchi depth data from the commonly used relationship

$$z_{eu} = 2.7 \times z_{secchi} \tag{B.1}$$

where the secchi depth is the depth at which a secchi disk lowered in the water column disappears from sight.

B.4 Nitrogen concentration

Measurement of reservoir concentrations of TKN, or direct measurement of TN, is only available for the period 1993 onwards. Estimates of TN prior to this period were based on the sum of inorganic N forms and Chlorophyll 'a' measurements:

$$TN = \sum inorganic\ N + (5 \times Chlorophyll\ 'a') \tag{B.2}$$

where organic N was calculated from organic P using the Redfield gravimetric ratio:

$$organic\ N = organic\ P \times 7.2 \tag{B.3}$$

and organic P was calculated from Chlorophyll 'a':

$$organic\ P = 0.7 \times Chlorophyll\ 'a' \tag{B.4}$$

B.5 Internal reservoir nutrient loading

Internal nutrient loads in the Murrumbidgee arm of the reservoir were calculated on a reach by reach basis. Each reach, or pond, is treated as a separate system with inputs, outputs and current and previous states. For any reach, input load comes from the upstream pond, and output goes to the next downstream pond. The current state is a function of input, output and previous state, with the mass balance equation:

$$Input + Previous\ State = Output + Current\ State. \tag{B.5}$$

The current state is comprised of up to three components and two transfers. The first pool is assumed to be fully mixed and so has a nutrient load in the water and also in the sediment and a transfer between sediment and water. Subsequent pools are stratified, so the nutrient load in these pools is further broken down into surface and bottom waters and a transfer of nutrients between the two stratified layers.

This model for the Murrumbidgee arm is shown in Figure B.1. Pool 1 is the reach from Station 201 to 101, Pool 2 is from Station 101 to 102, and so on until Station 104.

Input to Pool 1 consists of the nutrient load calculated for the Murrumbidgee upstream of Station 201. Both point and non-point sources contribute to this load, including the catchments of the Murrumbidgee River and Ginninderra Creek and the output from Lower Molonglo Water Quality Control Centre. Transfer of nutrients to and from the sediment is calculated using the mass balance equation:

$$L_{in} + L_{n-1} = L_{out} + L_n + T_{sed} \tag{B.6}$$

where

L_{in} is the nutrient load into the pool from the Murrumbidgee;
L_{out} is the nutrient load out of the pool, to Pool 2;
L_n is the nutrient load in Pool 1 at time n;
T_{sed} is the transfer of nutrients to the sediment.

This pool is fully mixed so the input into Pool 2, which is stratified, can enter either at the surface or bottom. Whether the inflow to Pool 2 enters at the surface or bottom waters is calculated from the volume of inflow to Pool 1, a greater volume over the time period signifying a plunging flow (see Section B.8). The transfer of nutrient between the surface and bottom layers of Pool 2 is calculated from:

$$Ls_{in} + Ls_{n-1} = Ls_{out} + Ls_n + T_b \tag{B.7}$$

where

Ls_{in} is the load into the surface layer from Pool 1;
Ls_{out} is the load out of the surface layer of the pool, to Pool 3;
Ls_n is the load in the surface layer of the pool at time n;
T_b is the transfer of nutrients to the bottom water layer.

Sediment transfer in Pool 2 occurs only with the bottom water, so the previous sediment transfer mass balance now becomes:

$$Lb_{in} + Lb_{n-1} + T_b = Lb_{out} + Lb_n + T_{sed} \tag{B.8}$$

where

Lb_{in} is the load into the bottom water layer from Pool 1;
Lb_{out} is the load out of the bottom layer of the pool, to Pool 3;
Lb_n is the load in the bottom water layer of the pool at time n;
T_b is the transfer of nutrients to the bottom water layer;
T_{sed} is the transfer of nutrients to the sediment.

Pools 3 and 4 are also stratified and so are modelled in the same way as Pool 2. Results from this analysis can be found in Section 4.3.

B.6 External loading on the Reservoir

The analysis of algal biomass and succession patterns in Burrinjuck Reservoir over the 1976 to 1998 period requires the analysis of daily water, nutrient (C, N, P, Si) and heat loadings on each of the reservoirs arms, the Murrumbidgee, Yass and Goodradigbee.

These external loads were calculated on a daily frequency from total daily flow, $\sum f(t)$, and from concentration, c, measured as a point quantity. When these concentration measurements are assumed to represent the daily average, a constant $\overline{c}$, nutrient load, l, can be calculated as

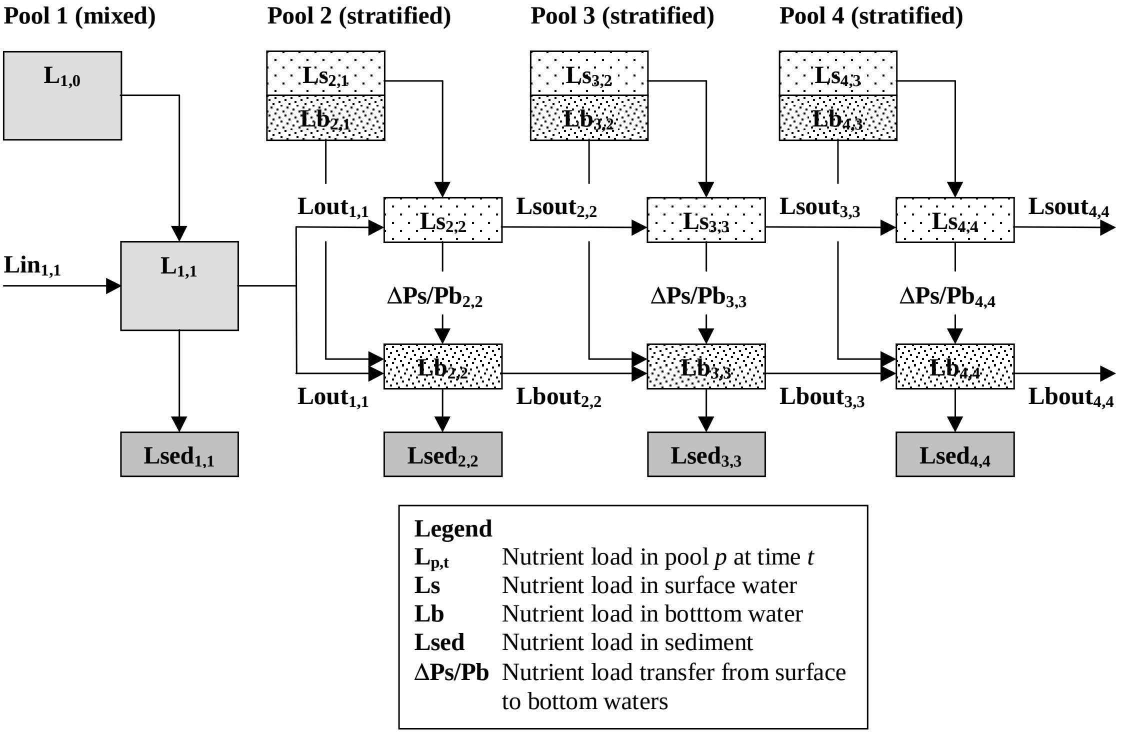

Figure B.1: Reach based internal reservoir loading.

$$l = \overline{c} \sum f(t). \tag{B.9}$$

While daily measured values for total flow and instantaneous concentration are available, gaps do exist in the data and for analysis purposes these were filled to bring the complete data set to daily frequency. The approach taken for flow was to fill gaps with data from other upstream stations, summed and adjusted for catchment size in order to approximate the downstream flow. The adjustment for catchment size was calculated as a ratio of catchment areas to the power of 0.7 (Fitzgerald 1975, pers. comm.) i.e.

$$catchment\ adjustment = \frac{catchment\ area^{0.7}}{upstream\ catchment\ area^{0.7}}. \tag{B.10}$$

Periods of no data in the chemistry data sets were much larger than those in flow, with monitoring for some analyands commencing after the start of the study period. To estimate the missing data the chemistry data was modelled with a simple linear or curvilinear regression with flow. Where a wastewater treatment plant discharge occurred, the data was separated into pre and post discharge periods (see Section 2.2.1) and a regression line was calculated for each period.

Generally, to estimate missing sewage treatment plant effluent concentrations, two approaches were taken:

1. Where gaps were small a linear line fit was applied to the outlying points
2. For Belconnen WPCC, Weston Creek STW, and the early period of LMWQCC operation, up to April 1983, reported average concentrations from the Environment and Process Audit were used (SCM Consultants 1992).

The calculation of nitrogen concentrations from LMWQCC was more complex as the data set is sparse, and also because several periods of trial denitrification occurred between 1978 and 1993. From the commencement of operation in 1978 to May 1983, total nitrogen values are taken from LMWQCC Environment and Process Audit (SCM Consultants 1992). During this period NO_x and NH_3 are calculated as 80% and 10% of total nitrogen respectively. During the periods when denitrification occurred these proportions changes to 60% and 30% respectively. From 1983 when trial denitrification ceased, up until June 1985, both NO_x and NH_3 are estimated from a regression with flow on the measured data that exist from July 1985 to the end of the study period. During this time and up until November 1993 when measured data commences, total nitrogen is calculated as the maximum of the sum of NO_x, NH_3 and a constant factor to represent organic nitrogen, and the reported median values in *LMWQCC Environment and Process Audit* (1992).

B.7 Organic loading

This analysis relates to the role of internally or externally derived P (Hypolimnetic P) analysis.

Internal organic load

The internal load was calculated for:

1. an average Reservoir depth of 40 m summer;
2. a 3000 ha surface area.

In the period before nutrient removal at LMWQCC, average algal biomass was 15 μg/L Chlorophyll 'a'. BOD (decay of algae) was calculated as:

$$\begin{aligned} \mathrm{BOD_{load}} &= 3 \times 10^7 \text{ m}^2 \text{ area} \times 15\ \mu\text{g/L Chlorophyll } 'a' \\ &\quad \times 0.7 \text{ g P/g Chlorophyll } 'a' \times 41 \text{ g C/g P} \\ &\quad \times 2.1 \text{ g BOD/g C} \qquad \text{(B.11)} \\ &= 2.3 \text{ g/m}^2\text{/a.} \end{aligned}$$

In the period after nutrient removal at LMWQCC, average algal biomass was 5 μg/L Chlorophyll 'a'. BOD (decay of algae) was calculated as in Equation B.11:

$$\mathrm{BOD}_{\mathrm{load}} = 0.8 \text{ g/m}^2\text{/a.}$$

External organic load

In the period after nutrient removal at LMWQCC, outputs of phosphorus were 8000 kg/day. External TOC loading was calculated as:

$$\begin{aligned} \mathrm{TOC}_{\mathrm{load}} &= 8000 \text{ kg/day P} \times 41 \text{ g TOC/g P} \\ &= 2920 \times 10^3 \text{ kg TOC/a} \\ &= 98 \text{ g/m}^2\text{/a.} \end{aligned} \tag{B.12}$$

In the period after nutrient removal at LMWQCC, outputs of phosphorus are 800 kg/day. External TOC loading was calculated as:

$$\begin{aligned} \mathrm{TOC}_{\mathrm{load}} &= 800 \text{ kg/day P} \times 41 \text{ g TOC/g P} \\ &= 292 \times 10^3 \text{ kg TOC/a} \\ &= 9.8 \text{ g/m}^2\text{/a.} \end{aligned} \tag{B.13}$$

B.8 Temperature of inflow to Reservoir

A substantial stream flow temperature data set (weekly to fortnightly) was available for the Murrumbidgee River at Uriarra Crossing, along with streamflow data. A regression analysis was undertaken of the 22 years of temperature data as a function of flow and month. A significant correlation was indicated between temperature and flow on a monthly basis ($R^2 = 0.1$ to 0.4, n = 60/month).

This regression analysis was used as the basis for estimating the temperature of stream inflow to Burrinjuck Reservoir. It was assumed that there was no significant change in temperature for the 40 km of further travel of water downstream from Uriarra Crossing to Taemus Bridge (inlet zone to Reservoir). This is typically a travel time of 1 to 2 days within a deep gorge.

The temperature of inflow was then compared with the average surface temperature for the month for the Murrumbidgee River arm of the Reservoir in order to ascertain the location of inflow:

1. where inflow temperature > surface water temperature, inflow is to the surface mixed layer;
2. where inflow temperature < surface water temperature, inflow is to the bottom water layer.

B.9 Inlet depositional zone redox analysis

A process based water quality model developed for Canberra's lakes and ponds was applied to the inlet zone of the Reservoir. The model comprises daily analysis of:

1. inflow, washout and mixing for TP TN, SS, BOD and algae;
2. sedimentation of particulates (including adsorbed nutrients) as a function of reach volume and surface area;
3. inventory of settled organic material, less microbial utilisation;
4. DO balance in bottom layer and sediment redox levels;
5. daily transfer of DO through the water column, as a function of wind velocity, depth and temperature, offsetting (oxidation) reducing levels;
6. reduction of Fe(III) to Fe(II) and release of PO4 to the water column;
7. uptake of released P by algae (Chlorophyll 'a').

The volume and surface area of the reach was adjusted on a daily basis to reflect Reservoir drawdown conditions (based on Reservoir level and hypsometric curves for the reach).

Model estimates of TP concentrations and Chlorophyll 'a' were compared with monitored values for the analysis period.

B.10 Hypolimnetic P analysis

The FRP concentration of bottom waters and the surface mixed layer immediately prior to mixing (turnover) in autumn was determined for each year, and the mixed concentration of FRP following turnover calculated:

$$\mathrm{FRP}_{\mathrm{mixed}} = \frac{\mathrm{Vol}_{\mathrm{SML}} \times \mathrm{C}_{\mathrm{SML}} + \mathrm{Vol}_{\mathrm{BW}} \times \mathrm{C}_{\mathrm{BW}}}{\mathrm{Vol}_{\mathrm{SML}} + \mathrm{Vol}_{\mathrm{BW}}} \tag{B.14}$$

where

$\mathrm{Vol}_{\mathrm{SML}}$ is the volume of the surface mixed layer;
$\mathrm{C}_{\mathrm{SML}}$ is the FRP concentration in the surface mixed layer;
$\mathrm{Vol}_{\mathrm{BW}}$ is the volume of the bottom waters;
C_{BW} is the FRP concentration in the bottom waters.

Regression analysis was undertaken for the Chlorophyll 'a' vs the $\mathrm{FRP}_{\mathrm{mixed}}$ for the previous autumn, with separation of the years 1976 to 1980 from 1984 to 1998.

A correlation coefficient close to 1.0 was interpreted as indicating that the hypolimnetic FRP represented a substantial component of the P driving algal growth in the subsequent growth period. A correlation coefficient less than 0.4 was interpreted as indicating that the hypolimnetic P was only a minor source of FRP driving algal growth in the subsequent growth period.

B.11 Algal biomass

In the case of Cyanobacteria Division alga, the 'Cyanobacteria' Chlorophyll 'a' estimates were based on:

1. regression analysis of total Chlorophyll 'a' versus Cyanobacteria cell numbers for those periods where Cyanobacteria were dominant;
2. application of regression relationship to Cyanobacteria cell counts for the whole of the data period.

Appendix C

Glossary

Abiotic particulates Soil particles comprising crystallized minerals.

Adsorption The adherence of nutrients, metals, organics to a surface.

Alga Simple, usually unicellular, organisms capable of photosynthesis.

Algal blooms Excessive number of algae in a water body, often associated with an over abundance of nutrients in combination with suitable physical conditions.

Anoxic The absence of oxygen.

Attached algae Algae which are attached to a substrate (macrophytes, rocks, sand)

Anabaena A genus of **Cyanobacteria** (blue-green algae). *Anabaena* is widespread in Australia and is one of the toxic bloom forming blue-green algae. As *Anabaena* have the ability to fix nitrogen from the atmosphere, these organisms can overcome a nitrogen limitation in the water and thus are advantaged over competing algae in a nitrogen limited environment.

Benthic Benthic organisms are those that inhabit the bottom substrates of their (freshwater) habitat.

Benthic oxygen demand The ongoing oxygen demand imposed by sediments on the water column. Associated with the accumulation of more refractory (low rate of bio-availability) organic material in the sediments.

Bio-available Nutrients in a dissolved form, free of adsorption or other complexity, such that they are readily available for plant uptake, or organic material in a labile form.

Biochemical oxygen demand (BOD) The oxygen demand associated with the microbial decomposition of organic material. Normally measured as the oxygen depletion (mg/L) in a sample of water containing the organic material after 5 days.

Biofilm Film on a range of subtrates created by micro-organisms, including **benthic algae** and bacteria.

Biomass The weight of living organisms.

Biotic A process that requires the action of living organisms.

Chelated Complex molecules comprising metal ions and non-metal atoms (ligands).

Chemical oxygen demand (COD) The amount of oxygen required to oxidise all organic matter that is susceptible to **oxidation** by a strong chemical oxidant.

Chlorophyta (green algae) A division of algae. Green algae are dependent on vertical mixing in the water column to cycle them through the **euphotic zone**.

Conductivity The electrical conductivity of water (μS/cm), as a measure of the total dissolved salts concentration of the water. Total Dissolved Salts are typically 0.68 x conductivity (μS/cm)

Cyanobacteria (blue-green algae) A division of algae, some species of which commonly form nuisance blooms in Australian waterways. Cyanobacteria have buoyancy vacuoles allowing them to regulate their vertical position in the water column, giving them an advantage over other algae when mixing moves the algae out of the **euphotic zone** for significant periods of time. Certain species of blue-green algae, for example **Anaebena** can capture nitrogen gas that has dissolved into the water from the atmosphere and are able to use this as a source of nitrogen.

Dendritic Having a branching form.

Destratification When the temperature of the **surface mixed layer** and the bottom waters equilize allowing mixing between the two layers.

Detritus Disintegrating organic material. In the case of algae, the dead cell matter.

Diatoms A division of algae. The cell walls comprise overlapping silica shells.

Epilimnion **Surface mixed layer** in stratified water bodies

Euphotic depth (z_{eu}) The point in the **water column** at which light intensity has reduced to 1% of its intensity at the surface.

External loading The supply of nutrients to the reservoir from sources outside of the reservoir, for example catchment runoff delivered via an input stream.

Filterable reactive phosphorus (FRP) The amount of phosphorus passing a fine filter. In this report, unless stated otherwise, FPR refers to the filtrate from a 0.45 μm filter.

Flagella tail like extension used by the alga for movement.

Hypolimnion the bottom water layer, extending from the **sediment** to the base of the **thermocline**.

Inlet depositional zone The zone over which the bulk of particulate materials discharged by streams into reservoirs is sedimented.

Inorganic The non-biological forms of nutrients, such as nitrate, nitrite, ammonia and phosphate.

Internal loading The release of nutrients from sediments and from recycling between algae within the reservoir.

Isothermal Single temperature throughout the reservoir

Labile carbon Forms of carbon which are more readily available for uptake by heterotrophic bacteria associated with the decomposition of organic material.

Littoral zone Shallow edge waters.

Macro-algae Large algae such as seaweed, or algae such as Hydrodictyon, Cladophora and Spirogyra comprising large colonies or long filaments of interlinked cells.

Macrophytes Large vascular aquatic plants. May be attached to sediments and emergent or submerged, or may be free floating.

Metalimnion The zone intermediate between the **epilmnion** and **hypolimnion**. Also referred to as the **thermocline**.

Micro-algae Very small single cell, colonies or filaments generally requiring a microscope for identification.

Microcystis A genera of blue-green alga that commonly cause algal blooms. These blooms can be toxic and have been implicated in severe dermatitis in humans, and poisoning of animals that injest the chemicals secreted by these algae.

Mineralisation Oxidation of organic material

Mixing depth (z_{mix}) The depth at which the buoyant energy of the surface layer (temperature reducing with depth) is equal to the kinetic energy resulting from surface wind stress.

Nitrification The oxidation of organic nitrogen to form nitrate or nitrite or ammonia.

Nitrogen One of several essential plant nutrients required for photosynthesis in lakes and streams. It occurs in a number of forms, including nitrite NO_2^-, nitrate NO_3^-, ammonia NH_3 and organic forms (measured as Total Kjeldahl Nitrogen). Total Nitrogen is the sum of all forms of nitrogen.

Non-point source A diffuse source of nutrients that does not originate from a single point. eg. catchment runoff.

Oxic The presence of oxygen.

Oxidation A chemical process where a molecule loses an electron.

Particulate Abiotic particles of minerals and biotic particles.

Plankton Organisms (animal or plant) that drift in the water column.

Phosphorus One of several essential plant nutrients required for photosynthesis in lakes and streams. It occurs in a number of forms, including inorganic phosphate PO_4^{3-}, HPO_4^-, organic P. Total Phosphorus is the sum of all forms of phosphorus.

Photosynthesis The process of synthesising organic material from water, carbon dioxide and salts using sunlight as the source of energy, and Chlorophyll 'a' as a catalyst.

Phytoplankton Free-floating microscopic plants in water bodies.

Point source A source of nutrient input to the reservoir that originates from a point, for example the effluent from a wastewater treatment plant.

Pore water Water trapped in the voids of soil or sediments.

Redox A measure of the electron activity or oxidising-reducing conditions of sediments.

Reduction A chemical process where a molecule gains an electron.

Refractory carbon Forms of carbon which are less readily available for uptake by heterotrophic bacteria associated with the decomposition of organic material.

Remobilisation The chemical transformation of nutrients to soluble forms, such as nitrification of organic nitrogen, or release of nutrients as a result of transformation of metals from an insoluble to soluble form. eg: the reduction of ferric iron to ferrous iron, with the release of PO_4^{3-}.

Reservoir turnover The transition of a stratified reservoir to a fully mixed reservoir, usually around April for temperate regions.

Riffle zones Shallow reaches of streams comprising beds of gravel or cobbles, upon which biofilm attaches.

Riparian zones Zone of ephemeral and terrestrial plants along banks and edges of streams.

Scouring Physical re-suspension of sediment or sloughing of biofilm and attached algae as a result of elevated streamflow velocities.

Sediment Accumulation of abiotic and biotic materials on the beds of streams, lakes and reservoirs.

Sediment oxygen demand expressed ad $g/m^2/day$, resulting from accumulation of organic material in the sediment.

Stratification The warming of reservoir surface water relative to deeper waters creates a physical separation, **thermocline**, of the surface and bottom waters in terms of density resistance to mixing.

Suspended solids (SS) Particles retained on a 0.45 μm filter.

Surface mixed layer (SML) The surface layer of lakes or reservoirs which is isothermal as a result of mixing energy resulting from surface wind stress, or thermal cooling of surface waters.

Thermocline The point of greatest temperature gradient in the water column. The thermocline separates the **surface mixed layer** or **epilmnion** from the bottom waters or **hypolimnion**.

Thermistor A temperature sensitive electrical resistor used for monitoring water temperature.

Turbidity A measure of the light absorption by suspended abiotic and biotic particles in a water body.

Water column A theoretical 'column' of water representative of the vertical physical and chemical properties of a lake or reservoir.

Zooplankton The animal portion of **plankton**.

Appendix D

Abbreviations

ACTEW	ACT Electricity & Water
AHD	Australian Height Datum
AWT	Australian Water Technologies
BOD	Biochemical oxygen demand
COD	Chemical oxygen demand
CRCFE	Co-operative Research Centre for Freshwater Ecology
CSIRO	Commonwealth Science & Industry Research Organisation
DIN	Dissolved inorganic nitrogen
DLWC	Department of Land & Water Conservation
DNR	Department of Natural Resources
DYRESM	Dynamic Reservoir Simulation Model
EPA	Environment Protection Agency
FRP	Filterable reactive phosphorus
LMWQCC	Lower Monlonglo Water Quality Control Centre
LWRRDC	Land & Water Resources Research & Development Corporation
MDBC	Murray Darling Basin Commission
N	Nitrogen
NEMP	National Eutrophication Management Program
P	Phosphorus
SML	Surface mixed layer
SOD	Sediment oxygen demand
SS	Suspended solids
STW	Sewage treatment works
THM	Tri-halo methanes
TKN	Total kjeldahl nitrogen
TN	Total nitrogen
TP	Total phosphorus
WWTP	Waste water treatment plant
XRF	X-Ray Fractionation
z_{mix}	Mixing depth
z_{eu}	Euphotic depth

Units

Algal cells	
no./mL	Number of cells per milli-litre (10^{-3} litres) of water
Concentration	
mg/L	Milli-grams per litre — 10^{-3} grams per litre
μg/L	Micro-grams per litre — 10^{-6} grams per litre (equivalent to mg/m^3)
Load	
kg/day	Kilograms per day
Conductivity	
μS/cm	Micro-siemens per centimetre
S m^{-1}	Siemens per metre.
Temperature	
deg.C	Degrees celcius
Time	
d	days
Volume	
ML	Mega-litres — 10^6 litres (equivalent to 1000m^3)
GL	Giga-litres — 10^9 litres