NATIONAL EUTROPHICATION MANAGEMENT PROGRAM

Factors controlling algal growth and composition in reservoirs:

Report of Reservoir Managers' Workshops January 2000

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The CRC for Freshwater Ecology 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.

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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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Executive summary

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, entitled *Physical and nutrient factors controlling algal succession and biomass in Burrinjuck Reservoir*, 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 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.

This report summarises the findings of the Burrinjuck algal succession project and uses these, along with data from other Australian reservoirs, to discuss the management implications arising from these findings.

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

A range of important vertical and longitudinal physical partitioning conditions have an impact on nutrient pathways and on algal biomass and composition. There is a strong pattern of thermal gradients for all water bodies over summer periods. In the case of water bodies having a depth greater than 3 metres, there is a potential for physical separation of the water body into a surface mixed layer and bottom water layer, separated by a thermocline.

There is also a strong pattern of longitudinal partitioning, with well mixed and highly active inlet zones in the upper reaches, stable stratified zones across the middle reaches, and bottom water up-welling (in the case of surface level releases) across the lower reaches.

There is a high potential for light limitation or low euphotic depth to mixed depth ratios as a result of elevated turbidity. The majority of Australian waters are sodium dominant ionic systems, often characterised by sustained high levels of abiotic fine suspended 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. The pattern of light limitation also means that algal growth is limited over summer periods to the surface mixed layer.

Algae dependent on mixing currents for circulation (green algae) through the euphotic zone are also disadvantaged under the low mixing conditions which commonly prevail over summer periods across Australian temperate regions.

Nutrient availability

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 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:

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. 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 level of bio-availability of organic carbon is a critical factor determining microbial growth rates potentially resulting in reducing conditions in sediments.

The research identified that reservoir sediments are the major pool of nutrients, and 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 reservoirs. The level of algal biomass may however be modified by light limitation or grazing.

Algal composition

Algal composition largely reflects seasonal factors such as:

1. elevated levels of inflow and associated mixing, and silica concentrations in Spring;
2. reduced inflow and thermal stratification (reduced levels of mixing and nutrients) over summer;
3. potential nutrient limitation and depressed mixing regimes in late summer.

These seasonal patterns are reflected by a pattern of:

1. dominance of Diatoms in early Spring, followed by green algae in early Summer;
2. blue-green algae (under high ammonia or reducing conditions) or motile forms of green alga (under low ammonia - high nitrate conditions) in mid-Summer;
3. N fixing blue-green algae in situations where nitrogen becomes limiting (typical of reservoirs receiving high sewage effluent loads) over the summer period.

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

There was a realisation that 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.

It was also noted that 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 — raising awareness of community (living with blue-green algae), and managers (pressure-state pathways and processes and management options).

2. Catchment management strategies — at-source management, interception and in-stream management strategies.

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 this Report.

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.

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. the form and pattern of delivery of nutrient and organic material to reservoirs;
2. inlet and shallow depositional zone processes and impact of rapid drawdown;
3. development of a reservoir classification system as the basis for translation of broadly based management option guidelines to local conditions;
4. development of improved models for estimating mixing and light conditions.

Chapter 1

Background and purpose of workshop

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.

As part of the Burrinjuck Algal Research Project technology transfer program, a Reservoirs Managers Workshop was identified as an important vehicle for exchanging information between scientists and managers, with the objective of better informed research and management.

The primary purpose of the workshops comprised:

1. the presentation of emerging understanding of the major determinants of reservoir algal biomass and composition;
2. the identification of the major operation issues for reservoir managers;
3. the identification and assessment of a range of possible reservoir algal management options;
4. the assessment of the implications of the Workshop findings and possible management options for management information, design of monitoring and further research needs.

In the interest of developing a broad appreciation of management issues, the Workshops drew on a range of recent research projects including the Burrinjuck algal succession project, the Chaffey Dam de-stratification and water quality project, and the Murrumbidgee Weir pools project.

The Workshop of 9th September comprised Reservoir Managers from all of the eastern States and Territories. The Workshop identified a comprehensive list of reservoir algal management issues and management options and associated information needs.

Chapter 1. Background and purpose of workshop

The Workshop of 11th November comprised Reservoir Managers from Victorian regional water authorities. The Workshop further expanded the lists of issues and management options, addressed the wider reservoir management objectives, and began the task of development algal management guidelines.

Further workshops are scheduled within individual agencies.

A list of the attendees is attached to this report at Appendix A.

Chapter 2

Factors determining algal growth and composition

2.1 Background

Availability of nutrients, light and mixing conditions and 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, land uses and management, and reservoir depth, shape and drawdown conditions.

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

2.2 Physical mixing conditions

2.2.1 Stratification

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 is inversely proportional to temperature, the warming of the surface layer 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 (SML) is a function of the solar radiation, differences in air and water temperatures, evaporation rates and wind driven eddy currents.

Figure 2.1 illustrates the pattern of thermal stratification over summer months for Burrinjuck Reservoir, with deepening of the SML in the autumn period until the whole depth is isothermal (mixed).

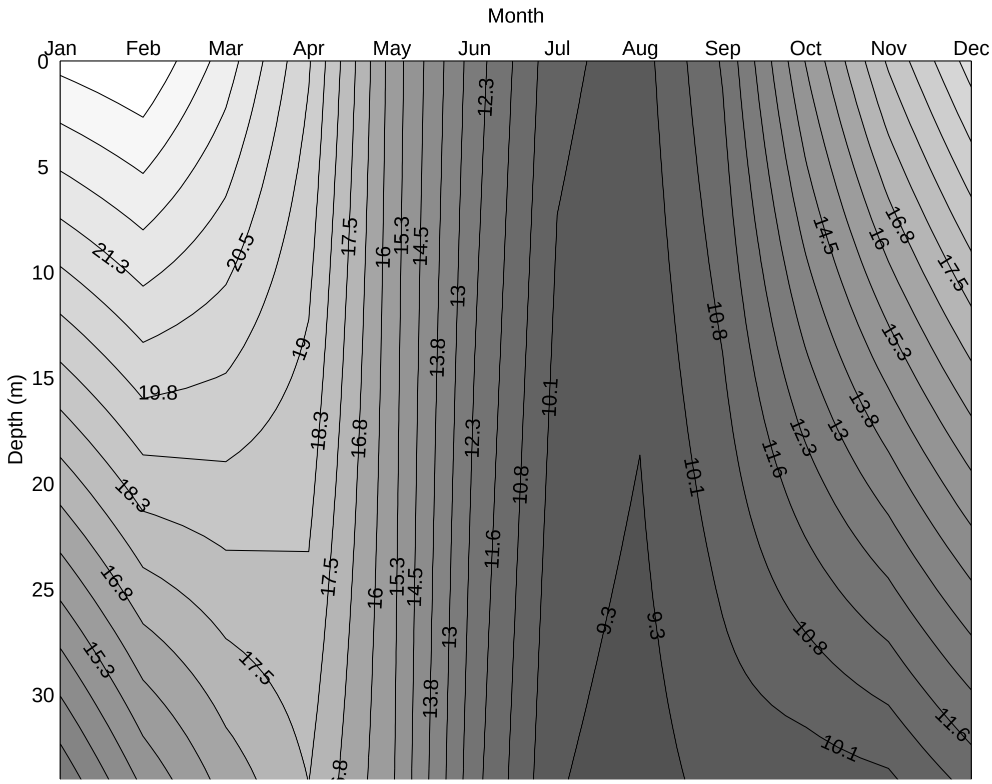

Figure 2.1: Average temperature profile, Burrinjuck Reservoir.

Stratification has significant implications for lake water quality and biological processes. The thermocline (the boundary between the surface mixed layer and bottom waters) 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. The level of mixing within the surface mixed layer is a function of wind strength and travel distance over the water surface.

2.2.2 Mixing and inflow pathways

Upstream shallow reaches behave as mixed systems, while downstream and deeper reaches behave as thermally stratified systems over summer and early autumn periods. Low/base inflows in the summer will flow into the surface mixed layer (SML) as the inflow has time to equilibrate with the atmosphere and a shallower depth will reach a higher temperature. Elevated/event inflows plunge (colder temperature) and flow into the bottom waters. This is illustrated in Figure 2.2 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 avail-

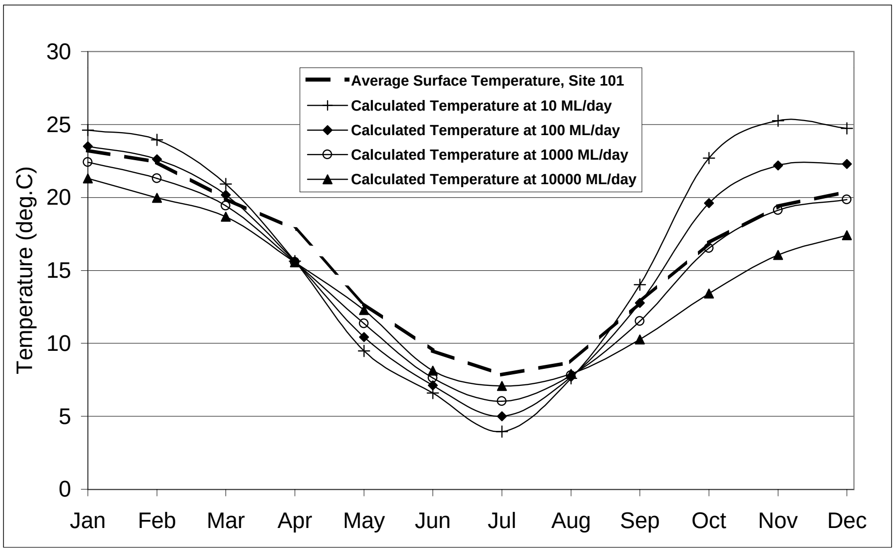

Figure 2.2: Surface temperature and inflow temperature at Burrinjuck Reservoir showing an average decrease in temperature with increasing flow. When the temperature of the inflow drops below that of the Reservoir the inflow will flow into the bottom waters.

ability of nutrients to surface water algae over summer periods.

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 mixed layer. The level of the intrusion was determined by the temperature of the inflow relative to thermal stratification within the Reservoir (Figure 2.3). In Chaffey Reservoir, nutrients that accumulated in the hypolimnion were a significant determinant of the following year's average annual algal biomass. Artificial destratification 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 (Figure 2.4).

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.

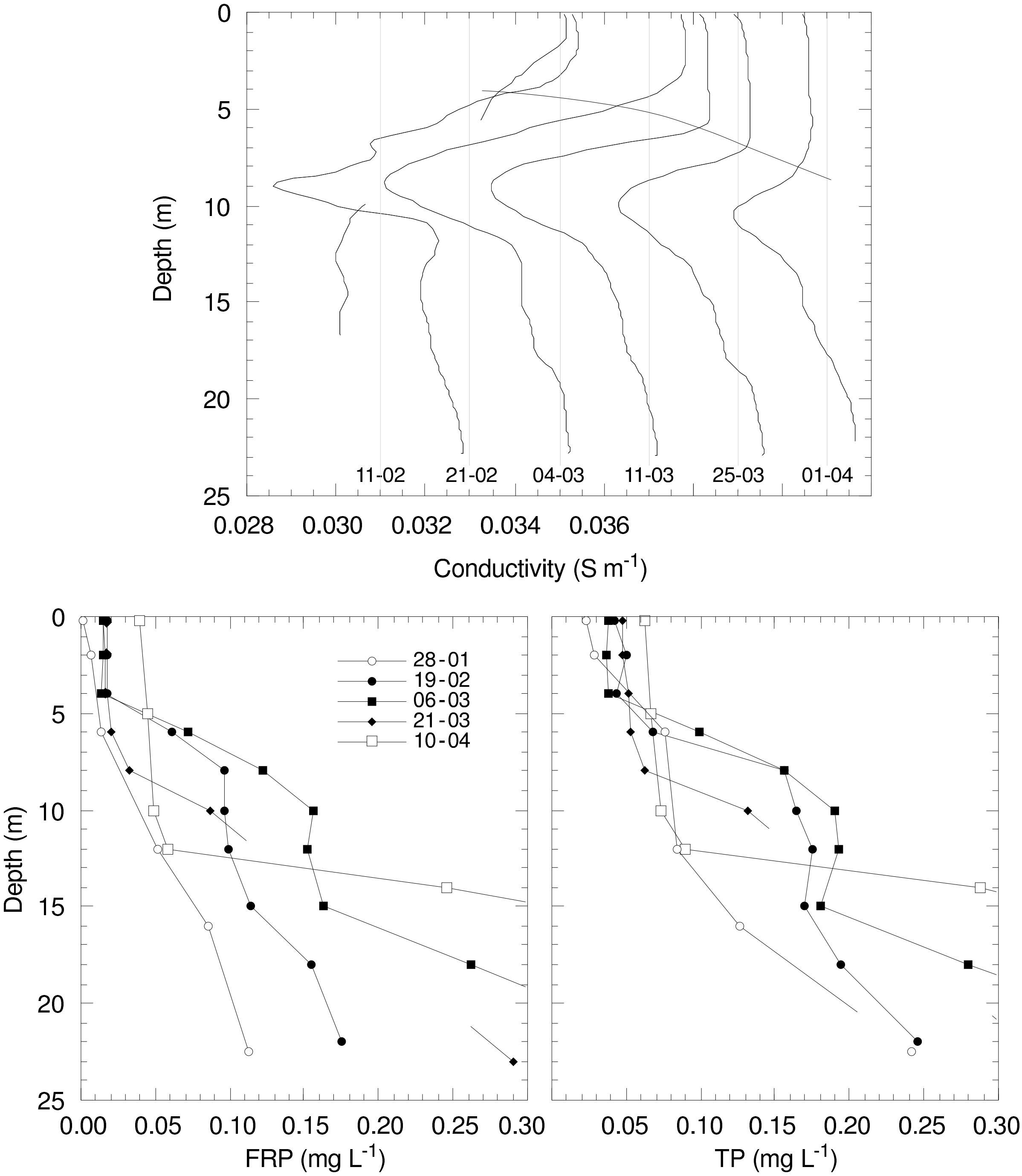

Figure 2.3: Conductivity (top) and FRP and TP (bottom) profiles measured at Chaffey Reservoir before and after the Feb 97 inflow. Conductivity profiles are offset by 0.002 S m^{-1}; grey vertical lines are located at 0.031 S m^{-1} for each profile. The trajectory of the maximum surface mixed layer depth between profile is shown by the heavy line in the upper figure. Reprinted from Sherman et al. (in press).

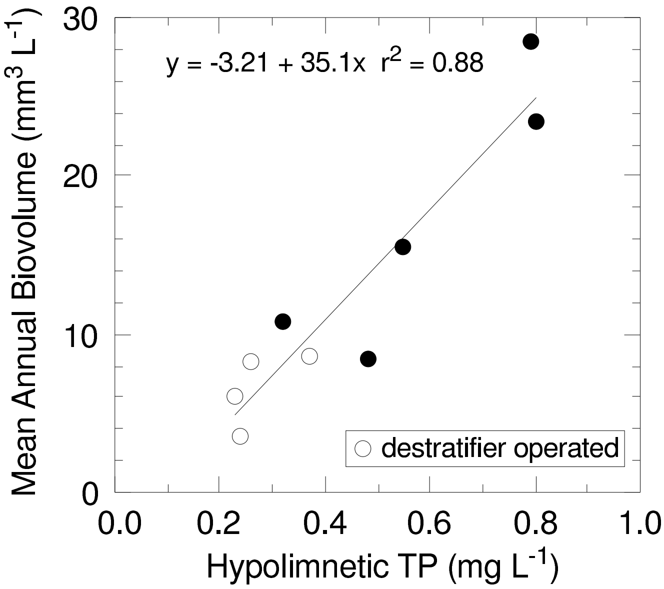

Figure 2.4: Maximum hypolimnetic phosphorus and mean annual algal volume just prior to turnover at the start of the algal growing year at Chaffey Reservoir. Open circles denote that the destratifier was operating

2.2.3 Impact of discharge arrangement on flow pathways.

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

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

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

These pathways are illustrated in Figure 2.5.

2.3 Light availability

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

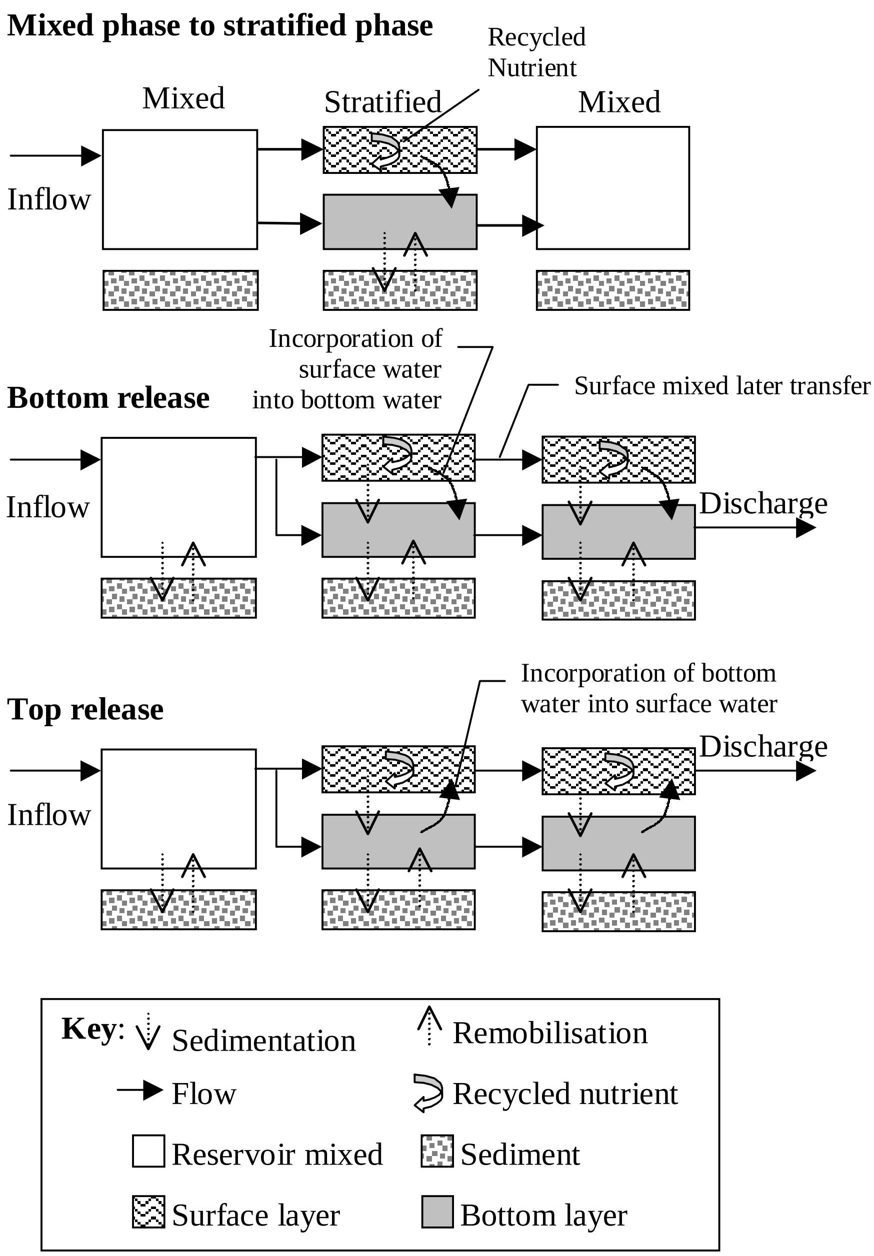

Figure 2.5: Reservoir dominant flow pathways

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 becomes insufficient to support algal photosynthesis is termed the euphotic depth (z_{eu}) and below this level the algal cells rely on using stored energy to maintain their growth.

However, stored reserves of energy are limited and will last only 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 2.6. 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.

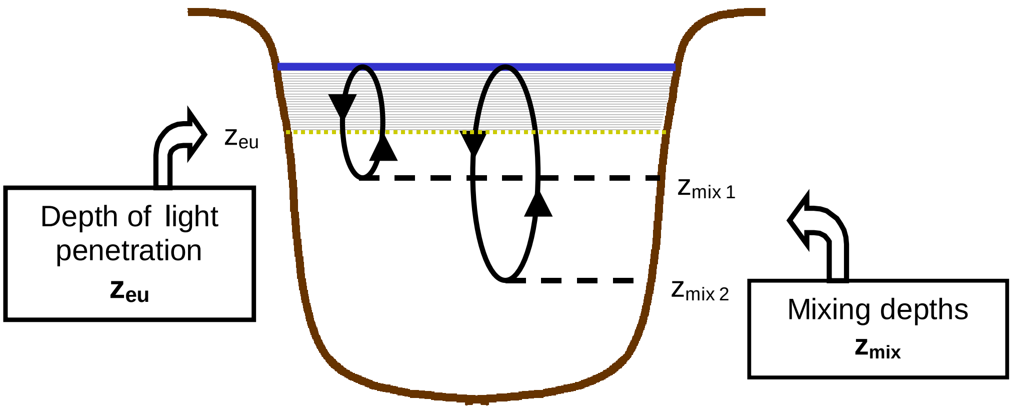

Figure 2.6: The effect of light availability on algal growth. The fraction of time that phytoplankton spend in light is given by the ratio of light penetration depth to mixing depth, z_{eu}/z_{mix}.

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.

2.4 Nutrient availability

2.4.1 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.

Section 2.2 described 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 mixed 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 hence of nutrient availability to surface water algae.

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.

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.

In Chaffey Reservoir, which is situated inland in the sub-tropics and has very calm meteorological conditions, 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, as shown in Figure 2.4. This phosphorus is mixed into the surface mixed layer (SML) when the resevoir is fully mixed and determines the concentration in the SML when temperature stratification re-develops. It is this phosphorus that supports algal growth in the next growing season.

The analysis of Burrinjuck Reservoir indicated that the nutrient rich bottom water was the major source of nutrients to the surface layer following Reservoir turnover, for the period preceeding sewage nutrient removal.

Development of anoxic sediments in shallow lakes.

Shallow lakes ($<$ 1m 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.

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 1.0 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.

An example of this is Burrinjuck Reservoir, which 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.

When nutrient release from the sewage treatment works was decreased around 1980 the peak algal biomass in the Reservoir also declined. This is shown in Figures 2.7 and 2.8 for Burrinjuck Reservoir, where external TP and TN loads are shown split into the components from the sewage treatment works, LMWQCC, and the rest of the Murrumbidgee arm. Recently increased algal growth has again occurred within Burrinjuck 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 STP.

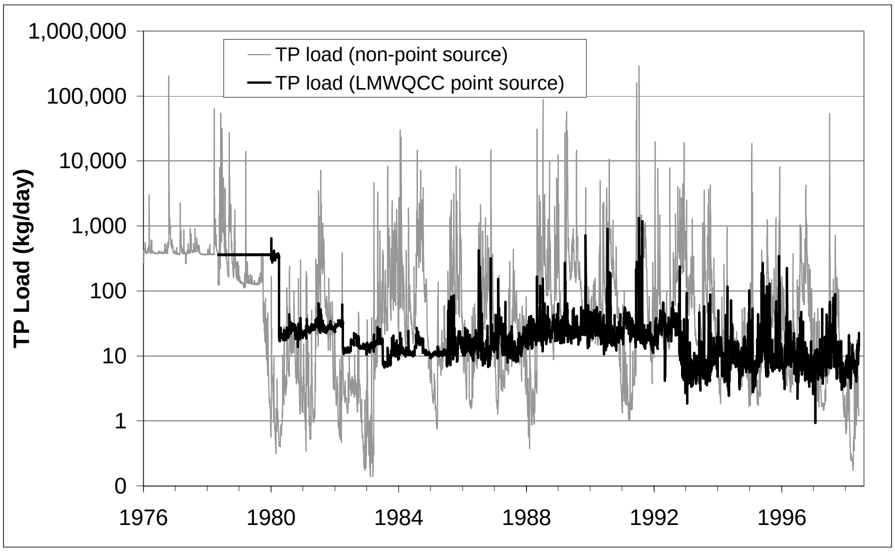

Figure 2.7: TP loads into Burrinjuck Reservoir

It appears that the recent increase in algal biomass is due to the 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 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 that also come from the sediments, including ammonia, and by analysis of sediment redox conditions.

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.

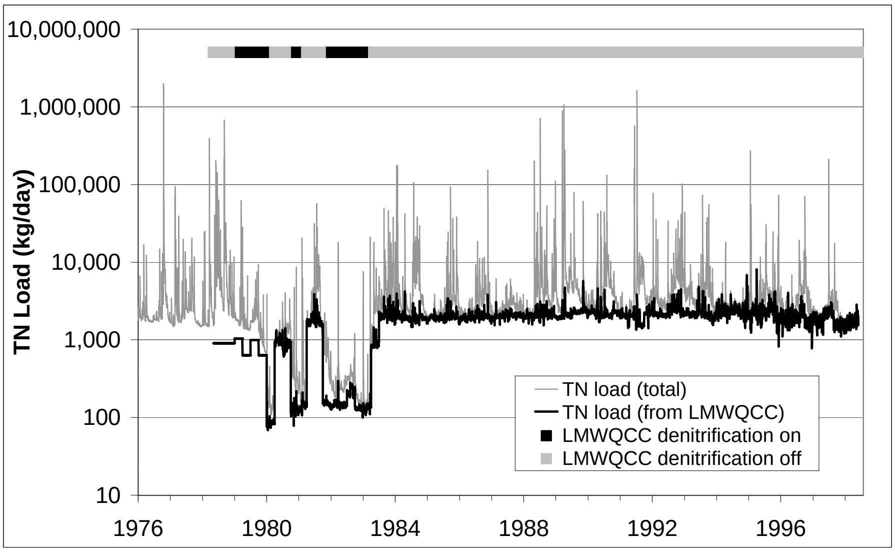

Figure 2.8: TN loads into Burrinjuck Reservoir

The analysis of data from Burrinjuck Reservoir indicates increases in algal levels over and above that explained by remobilisation of nutrients from the sediments in the inlet deposition zone. Analysis of pore water drainage from sediments exposed by rapid drawdown conditions indicate increases in nutrient availability and algal growth in the shallow surface waters consistent with monitored algal levels. Nutrients released into the mixed inlet depositional zone will be washed through (either as dissolved nutrients or algae) into surface waters of downstream reaches, 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.

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 (SML) 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.

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.

2.4.2 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.

Some portion of total phosphorus may be present in crystalline form and is not 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.

Some FRP 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 FRP 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, this potential source 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 component of total phosphorus (TP) is best measured by filtering the TP sample through a 0.003 μm filter to measure the filterable reactive phosphorus.

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 an equivalent weight of native vegetation derived material.

2.4.3 Role of the sediments

Mention was made in Section 2.2.2 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--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 dam but are more concentrated in the deepest parts.

Bacteria use oxygen in breaking down the organic matter leading to anoxic bottom waters and reducing conditions in persistently stratified reservoirs. Nutrient concentrations in the pore waters and bottom waters, particularly ammonia and filterable reactive phosphorus (FRP), build up to high concentrations under reducing conditions. Dissolved iron and manganese concentrations rise significantly in the pore waters and bottom waters also 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 FRP is bonded chemically with oxidised (ferric) iron.

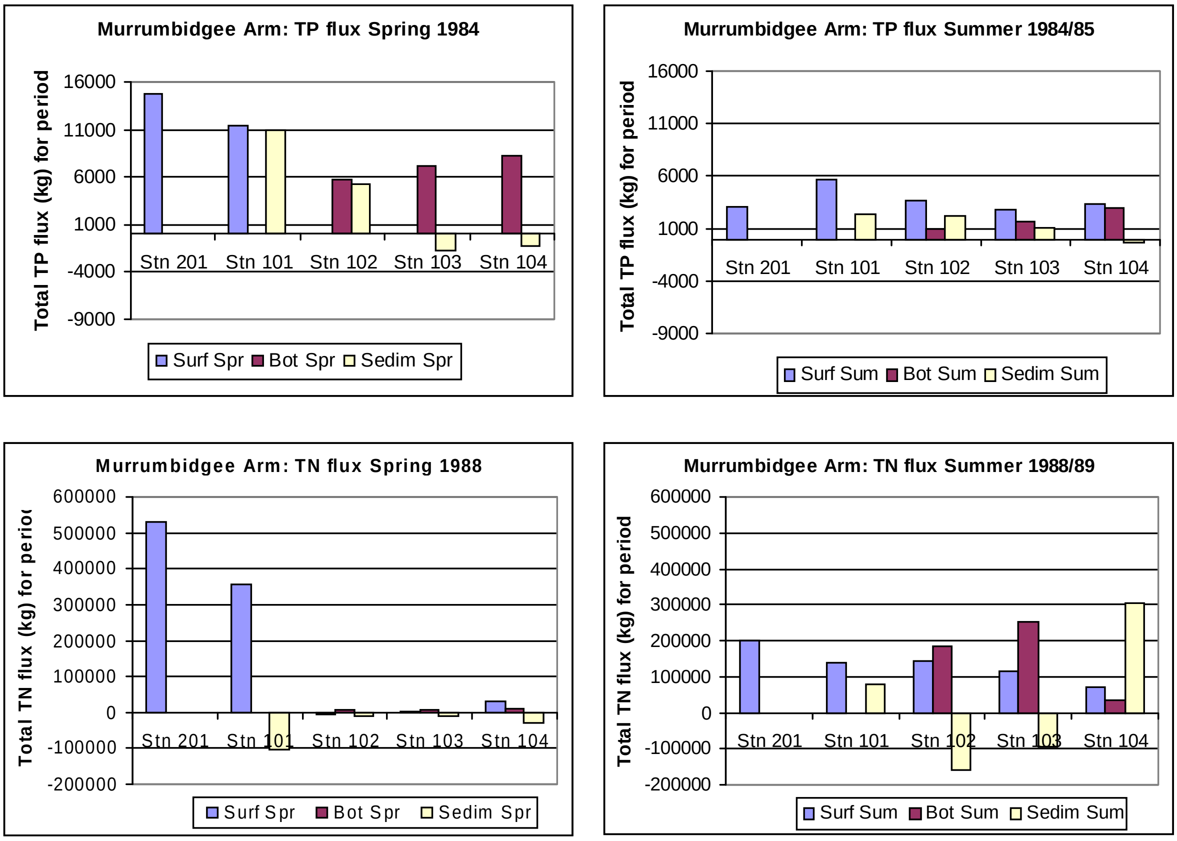

Figure 2.9: Reach based internal loading, Murrumbidgee arm of Burrinjuck Reservoir, Spring 1984 and Summer 1984/85.

Figure 2.9, reach based internal loading, illustrates the high net loss of SS, TP and TN to the sediments, particularly during the elevated inflow spring period, and particularly in the inlet depositional zone. The figure also demonstrates the high net sediment release of nutrients back into the bottom waters for the deeper downstream reaches. The figure indicates a net release of N from the sediments within the inlet (mixed) depositional zone for the spring period. 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 2.10 presents 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. The figure indicates the significant TP release from the sediments under the severe reducing conditions following inflow events. The modelled algal biomass (Figure 2.11) correlates closely with monitored values for the inlet depositional zone and downstream reaches. This is the major source of nutrients driving algal growth in the case of Burrinjuck Reservoir.

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.

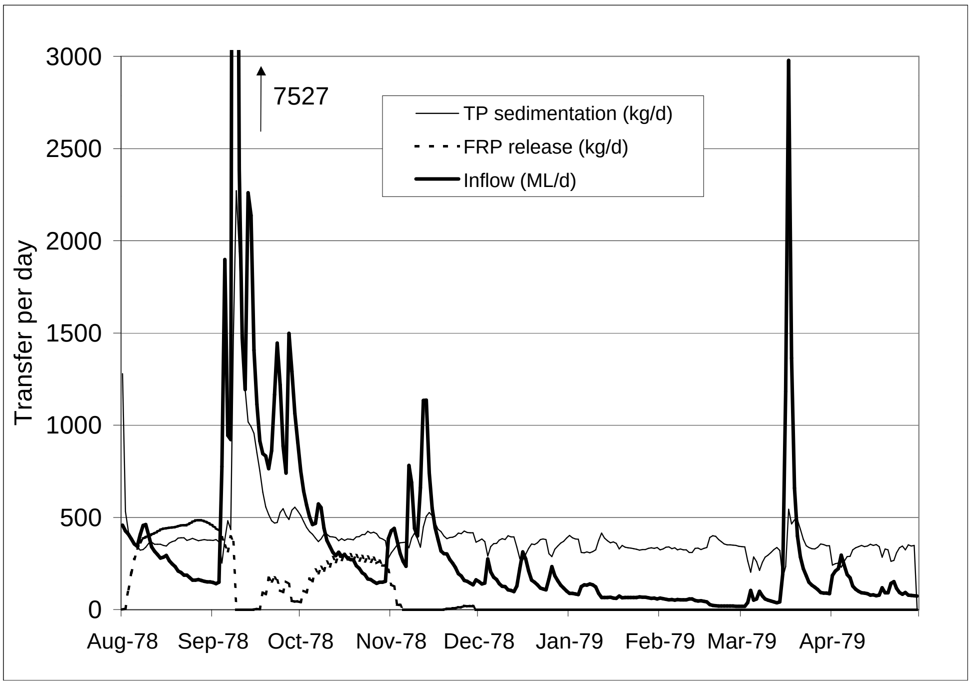

Figure 2.10: Nutrient sedimentation and remobilisation, Burrinjuck Reservoir inlet depositional zone.

Modifiers of sediment redox processes

There are a number of potential modifiers of these sediment redox conditions. Several processes are associated with these modifications:

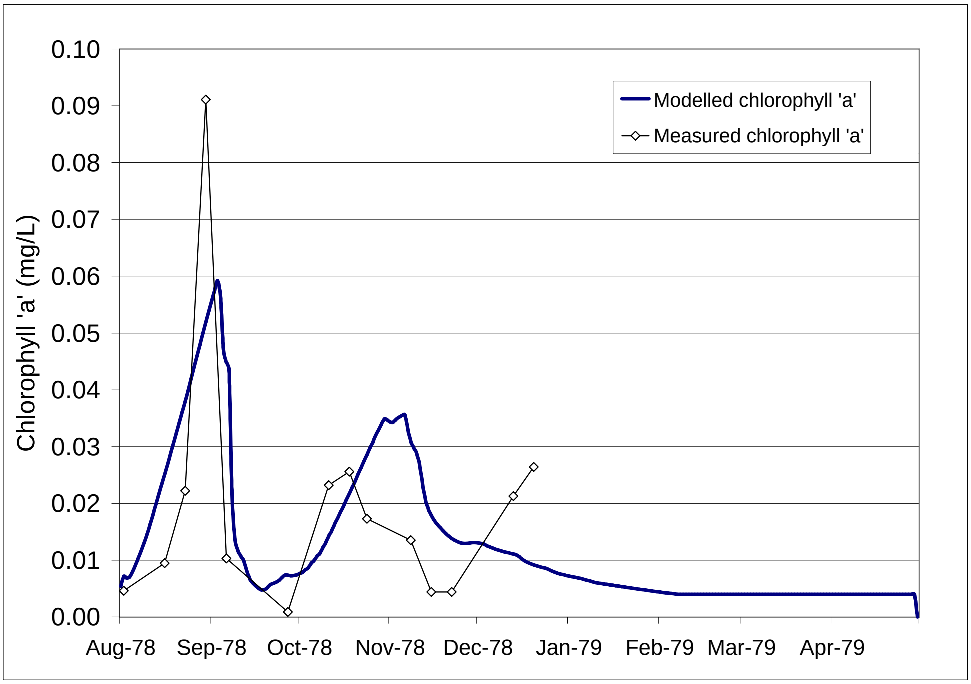

Figure 2.11: Lake redox model estimates of Chlorophyll 'a', Burrinjuck Reservoir inlet depositional zone.

1. elevated inflows causing re-suspension of previously sedimented material and transfer to deeper middle or downstream reaches in the reservoir.
2. extreme inflows and associated suspended solids loads, with significant blanketing of sediments in deeper waters.
3. discharges high in NO_3 act as a significant buffer to reducing conditions in bottom waters. The effect of the elevated inflows and blanketing with abiotic suspended solids is to reduce redox loads for a period of time. In situations where there is a high residue of organic material in the sediments as a result of earlier wastewater discharges (benthic oxygen demand), 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, effluents high in BOD or COD (such as NH_3) will exacerbate the redox conditions in the reservoir.

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 2.12. 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

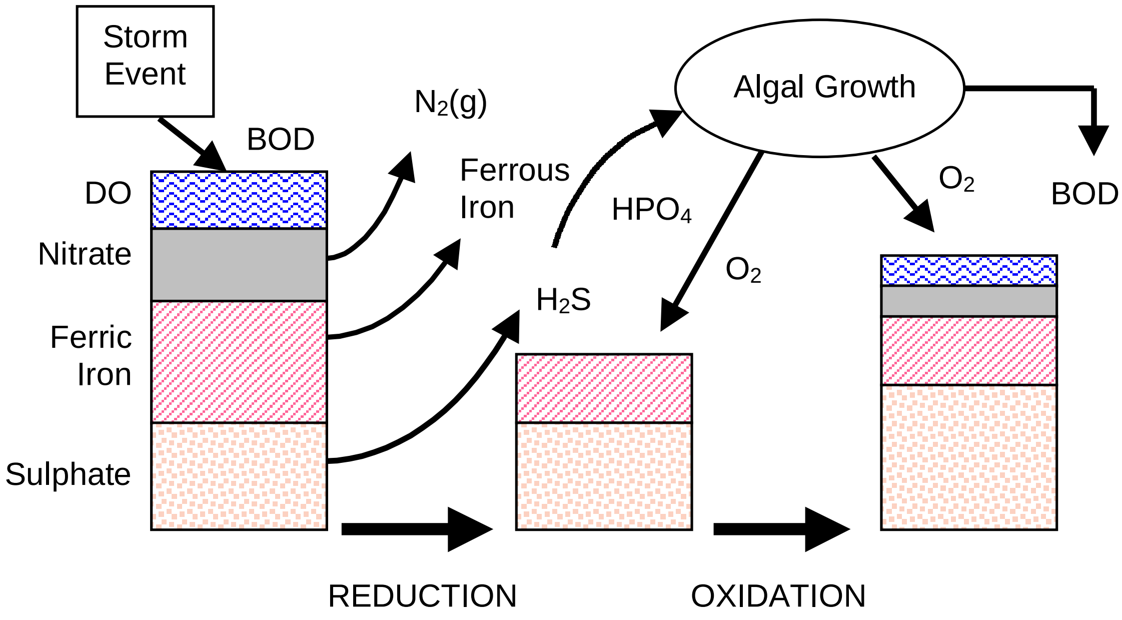

Figure 2.12: Outline of sediment redox processes

redox levels, releasing PO_4 to the water column. Sediments high in aluminium will require much higher energy to release the bonded PO4.

As noted previously, high levels of residual organic material in sediments may create a significant benthic oxygen demand before there is even external loading of organic material.

Consequently, sediments represent a major store (usually 90 to 98%) of phosphorus in reservoir systems. Organic material accumulates over the autumn and spring periods and is consumed with the release of nutrients into the water column over the late spring and summer periods.

2.4.4 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 2.4.1.

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 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 2.1.

Figure 2.13 and Figure 2.14 summarise the analysis of FRP and TP delivery to Burrinjuck Reservoir at Station 201 (Taemus Bridge) and its relation to inflow events. The time series plots illustrate the in-stream (biological) uptake of FRP between the Molonglo River confluence and Taemus Bridge (a distance of 40 km) under conditions of low flow, and the scouring of the attached algae and biofilm material (as organic P) with daily loads of TP at Taemus Bridge in excess of loads at the Molonglo River confluence for medium sized inflow events.

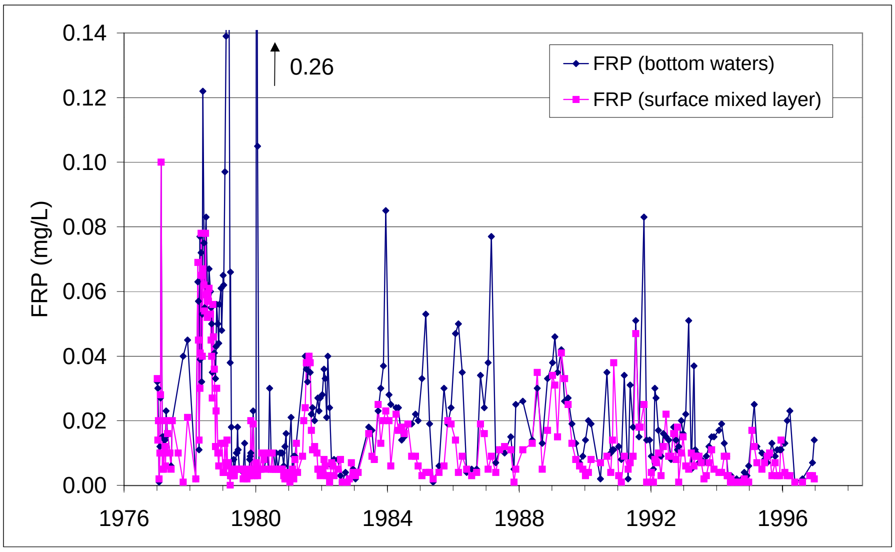

Figure 2.13: Burrinjuck Reservoir FRP Load, Taemus Bridge and External (Murrumbidgee Arm).

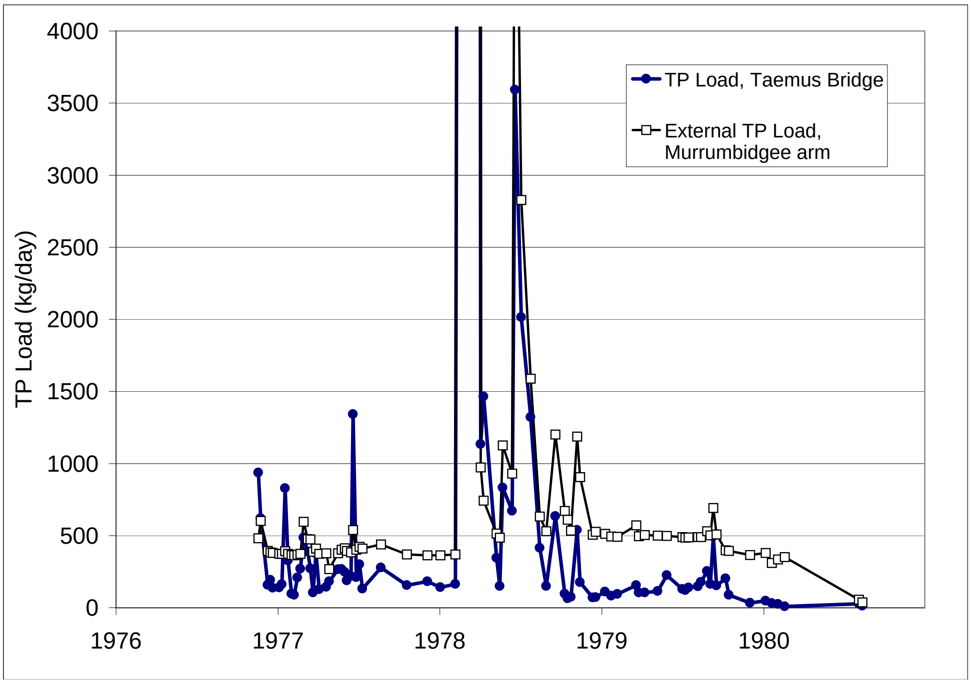

Figure 2.14: Burrinjuck Reservoir TP Load, Taemus Bridge and External (Murrumbidgee Arm).

Table 2.1: 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 biomass 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.	

2.5 Algal biomass

The management of algal blooms requires:

1. a knowledge of the environmental conditions conducive to algal growth;
2. suitable techniques for measuring these environmental conditions at scales relevant to algal responses;
3. a quantitative basis for relating algal growth to the measured environmental conditions.

Like all plants, algae require nutrients, light and an adequate temperature to grow (Figure 2.15). 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.

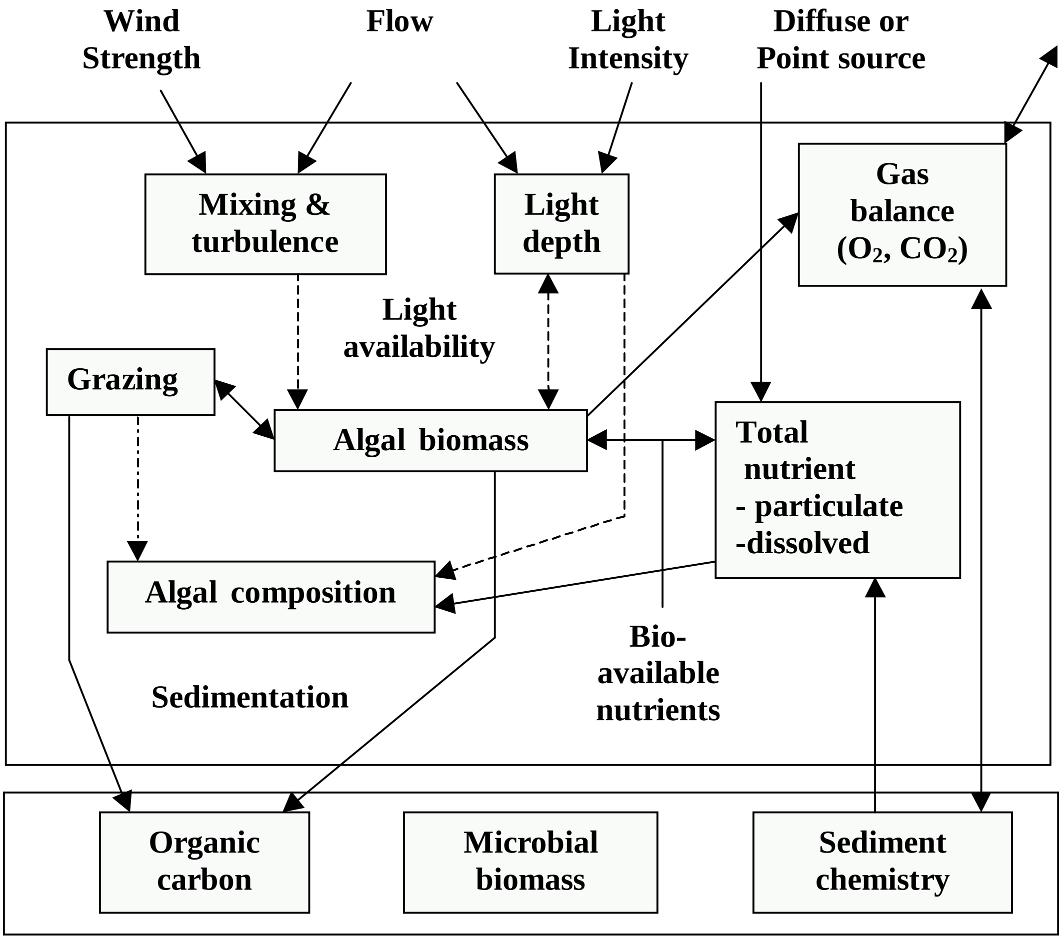

Figure 2.15: Factors influencing algal growth and composition

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 mixed layer.

The euphotic depth (z_{eu}) is described in Section 2.3 as the point in the water column at which light intensity has reduced to a level that can no longer sustain algal growth. A description of factors driving mixed depth is provided in Section 2.2. This section highlighted the importance of the z_{eu}/z_{mix} ratio as an indicator of availability of light. At ratios of less than 0.3, green (mixing dependant) alga will be disadvantaged in relation to other alga which have strategies for maintaining their position in the euphotic zone, for example, blue-green alga have buoyancy vacuoles and dino-flagellates have swimming flagella. Green alga (Chlorophyta) do not have the ability to maintain their vertical position in the water column and so require some vertical mixing to 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.

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 2.16. In these systems thermal stratification was persistent through the summer and nutrients were largely used from within the surface mixed layer.

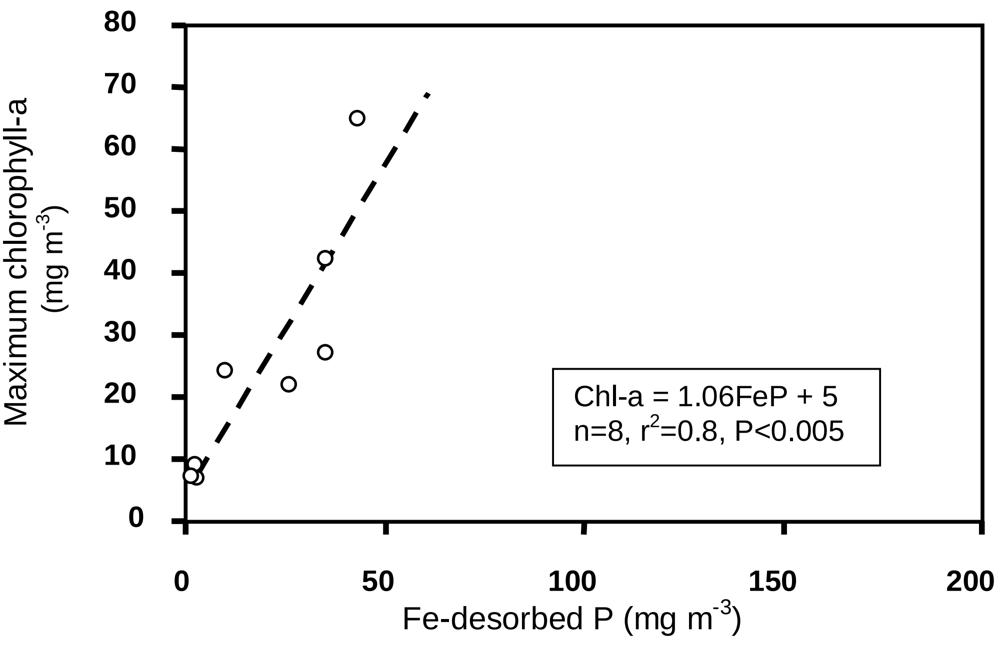

Figure 2.16: Maximum summer Chlorophyll-a concentration as a function of bioavailable phosphorus for eight reservoirs in SE-Australia.

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 and Murrumbidgee Rivers it has been shown that nitrogen can initially be the nutrient in shortest supply and the first to run out as algae grow. 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 on algal growth continued in these systems provided mixing of the water column disadvantaged the growth of buoyant blue-green algae. However, problematic blooms appeared as soon as flows declined and intense temperature stratification occurred. 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.

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. In addition, the ratios within the water may not provide a complete picture of the nutrient resource when re-supply of phosphorus and nitrogen can occur from the bottom sediments and in certain circumstances nitrogen can be re-supplied from the atmosphere. The management of algae through nutrient manipulation requires that the role of limiting nutrients is clearly identified and the sources are quantified.

Loss factors such as grazing and sedimentation modify the species composition of algal communities and can decouple relationships between nutrients and biomass. Time does not allow for these to be described here and much more information is required on these complex interactions. The complexity can be demonstrated by a decision support tree (Oliver and Ganf 1999) that was devised in an effort to explain the major factors influencing the appearance of particular genera of blue-green algae (Figure 2.17). 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 still to be tested in detail.

2.6 Algal succession

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; and
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 Cyanobacteria (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. Although this general pattern is often observed, it can be significantly modified depending on the physical and chemical characteristics of a particular reservoir.

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.

Table 2.2: 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

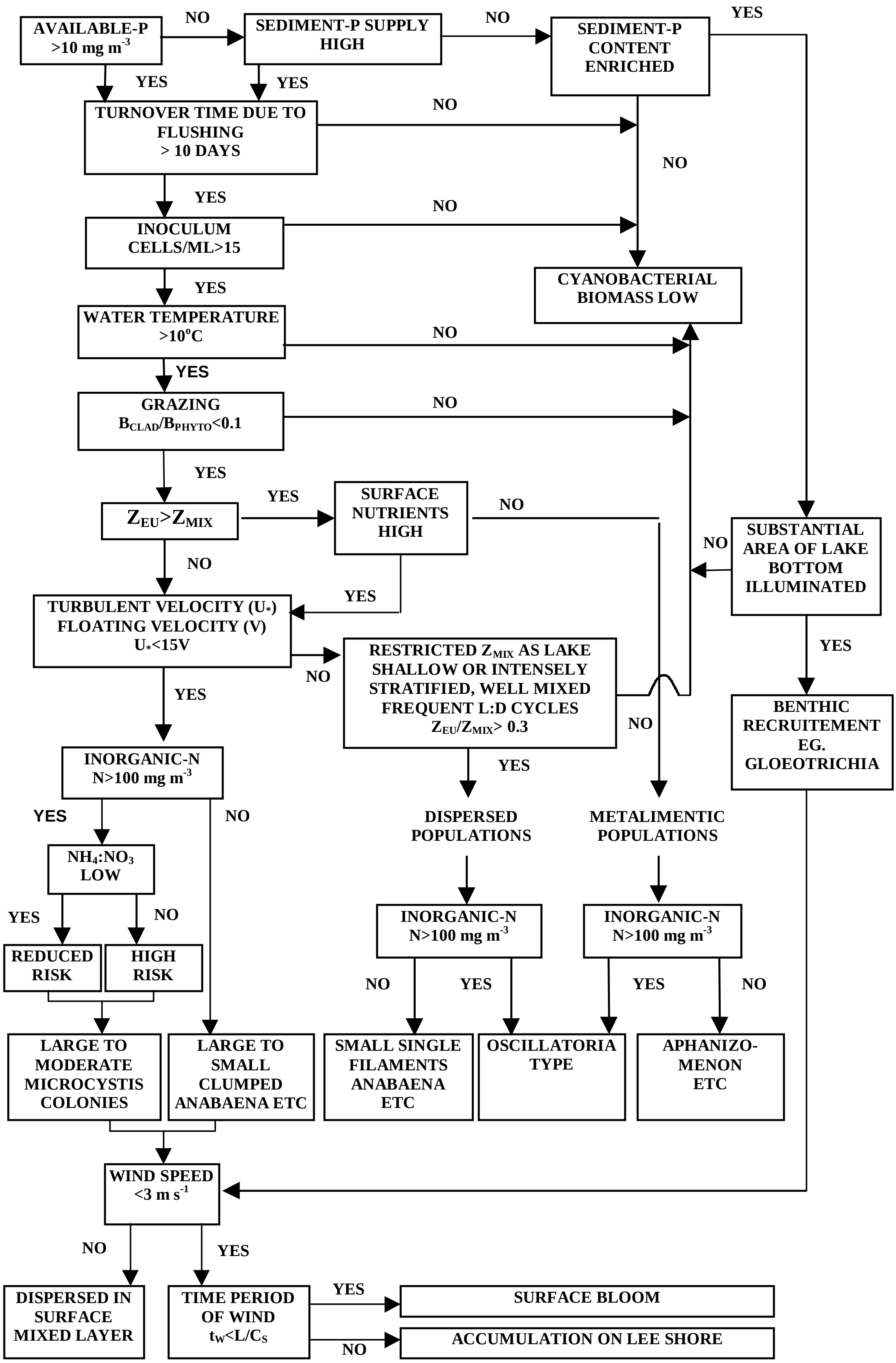

Figure 2.17: Flow chart summarising prominent environmental characteristics supporting the development of Cyanobacteria blooms and selecting for particular genera.

An example from Burrinjuck Reservoir in Figure 2.18 shows the succession of Diatoms, blue green and green algae. 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 physical and chemical characteristics of a particular reservoir.

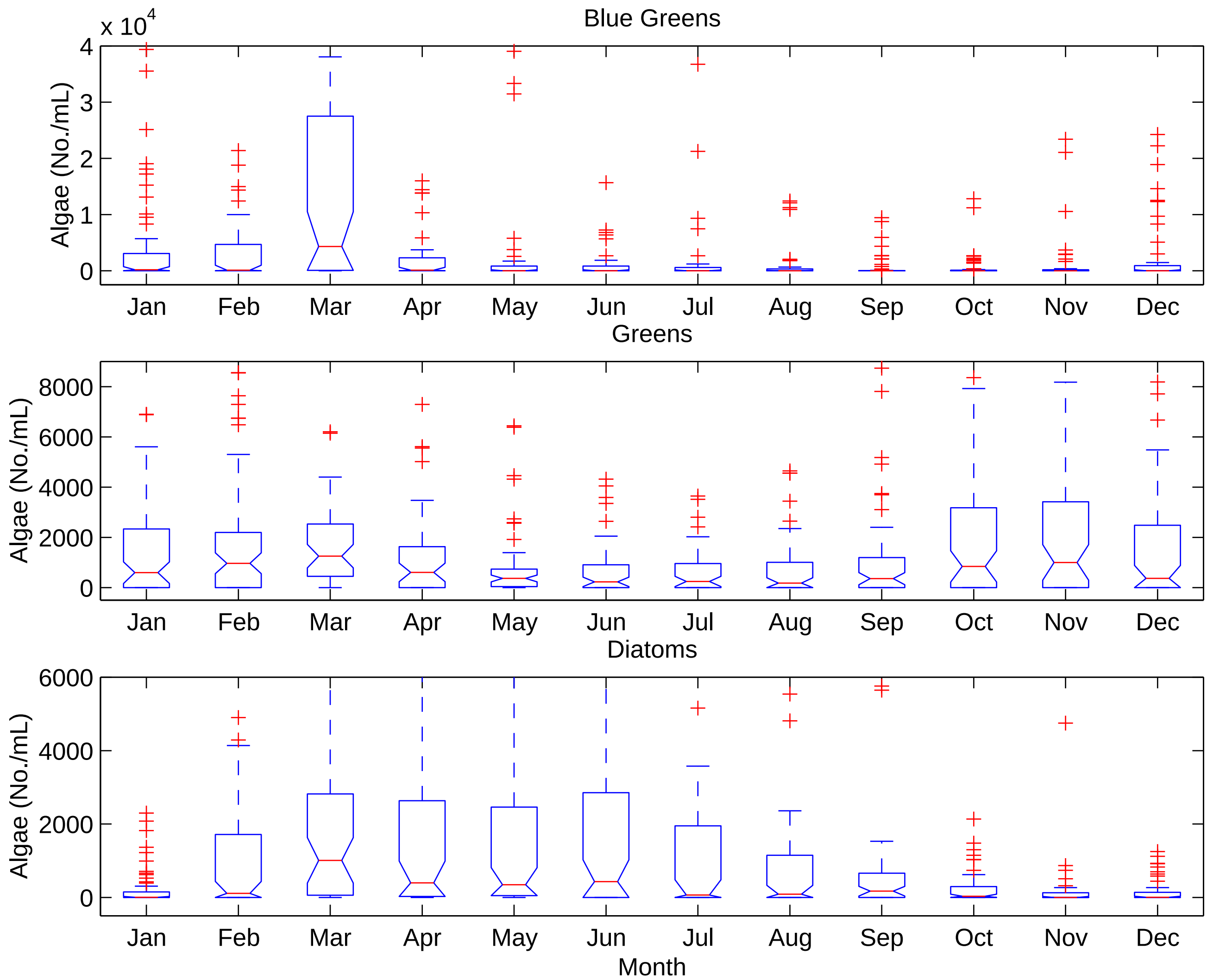

Figure 2.18: Succession of Cyanobacteria, Chlorophyta and Diatoms.

Chapter 3

Reservoir management issues

The workshop identified a wide range of management concerns related to algal and wider reservoir management issues. They included:

1. The serious impacts of algal blooms on treatability of water, treatment costs, recreational values, aesthetic values and ecology. How can the risk of algal blooms be better predicted, and how can reservoirs be better managed to limit the incidence of algal blooms and/or algal entrainment in water abstracted for water supply?
2. A need for improved guidelines on the design of monitoring programs related to both real time (daily operation decisions) and broad risk assessment and contingency planning.
3. The role of water supply reservoirs is just one line of defence in the management of pathogens. What are the reservoir policies related to minimising risk of abstraction of waters high in pathogens,and what are the monitoring requirements necessary to implement these policies?
4. The issue of thermal pollution associated with discharge of colder bottom waters. What are the means of addressing this issue?
5. The response to stratification of reservoir waters — the formation of odours, taste, colour, organics and toxicants in anoxic bottom waters under severe external and internal organic carbon loading conditions. How are reservoirs best managed under these conditions?
6. The conflicting management issues associated with multi-purpose reservoirs. What are the means, for example, of assessing the optimisation of level of water abstraction, or of balancing reservoir drawdown with downstream water supply demands?
7. Previously, catchment management and reservoir management and treatment were considered integrally. The fragmentation of some agencies, separation of purchaser and provider and out-sourcing (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?

8. 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?

9. The sheer diversity of structures, catchment and water use values. How can management related information be packaged in a way capable of addressing this diverse range of conditions?

Chapter 4

Management options

4.1 Reservoir management options

The workshop identified a wide range of possible management options related to algal management. They included:

1. The design of structures such as outlet facilities, fish ladders and monitoring facilities, enabling greater management response flexibility and information;
2. Pre-impoundment treatment, such as stripping organic soils and vegetation to minimise post inundation oxygen demand. Pre-stabilisation and/or isolation of dispersive soils (sediments). The stabilisation or isolation of reactive sediments;
3. The development, implementation and review of reservoir water quality management plans to safeguard:
   - in-reservoir water and ecological values;
   - downstream water and ecological values;
   - quality of water abstracted for supply purposes.
4. Littoral zone management by direct planting, removal of invasive species, exclusion of stock and manipulation of reservoir levels;
5. Outlet level selection — multiple off-takes, air curtains, drawdown rate and minimum level constraints;
6. Use of redox buffers, such as well nitrified inflows or nitrate treatment of sediments, where a residual sediment BOD exists, and/or it is not possible in the short to medium term to reduce organic loading on the reservoir;
7. Destratification and/or oxygenation — hypolimnetic aeration management options;
8. Optimisation of the distribution of inflows and circulation within the reservoir by way of design of inflow structures, baffles or islands;
9. Management of storage levels — limit drawdown rate, limit minimum depths;

10. Establishment of pre-treatment forebays or swales to enhance sedimentation and organic material interception (using macrophytes or aeration), thereby limiting organic loading on the main reservoir basin;
11. Use of bio-manipulation (macrophytes, fish) techniques to minimise algal problems. Habitat development (restoration) in the case of conservation ecology related management objectives. The establishment of fish stocking in the case of recreational fisheries or conservation ecology related management objectives;
12. The use of coagulants (gypsum) to reduce turbidity in the case of reservoirs having sustained high levels of abiotic suspended solids which limit light and promote dominance by nuisance blue-green algae;
13. Where multiple reservoir choices are available the selection of the water source (reservoir) and timing of abstraction to maximise the yield of algal free water supply;
14. The use of chemical precipitation of nutrients and/or algacides as an algal management contingency measure;
15. Provision of information to the community to raise community awareness of living with blue-green algae.

4.2 Catchment management options

1. Management of municipal and agricultural wastewater discharges and irrigation drainage returns. Ensuring well nitrified wastewater effluent or drainage returns that are low in BOD and P (direct and indirect sources of organic matter);
2. The development, implementation and review of catchment management plans, aimed at minimising both direct and indirect sources of organic loading and nutrients on reservoirs, and in minimising the discharge of suspended solids to streams and reservoirs;
3. Protection/restoration of river riparian zones, macrophyte pools and riffle zones, to maximise interception of dissolved nutrients and organic material, before discharge to reservoir;
4. The application of detention and indirect drainage techniques to reduce high stormwater discharges from urban areas, which exacerbate deposition of organic material in inlet zones of reservoirs.

Chapter 5

Management information needs

Following on from the identification of management issues and possible management options, the workshop identified a number of associated information needs. They included:

1. Better definition of management objectives, particularly in the case of multi-purpose reservoirs;
2. Better information on the major determinants of algal biomass and composition, and techniques for assessing the risk of bloom conditions. Better predictive tools, such as for assessment of the risk of release of water high in blue-green algae;
3. Better information on the range of available management options and guidelines on the selection of options appropriate to local conditions;
4. Information on the local reservoir operation environment. What are the major water and nutrient transport and transformation processes, and potential algal biomass and composition responses. Related to this understanding, what are:
    - the external loads (event, base flow) and discharges;
    - the light environment (light and temperature depth profiles, mixing depth);
    - the future catchment discharge and load exports (soil moisture, rainfall and runoff);
    - the water abstraction depth profiles (wind speed and direction, water column temperature, DO, alkalinity, colour and organics);
    - the impact of rapid drawdown and/or shallow depths in exacerbating algal biomass and a shift of dominant species to blue-green algae.
5. Guidelines on the design of an integrated management information program, including techniques for analysis of data, trigger levels, decision tools guiding selection of outlet off-take level and the provision of decision models meeting operation information needs. The models to be limited in their complexity and parameterisation requirements, but underpinned by a detailed scientific model;
6. Development of a reservoir classification system to aid managers in identifying algal response processes and management and monitoring protocols;

7. Profiles and watching briefs on emerging issues such as:
   - new technologies, for example, monitoring devices, analytical methods, destratification or hypolimnetic aeration;
   - management of pathogens, toxicants, organics and THMs.

Chapter 6

Management guidelines

6.1 Reservoir management: Selection of management options

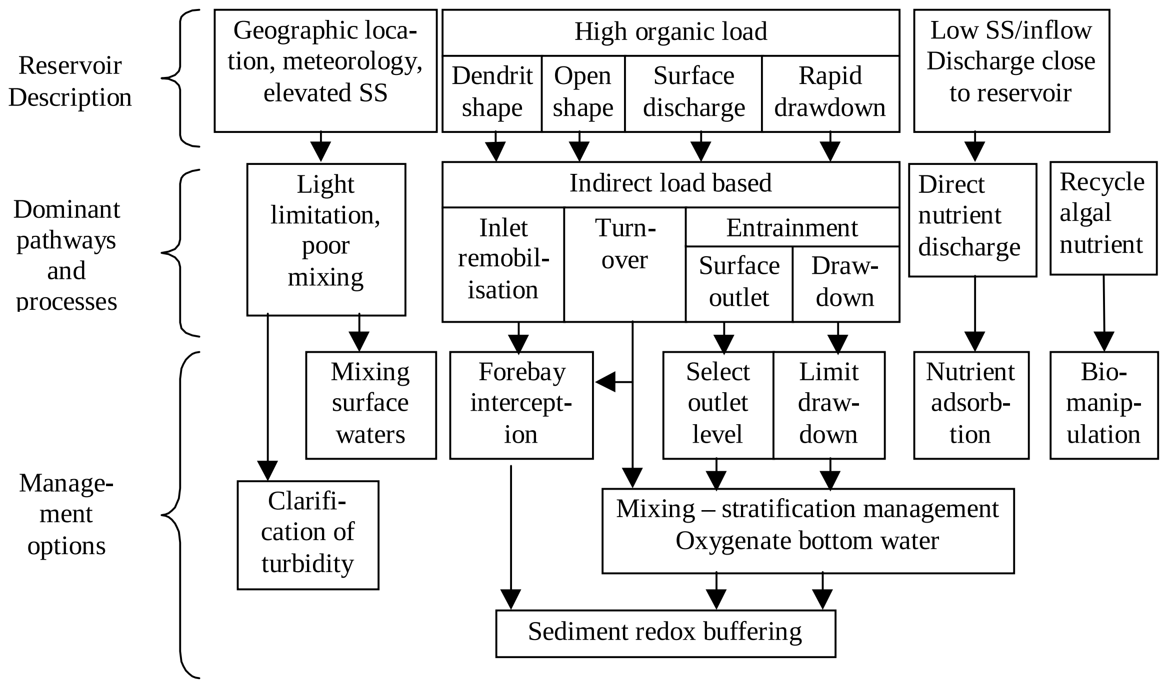

Figure 6.1: Reservoir management: Selection of management options

6.2 Catchment management: Selection of management options

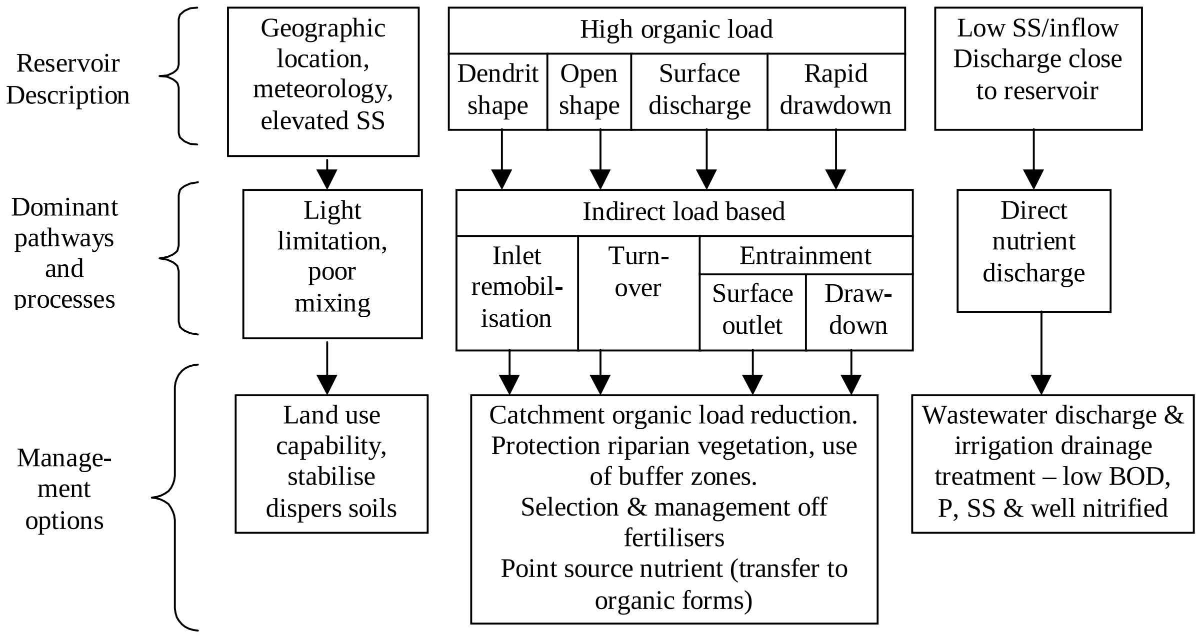

Figure 6.2: Catchment management: Selection of management options

Chapter 7

Monitoring implications

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.

Chapter 8

Further research needs

A number of further research needs were flagged during the workshop. 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 significance of the Burrinjuck and Chaffey water quality, biological and flow data was acknowledged by the research team.

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.

It was agreed that the research team should contact the providers/owners of the Burrinjuck Reservoir data to explore opportunities for making the data set more widely available and discuss how this might best be managed.

Chapter 9

Conclusion

The workshop has clearly demonstrated the tenuous nature of links between science and management in respect to reservoir management and the steep learning curve confronting reservoir managers. The Sydney cryptosporidium outbreak serves to illustrate the potential social and economic impacts and liability risks associated with reservoir management and the importance of understanding the dominant pollutant transport and transformation pathways in respect to internal loading, pollutant distribution, and off-take level selection. This then raised the question of how this knowledge is to be transferred across a diverse range of reservoirs?

The management issues identified in the workshops are broad — how are these to be prioritised? How are management option alternatives to be assessed? In the discussion on the role of models as decision support tools to enable managers to assess these issues, the managers stressed the need to limit the models to simple applications, as otherwise they would not be viable. How is this to be done where we are dealing with complex and dynamic processes and systems? Clearly, there will be a need for strong links between operation and the underpinning scientific models.

Operation, evaluation and performance audits all require substantial capture of data, and subsequent translation into information relevant to management and assessment. This aspect alone represents a major challenge.

Chapter 10

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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

Workshop participants

A.1 CSIRO Canberra, 9th September 1999

Workshop facilitated by the Burrinjuck Project team.

Managers Aspi Baria & Fiona Butterfield (ACTEW); Bryan Bycroft (DNR Qld); Wayne Byrnes (Sydney Catchment Authority); Bruce Campbell (MDBC); Tony Church (EPA NSW); Pat Feehan (Goulburn-Murray Rural Water Authority); Greg Keen (Environment ACT); Dr Nick Schofield (LWRRDC); Tim Smith (DLWC N-SW); Dr Dennis Steffenson (CRC for Water Quality).

Burrinjuck Project Team Dr Myriam Bormans, Dr Brad Sherman & Dr Phillip Ford (CSIRO), Ian Lawrence, Dr Rod Oliver & Gail Ransom (CRCFE).

A.2 Murray Darling Freshwater Research Centre, Albury, 11th November 1999

Workshop facilitated by Goulburn-Murray Rural Water Authority.

Managers Mark Bailey, John Bartell, Pat Feehan, Colin Fitzpatrick, Anne Graesser, Ian Howley, David Jeffrey & Bob Klos (Goulburn-Murray Rural Water Authority); Gareth Finlay (Central Highlands Water); Greg Ryan & Catherine Sandercock (AWT Victoria); Liz Vinnall (Deakin University); Greg Vinall (Murray Catchment Management Committee); Terry Wisener (North East Region Water Authority).

Burrinjuck Project Team Ian Lawrence & Dr Rod Oliver (CRCFE).

Appendix B

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 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.

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 C

Abbreviations

ACTEW	ACT Electricity & Water
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
DLWC	Department of Land & Water Conservation
DNR	Department of Natural Resources
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
P	Phosphorus
SML	Surface mixed layer
SS	Suspended solids
THM	Tri-halo methanes
TN	Total nitrogen
TP	Total phosphorus
WWTP	Waste water treatment plant
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
yr year
day days

Volume
ML Mega-litres — 10^6 litres (equivalent to $1000m^3$)
GL Giga-litres — 10^9 litres