

CONTROL STRATEGIES FOR CYANOBACTERIAL BLOOMS IN WEIR POOLS

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Management Strategy**



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1. Executive Summary

Previous studies have shown that discharge is the key regulating factor in the establishment of cyanobacterial blooms in the Murrumbidgee River. Why should discharge have such a profound effect on *Anabaena* concentrations? An obvious, or at least partial, explanation is that high discharge reduces the growing time for a cyanobacterial population being advected (transported by river flow) from one location to another. An additional or alternative explanation is that low discharges fundamentally alter the physical environment within weir pools in a way which is conducive to *Anabaena* growth.

This project was based upon the premise that within river weir pools, the flow velocities are sometimes sufficiently low that they are incapable of destroying the thermal stratification resulting from the absorption of solar energy close to the water surface. Density (thermal) stratification has the effect of inhibiting turbulent mixing and may even suppress it altogether. Under these circumstances a population of buoyant phytoplankton such as *Anabaena* will float into the well-lit water layer close to the water surface and so receive much more of the light necessary for its growth than a population mixed uniformly throughout the water column. We hypothesised that it was this mechanism that provides the main growth advantage to buoyant cyanobacteria under low discharge conditions.

Study Objectives

The study which we describe here has two objectives:

1. To investigate the effects of discharge on stratification and mixing within weir pools and to investigate the resulting effects on phytoplankton population growth and the formation of cyanobacterial blooms.
2. To devise and evaluate strategies for the control of cyanobacterial blooms based on the

knowledge of the physical factors influencing cyanobacterial population growth and spatial distributions. The strategies investigated involve manipulation of the physical conditions within the weir pool by varying the discharge, modifying the discharge height, selective withdrawal, and artificial destratification.

Data Collection

The study was undertaken within Maude Weir pool on the Murrumbidgee River in central New South Wales. Although the height of the weir is only 6 m, due to the small river slope the river backs up behind it as a pool to a distance of 35 km. Hay Weir, the next weir upstream, is located a further 40 km from the upstream end of the weir pool.

During the summers of 1993/1994 and 1994/1995, the weir pool was instrumented with three continuously recording thermistor chains in order to monitor its stratification behaviour. Meteorological variables including wind speed, humidity, air temperature and radiation were also measured in order to gauge their effects on stratification. Water samples were collected one to three times a week for phytoplankton counts from a location near the weir. On occasion, additional samples were collected from locations further upstream and from depths through the water column in order to describe the horizontal and vertical distributions of the phytoplankton populations.

Major Results

1. Based on measurements from this study in Maude Weir pool and on measurements made in previous years in Hay Weir pool it would appear that a necessary condition for the development of *Anabaena circinalis* blooms in these two weir pools is that discharge through the weir be less than about 1000 ML d⁻¹ (megalitres per day) for a period

- of one to two weeks. Growth of the *Anabaena* population occurred for discharges less than 500 ML d⁻¹, but there were no prolonged periods of discharge between 500 and 1000 ML d⁻¹ during the study so the limiting discharge for *Anabaena* growth is not known more precisely. Concentrations of the dominant river phytoplankter, the diatom *Melosira (Aulacoseira) granulata*, were reduced under low discharge conditions, but this species dominated the summertime phytoplankton assemblage when the discharges exceeded 1000 ML d⁻¹.
2. The discharge through the weir gates was varied substantially during both summers to meet domestic and irrigation demands further downstream which allowed us to investigate the relationship between stratification of the water column in the weir pool and the discharge. When the discharge was less than about 1000 ML d⁻¹, the weir pool remained stratified day and night (*persistent stratification*). Discharges greater than about 1000 ML d⁻¹ caused *diurnal stratification*; that is, stratification was established and destroyed on a diurnal (day/night) cycle. Turbulence generated by the flow along the bottom of the weir pool eroded the stratification. Winds over the river were generally weak due to sheltering by the continuous stand of trees lining both its banks and appeared to have little influence on the stratification status of the weir pool.
 3. When the water column was persistently stratified, the *Anabaena* population accumulated in the surface layer (1 or 2 m thick) and the *Melosira* population became concentrated towards the bottom. The ratio of the near surface concentration of *Anabaena* to that at 3 or 4 m depth was usually ten or greater, but a ratio of over 50 was measured on one occasion. These distributions are consistent with *Anabaena* having been positively buoyant and *Melosira* having been negatively buoyant when the water column was not actively mixing from top to bottom.
 4. Our measurements are consistent with our hypothesis that it is mainly the separation of the populations within the water column under persistently stratified conditions which allows the *Anabaena* population to thrive, and which causes the *Melosira* population to decline. The high turbidity in the river (~ 10–35 NTU) resulted in a euphotic depth of less than 1.5 m so that photosynthesis would have occurred in the top 30% of the water column only. The *Anabaena* population in the surface layer would have had access to the light necessary for growth, whereas the *Melosira* would have experienced darkness as well as losses due to sedimentation.
 5. Whether an *Anabaena* population can grow to problem proportions will also depend on its residence time in the weir pool. For discharges above 1000 ML d⁻¹, water moves through the weir pool approximately as a plug flow. Residence times of algae within the pool are simply the volume of the weir pool divided by the discharge. At low discharges when the weir pool is strongly stratified, the river flow into the upstream end of the pool flows along the pool at depth and out through the underflow weir. Under these conditions, the surface layer of the weir pool behaves as a long narrow lake. Such a surface layer containing an *Anabaena* population would have a very long residence time.
 6. Although low discharge and persistent stratification usually stimulated vigorous growth of the *Anabaena* population in Maude Weir pool, they were not sufficient conditions. On one occasion (early summer 1995), discharge and temperature conditions appeared appropriate for a bloom to occur, but none did. Interestingly, the bloom appeared to be developing, but the population suddenly “collapsed”. The reasons for this are unclear. Possible explanations are nutrient limitation (due to lack of spring rainfall), predation by zooplankton, or advection away from the phytoplankton measurement site by westerly winds.

7. The best example of an *Anabaena* bloom during this study in Maude Weir pool occurred during a five week period of persistent stratification in January–February 1994. The *Anabaena* concentration near Maude Weir increased exponentially with time, with a specific growth rate of 0.37 d^{-1} (doubling time roughly two days) for the first three weeks, then a relatively constant concentration for the next two weeks. It is probable that 0.37 d^{-1} is similar to the true *in situ* growth rate for *Anabaena*, since the discharge was low and the advection of *Anabaena* along the weir pool would have been small. This growth rate is reasonably consistent with *Anabaena* growth rates which have been reported elsewhere in the world. With a specific growth rate of 0.37 d^{-1} , it took about three weeks for the *Anabaena* concentration to increase from its initial value of 4 cells mL^{-1} to the level 2 alert of $10\,000 \text{ cells mL}^{-1}$.
8. Nutrient bioassay measurements were made on a regular basis during the summer of 1993/1994. Only once during the *Anabaena* bloom of January–February 1994 was there a weak suggestion of phosphorus limitation of phytoplankton function. Nitrogen limitation was indicated during times of *Melosira* dominance before and after the *Anabaena* bloom. Unfortunately, the nutrient bioassays were not repeated the following summer to establish whether or not nutrient limitation played a role in the failure of the *Anabaena* population to bloom during that time.

Management Strategies

The following points summarise our assessments of the management strategies we have considered for controlling cyanobacterial blooms in weir pools. These assessments are based on our measurements within the weir pool and the predictions of a stratification model of the weir pool. The two-dimensional model describes the time evolution of the thermal and flow structures through the water column, and along the axis of the weir pool, as they

respond to: meteorological forcing; the volume discharged through Maude Weir; and the temperature and discharge of the water flowing into the head of the weir pool. We validated the model by comparing its predictions of the vertical temperature profiles at two sites along the pool with measurements made by continuously recording thermistor chains.

The model allowed us to test various management strategies for their impacts on the mixing regimes and residence times within Maude Weir pool. From these impacts we inferred the likely effects on cyanobacterial growth within the weir pool. Although our assessments of the utilities of the various management strategies for controlling cyanobacterial blooms in weir pools are based on the simulations we performed for Maude Weir pool, we would expect that these assessments would carry over to other weir pools. An important caveat is that numerical values, such as the critical discharge for persistent stratification, are not likely to be applicable to other weir pools. However, the stratification model does provide us with the capability to estimate how such numerical values should be modified for other weir pools having differing geometries.

1. Maintaining the discharge through Hay and Maude Weirs at 1000 ML d^{-1} would almost certainly eliminate the problem of *Anabaena* blooms in Maude Weir pool in summer. This conclusion is based primarily on measurements from this study. The critical discharge for *Anabaena* control in Maude Weir pool may be as low as 500 ML d^{-1} . Factors which affect the critical discharge include the temperature of the inflowing river water, the water level in the weir pool, and the solar radiation.
2. Pulsing the discharge through the weir pool represents a promising method for controlling *Anabaena* population growth at times when the average discharge (over time) must be restricted. For Maude, we suggest that a 1500 ML d^{-1} pulse of a day's duration would easily be sufficient to mix the water column and restrain or reset cyanobacterial population

development. The pulse would be repeated at a regular interval. Optimally, the repetition interval would equal the inverse of the specific growth rate of the *Anabaena* population, which we infer to be about three days in Maude Weir pool, but repetition at longer intervals could still achieve the desired result of reducing population growth to below problem levels. This strategy of pulsing the discharge to control cyanobacterial blooms is sufficiently promising for it to be field tested. While a pulsed discharge strategy presents the river regulator with extra scheduling problems, it is not, from our assessment, an unrealistic prospect.

3. Based on the predictions from models of weir pool stratification and of withdrawal, it would seem that the degree of stratification within the weir pool under low discharge conditions would be similar if Maude Weir were an overflow weir rather than an underflow weir. However, the residence time of the surface layer in the weir pool, and hence the time available for the growth of an *Anabaena* population, would be substantially less than that for an underflow weir for discharges less than about 300 ML d⁻¹. The model-derived value of 300 ML d⁻¹ for the upper limit of the effectiveness of an overflow discharge for minimising blooms should be regarded as rubbery; models are only approximations to real phenomena. Siphons on the weir are a means of obtaining an overflow discharge through an underflow weir. Tests on the efficacy of siphons for controlling cyanobacterial blooms were carried out, but the results of these experiments are equivocal. A major problem for us was the lack of appropriate discharge conditions, at the right time of the year, to test the siphons properly.
4. Under stratified conditions, *Anabaena* concentrations from depth within Maude Weir pool were usually measured to be a factor of at least ten less than those measured in the surface layer. Consequently, the strategy of withdrawing water for domestic consumption from the bottom of a stratified weir pool

would be an effective strategy for minimising the concentrations of *Anabaena* in the water supply. Bottom water deoxygenation, and associated water quality problems (hydrogen sulphide odours, high dissolved manganese), did not occur. The in-flowing water moving along the bottom of the weir pool seemed to have a short enough residence time to maintain oxygen in the bottom waters.

5. Artificial destratification is a strategy which has been employed in reservoirs with the aim of reducing cyanobacterial growth. Destratification is usually accomplished with bottom mounted bubblers or by mechanical mixers. As a potential, cost-effective strategy for minimising *Anabaena* blooms, the destratification technique deserves serious consideration. Based on our model simulations, we expect that the technique would reduce *Anabaena* growth rates by mixing the *Anabaena* through the water column in the vicinity of the destratification devices and by increasing the thickness of the surface layer. Artificial destratification has the potential to reduce significantly the discharge required to maintain diurnal mixing in the weir pool. It would also ensure bottom waters remain oxygenated.

Conclusions

All five of the strategies we have examined in this study hold the prospect of minimising the occurrences or impacts of cyanobacterial blooms in weir pools. At this stage, increasing the discharge through the weir pool to beyond a critical level is the most certain way of preventing blooms, but such a strategy may prove to be unacceptable because of the volume of water required to be sent downstream. Nonetheless, our data enables economic trade-off analyses to be undertaken for an increased base-flow strategy. Withdrawing water from depth in the weir pool is a way of minimising phytoplankton concentrations in water supply during blooms of buoyant cyanobacteria such as *Anabaena*. The other three strategies considered, namely pulsing the weir discharge, withdrawing water over the weir wall rather than under it (using

siphons), and artificial destratification, would all appear to be viable on the basis of their model predicted effects on stratification and surface layer retention times. These strategies should be field tested to confirm their effectiveness. Unfortunately, the tests we have undertaken on the use of siphons are equivocal due to a lack of suitable stratification and cyanobacterial conditions during the time they were trialed.

The findings of this study further confirm our hypothesis that the occurrence of *Anabaena* blooms in weir pools has much to do with the onset of thermal stratification of the water column under low discharges. From this study, we have developed the capability to model the stratification in Maude Weir pool as it responds to discharge. We are confident that we can extend this capability to other weir pools without difficulty. The potential exists to model the growth of phytoplankton populations in weir pools as well. Such modelling would provide a better

understanding of the factors which lead to the occurrences of cyanobacterial blooms and would be very useful for the optimisation of some of the control strategies we have proposed.

The structure of a suitable growth model already exists, but we are missing crucial information for its application to *Anabaena*. Required information includes this cyanobacterium's growth response to light and nutrients, its buoyancy response to physiological state, the origins and size of seed populations in weir pools, and loss mechanisms such as predation or photooxidative cell lysis. Laboratory studies are currently addressing some of these information needs. These studies need to be maintained and extended where they are deficient. Ultimately, we need to test a model for *Anabaena* growth in a suitable weir pool. Such a test would need to account for the nutrient dynamics in the weir pool and could very well be conducted in conjunction with tests of a cyanobacterial management strategy such as pulsing the discharge.

2. Introduction

In recent years, blooms of the toxic cyanobacterium *Anabaena circinalis* have been a problem in the major rivers of the Murray-Darling Basin in the interior of Australia. Although nutrients, introduced into the rivers by natural processes or as a result of human activities, are certainly a requirement for such blooms to occur, the incidence of bloom formation has been observed to be strongly related to river discharge (Jones, 1993; Hötzel and Croome, 1994).

The rivers of the Murray-Darling Basin are generally slow flowing, due to the small bed slope over most of its area. Weirs placed along the rivers to provide water storage result in impoundments which further slow the flow. Elevated *Anabaena* concentrations usually occur in these weir pools when the flow through them is relatively low. Figure 2.1 illustrates the effect of river discharge on the concentrations of *Anabaena* in the impoundment behind Hay Weir on the Murrumbidgee River during the summer of 1991/1992 (Jones, 1993). One might expect that concentrations of phytoplankton should be high during the summer months, due to growth enhanced by elevated water temperatures and sun elevation. However, the discharge pulse occurring in the latter part of December was associated with a reduction in *Anabaena* numbers. Cyanobacterial numbers were reduced sharply again when discharges were increased in early February.

Why should discharge have such a profound effect on *Anabaena* concentrations? An obvious, or at least partial, explanation is that high discharge reduces the growing time for a cyanobacterial population being advected from one location to another. An additional or alternative explanation is that low discharges fundamentally alter the physical environment within weir pools in a way which is conducive to *Anabaena* growth. A feature of the inland rivers of the Murray-Darling Basin is their high turbidity due to high suspended clay concentrations. Within weir pools, the flow velocities are sometimes sufficiently low that they are incapable of destroying the thermal stratification

resulting from the absorption of solar energy close to the water surface. Density (thermal) stratification has the effect of inhibiting turbulent mixing and may even suppress it altogether. Under these circumstances a population of buoyant phytoplankton such as *Anabaena* will float into the well-lit water layer close to the water surface and so receive much more of the light necessary for its growth than a population mixed uniformly throughout the water column. This is the mechanism described by Humphries and Lyne (1988) for providing a growth advantage to buoyant cyanobacteria under stratified conditions.

Most samples collected for the estimation of phytoplankton abundances are withdrawn from near the water surface. If buoyant phytoplankton have accumulated near the surface under stratified conditions, then such samples will contain phytoplankton concentrations which are above the average concentration for the water column. In other words, a surface sampling strategy may cause the population of buoyant phytoplankton to be substantially overestimated under stratified conditions.

Many of the weirs along the major rivers in the Murray-Darling Basin are underflow weirs; that is, the discharge is released under gates which can be raised or lowered. Under stratified conditions, it might be expected that the flow through such a weir would be drawn preferentially from the lower, cooler part of the water column. The reduced density of the warm surface layer compared to deeper water restricts its induction into the outflow. We might expect that near an underflow weir, the deeper water flows as a stream through the weir under a stalled, warmer surface layer. We hypothesise that buoyant phytoplankton encountering such flow conditions would tend to accumulate behind the weir within the warm surface layer, where they would experience conditions which are conducive to their growth, rather than being discharged downstream, where they would be extinguished. In summary, we hypothesise that stratified conditions within a weir pool enhance the

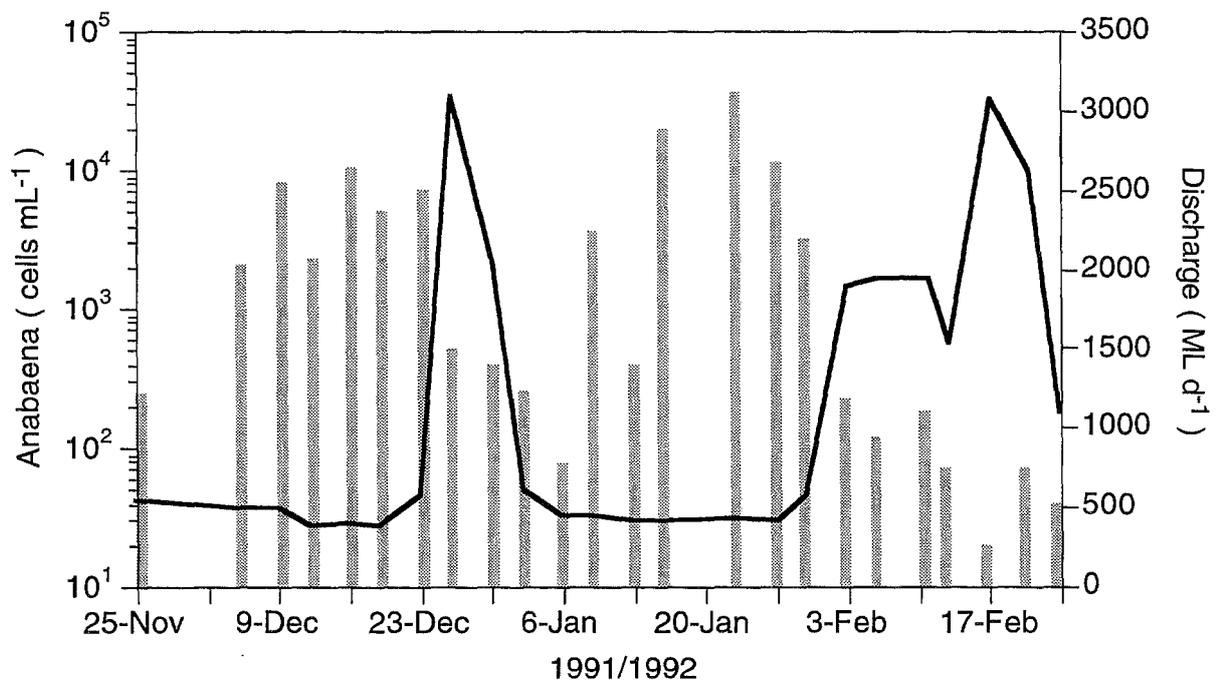


Figure 2.1 Anabaena concentrations (bars) in Hay Weir pool and Hay Weir discharge (line) for the summer of 1991/1992. Adapted from Jones (1993).

population growth of buoyant phytoplankton such as *Anabaena* by increasing its exposure to light and in the case of underflow weirs by trapping the population in an environment where it can flourish.

The reduction of nutrient loads to Australian rivers is a long term goal that is unlikely to lead to reductions in cyanobacterial blooms for several years. It would be desirable to implement complementary strategies that ameliorate the cyanobacterial problem whilst the long term nutrient strategy is taking effect. Our study addresses this need. We believe that management of the physical conditions within weir pools can lead to major reductions in cyanobacterial blooms. In particular, if our hypotheses concerning the relationship between stratification and cyanobacterial growth are correct, then a number of strategies for bloom minimisation based on this nexus could be implemented more or less immediately.

The scientific part of the study involves the investigation of a series of relationships which together comprise our stratification-growth hypothesis. These relationships are: firstly, that between discharge and stratification; secondly, the relationship between mixing and flow conditions and the vertical and horizontal distributions of phytoplankton in the weir pool; and thirdly, the relationship between the stratification and phytoplankton population growth in the weir pool. The scientific part of the study involved the collection of physical, chemical, and biological data from Maude Weir pool over three years. Maude Weir, situated on the Murrumbidgee River, is an underflow weir. The pool behind it is fairly typical of the long, relatively shallow and narrow impoundments which occur along the Murray, Murrumbidgee, and Darling Rivers. Results from this part of the study have been presented by Sherman *et al.* (1994).

A key component of the study is the adaptation and verification of a numerical model for predicting the circulation and mixing within Maude Weir pool. The numerical model provides us with a useful aid in interpreting the data, particularly on stratification. It provides a measure of the currents

and mixing regimes through the weir pool which were not measured directly. It permits testing of management strategies without disrupting the discharge patterns which had been set for the river during the irrigation season. Finally, by adapting the model to other weir pools, it allows for the derivation of management strategies for other systems, taking into account their differing dimensions and flow regimes.

The second major part of this study is the testing of a set of management strategies for minimising cyanobacterial bloom formation. As will be demonstrated, flow speeds are a prime determinant of the degree of stratification in the weir pool, so that altering the timing and size of the discharge through the weir must be seen as a significant management strategy. We shall consider how big the discharge must be in order to reduce stratification. We also shall consider whether pulsing the discharge might be a way of achieving the desired reduction in cyanobacterial population growth without releasing large amounts of water downstream. We shall evaluate the usefulness of artificial destratification systems, such as bottom mounted bubblers, which have been used in reservoirs to minimise cyanobacterial population growth. Another strategy we shall test is the use of a siphoning system over the weir wall to reduce the population of cyanobacteria by simply removing the surface water layer where it is found. With siphons in place at Maude Weir in the summer of 1991/1992, there was a greater than 90% reduction in cyanobacterial problems compared with Hay Weir pool immediately upstream (Jones, 1993). This result looks encouraging, but we wish to determine whether or not it was just fortuitous.

This report on the Maude study commences with descriptions of the site and of the data collection methods and timing. The results of the measurement program will then be presented in the context of our set of hypotheses. Then we describe the numerical model and its adaptation to Maude Weir pool. Following this is the examination of possible management strategies for minimising cyanobacterial blooms. The final section of the report summarises the major findings of the study and discusses their application.

3. Data Collection

a) Site Description

Maude Weir is located on the Murrumbidgee River 50 km west of Hay, NSW (Figure 3.1). The Murrumbidgee is one of the major inland rivers of Australia, characterised by high turbidity and low bed slope (~ 1:10 000) as it flows across the Hay Plain. Due to its sinuous nature the river distance between Maude and the next weir upstream near Hay is about 75 km. Along most of this section, the river is lined on both banks by trees, mostly river red gum and box. These trees act to significantly reduce wind speeds over the river and thereby have a pronounced effect on wind-mixing near the water surface and evaporation.

Maude Weir has three 17.4 m wide gates which can be individually lifted to regulate the discharge. Typically, for low to medium discharges, only the middle gate is required to be lifted. Although the height of the weir is only 6 m, the low river slope causes the river to back up behind the weir as a pool to a distance of approximately 35 km. Hay Weir, the next weir upstream, is located a further 40 km from the upstream end of the weir pool. When full, the Maude Weir pool has a capacity of 5000 ML. On occasion considerable volumes of water for irrigation are diverted from the weir pool through Nimmie Creek located 6 km upstream from the weir. Up to 400 ML d⁻¹ (megalitres per day) can be pumped out of the pool at a series of riparian offtakes located further upstream. Sometimes much more water is diverted from the weir pool for irrigation than is discharged through the weir. Local history has it that the river can even flow backwards during low discharges when upstream pumping is at a maximum. The capacity of the largest single pumping site (295 ML d⁻¹) is larger than the not uncommon summer low discharge through the weir of 100–150 ML d⁻¹.

During February 1993, we undertook a bathymetric survey of the weir pool to a distance of 6.2 km upstream from the weir. Figure 3.2 shows depths measured along the centreline of the pool along this length referenced to a water level representing a full

weir pool. These water depths undergo significant undulations varying between a maximum of 10.2 m in Luke's Hole, which is 2 km upstream from the weir, to a minimum of 2.5 m, about 1.5 km further upstream. During the bathymetric survey, we obtained depths along thirty transects across the pool. The depths along three of these transects are also shown in Figure 3.2. The width of the pool varies along its length, but we take a nominal average width for the pool to be 40 m.

b) Study Plan

Data were collected from the weir pool in the summers of 1992/1993, 1993/1994, and 1994/1995. The cyanobacterial problem in the rivers of the Murray-Darling Basin is most prevalent during the summer. Due to irrigation demand along the length of the Murrumbidgee River in the summer, the discharge at Maude can be less than 1% of the discharge into the river from Burrinjuck and Blowering Reservoirs.

In the following, we outline the tasks undertaken and the equipment installed during each of the three study periods. The locations of the sampling sites and the recording instrumentation are presented in Figures 3.1 and 3.3. The periods of the equipment installations are outlined in Figure 3.4. More detailed descriptions of the instrumentation used in the study and the analysis methods are provided in Appendix A.

i) 1992/1993

This project was to have commenced in the spring of 1992, but the commencement of the project was delayed due to unusually high flows in the Murrumbidgee River during this time. Phytoplankton numbers were monitored twice a week, but numbers remained low during the whole of the summer of 1992/1993. They did not rise high enough to warrant undertaking the full experimental program which was planned for that season. In any event, the discharge at Maude did not fall sufficiently for field work to commence until

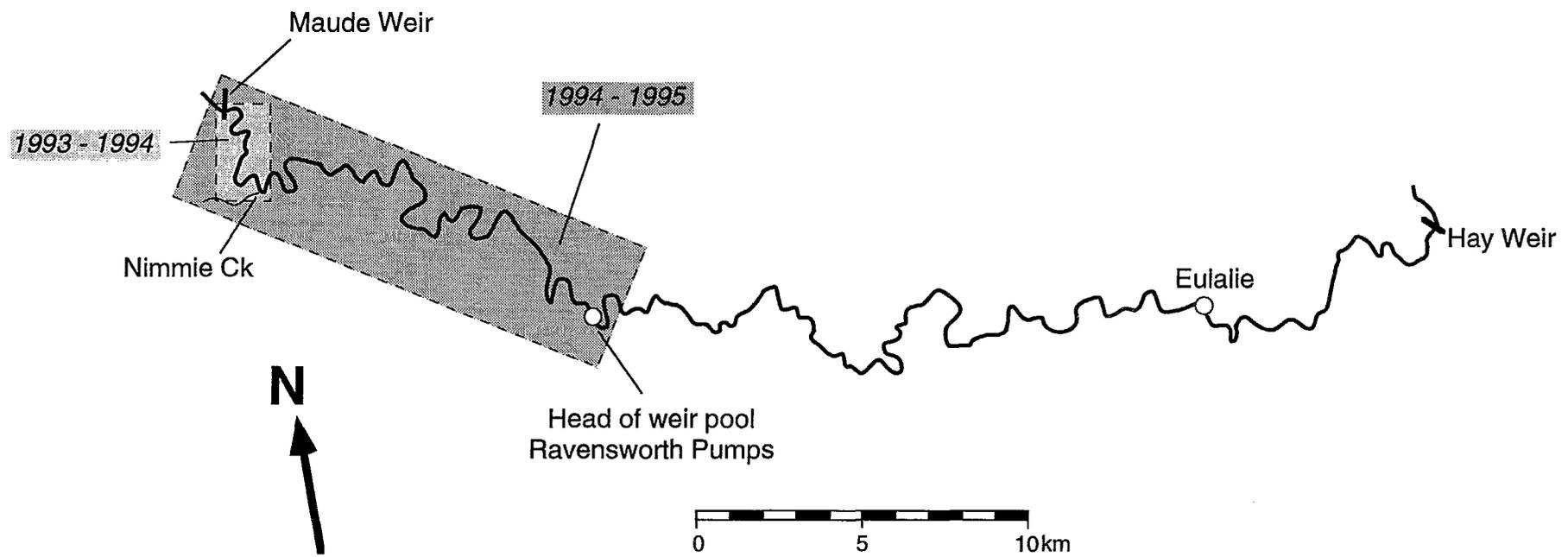


Figure 3.1 Locations of the study areas during the summers of 1993/1994 and 1994/1995

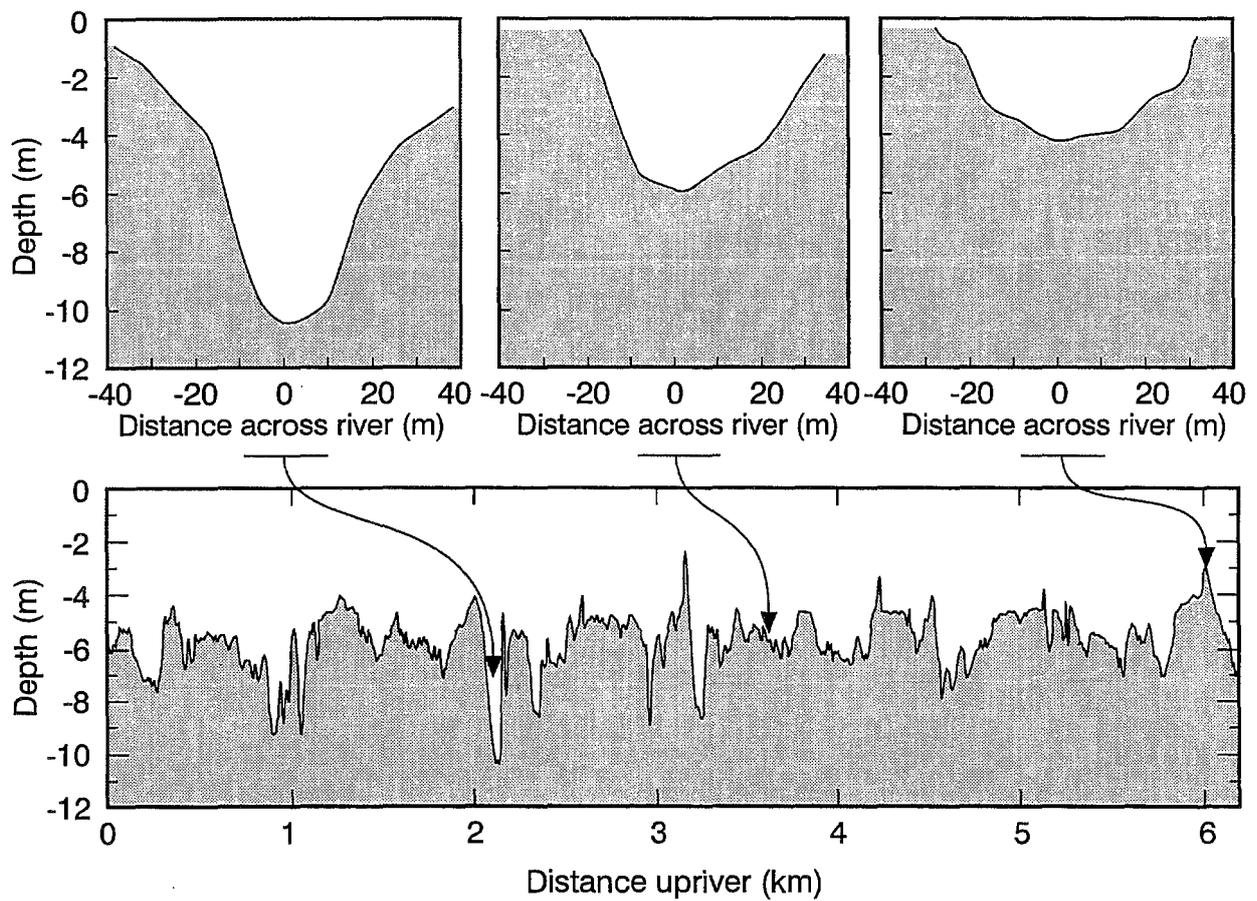


Figure 3.2 Bathymetry along the centreline of Maude Weir pool within 6 km of the weir. Also shown are three selected bathymetric cross-sections.

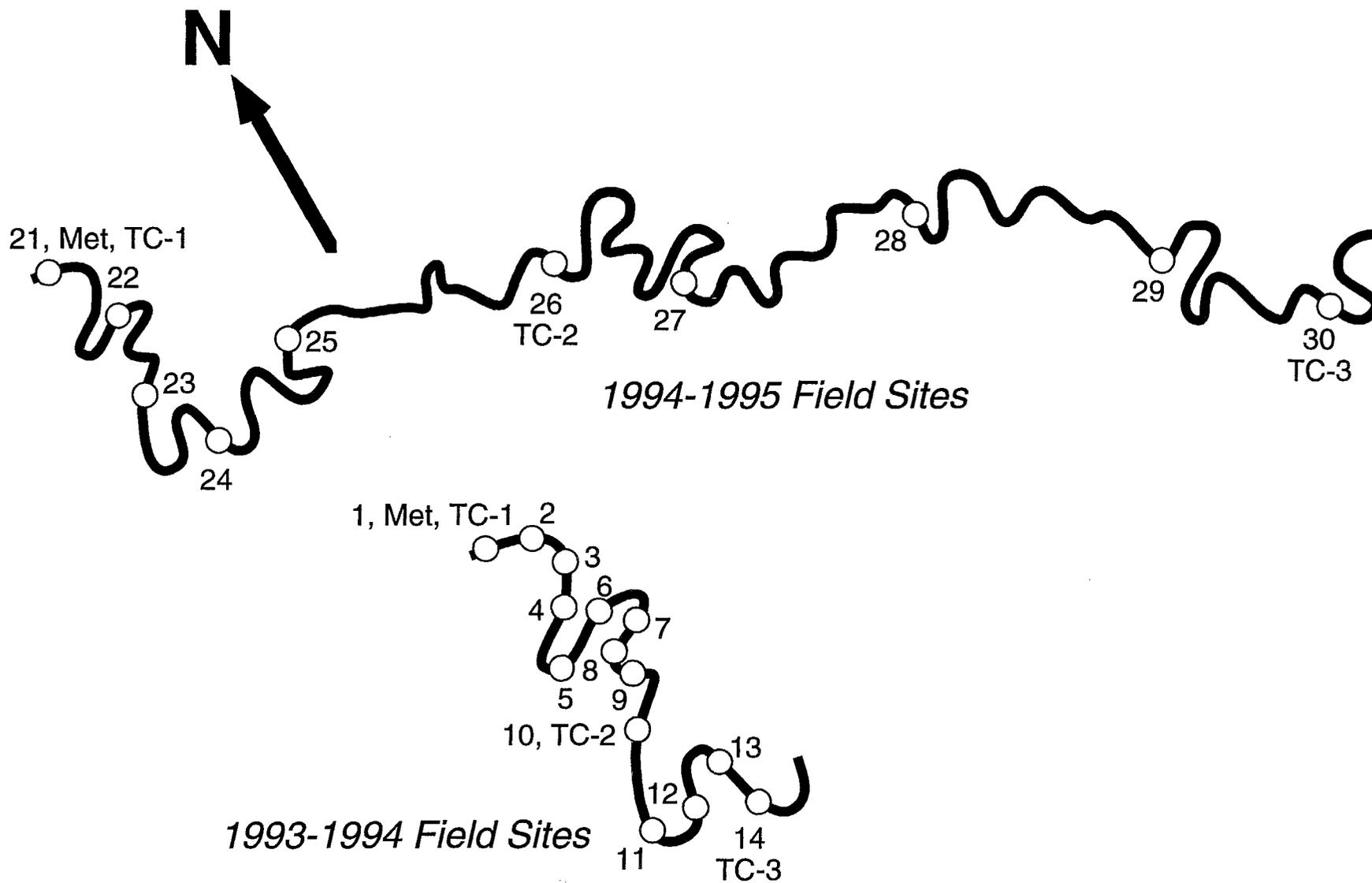


Figure 3.3 Locations of the sampling stations and instrumentation during the summers of 1993/1994 and 1994/1995.

Physical data availability

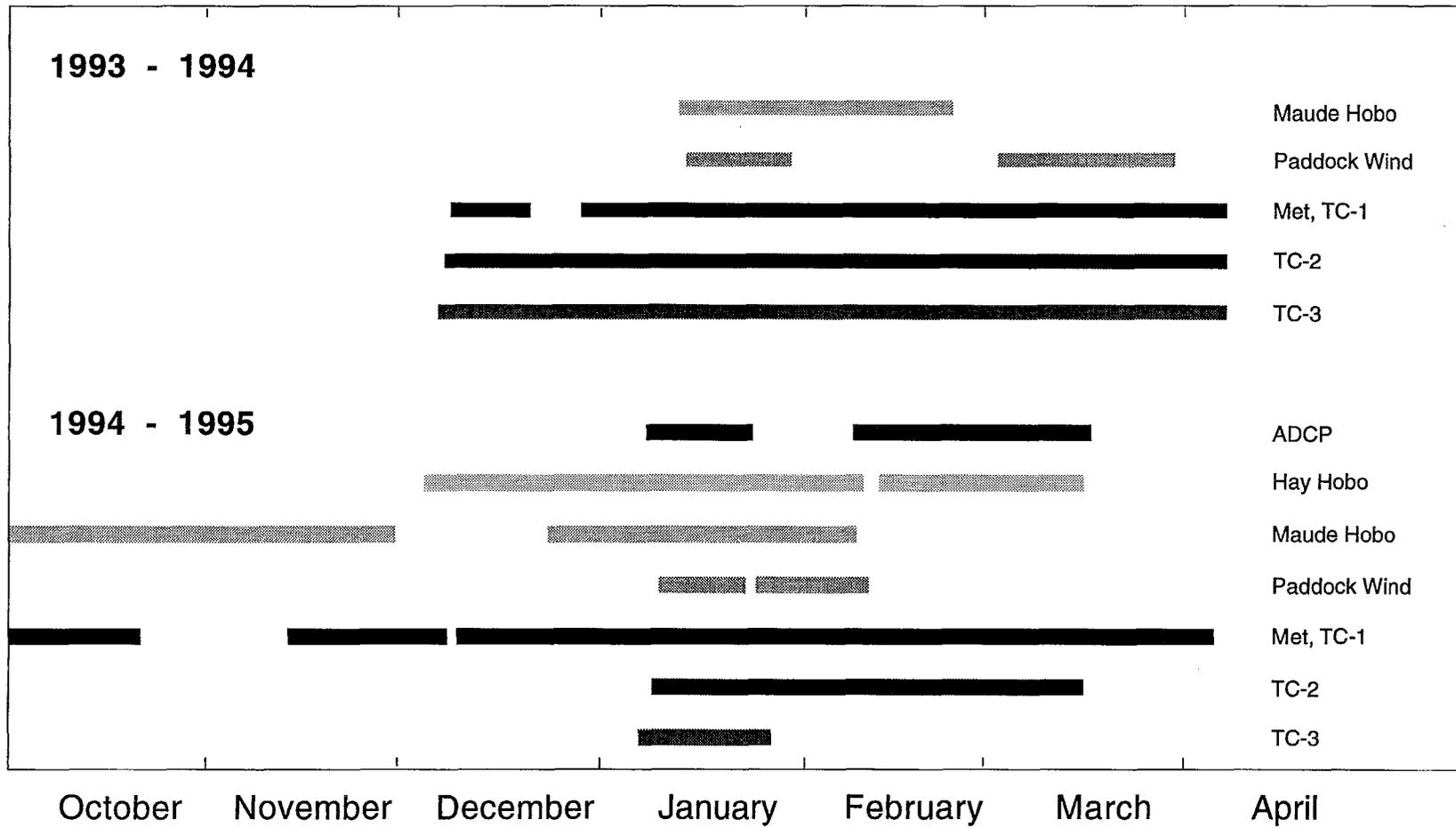


Figure 3.4 Timelines for the periods of operation of the physical monitoring instrumentation.

February, 1993. Instead of the three intensive field trips to the weir pool, we undertook one between February 22 and 26, 1993. This trip provided us with the opportunity to complete a bathymetric survey of the study area, to measure temperature structure within the weir pool and to measure features of the temporal variations in water chemistry and phytoplankton concentrations. Phytoplankton concentrations were obtained directly by counting cells or colonies in collected samples. Concentrations of chlorophyll-a were estimated from fluorescence measurements obtained from our temperature-fluorescence-depth (TFD) profiler. The distribution of temperature and chlorophyll were measured along a 6 km section of the weir pool upstream of the weir. Also, we obtained a series of profiles of phytoplankton concentrations and temperature at one site 2 km upstream from the weir to determine the diurnal variations in these properties.

ii) 1993/1994

Three thermistor chains were installed during the week of December 5 1993, and removed on April 5 1994, at sites TC-1, TC-2, and TC-3 within a 6 km long section of the weir pool upstream of the weir (Figure 3.3). A thermistor chain continuously measures the profile of water temperature through the water column. A meteorological station was also installed on the raft supporting the thermistor chain closest to the weir (TC-1). This station measured a number of parameters liable to affect the stratification behaviour of the weir pool, including wind speed and direction, solar radiation, air temperature, and humidity. It became apparent that our wind measurements on the raft would reflect wind strengths in a river channel having an east-west orientation only, but the channel is very sinuous in the study area. Accordingly, a second anemometer station was established in an exposed location on January 13, 1994 to measure prevailing winds. It was intended to use these measurements to estimate wind exposures in all sections of the river channel.

Integrated samples (surface to 5 m depth) for phytoplankton analysis were collected three times per week from Maude Weir pool during the peak phytoplankton growth season (mid-November to late February). Samples were collected weekly or monthly during the rest of the year.

Other continuously recording equipment installed during this season included a Hobo™ temperature logger and a QUALTEL water quality monitor. The Hobo was placed within the outflow from Maude Weir to continuously monitor its temperature so that we could estimate the depths from which the outflow was derived. The QUALTEL unit was installed for a period of six weeks on a raft near thermistor chain TC-1 to measure a suite of physical and chemical parameters within the water column. During this study, season samples were also collected for NIFT analysis. This is a laboratory procedure which determines whether phytoplankton growth is being limited by phosphorus or nitrogen (Wood and Oliver, 1994).

In this season, we undertook three major sampling trips to the weir pool. In order to determine information on the spatial (horizontal and vertical) variability of the stratification and the phytoplankton, we obtained measurements with the TFD profiler at fourteen stations spread along the 6 km length of our study area. Samples along the weir pool from a series of depths through the water column were collected on a diurnal basis for cyanobacterial population analysis at two sites. Surface samples were collected at several sites along the weir pool.

iii) 1994/1995

As in the previous summer, a full sampling program was undertaken in Maude Weir pool in the summer of 1994/1995. Four intensive sampling trips were performed and continuously recording equipment was installed in the weir pool. Thermistor chains were operated at three sites along the weir

pool, but two of the chains were placed at positions much further upstream than in the previous summer. One of the thermistor chains was located 30 km upstream from the weir, which is close to the end of the weir pool. Also in 1994/1995, a Hobo temperature logger was installed to measure the temperature of the outflow from Hay Weir. Our stratification modelling showed the necessity to properly define and understand how the river between Hay and Maude gains or loses heat. The installations of the thermistor chains further upstream and the temperature logger at Hay were intended to address this data need. During the intensive field visits we defined the temperature structure and distribution of chlorophyll-a further upstream than we did during the previous summer.

We installed an Acoustic Doppler Current Profiler (ADCP) at a site close to the weir for two periods totalling six weeks. The ADCP continuously measures the current velocity between the water surface and the bottom. Siphons were installed on Maude weir during the latter part of the second installation period of the ADCP. During the 1994/1995 field season we had planned to test the effects on cyanobacterial population

growth of a series of discharge strategies, including pulsed flow. Unfortunately, due to erratic rainfall patterns during the study season, which caused rainfall rejection of irrigation water, it was not possible to obtain the flow conditions in the river necessary for the completion of the experiments.

Samples were collected for phytoplankton counts throughout the year from Maude Weir pool on an approximately weekly basis during the cooler months of the year, and on a twice or thrice weekly basis during the warmer months. The frequency of sampling was high during the summer because of our desire to obtain good growth rate estimates for key cyanobacterial species. During the 1994/1995 study period, a major effort went into determining the advection and potential growth of cyanobacteria along a larger stretch of the river than just Maude Weir pool. For an approximately four week period, samples were collected daily from immediately below Hay Weir, from Eulalie, 14 km downstream from Hay Weir, and from Maude Weir pool. Diurnal depth profile sampling was also undertaken as in the previous summer. Cyanobacteria were counted microscopically using a Sedgewick-Rafter counting chamber.

4. Results

a) Discharge and Stratification

The discharge through the weir gates was varied substantially during the summer months to meet domestic and irrigation demands further downstream. The salient feature of the temperature structure of the water column in the weir pool is that it stratified under low discharge conditions (Sherman *et al.*, 1994). This behaviour is exemplified by Figure 4.1 which shows temperatures measured at four depths from the thermistor chains, located 300 m, 15 km, and 30 km upstream from Maude Weir, during the two week period starting on January 8, 1995. The discharges through Maude Weir during this period are also shown.

At thermistor chains TC-1 and TC-2, which were sited at the downstream end and in the middle of the weir pool, respectively, there was a pronounced diurnal cycle of stratification on most days during this period. Surface waters heated during the day due to the absorption of solar radiation, but on most days the turbulence due to the wind acting on the water surface and the turbulence generated by the flow over the bottom were insufficient to mix this heat throughout the water column. Typically, surface temperatures reached their maxima in mid to late afternoon. During the night, the degree of stratification diminished due to cooling of the surface waters, usually reaching a minimum after dawn. By contrast, at chain TC-3 near the upstream end of the weir pool 30 km from Maude Weir, the degree of diurnal stratification was much less pronounced than it was at the other two chains further downstream. On about half the days within the portion of the record shown, the water column did not stratify at all. Rather, on these days, the heat absorbed by the sun was mixed from top to bottom causing a uniform increase in water temperature through the water column. This behaviour is consistent with this chain being near the transition between weir pool and river. There were significant differences between the stratification behaviours at TC-1 and TC-2 which we attribute to their different positions along the weir pool.

The stratification behaviour at all three chains is clearly related to the discharge through the weir. At TC-3, diurnal stratification is evident during the period between January 10 and 16 when the discharge was down to 350 ML d⁻¹. The drop in discharge from 1150 ML d⁻¹ to 350 ML d⁻¹ on January 9 was associated with the appearance of "persistent" stratification at TC-1 and at TC-2 two days later. By persistent stratification we mean that some stratification remained even after night-time cooling had occurred. This is manifest initially in the time series shown by the divergence of the temperature traces for depths of 2.5 and 5 m. Persistent stratification indicates that mixing has not occurred from surface to bottom at any time on a given day.

Persistent stratification is evident in the record shown in Figure 4.1 until the morning after the discharge was increased to 2000 ML d⁻¹ on January 17. At TC-1, the increased vertical mixing associated with the increase in the discharge caused the bottom waters to warm as warm surface water was mixed downwards. Surface waters cooled as a consequence of the same process. By contrast, at TC-2 bottom waters warmed but so did the surface water at the time of the increased discharge. In effect, the average temperature of the water column increased. We surmise that the increase in temperature must have been caused by the advection of warmer water along the weir pool. This behaviour illustrates that our description of the thermodynamics of the water column in a flowing weir pool such as Maude must consider horizontal transport processes as well as vertical mixing.

Figure 4.2 shows a series of vertical profiles of temperature measured by the thermistor chain at TC-1 on January 13/14, 1995, a day typical of one experiencing persistent stratification. The first profile from 0800 shows a surface layer of uniform temperature to a depth of 1.6 m. On most days in both years of thermistor chain measurements, the minimum stratification of the water column was observed to occur at about this time in the morning.

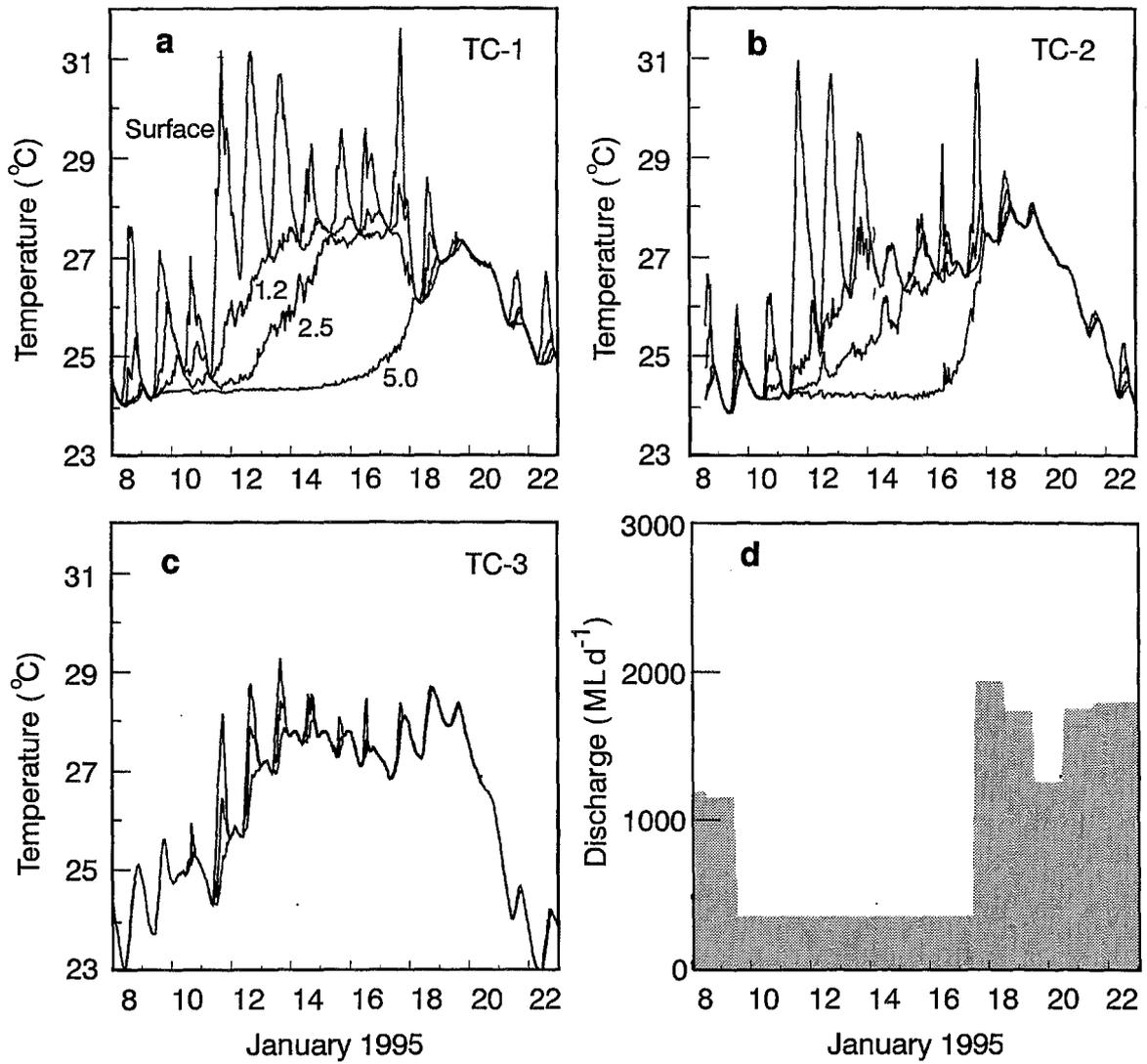


Figure 4.1 **a,b,c)** Time series of measured temperatures from surface, 1.2, 2.5 and 5m depths at the thermistor chains.
d) Discharge through Maude Weir.

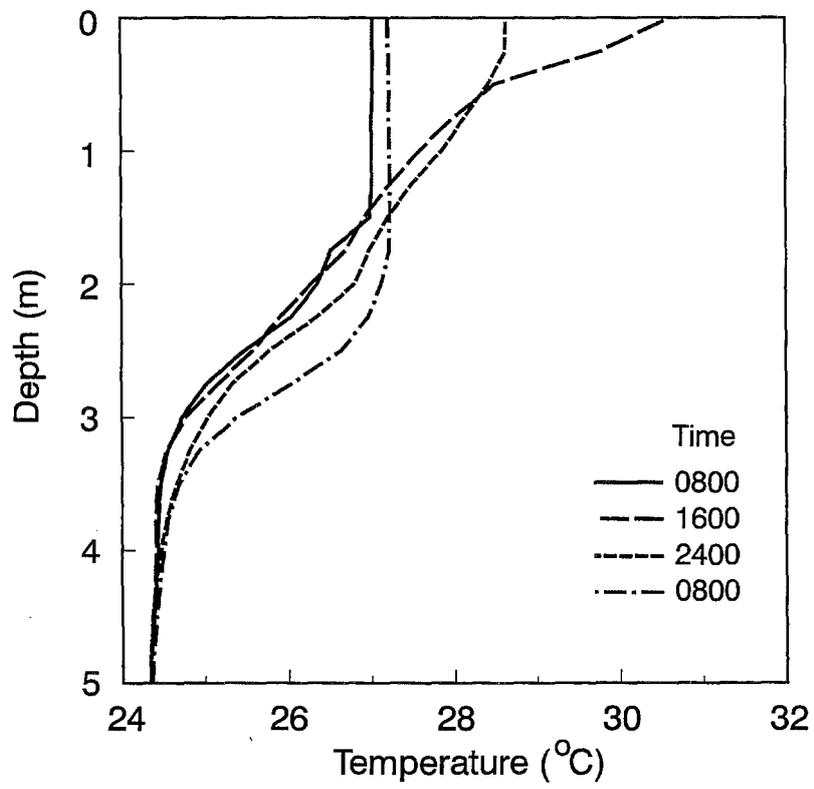


Figure 4.2 Temperature profiles measured by thermistor chain TC-1 on January 13/14, 1995.

The profile for 1600 shows the temperature at the time of maximum stratification. At this time, the surface water temperature reached 31.6°C compared to a bottom temperature of 24.3°C.

Winds on this particular day were light and not strong enough to cause a near surface mixing layer of near uniform temperature—the stratification was strong all the way to the water surface.

After sunset the surface water started to cool due to evaporation and longwave radiation emission. The distribution of heat near the water surface during the cooling phase would have been determined by a combination of wind stirring and penetrative convection. With penetrative convection, water cooled at the surface becomes denser than the underlying water, sinks, and mixes to such depths that static or neutral mechanical stability is restored. The end result is that the stratification is peeled back from the surface. A surface mixed layer forms which gradually deepens. Penetrative convection due to night-time cooling is ubiquitous in lakes and has been described by Imberger (1985) and Spigel *et al.* (1986), for example. By midnight on January 13, the surface had cooled to 28.7°C. A surface mixed layer of thickness 0.3 m had formed, presumably caused by penetrative convection. Further cooling during the night caused this mixed layer to deepen to 1.8 m at 0800 the following morning. At this time the surface waters were about to start heating again due to solar radiation.

Between 2 and 3 m the stratification remained largely intact through the diurnal cycle even though it did deepen by about 0.5 m during this period. The temperature time series at TC-3 shown in Figure 4.1 show that the water being advected into the weir pool was becoming warmer in the days prior to January 13. We suggest that the increase in water temperatures between 2 and 3 m depth on January 13 was primarily due to downstream advection of warmer water through this depth range rather than due to the downward mixing of warmer near surface water. We contend, therefore, that during the night of January 13 mixing had occurred to a depth of about 1.8 m; on the previous night mixing had occurred to 1.6 m depth. A depth of night-time mixing of between 1 and 2 m seems to have been typical of most days with persistent stratification

which we observed during the study period; that is, on days of persistent stratification, vertical mixing generally occurred within the upper half of the water column only.

It is clear from this scenario that whether persistent stratification occurs or not is of enormous significance for the vertical distribution of phytoplankton and for the transfer of nutrients and dissolved oxygen through the water column. A useful parameter for defining whether persistent stratification occurred on a particular day is ΔT_{\min} , which is the minimum daily difference in measured temperatures between the top and bottom thermistors on a thermistor chain. If $\Delta T_{\min} = 0$ then mixing had occurred from the surface to the bottom at some time during the 24-hour period. In this circumstance, we expect that phytoplankton, nutrients, and dissolved gases would have been distributed uniformly through the water column sometime during the day. If $\Delta T_{\min} > 0$ then the water column was persistently stratified on that particular day and the amount of vertical mixing would have been limited.

Figures 4.3a and 4.3b show measured ΔT_{\min} at TC-1 versus discharge through Maude Weir for the summers 1993/1994 and 1994/1995. Both summers show the same relationship between the occurrence of persistent stratification and discharge. As expected, high values of ΔT_{\min} are associated with low discharges. Discharges greater than 1000 ML d⁻¹ always caused ΔT_{\min} to be reduced to zero within a day, but it is difficult to gauge precisely how much discharge is necessary to destroy persistent stratification. On February 8 and 9, 1994 the discharge of 657 ML d⁻¹ was not large enough to reduce ΔT_{\min} to zero in two days, but during this period the degree of persistent stratification was diminished substantially. Perhaps if this discharge had been maintained for another day, ΔT_{\min} would have been reduced to zero.

It is apparent from the stratification behaviour observed during March 1995 that low discharge does not guarantee the presence of persistent stratification. For all but the last three days of this month discharges were less than 250 ML d⁻¹, yet on six days within this period ΔT_{\min} was zero. We

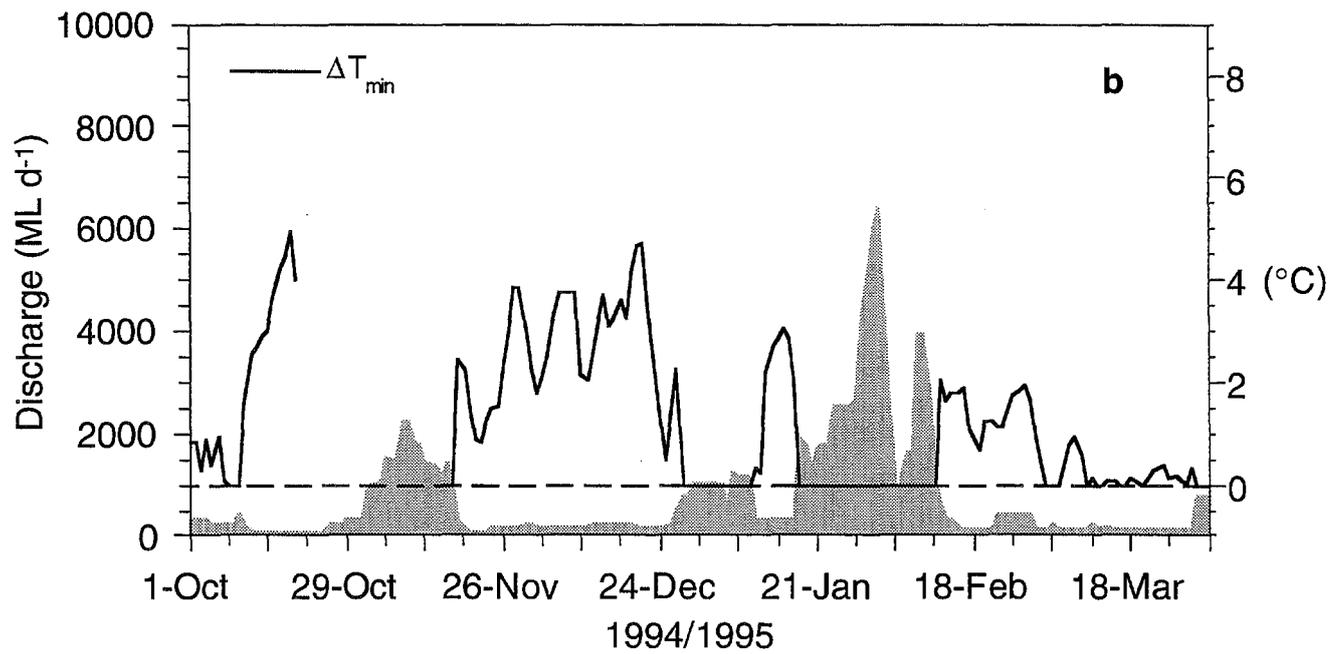
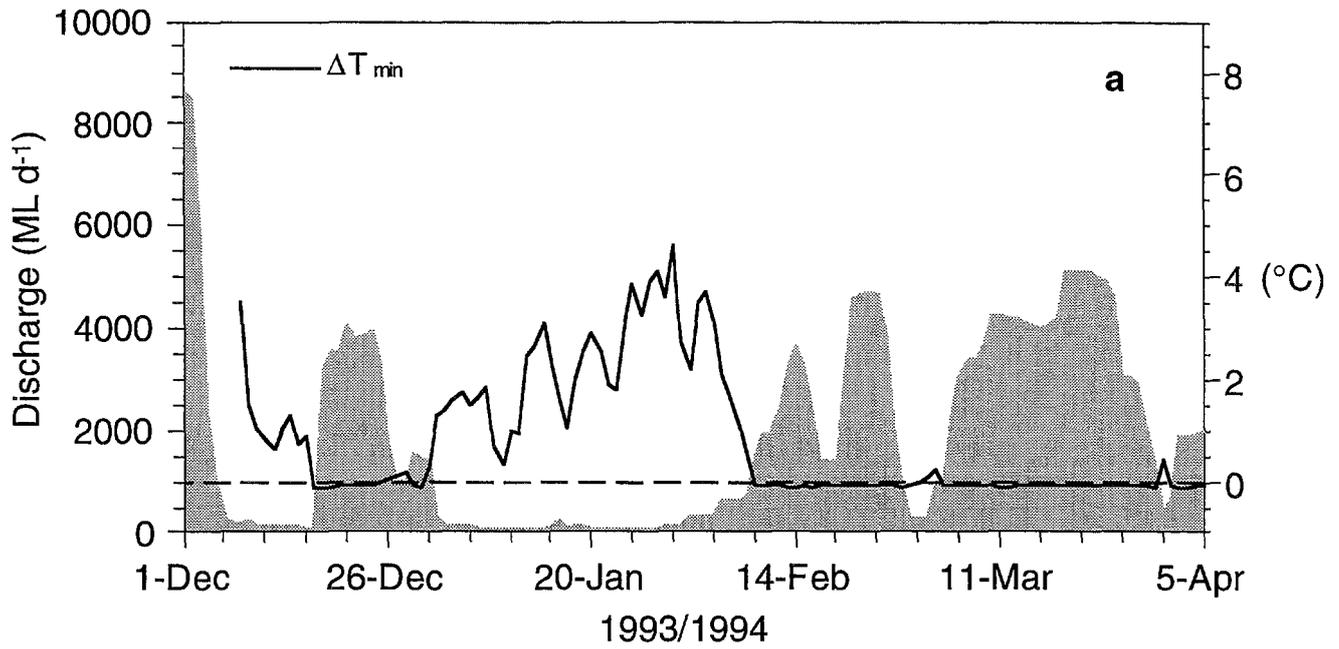


Figure 4.3 Discharge through Maude Weir (shaded) and ΔT_{\min} (solid line) at TC -1. A discharge of 1000 MLd^{-1} and $\Delta T_{\min} = 0$ are indicated by the horizontal dashed line.

expect that stratification is dependent on the heat fluxes across the water surface, on wind mixing, on the temperature of the water released from Hay Weir as well as on the turbulence generated by the flow over the bottom. By March, 1995, conditions were not as conducive to the formation of stratification as they had been earlier in the year due to lower sun elevations and cooler air temperatures reducing the heat flux into the water column. Siphons installed on the weir during this month probably played a small role in diminishing the degree of stratification. Nevertheless, during the summer months at least, our study indicates that the presence or absence of persistent stratification depends primarily on the discharge. When the discharge exceeded 1000 ML d^{-1} (flow speed $\sim 50 \text{ mm s}^{-1}$) the water column was completely mixed during the night even though solar radiation usually caused some stratification in the upper part of the water column during the day.

In terms of the stratification behaviour of the weir pool, we shall define discharges less than 1000 ML d^{-1} as low discharges; discharges greater than 1000 ML d^{-1} as being high discharges.

b) Residence Times

i) ADCP Measurements

It is well known that the character of the discharge through a dam is affected by the stratification in the impoundment behind the barrage. In particular, the depth range through which withdrawal occurs is diminished by stratification. Under stratified conditions extra energy is required to draw lighter fluid down, and to raise heavier fluid up, to the withdrawal depth. It is expected that the strong stratification in Maude Weir pool at times would cause the outflow under the weir gates to be derived preferentially from the deeper parts of the water column. We wished to determine the extent to which the through-flow of surface water carrying the *Anabaena* was stalled under stratified conditions in the weir pool.

The currents through the water column were measured using an ADCP mounted on the

bottom looking upwards at station TC-1 located 300 m upstream from the weir. The ADCP measures currents at 0.5 m intervals from the surface to the bottom using an acoustic measurement technique (Appendix A). The ADCP measurements were obtained for a total period of six weeks between January and March 1995 (Figure 3.4). Figure 4.4 shows the along-channel component of velocity derived from the ADCP record for a period of low discharge (350 ML d^{-1}). Positive velocity is towards the weir. Two days before the start of this record, the discharge had been reduced from 1150 ML d^{-1} and on January 17 the discharge was increased from 350 ML d^{-1} to 1930 ML d^{-1} (Figure 4.1). Also shown in Figure 4.4 are the temperature contours obtained from the thermistor chain at TC-1.

At the beginning of the record shown, both the temperatures and velocities were uniform from surface to bottom. One would expect flows through the weir pool to have been approximately uniform with depth when the water column was not stratified. By the following day, persistent stratification had set in. The depth of the main thermocline (the 26°C isotherm, say) gradually deepened with time through the low discharge period. At the same time, the flow through the weir pool became more strongly concentrated near the bottom. During the low discharge period, secondary diurnal stratification occurred within the top metre of the water column. Also, we see that there was some diurnal variability in the velocities near the water surface. At times surface velocities were negative, that is the flow was upstream away from the weir. Usually this happened in the morning. An analysis of the wind records from the raft at TC-1 suggests that the diurnal fluctuations in surface currents were due primarily to the winds.

When the discharge was increased to 1930 ML d^{-1} in the afternoon of January 17 the currents at all depths immediately increased. The deeper isotherms changed

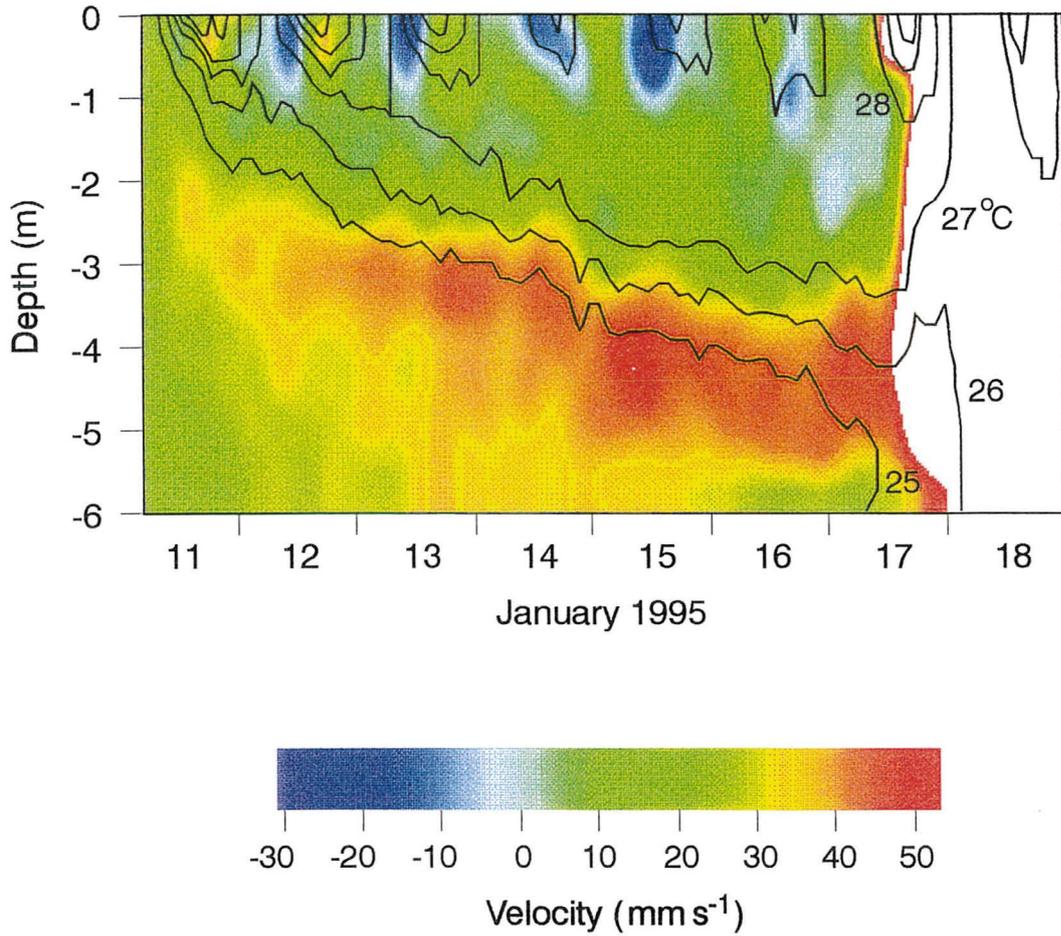


Figure 4.4 ADCP measured velocities and measured temperatures at TC-1. White region represents velocities $>50 \text{ mm s}^{-1}$, positive velocity is towards weir.

depth soon afterwards, but the surface stratification remained intact for some hours until it had been reduced by night-time cooling across the water surface. Clearly the mixing which destroyed the stratification was derived from turbulence generated at the bottom of the weir pool. By the morning of January 18 the stratification had been eliminated entirely even though diurnal stratification was evident after this time.

Figure 4.5 shows the profiles of ADCP measured currents averaged over 24 hours for January 12 and 16, 1995 and for February 15 and 27, 1995. The latter two profiles were taken from the second section of ADCP record when conditions in the weir pool were also stratified. All four profiles show that the majority of the discharge through the weir occurred at depth. In the top 1.5 to 2 m, which is where we observed the *Anabaena* to be concentrated under stratified conditions, the velocities shown for the profiles taken on January 12 and 16 were generally less than about 10 mm s^{-1} . By contrast the velocities at depth exceeded 35 mm s^{-1} on both days. Even though the flow speeds above 2 m on February 15 and 27 declined towards the surface, closer to the surface their magnitudes increased. On February 15, the surface flow velocity was 56 mm s^{-1} . On February 27 the surface flow velocity reached -13 mm s^{-1} . The strong surface currents on February 15 were certainly due to vigorous easterly winds experienced on that day, whereas the surface current away from the weir on February 27 was due to a westerly wind. On the days shown and on most of the other days for which we have ADCP measurements, it appears that the direction and magnitude of the near surface currents in the weir pool under stratified conditions had more to do with the wind strength and direction than with a flow pattern imposed by the discharge through the weir.

On several occasions, we observed that scums (sometimes cyanobacteria, sometimes

pollen) floating up against the weir under calm conditions early in the morning were dissipated upstream when westerly winds picked up later in the morning. However, we still expect that the average pattern of discharge under stratified conditions through Maude to be one in which the surface layer is stalled and most of the discharge occurs at depth.

ii) Model Predictions

ADCP measurements are available for 1995 only, but here we extend our discharge analysis to the summer of 1993/1994 using a model of selective withdrawal (Hocking *et al.*, 1988). The model predicts the composition of the discharge from a reservoir from knowledge of the temperature profile in the interior of the reservoir and from the volume and depth of the discharge. In our application of the model we specified the temperature profile to be that measured by the thermistor chain at TC-1.

Figure 4.6 compares the predictions with measurements for a period coincident with the ADCP measurements shown in Figure 4.4. Also shown are the average temperatures of the water column, the near surface water temperature and the near bottom temperature. For the whole period of the record shown, the predicted and measured discharge temperatures are within 0.5°C of one another; usually, the temperature difference is much less than this. If the withdrawal was occurring uniformly from all depths, the temperature of the discharge would be the average water column temperature, but both measured and predicted temperatures are substantially less than this during stratified conditions, indicating that the majority of the discharge occurred at depth. These results are consistent with the description of the discharge already derived from the ADCP measurements.

Figure 4.7 shows the ratios of the average withdrawal speeds, based upon the weir

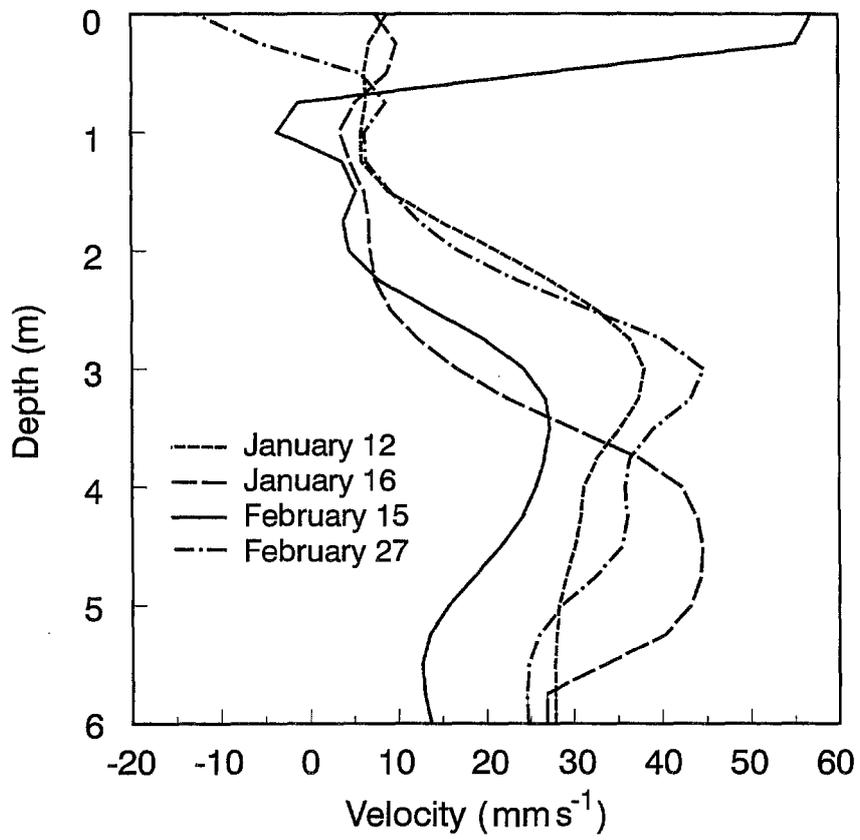


Figure 4.5 ADCP measured velocities at TC-1 during 1995.

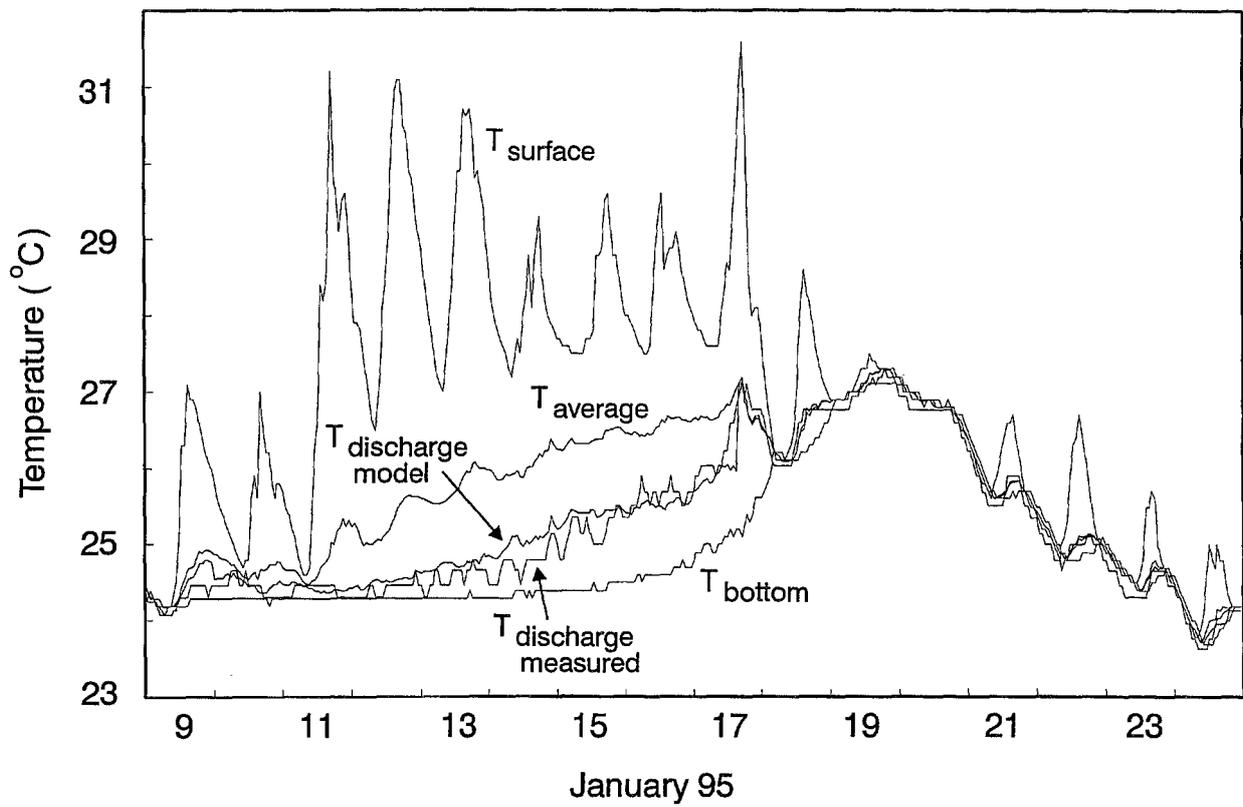


Figure 4.6 Comparison between model-predicted and measured temperatures in the Maude Weir discharge. Also shown are measured surface, bottom and depth-averaged temperatures at TC-1.

discharge to the withdrawal speeds for the top 2 m of the water column. These were estimated using the theory of Hocking *et al.* (1988) for the periods when we obtained thermistor chain measurements at TC-1. A value of unity for the ratio means that the discharge is drawn uniformly from all depths. If the ratio is much greater than one, the discharge is drawn primarily from the deeper parts of the water column. Because the measured stratification at a particular discharge showed considerable variability, these ratios are not a fixed function of discharge. Nevertheless, generally as the discharge decreased the values of the ratio increased. For discharges greater than 300 ML d⁻¹ the ratios are calculated to be around 2 or less; that is, the discharge is drawn fairly uniformly from all depths in the weir pool. For smaller discharges, the ratios tend to increase sharply so the withdrawal becomes strongly concentrated from the bottom half of the water column.

The volume of Maude Weir pool when full is 5000 ML. The bulk residence of the weir pool when full is therefore

$$T_r = 5000/D \quad (4.1)$$

where T_r is measured in days and the discharge D is measured in ML d⁻¹. Thus, for a Maude base discharge of 350 ML d⁻¹, the bulk residence time of water in the weir pool is calculated to be fourteen days. Under stratified conditions, when discharges are less than 300 ML d⁻¹ or so, the water from the weir pool is withdrawn preferentially from depth. Hence the effective residence times of the surface waters where the *Anabaena* is found will be greater than those calculated from Equation 4.1.

c) Phytoplankton Measurements

i) Abundances

The phytoplankton counts from the three sampling seasons 1992/1993, 1993/1994, and 1994/1995 were co-dominated by

Anabaena and *Melosira*. Eleven *Anabaena* taxa were recognised (Baker, 1991): *A. affinis*, *A. aphanizomenioides*, *A. circinalis*, *A. flos-aquae* f. *flos-aquae* morphotypes 1 and 2, *A. inequalis*, *A. solitaria*, *A. spiroides* f. *spiroides* morphotypes 1 and 2, *A. spiroides* f. *crassa* and *A. spiroides* v. *minima*. The most commonly observed taxa were *A. solitaria*, *A. circinalis* and *A. spiroides* f. *spiroides* morphotypes 1 and 2. Interestingly, all *Anabaena* species largely co-varied and there was no discernible succession between the species (Figure 4.8).

In the three years of the study, as in the prior two years research under NRMS grant N103 (Jones, 1993), the species dominance of the phytoplankton appeared to be strongly linked to changes in weir discharge and surface water temperature (Figures 4.9 a, b, and c). The typical seasonal phytoplankton populations and successions were:

Winter Discharges typically low as headwater releases are kept to a minimum (no irrigation), except for times following major rainfall events in the catchment. Little phytoplankton present, but tending to be dominated by *Melosira*.

Spring In early to mid-spring, discharges are often very high as snows melt in the Snowy Mountains—water temperatures are still low to moderate. Irrigation is yet to commence. Little phytoplankton present. In late spring, irrigation demand commences. Discharges in the lower Murrumbidgee start to decrease, although the exact timing of this decrease depends largely on the year's snowfall. The phytoplankton in this period are dominated by the diatom *Melosira* and by colonial green algae such as *Volvox* and *Eudorina*.

Summer Discharges during the summer can range from as low as 100 ML d⁻¹ to 2000 ML d⁻¹, depending on upstream irrigation demand, rainfall in the irrigation areas (rainfall "rejections"), and routing of water from Blowering Dam via the

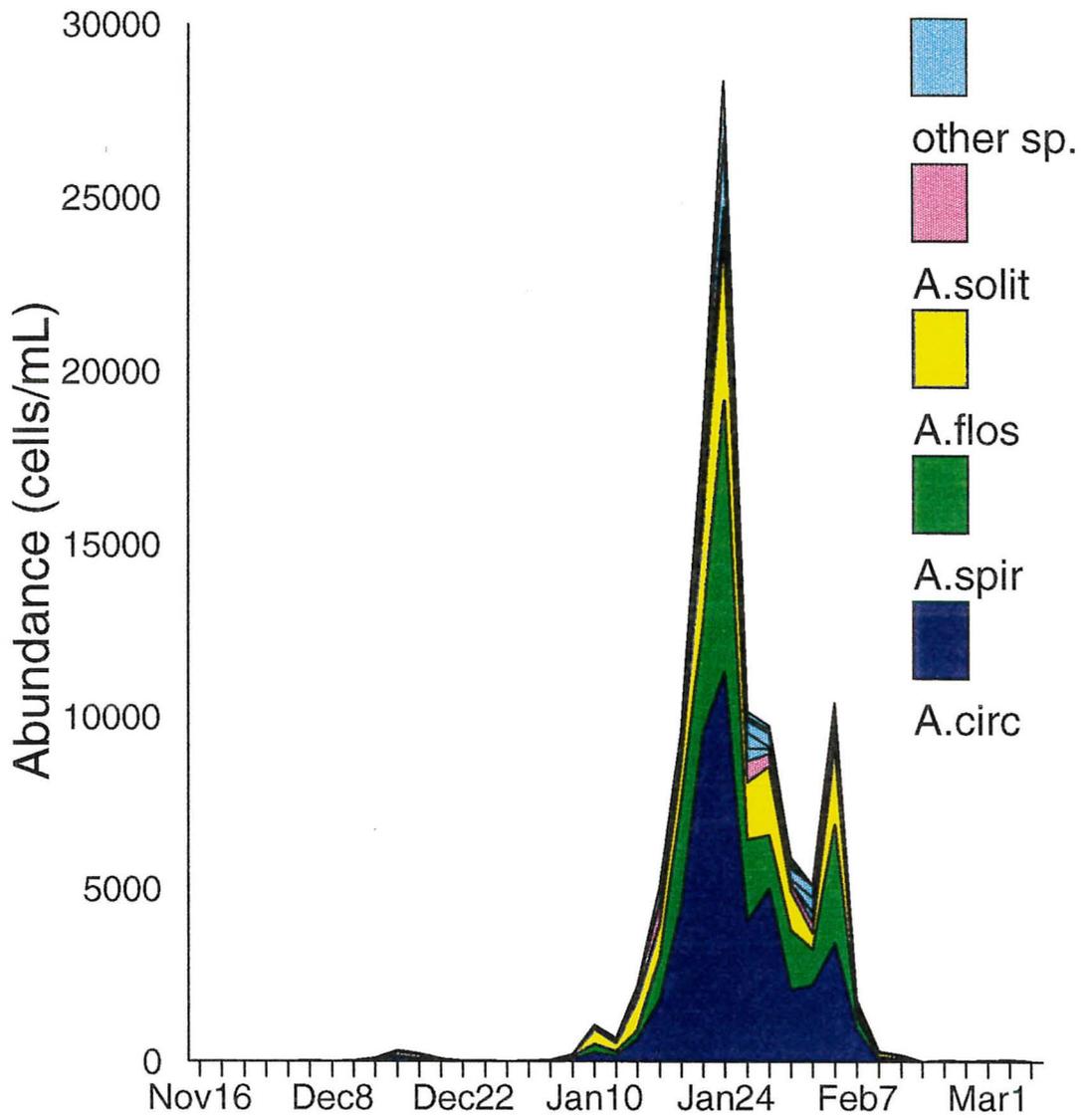


Figure 4.8 Abundance of major *Anabaena* species during summer 1993/1994.

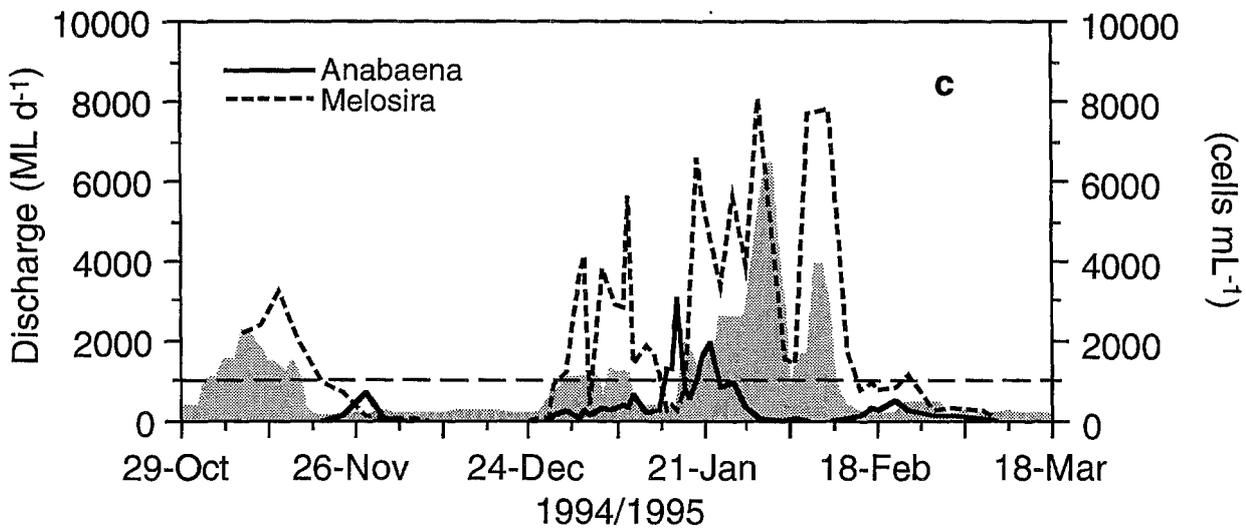
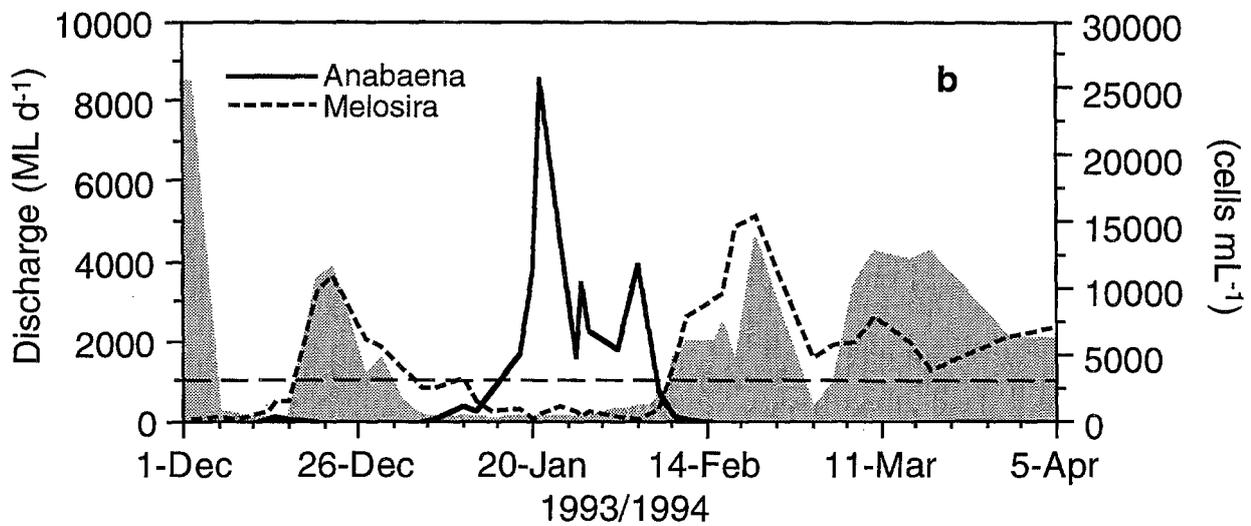
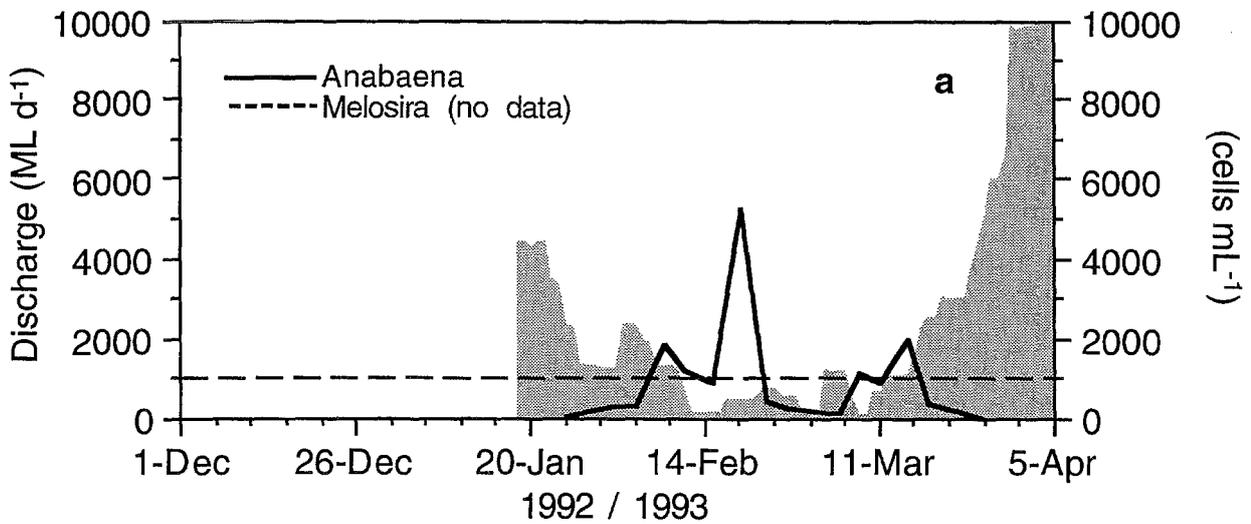


Figure 4.9 *Anabaena* and *Melosira* concentrations and discharge (shaded) through Maude Weir for the three summers of the project. A discharge of 1000 MLd⁻¹ is indicated as the horizontal dashed line.

Murrumbidgee River to South Australia. In the early summer, colonial greens tend to disappear and *Melosira* becomes dominant. If discharges drop below 500 ML d^{-1} , the water column quickly stratifies and *Anabaena* sp. population begins to increase exponentially. If discharges remain low for more than two weeks, *Anabaena* sp. become dominant, and *Melosira* are lost through sedimentation. This situation is rapidly (within one week) reversed if a sudden increase in discharge occurs. In late summer, the phytoplankton population tends to decline as the water temperature decreases.

In the summer of 1992/93, *Anabaena* abundance in Maude weir pool reached moderate levels ($1000\text{--}5000 \text{ cells mL}^{-1}$) during a brief period of low discharge in early to mid-February 1993, but *Melosira* dominated during the rest of the summer (Figure 4.9a). In the summer of 1993/94, two periods of low discharge ($< 500 \text{ ML d}^{-1}$) were experienced. Through the first two week period in mid-December, the concentrations of both *Anabaena* and *Melosira* increased, but the increase in *Anabaena* sp. appeared to be arrested by a rapid increase in discharge in mid-December (Figure 4.9b). The second low discharge period (late December to early February), which lasted six weeks, saw the *Melosira* concentrations undergo a steady exponential decline from a high of around $10\,000 \text{ cells mL}^{-1}$ to approximately $100 \text{ cells mL}^{-1}$, while the *Anabaena* concentration underwent a steady exponential increase to concentrations of around $2000\text{--}10\,000 \text{ cells mL}^{-1}$ during the first half of this period. The observed net growth rate of 0.37 d^{-1} corresponded to a doubling time of 1.9 days. Thereafter *Anabaena* concentrations remained fairly constant for the second half of the low discharge period. When discharges increased to above 2000 ML d^{-1} in mid-February 1994, *Anabaena* concentrations declined and *Melosira* concentrations increased. This

extended low discharge period will be discussed in more detail in section 4e.

During the summer of 1994/1995, abundances of *Anabaena* and *Melosira* again underwent considerable fluctuations which appeared to be related to variations in discharge through Maude Weir (Figure 4.9c). The discharge dropped in late November and, as in the previous summers, *Melosira* abundance underwent an exponential decline and *Anabaena* abundance began to increase exponentially ($\mu = 0.35 \text{ d}^{-1}$). This drop in *Melosira* and rise in *Anabaena* concentrations after the discharge dropped to around $150\text{--}200 \text{ ML d}^{-1}$ in mid-November are consistent with the pattern observed previously. However, after rising for the first two weeks of the low discharge period, *Anabaena* concentrations plummeted to very low levels ($\sim 1 \text{ cells mL}^{-1}$) in mid-November where they remained for the rest of the low discharge period. This was by far the lowest *Anabaena* abundance observed during a spring or summer period throughout the entire study.

Concentrations rose sharply for both *Anabaena* (to $100\text{--}300 \text{ cells mL}^{-1}$) and *Melosira* (to $2000\text{--}5000 \text{ cells mL}^{-1}$) when the discharge increased to 785 ML d^{-1} on December 28, 1994. This increase in abundance was too rapid (2.4 d^{-1}) to be explained by cell growth, and must be indicative of advection of a phytoplankton population from upstream. A period of high discharge exceeding 2000 ML d^{-1} at the end of January was associated with a rapid decline in *Anabaena* numbers. During the low discharge period which followed, *Anabaena* concentrations rose for the first ten days to around $700 \text{ cells mL}^{-1}$ then declined. Observed net growth rate was approximately 0.39 d^{-1} .

The maximum depth-averaged concentration of *Anabaena* in Maude weir pool appeared to be around $20\,000 \text{ cells mL}^{-1}$ and the

maximum depth-averaged concentration of *Melosira* was about 10 000 cells mL⁻¹. Our measurements show that the biovolume of a typical *Anabaena* cell is approximately 140 µm³ and that of *Melosira* about 1340 µm³. Chemical analyses during separate times of *Anabaena* and *Melosira* abundance indicate cellular chlorophyll-a contents of 0.5 pg cell⁻¹ for *Anabaena* and 2 pg cell⁻¹ for *Melosira*. Thus, the maximum population of *Melosira* appears to be 2 or 5 times larger than that of *Anabaena* on a biomass (chlorophyll-a) or biovolume basis respectively.

ii) Relationship Between Cyanobacterial Abundance and Discharge

It was clear from the data obtained during this three year study, and from the previous related NRMS project (Jones, 1993), that discharge was the primary factor controlling the abundance of cyanobacteria in the spring and summer. Two stages in population succession could be easily recognised in relation to discharge and stratification (see also Figure 4.10):

(a) High spring, summer discharges (> 1000 ML d⁻¹) when *Melosira* was the dominant phytoplankton species, along with colonial greens such as *Eudorina* (mostly spring/early summer only). *Anabaena* concentrations always low (< 100 cells mL⁻¹).

(b) Low summer discharges (< 500-1000 ML d⁻¹) when *Anabaena* dominated (2000–20 000 cells mL⁻¹) and *Melosira* declined to low levels (100-200 cells mL⁻¹).

If the abundance of *Anabaena* is plotted against daily discharge, no obvious relationship between the two can be discerned. However, examination of the data for the six week period in January 1994 reveals a time lag between the onset of low discharge and peak *Anabaena* abundance (Figure 4.11a). If the discharge is

retrospectively averaged and *Anabaena* abundance plotted against the average discharge over a range of preceding time periods, a peak coefficient of variation is observed at a 14-day averaging period (Figure 4.11b). Thus, the hysteresis in the data can be compressed to give a linear relationship between *Anabaena* abundance and 14-day average discharge ($r^2 = 0.894$) (Figure 4.11c).

Over four years of monitoring, 14-day averaged discharge explained about 60% of the variation in *Anabaena* abundance (Figure 4.12). Furthermore, during the five years of our combined monitoring projects *Anabaena* abundances of > 5000 cells mL⁻¹ occurred only when discharges had been < 500 ML d⁻¹ for fourteen days. However, it is important to be aware that this does *not* mean that a cyanobacterial bloom will occur on *every* occasion when these low discharge conditions are met, rather that these are requisite conditions for bloom formation.

iii) Vertical Distribution of Phytoplankton

Vertical distributions of *Anabaena* and *Melosira* in Maude Weir pool were studied by taking samples at set depths at regular time intervals over a 24-hour period at fixed sites. These 24-hour sampling studies were undertaken on three occasions during low discharge periods. Figures 4.13a and 4.13b show results obtained from the 24-hour study undertaken on January 19/20, 1994 at a site located about 1 km upstream from Maude Weir. For this study, samples were collected at 4-hour intervals. By January 19, discharges had been low for more than two weeks and the water column had been persistently stratified for all of this period. *Anabaena* concentrations were increasing and *Melosira* concentrations had been steadily decreasing (Figure 4.9b).

Although the concentrations of phytoplankton at a particular depth varied through the 24 hours, the pattern of concentration distribution was always the

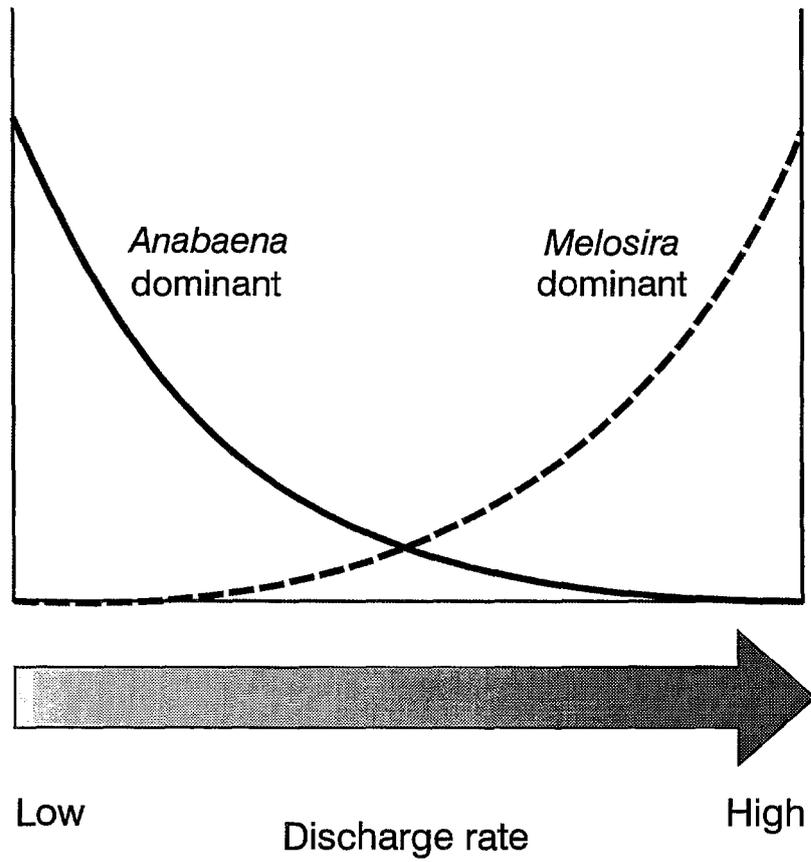


Figure 4.10 Schematic of the relationship between algal growth and discharge in Maude Weir pool.

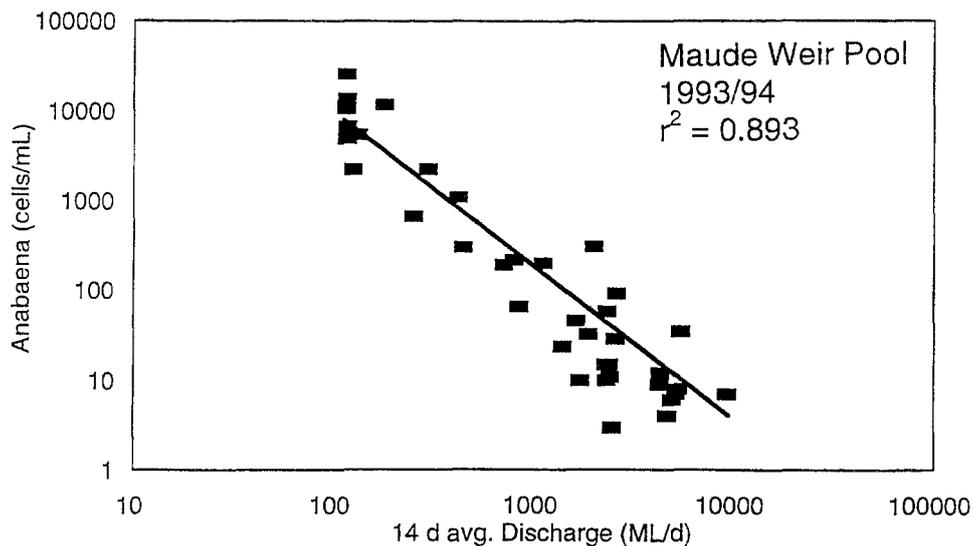
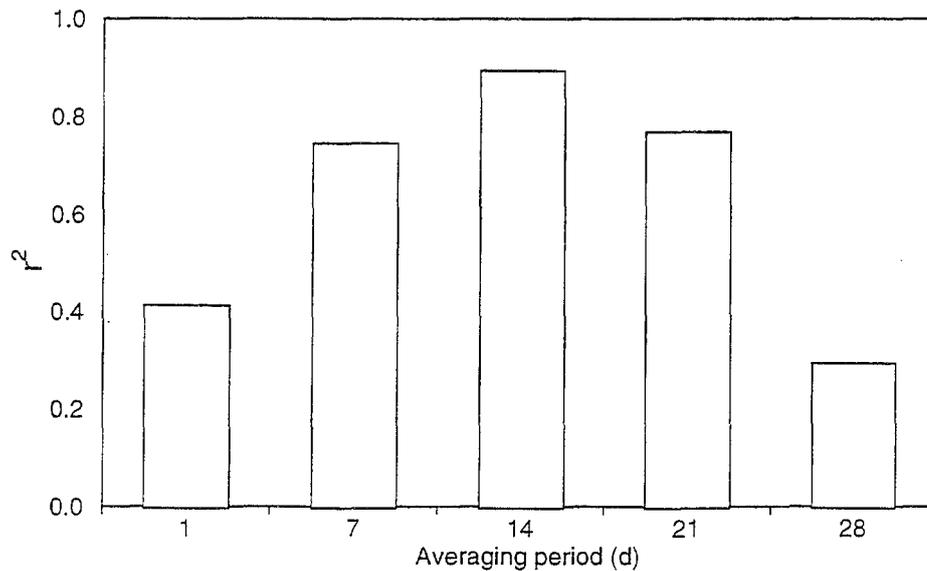
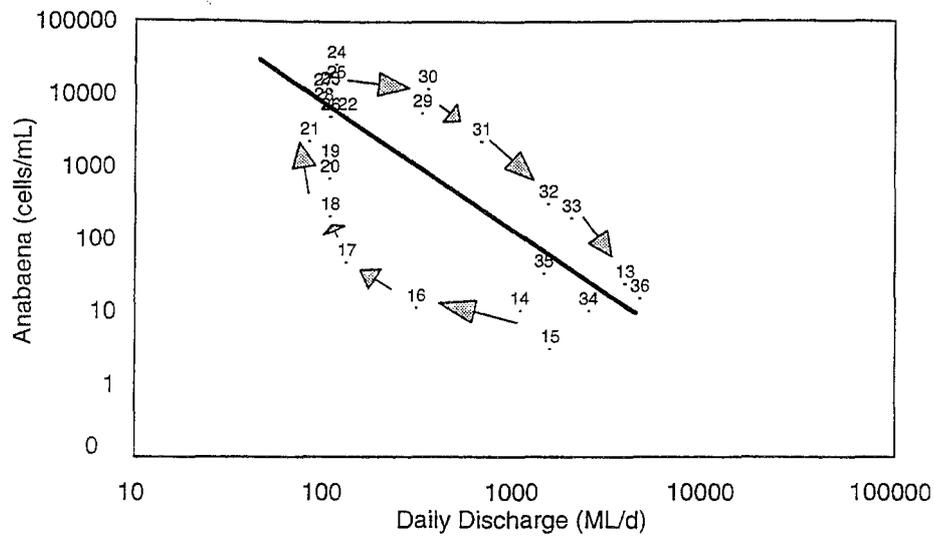


Figure 4.11 (a) *Anabaena* abundance plotted against daily discharge with sequential samples numbered, (b) coeff. of variation against averaging period, (c) *Anabaena* abundance as a function of 14 day average discharge

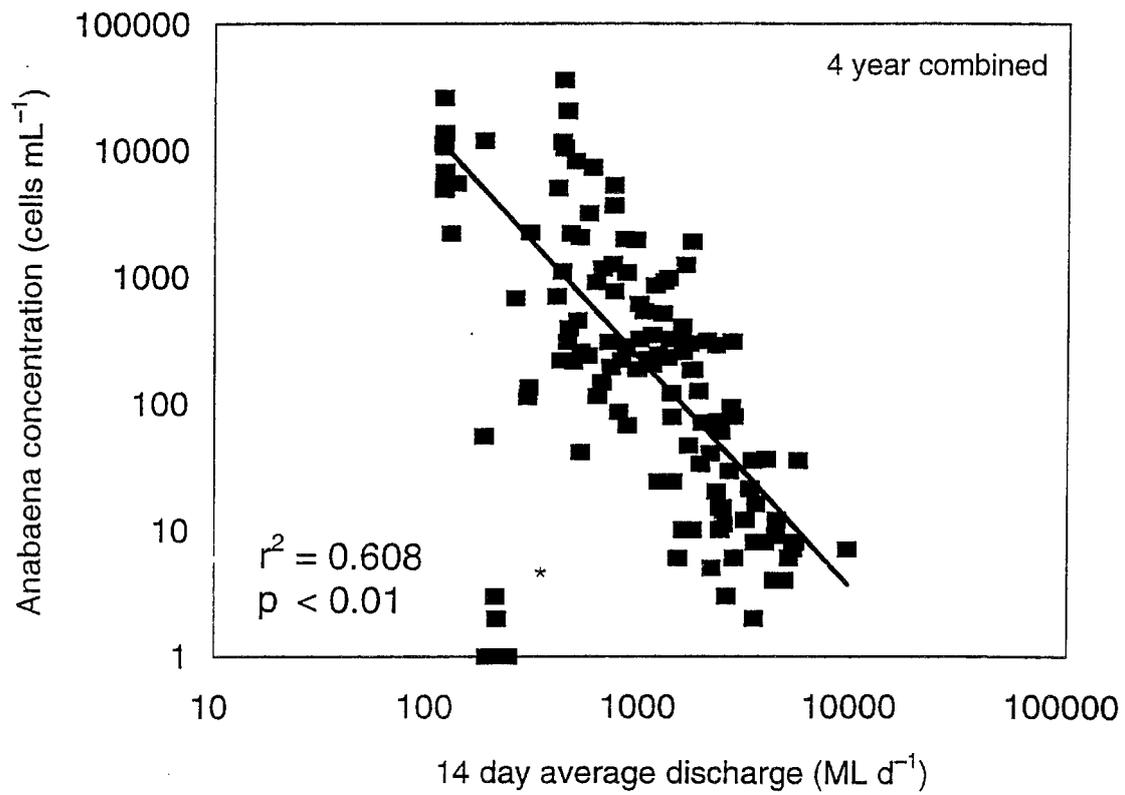


Fig. 4.12 *Anabaena* abundance (cells mL⁻¹) as a function of 14-d average discharge from 1991/92 to 1994/95. * Low abundance data from December 1994 not included in regression.

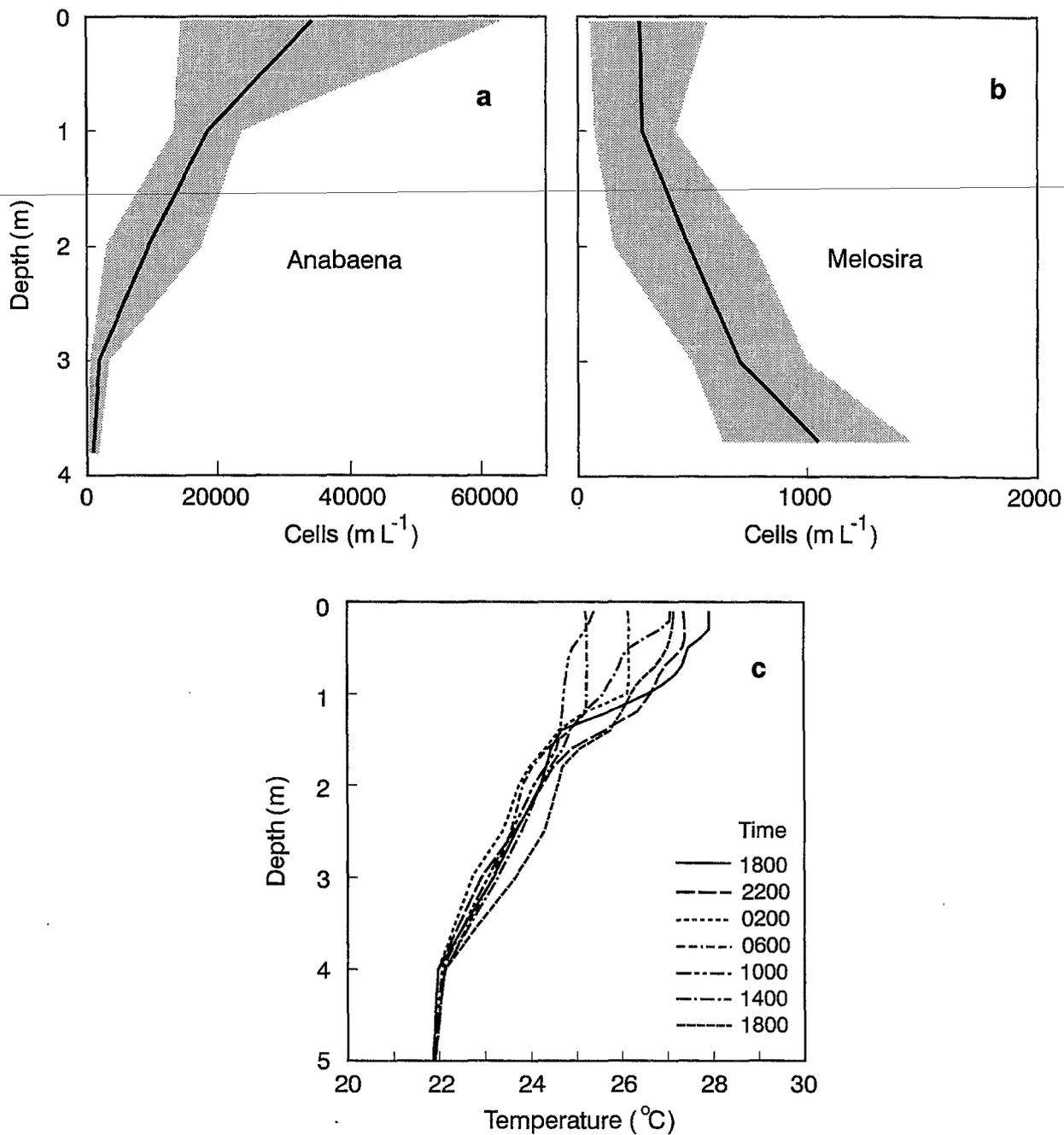


Figure 4.13 **a,b)** Average profiles of algal concentrations obtained during the 24-hour sampling study on January 19/20, 1994, 1km upstream from Maude Weir. Shaded regions show ranges of concentrations measured. **c)** Temperature profiles measured during the same period at TC-1.

same. Concentrations of *Anabaena* were always highest at the surface, decreasing steadily with depth. The average surface (top 1–2 cm) concentration of *Anabaena* was 34 000 cells mL⁻¹, decreasing by a factor of 53 to 640 cells mL⁻¹ at 3.8 m depth. This top-heavy distribution of *Anabaena* highlights how surface “bottle” sampling can substantially overestimate the mean concentration of cyanobacteria in a water body. On average, *Melosira* concentrations increased towards the bottom although individual profiles did not all exhibit a steady increase with depth. The average concentration of *Melosira* increased from 265 cell mL⁻¹ to 1040 cells mL⁻¹, a factor of four. A top heavy *Anabaena* distribution and a bottom heavy *Melosira* distribution are exactly as expected under stratified conditions when vertical mixing is limited. The temperature profiles in Figure 4.13c show that during the 24-hour study on January 19/20, 1994, mixing was largely confined to the top 1.5 m of the water column. We attribute the depression in the depth of the thermocline at 1800 on January 20 to wind tilting of the thermal structure rather than to vertical mixing. The pattern of *Anabaena* and *Melosira* distribution shown in Figure 4.13a and 4.13b was also evident in other depth profiles of phytoplankton distribution obtained under stratified conditions.

An interesting observation to arise from the 24-hour study on January 19, 1994 was the formation and accumulation of surface scums during the night, and the subsequent dispersal of these scums the following morning. This phenomenon can be clearly seen in Figure 4.14a which shows the concentration of *Anabaena* in the surface 1–2 cm during the day and night. In the evening, this surface population was blown towards the leeward (north) shoreline by a light southerly wind, where it accumulated between 2200 and 0200 (Figure 4.14b). This caused a decrease in the surface *Anabaena* abundances at the sampling station in

mid-stream. The following morning (between 0600 and 1000), freshening winds from the east dispersed the scum back out across the river, leading to temporary increases in surface *Anabaena* abundances at the sampling station. By 1400 the cells had apparently been mixed back into the water column.

Subsequent examination of similarly orientated river reaches upstream confirmed the general observation that night-time surface scum accumulation along the leeward shoreline, and subsequent morning dissipation, is a regular diurnal feature of the river *Anabaena* population under low discharge/low mixing conditions. Wind-tunnel experiments and lake observations have shown that buoyant phytoplankton will tend to accumulate on the surface as a scum if wind speeds are less than about 2–3 m s⁻¹ (7–11 kph) (Webster and Hutchinson, 1994). Night-time scum formation and day-time dispersal in Maude Weir pool were probably a consequence of diurnal variations in wind strength. Winds at Maude tended to be lighter at night than during the day. If winds were light during the day as well, surface accumulations of *Anabaena* would not be mixed back into the water column at all. In this situation a scum would accumulate over several days where it could be subject to high rates of photooxidative cell lysis (Walsh *et al.*, 1996a, b). This represents a mechanism for reducing the growth of an *Anabaena* population in what might otherwise constitute favourable conditions.

iv) Horizontal Distribution of Phytoplankton During the summers of 1993/1994 and 1994/1995 we estimated vertical profiles of chlorophyll fluorometrically at a series of sites along the 6 km long section upstream from Maude Weir. From these profiles we are able to examine the longitudinal variation in chlorophyll concentration as a surrogate for phytoplankton concentration. Figure 4.15a shows the contours of chlorophyll and temperature obtained at

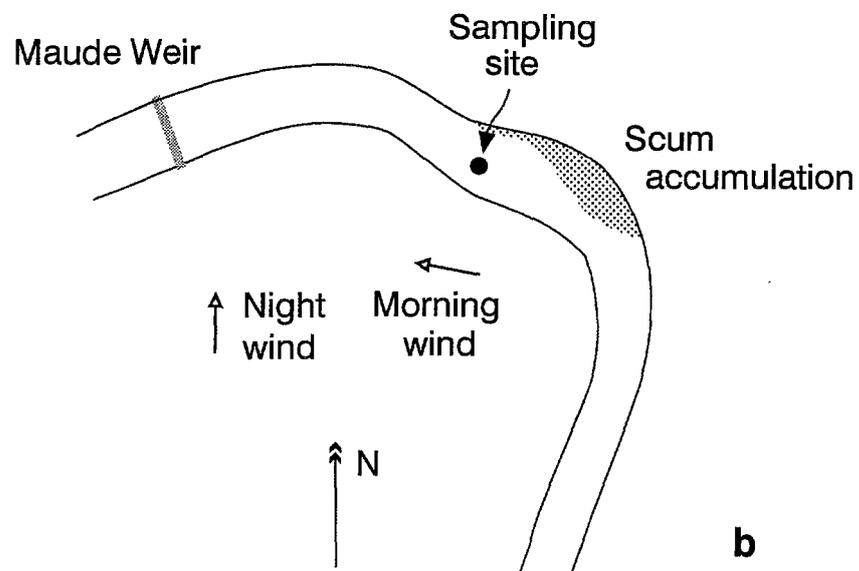
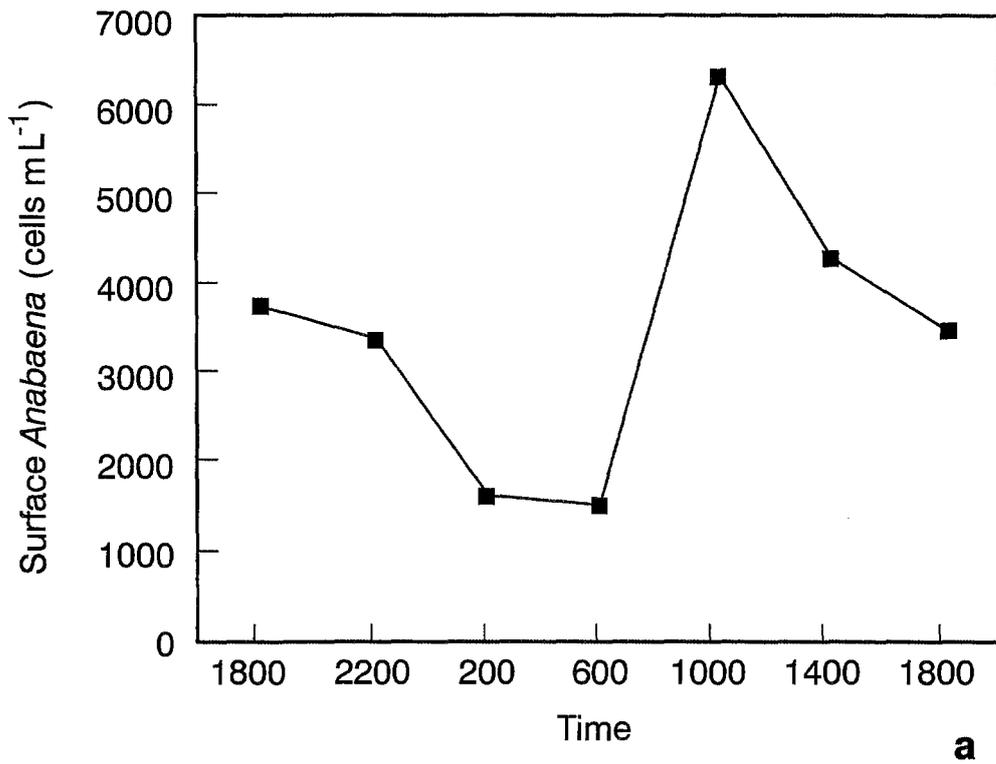


Figure 4.14 a) Near-surface *Anabaena* concentrations measured on January 19/20, 1994, 1km upstream of Maude Weir.
 b) Schematic showing winds and scum accumulation during this time.

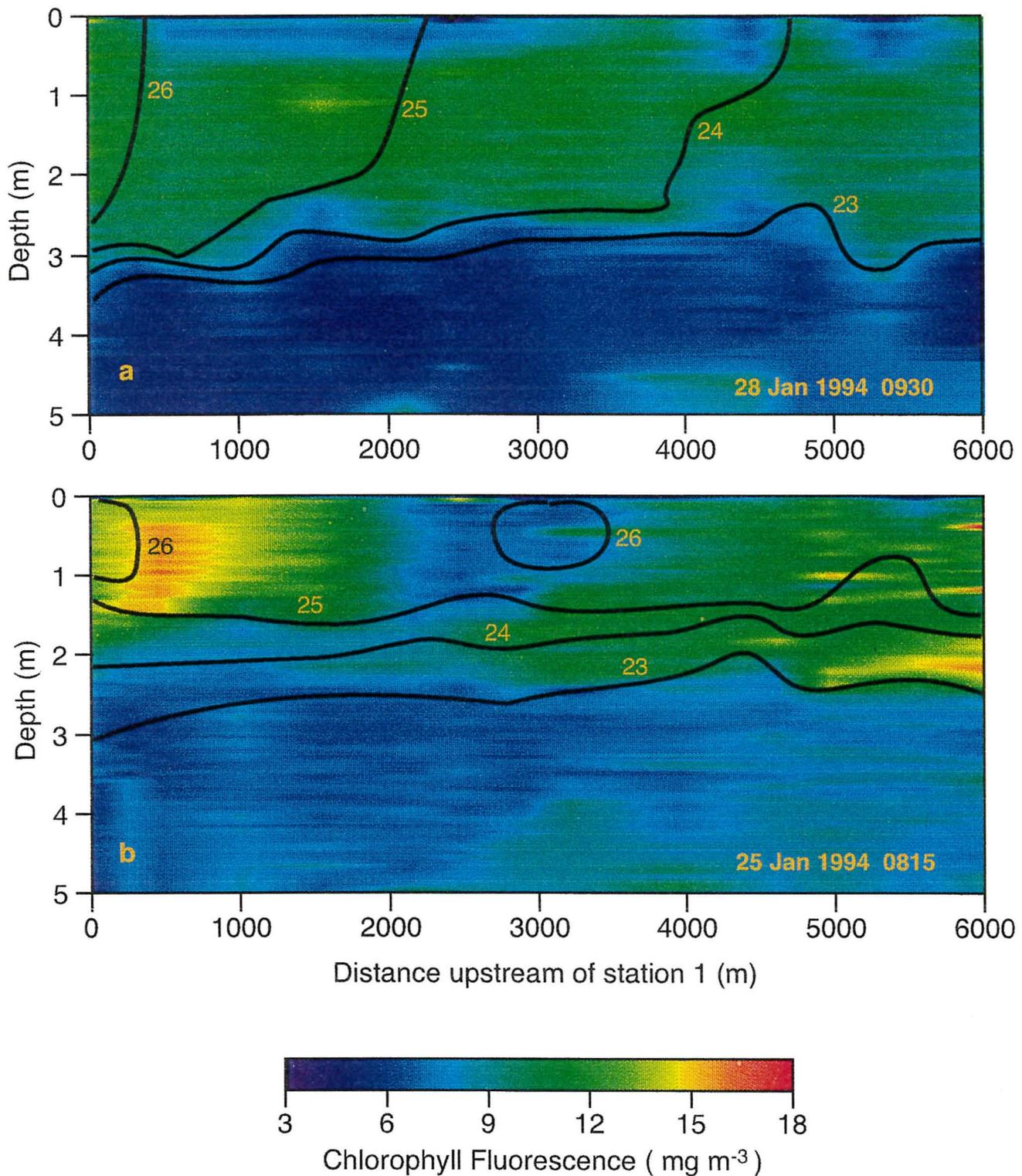


Figure 4.15 Longitudinal cross-section of chlorophyll fluorescence (as equivalent Chl-a concentration) and temperature contours showing the 23, 24, 25 and 26 °C isotherms.

0930 on January 28, 1994 as an example of the results obtained under low discharge conditions. The higher levels of chlorophyll in the upper part of the water column would be mostly due to *Anabaena*; the lower levels below 3 m or so would be mostly due to *Melosira*. Note that the apparently reduced levels of chlorophyll near the water surface are due to a reduction in fluorometric response to chlorophyll caused by the photoadaptation of the phytoplankton to light and do not reflect reduced phytoplankton concentrations there. On this particular day, winds were moderately strong and the thermocline was in the process of deepening due to active mixing in the surface layer. In the figure one can see that the bottom of the *Anabaena* zone approximately coincides with a temperature contour, indicating that the mixing responsible for the vertical transport of heat is also mixing the phytoplankton. Horizontal variations in chlorophyll profiles appear to be associated primarily with variations in the depths to which the surface layer has been mixed. The vertically integrated chlorophyll concentration varied by less than 5% through the fourteen stations at which profiles were taken.

The horizontal distributions of chlorophyll measured on most of the transects tended to be fairly uniform, as are those shown in Figure 4.15a, but sometimes horizontal variations were substantially larger. The transect taken at 0815 on January 25, 1994 (Figure 4.15b) shows surface layer chlorophyll concentrations to be a maximum ($16 \mu\text{g L}^{-1}$) 600 m upstream from the weir and to be a minimum ($8 \mu\text{g L}^{-1}$) about 2500 m upstream. Winds were light ($< 1 \text{ m s}^{-1}$) prior to the time of the transect. We might expect variations in phytoplankton concentrations to be more significant under light wind conditions when scum formation is more likely. Scums which represent a concentrated mass of *Anabaena* can be readily blown from one location to another by the wind. The analysis of two series of

surface samples (top 2 cm), collected in late January 1994 at three locations across the channel at each of eleven stations spread between Maude Weir and 6 km upstream, showed the lateral variations in *Anabaena* concentration to be statistically insignificant.

Horizontal variations in *Anabaena* population may be caused by another mechanism besides the advection of a surface scum by the wind. The interaction between circulation induced by wind, turbulent mixing, and the tendency of phytoplankton to float can cause phytoplankton accumulations against a downwind shore (Webster, 1990). The length scale for the horizontal variations in concentration decreases with wind speed. In other words this theory predicts less spatial uniformity in a floating phytoplankton population at lower wind speeds.

d) Verification of the Stratification-Growth Hypothesis

The concentration pattern, which is consistent over the three study periods, is that *Anabaena* concentrations were always depressed under high discharge conditions, but also that concentrations usually increased under low discharge conditions. We use the terms high and low discharges as being greater than or less than 1000 ML d^{-1} , which is the cutoff discharge for persistent stratification. *Melosira* numbers always tended to decline when the discharge was low. These relationships are consistent with our growth-stratification hypothesis outlined in the Introduction. High discharge enhances vertical mixing which produces an environment not conducive to *Anabaena* population growth. Low discharges are associated with reduced vertical mixing in the weir pool which allows the *Anabaena* to accumulate near the water surface where they can flourish. Low discharge also causes the *Melosira* to sink to the bottom where they are denied the light necessary for population growth.

For Maude Weir pool, we suggest that a discharge of 1000 ML d^{-1} also represents a significant transition in effective residence times for the

Anabaena population within the weir pool. It took about two weeks for *Anabaena* to grow to problem concentrations during the low discharge period in the summer 1993/1994. At a discharge of 1000 ML d^{-1} the bulk residence time calculated using Equation 4.1 is five days, which is not long enough to permit the *Anabaena* numbers to increase to high concentrations. As we have demonstrated in section 4b, the residence times of the surface waters where the *Anabaena* accumulate under stratified conditions should increase dramatically when stratification is established at discharges below about 1000 ML d^{-1} .

Our stratification-growth hypothesis suggests that *Anabaena* should thrive under low discharge conditions when the formation of persistent stratification would allow them to accumulate into the surface layer. During the two major periods of low discharge in the summer of 1994/1995 the *Anabaena* population first increased as our hypothesis would predict then it declined precipitously. Why should these declines have occurred?

During the first period, the *Anabaena* concentrations collapsed to about 1 cell mL^{-1} after they had increased to about $1000 \text{ cells mL}^{-1}$ during the first two weeks of the low discharge period. We suggest two possible reasons for this behaviour. Samples collected for phytoplankton analysis showed unusually high concentrations of zooplankton at this time. One explanation for the drop in *Anabaena* number is predation. The stratification during this time was stronger than at any other time during the study. Strong stratification may have permitted the accumulation of *Anabaena* into surface waters, but it also would have restricted potential replenishment of the nutrients necessary for population growth. Predation by zooplankton would be more effective in reducing phytoplankton numbers if growth rates were reduced by nutrient limitation.

The time when the *Anabaena* numbers suddenly dropped coincided with a shift in the wind direction from generally easterly to generally westerly. Winds after this direction change were weak. These conditions combined with strong stratification were

ideal for allowing *Anabaena* to float to the surface as a scum. A second explanation for the sudden drop in *Anabaena* numbers is that they floated to the surface and were blown downwind away from the sampling station near the weir. *Anabaena* numbers suddenly increased to over $100 \text{ cells mL}^{-1}$ after December 28, 1994. This increase coincides with a weakening in the westerly winds and an increase in the discharge to over 785 ML d^{-1} . As already noted, the increase was far too sudden to have been caused by growth, but could have been due to *Anabaena* being advected from upstream with the increasing flow speed and the change in wind direction.

Low discharges prevailed again from the middle of February, 1994 onward. *Anabaena* numbers increased during the first two weeks of this period and then started to decline. Persistent stratification was evident up to the beginning of March, but was intermittent after this time (Figure 4.3b). Also after the beginning of March, the measurements at TC-2 showed diurnal mixing to have been prevalent in the central section of the weir pool. We suggest that the *Anabaena* requires a prolonged period of persistent stratification to allow it to achieve and maintain dominance in the phytoplankton assemblage. Intermittent mixing of the water column would cause the *Anabaena* to mix through the water column. The relative advantage of such a floating species to light access would only be restored after a significant portion of the population had floated back into the surface layer.

e) The January 1994 *Anabaena* Bloom

The highest concentrations of *Anabaena* within Maude Weir pool occurred in January 1994. The bloom coincided with the period of the most intensive field data acquisition.

i) Antecedent Hydrodynamic Conditions

In section 4d, the persistent stratification ($\Delta T_{\min} > 0$) that accompanies low weir discharges was identified as a necessary condition for the establishment of an *Anabaena* bloom. On December 31, 1993 the release from Maude weir decreased from 1470 ML d^{-1} to 298 ML d^{-1} satisfying the

criterion for persistent stratification (Figure 4.16a). Until January 4, 1994 the discharge upstream of site 14 exceeded 500 ML d^{-1} due to irrigation releases down the Nimmie creek regulator located 6 km upstream of the weir. From January 6 to 27, the average weir discharge was just 111 ML d^{-1} after which it increased in three steps to 770 ML d^{-1} on February 7. On February 8 the discharge increased to 1490 ML d^{-1} and the persistent stratification within the weir pool was eliminated.

Figure 4.16b shows the corresponding daily maximum surface layer depths at the three thermistor chains. The surface layer depth is the depth to which the water column is isothermal. Differences in the mixed layer depths between the three thermistor chains can be attributed to differences in the local orientations of the weir pool with respect to the prevailing winds. Surface layer depths were typically 0.5–1 m deeper between January 1 to 10 than during the following four weeks due to higher-than-average winds blowing from the west.

ii) Phytoplankton Population Dynamics

The time histories of *Anabaena* and *Melosira* abundances, as well as chlorophyll-a during the period of persistent stratification, are shown in Figure 4.16c. These data are for 5 m integrated samples. Also shown is the fluorescence at 2.5 m depth until January 23 when the fluorometer was removed for use in the profiling operations. The decrease in discharge after December 26, 1993 was accompanied by a steady decrease in *Melosira* abundance (Figure 4.9b); there was insufficient turbulence to sustain high concentrations of *Melosira* in the top half of the water column. Between January 3 and 10, 1994, *Melosira* abundances and fluorescence at 2.5 m were relatively constant. The absence of a further decrease in *Melosira* abundance was likely due to the increased irrigation diversions through Cairn and Nimmie Creeks. The resulting increased turbulence levels

accompanied by deeper surface layer depths at TC-2 and TC-3 would have sustained a higher concentration of *Melosira* to within 6 km of the weir. (The travel time for a release of 100 ML d^{-1} occurring through the bottom 2.5 m of the water column would be approximately four days. Assuming a sinking velocity of 1 m d^{-1} , one would expect a significant decrease in *Melosira* abundance to lag a decrease in the diversion to Nimmie Creek by at least three days). Significant shallowing of the surface layer did not occur at chains TC-2 and TC-3 until January 11. The following three days witnessed a further rapid decrease in *Melosira* abundance to a baseline value of approximately $600 \text{ cells mL}^{-1}$.

Figure 4.17 shows that the *Anabaena* population increased exponentially for a three week period between December 29, 1993 and January 20, 1994. The rising of *Anabaena* cells into the surface layer from below provided a negligible component of the observed increase in abundance and could only have increased the “seed” population within the euphotic zone by at most 10 cells mL^{-1} . The observed increase represented *in situ* growth of the *Anabaena* population. The specific growth rate for *Anabaena* estimated as the best exponential fits to the cell abundance data during the exponential growth phase was 0.37 d^{-1} . Our estimate of average observed net growth rate for *Anabaena* during this project is 0.35 d^{-1} corresponding to a doubling time of two days.

During the period January 20 to February 4, 1994, the *Anabaena* population reached a plateau. Because water was released from the bottom of the weir pool and the thermal stratification confined the withdrawal region to below the euphotic zone, there was no mechanism to remove *Anabaena* from the weir pool. This implies that some other factor was limiting the biomass, possibly photooxidation or nutrient limitation.

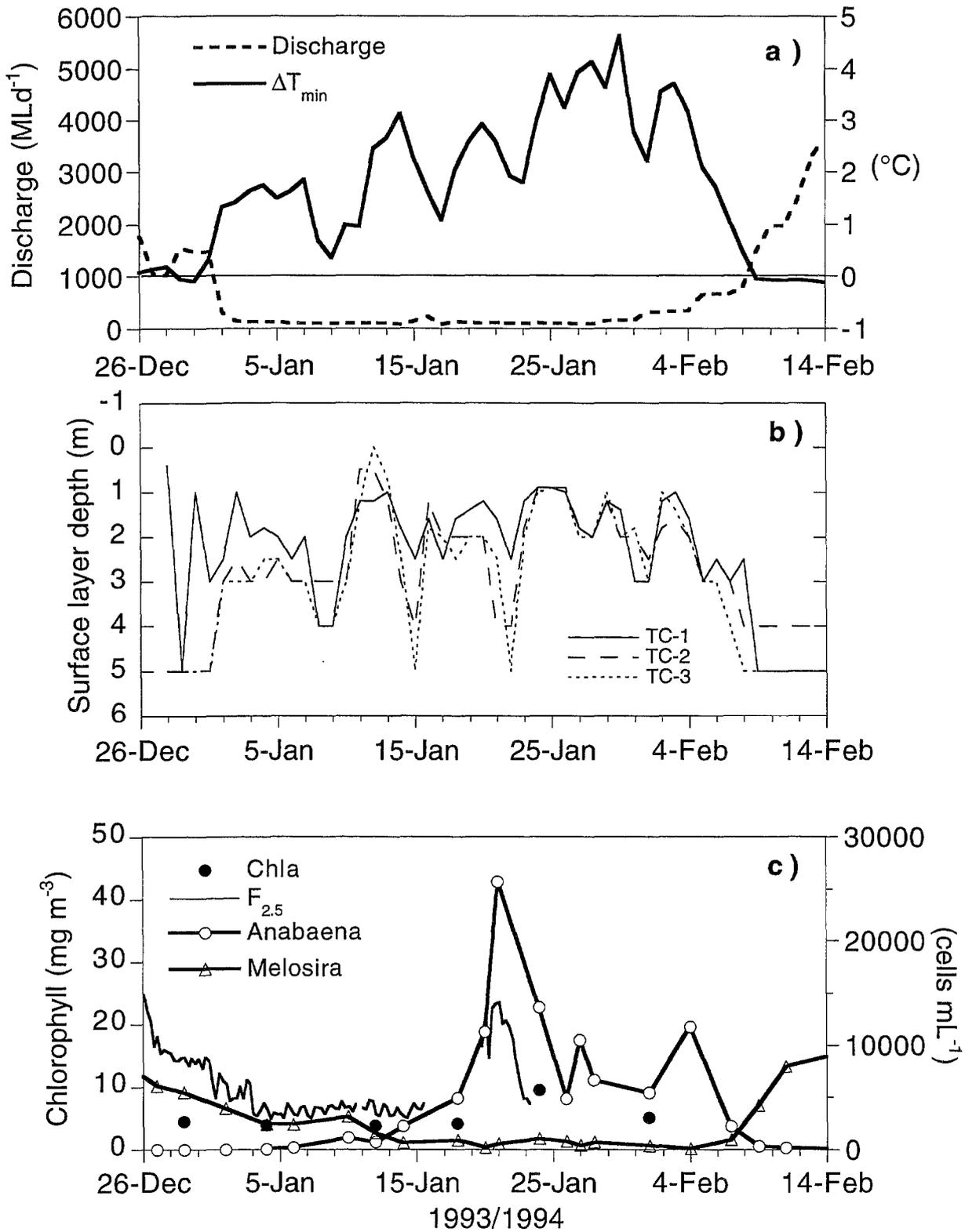


Figure 4.16 a) Maude Weir discharge and ΔT_{\min} at TC-1. b) Surface layer thicknesses at the three thermistor chains. c) Laboratory determined Chl-a concentration from 5 m-integrated samples (Chl-a), chlorophyll fluorescence measured at 2.5 m depth ($F_{2.5}$), and measured algal abundances.

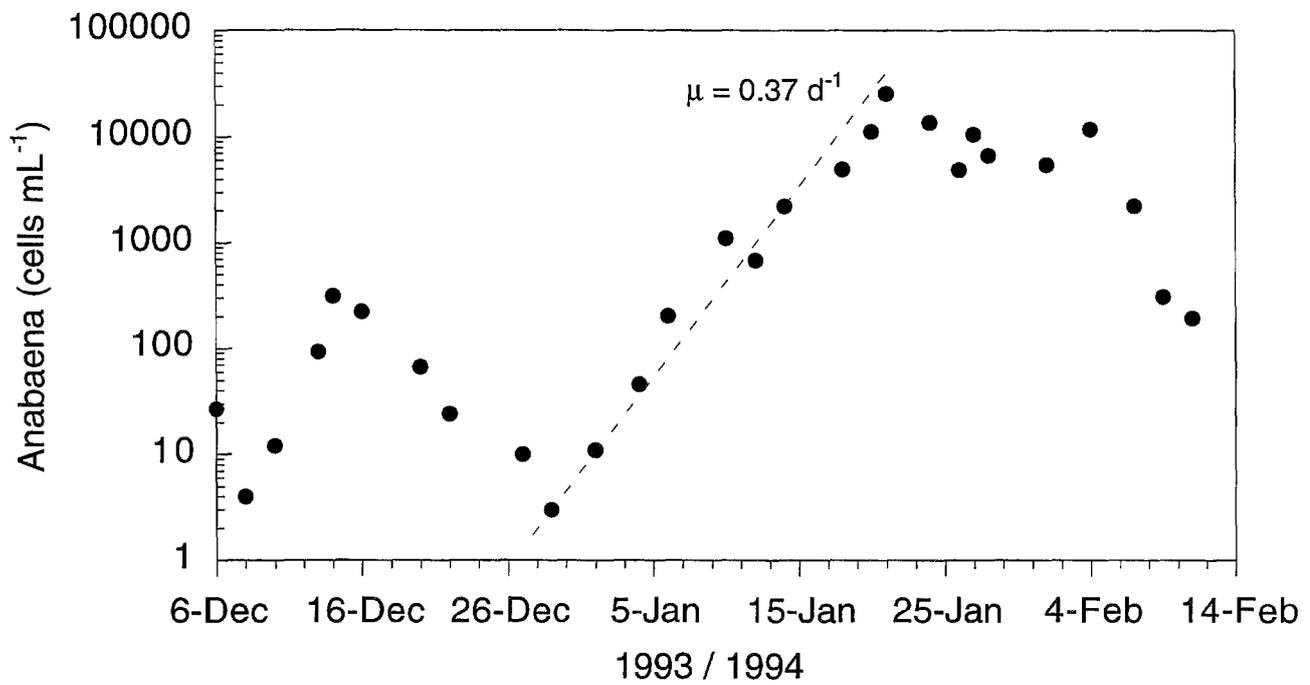


Figure 4.17 Measured *Anabaena* concentration during the period of exponential growth.

iii) Nutrient Dynamics

A number of chemical and biological measurements were made during the 1993/1994 field season. *In situ* turbidity, total reactive phosphorus (TRP), dissolved oxygen, conductivity, and pH measurements were made using a QUALTEL system that automatically sampled every 6 hours at four depths: the surface, 1.5, 2.5 and 7.0 m. Total reactive phosphorus was measured using the ascorbic molybdate method (Murphy and Riley, 1962). The determination includes acid labile forms of phosphorus some of which derives from organic and inorganic particles. The precision of the QUALTEL TRP data is $\pm 3 \mu\text{g L}^{-1}$. The QUALTEL system was deployed from December 23, 1993 to February 15, 1994. Bottle samples were collected weekly at the weir pool from October 16, 1993 to April 6, 1994 and analysed at the laboratories of the Murray-Darling Freshwater Research Centre for nitrogen, phosphorus, turbidity, phytoplankton abundance, chlorophyll-a, pH, and conductivity. In addition, NIFT bioassays were performed on the samples to determine which nutrient limited phytoplankton growth at the time of sample collection.

In the laboratory, phosphorus concentrations were measured for total phosphorus (TP) and TRP using standard techniques and two non-standard methods. One non-standard method used smaller porosity filters ($0.2 \mu\text{m}$ rather than the usual $0.45 \mu\text{m}$) to improve the estimate of the dissolved phosphorus concentration by reducing contamination due to phosphorus associated with very small particles (Hart *et al.*, 1995, Oliver, 1993). This measurement provides an estimate of the phosphorus immediately available for cell growth. The other non-standard method used strips of filter paper coated with a precipitate of iron-oxide to adsorb labile forms of phosphorus (Oliver *et al.*, 1993). This method determines the total amount of available phosphorus, which includes labile

phosphorus associated with suspended particles and the phosphorus in solution.

When comparing the QUALTEL data with those from the laboratory, one should bear in mind that while the QUALTEL data provide better temporal and spatial resolution, the laboratory data generally provide better precision and a lower detection limit for phosphorus determinations ($3 \mu\text{g L}^{-1}$ vs $6 \mu\text{g L}^{-1}$ for QUALTEL). Also, the QUALTEL turbidity data are consistently much greater than the values determined from samples collected in the field. The discrepancy may be due to different methods of determination; QUALTEL measures absorption plus scattering along the beam whereas standard turbidity measurements using nephelometers measure scattering at right angles to the incident light path.

Figures 4.18a and 4.18b show time series of turbidity and phosphorus. Turbidity and TRP data from 5 m integrated samples are denoted by solid markers whereas TP and TN are shown by open markers. Turbidity declined at all depths as the discharge decreased from 4000 ML d^{-1} on December 23, 1993 to 150 ML d^{-1} on January 2, 1994. Concomitant decreases in TRP also occurred implying that a significant portion of the turbidity contained easily digested phosphorus. Presumably much of the decrease reflected the sinking out from the surface layer of the *Melosira* population. From January 3 to 15 the turbidity was virtually unchanged at all depths whereas the TRP continued to decrease between the surface and 2.5 m while remaining steady at 7 m depth. These observations imply that the particulate flux downwards out of the surface layer stopped within a few days of the reduction in discharge. The continuing decrease through to January 18 in TRP above 2.5 m suggests its transformation into another form, presumably phytoplankton biomass; this period coincided with the onset of the

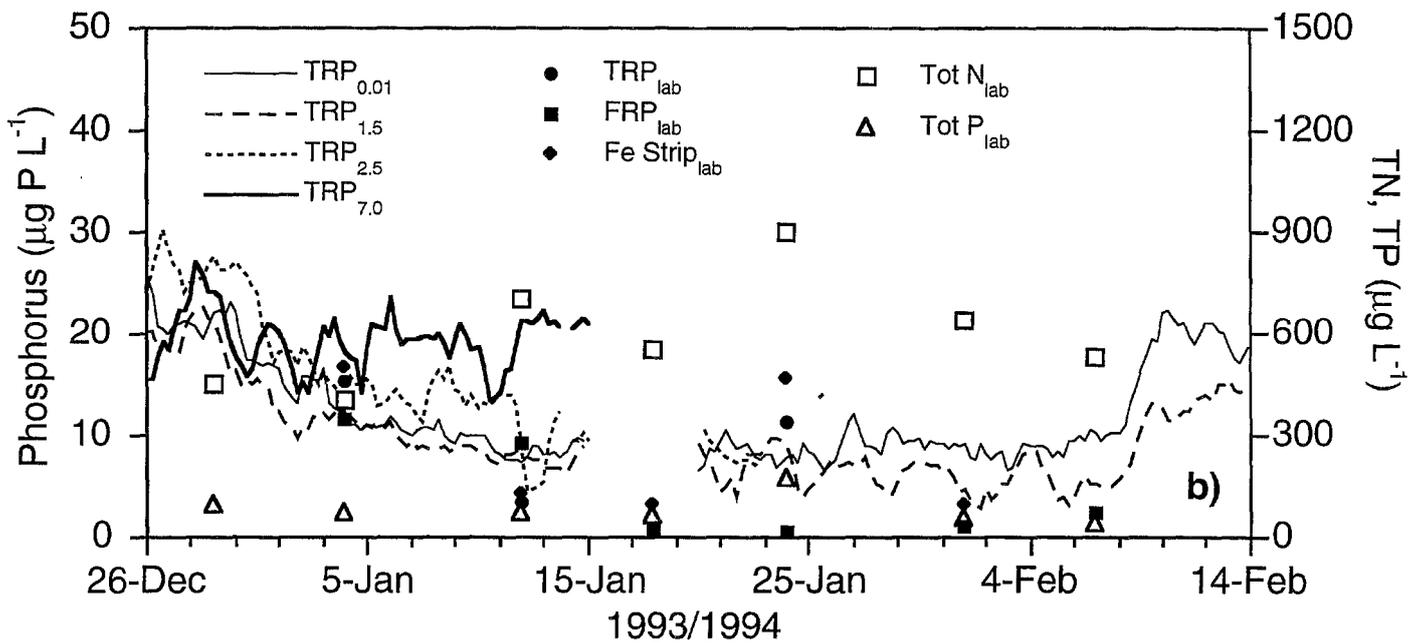
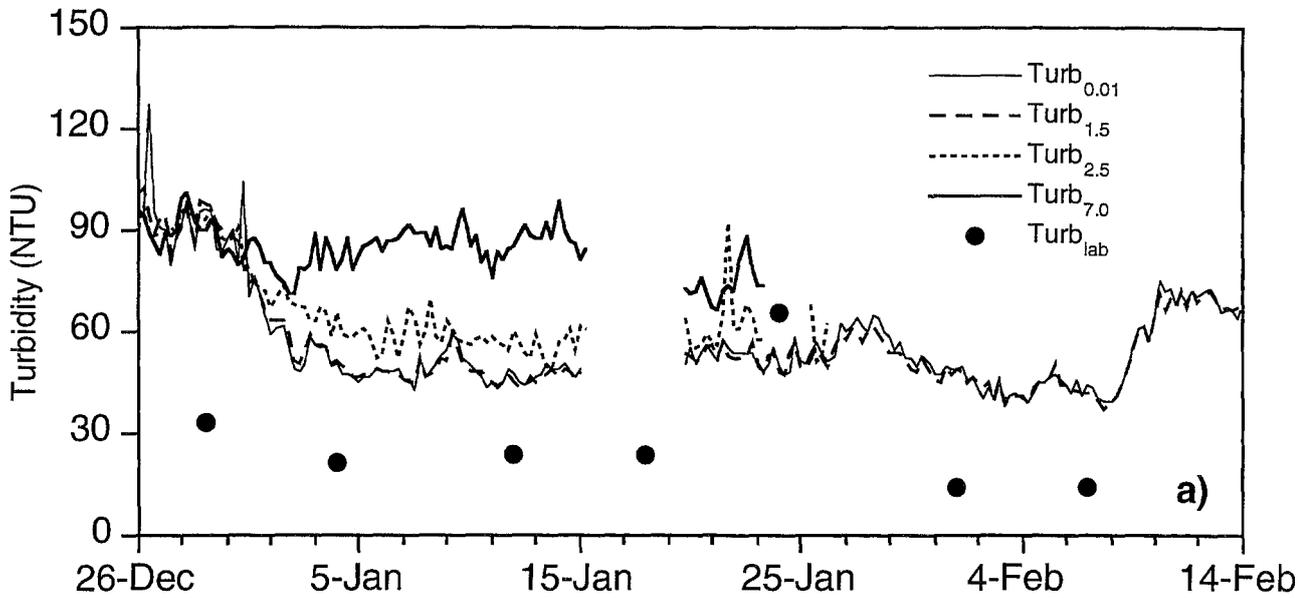


Figure 4.18 a) QUALTEL *in situ* measured turbidities at four depths (0.01, 1.5, 2.5, and 7.0 m) and laboratory turbidity for 5 m-integrated samples. b) QUALTEL TRP determinations at four depths, and laboratory phosphorous and nitrogen determinations for 5m integrated samples.

Anabaena bloom. Concentrations close to the bottom did not decrease as rapidly because of the turbulence generated at the bottom by the flow through the weir pool. The thermal stratification confined the turbulent region to within a few metres of the bottom.

From January 18 to February 7, QUALTEL P and laboratory FRP concentrations were at the limits of detection. The spikes in the laboratory values of TP, TRP, Fe-strip P, TN, chlorophyll-a, and turbidity for the sample collected on January 24, three days after the peak *Anabaena* concentration, are not understood. Riverine transport of nutrients into the weir pool is unlikely as there was no significant change in the discharge regime. There were also no rain or dust storms on or before January 24, so airborne deposition is unlikely. It is most likely that the increases in P and N were due to sample contamination.

Total nitrogen was quite variable during the year but did increase from less than $500 \mu\text{g L}^{-1}$ to more than $600 \mu\text{g L}^{-1}$ during the *Anabaena* bloom. A possible explanation for the increase in TN is fixation of N_2 and subsequent extracellular release by the *Anabaena*. Dissolved oxygen concentrations never fell below 70% saturation ($\sim 6 \text{ mg L}^{-1}$), even at the bottom of the water column after three weeks of persistent stratification. The maximum rate of oxygen consumption was $0.15 \text{ mg L}^{-1} \text{ d}^{-1}$ and occurred at 7 m depth. This implies that sediment nutrient release caused by anoxia in the overlying water is unlikely when underflow weirs are used.

The NIFT bioassays showed that nitrogen was potentially limiting *Melosira* growth on two occasions. The first occurred from the peak in *Melosira* biomass on December 22, 1993 through to January 4, 1994, just prior to the *Anabaena* bloom. The second time was in the latter half of March during a period of high discharges when *Melosira*

was again the dominant phytoplankton species. There was no strong evidence of nutrient limitation during the *Anabaena* bloom between January 14 and February 4.

Using only physical arguments, it is easy to show why *Anabaena* should replace *Melosira* during low discharge conditions. Not so clear is why motile species (e.g. *Volvox*, *Eudorina*) were not observed in the surface layer during low discharge periods. The NIFT results offer a possible explanation in that prior to the onset of persistent stratification the *Melosira* may have consumed most of the available nitrogen. When the water column stratified, the *Anabaena* took advantage of their nitrogen-fixing capabilities and were able to grow. Motile species, on the other hand, were unable to thrive because they could not satisfy their nitrogen requirements.

f) Advection of *Anabaena* from Hay Weir

For a period during January 1995 we collected samples for *Anabaena* analysis from three sites along the Murrumbidgee River between Hay and Maude Weirs in order to investigate the importance of the advection of *Anabaena* from Hay Weir pool on concentrations in Maude Weir pool. Samples were collected daily in the discharge from Hay Weir, from the river at Eulalie 14 km further downstream, and from station TC-1 near Maude Weir. The results of the analyses of these samples are shown in Figure 4.19 together with the average of the discharges from Hay and Maude Weirs during this time. The concentrations in the Hay Weir discharge and at Eulalie are similar to one another though there is often a lag of the order of a day or less in the concentrations measured at the latter site. The calculated travel times of water between Hay Weir and Eulalie are mostly around a half day. The concentrations averaged over the period shown are $940 \text{ cells mL}^{-1}$ for the Hay Weir discharge and $1050 \text{ cells mL}^{-1}$ at Eulalie—a difference of only 10%. These results suggest that *Anabaena* is being transported downstream through this river section without significant loss or growth. The consistent correspondence between *Anabaena*

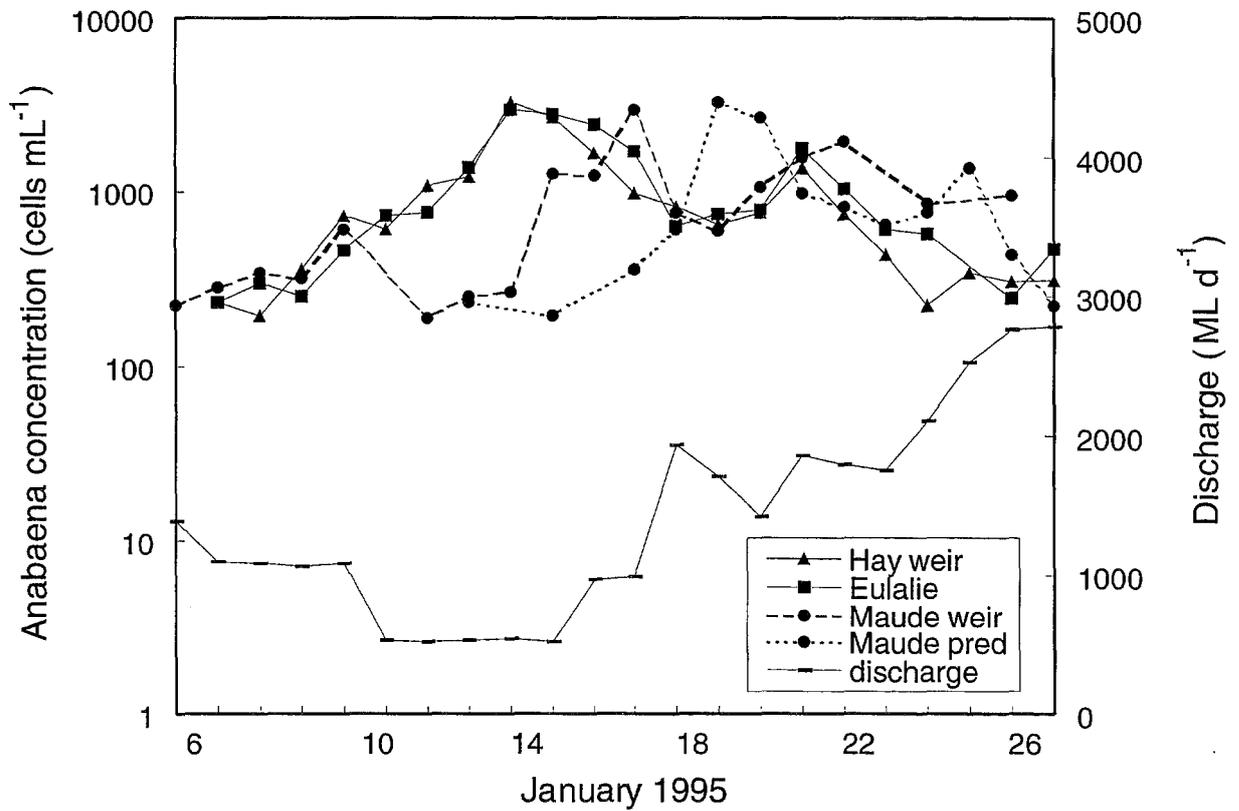


Figure 4.19 *Anabaena* concentrations measured in the discharge from Hay Weir, at Eulalie, in Maude Weir pool (close to weir). Also shown are predicted concentrations for Maude Weir pool assuming downstream advection from Hay Weir and the discharge through Maude Weir.

concentrations in the Hay Weir discharge and at Eulalie also suggests that the spatial heterogeneity in the river concentrations was not large.

Also shown in Figure 4.19 are the daily *Anabaena* concentrations at the Maude Weir pool site and the concentrations we would have obtained at this site if the concentrations measured in the discharge from Hay Weir had been advected downstream unaltered in the flow between Hay and Maude. The latter concentration time series is calculated by integrating the positions of parcels of water forward in time using flow speeds which are derived from the known discharges through Hay and Maude Weirs. When the advected Hay concentration first arrives at Maude around January 13, this concentration is similar to that measured at Maude. For the next few days of average discharge less than 1000 ML d^{-1} the measured concentrations exceed the advected concentrations, perhaps due to growth

of the *Anabaena* under stratified conditions in the weir pool. The relative concentrations reverse in the period following the increase in average discharge to beyond 1000 ML d^{-1} on January 17. Why this should happen is not clear. At an average discharge of about 1500 ML d^{-1} , appropriate to this time, it would have taken about three days to flush the weir pool. If *Anabaena* concentrations were elevated along the weir pool at the end of the stratified period due to growth, we should have measured elevated concentrations at the pool's downstream end (Maude) for a few days after the increase in discharge. After January 20, measured and advected concentrations at Maude were within a factor of two of one another, suggesting that growth or destruction of the *Anabaena* population in the three or four days that it would have taken to advect it from Hay Weir to Maude Weir was not significant.

5. Stratification Model

In our analysis of the weir pool measurements so far in this report, we have used the nature of the thermal stratification as the indicator of how turbulent mixing is taking place in the water column. In effect the heat input through the water surface mainly by solar radiation is used as a tracer of mixing. A zone in the water column having uniform temperature is assumed to be one through which active mixing is or has been taking place. Similarly, a zone having a significant temperature gradient is taken to be a region where mixing is suppressed or perhaps reduced to zero.

Thermal stratification has an important dynamic significance as well. Thermal stratification suppresses the turbulence leading to vertical mixing. In order to erode stratification the turbulence must supply kinetic energy. Ultimately, whether stratification can be sustained depends upon the relative supply rates of stratifying thermal energy and of destratifying turbulent kinetic energy. In the weir pool thermal energy is supplied mainly by the sun, whereas we expect the turbulent kinetic energy to derive mainly from the wind blowing on the water surface and from the flow of the river over its bed.

In section 4 we demonstrated that limited mixing of the water column, as evidenced by the presence of persistent stratification, is the condition which is conducive to the growth of the *Anabaena* population. Here, we develop and verify a "stratification" model which we will use as an aid in interpreting measurements from Maude Weir pool. The model also will be used to obtain predictions of the likely effects of various management strategies on the stratification behaviour of the weir pool. The stratification model is really a hydrodynamic model which is centred on describing the mixing and circulation within the weir pool. We have termed it a stratification model because its principal point of comparison with the measurements will be its predictions of the thermal structure of the weir pool. Also, we will continue to use stratification status as a useful surrogate for weir pool mixing.

a) Model Description

The model chosen to study the mixing and stratification evolution in the Maude Weir pool is the Princeton Ocean Model (POM) developed by Blumberg and Mellor (1983, 1987). It is a time-dependent model which simulates the turbulent mixing and horizontal advection of momentum and heat through a water body. We use POM in a two-dimensional configuration (along-pool and vertical); we ignore any variation across the weir pool. The parameterization of the turbulence within the model takes into account the suppression of turbulent mixing in the vertical by thermal stratification. The flow through the modelled weir pool would be very different under stratified conditions if we did not include the effect of thermal stratification on mixing.

The model domain is assumed to extend from the weir to 35 km upstream, which is near the upstream end of the weir pool. The bed slope is assumed to be constant and equal to the average measured slope of 1/11 000. Although the actual weir pool depth undulates up and down, these variations are ignored. The model predicts the temperature and velocity profiles everywhere in the weir pool as a function of time.

The boundary conditions for a model such as POM are all important for determining the solution in the interior of its domain (Figure 5.1). River discharges into the upstream end of the weir pool were deduced from consideration of water volumes using recorded discharges through Hay and Maude Weirs and pool water levels. In the model, upstream water temperatures were specified to be equal to the temperatures measured by the thermistor chain TC-3.

To simulate the discharge through an underflow weir, we specified that all the downstream flow occurred uniformly through the bottom half of the water column. The total discharge was set equal to the weir discharge recorded daily by the weir keeper. Such a discharge specification does not

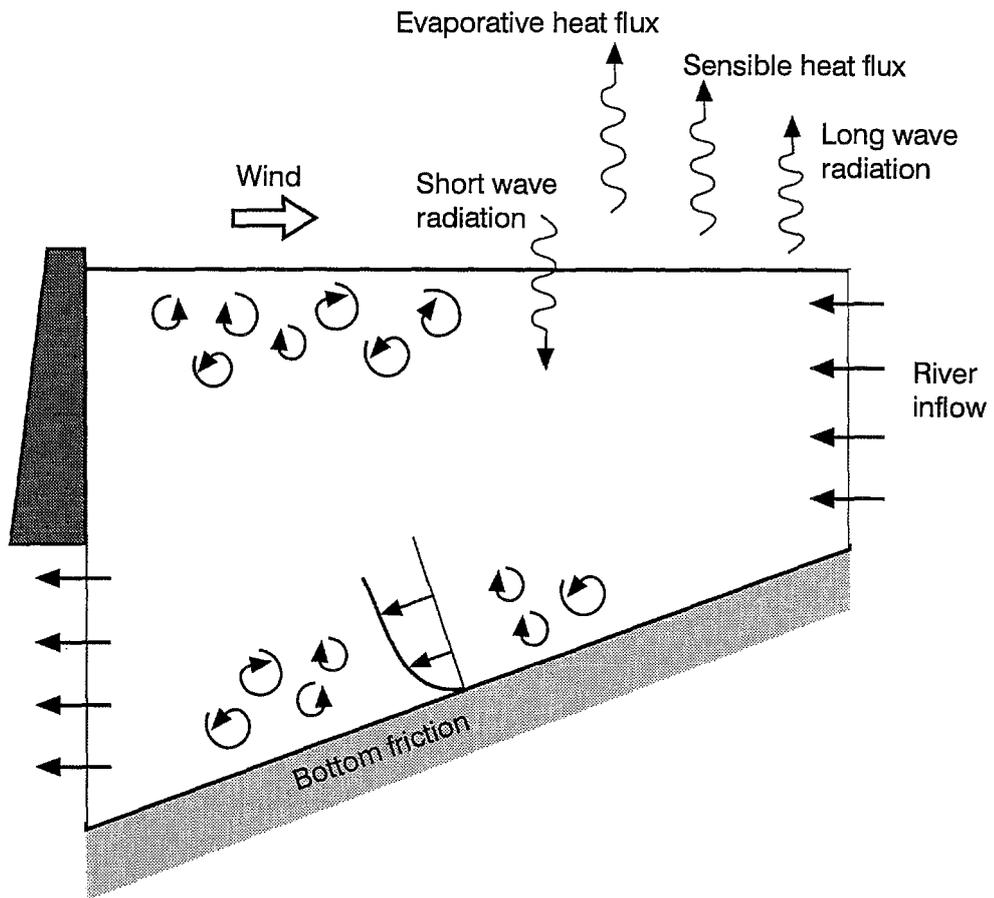


Figure 5.1 Schematic longitudinal section of Maude Weir pool showing the principal factors influencing stratification which have been included in the model.

accommodate the details of the outflow hydraulics, but it is broadly consistent with our observation that under stratified conditions most of the discharge occurred through the bottom part of the water column (Figures 4.4 and 4.5). In reality, under non-stratified conditions the discharge would be drawn from all depths. In this circumstance, our model discharge would have adjusted itself to such a condition only a short distance upstream from the weir.

The correct prescription of the bottom shear stress (friction) is of prime importance in proper modelling of the stratification dynamics of the weir pool. The coefficient of friction used in the function relating bottom stress to flow speed was determined by optimising the agreement between measured and predicted temperature profiles within the weir pool. With our measurements of temperature profiles obtained during a large range of weir discharges, the coefficient of bottom friction is tightly constrained.

At the water surface, we impose the heat flux which is the sum of the radiative, evaporative, and conductive heat fluxes. The fluxes due to short- and longwave radiation were those measured on the meteorological raft at TC-1. In the model, the shortwave radiation crossing the water surface is assumed to be attenuated within the upper water column exponentially by turbidity and water colour. The attenuation coefficient was estimated from measured light profiles obtained periodically. Longwave (thermal) radiation is absorbed and emitted from within the top millimetre of the water surface which in the model is taken to be the top grid cell.

Evaporation is the most important mechanism causing heat loss from the water column. The conduction of heat between the air and water can be up or down, depending on whether the overlying air is cooler or warmer than the water surface, but it can be significant. For the model, we estimated the evaporative and conductive heat fluxes with bulk formulae involving wind speed, air temperature, water temperature and relative humidity measured at TC-1. The exchange coefficients used in these bulk formulae had to be adjusted to account for the

modification to the airflow over the weir pool surface caused by the trees lining its banks.

The stress of the wind on the water surface (the surface momentum flux) is a source of turbulent kinetic energy available for mixing out the stratification. For the model, we estimated the wind stress as the product of a drag coefficient and the square of the measured wind speed at TC-1. Proper estimation of wind stress is difficult for Maude Weir pool. The direction of the wind stress relative to the meandering river channel changes continuously (Figure 3.3). Also, the width of the pool is only 40 m or so and sheltering effects are expected to be substantial as there is a dense stand of eucalyptus trees about 20 m tall along its banks. The measured temperature profiles at all thermistor chains show that during day-time, especially at the time of maximum irradiance, the surface mixed layer was often less than 20 cm in thickness. This observation suggests that wind mixing of the surface waters was not vigorous. We have run the model with and without a wind stress applied at the surface and have obtained much better agreement with measured temperature profiles when the wind stress was set to zero.

b) Comparison with Measurements

We present here a comparison between model predictions and measurements of temperature at TC-1 for a period of 18 days in February 1995. During this period, the discharge varied significantly while the temperature of the discharge into the upstream end of the weir pool remained approximately uniform at 24°C. These comparisons illustrate how the model copes with the range of discharge conditions typical of summer at Maude Weir.

The time series of the measured and predicted temperatures at four depths from TC-1 are shown in Figures 5.2a and 5.2b, respectively. These data clearly reflect the influence of discharge on the stratification behaviour of the weir pool. When the discharge was between 1000 and 2000 ML d⁻¹ until February 7, there was a pronounced diurnal cycle of stratification. On February 8 and 9, the discharge increased to 4000 ML d⁻¹ and the entire water

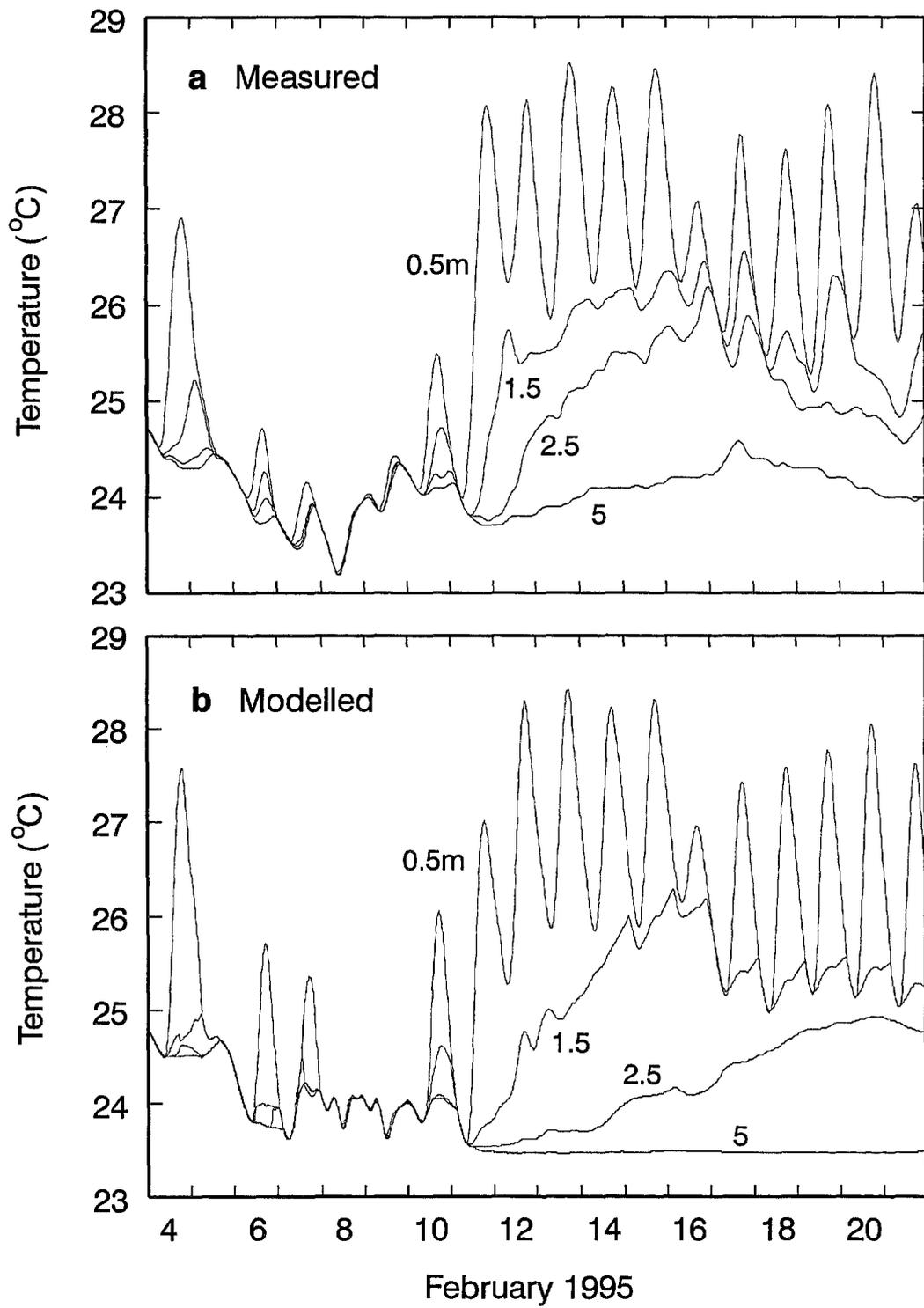


Figure 5.2 a) Measured and b) modelled temperatures at TC-1

column stayed well mixed due to strong bottom mixing. The drop in discharge below 1000 ML d^{-1} on February 11 was associated with the appearance of stratification which persisted throughout the diurnal cycle. Persistent stratification was then maintained through to the end of the record due to continuing low discharge conditions ($\sim 150 \text{ ML d}^{-1}$).

The major features of the evolution of the thermal structure are accurately reproduced. These include the transitions between completely mixed, diurnally stratified, and persistently stratified, as well as the size of the vertical gradients. The depth of the surface mixed layer at night under persistent stratification is also well reproduced.

6. Management Strategies

Here, we discuss and evaluate five strategies for minimising the occurrences and severity of cyanobacterial blooms within a weir pool based on manipulation of weir discharges and physical conditions within the pool. Our evaluation of these strategies is based partly on the measured behaviour of the weir pool and partly on the results of computer simulations of the effects of altered operations. We had planned to test some of the strategies directly during the 1994/1995 study period, but rainfall conditions in the irrigation regions upstream from Maude prevented us from obtaining the discharge conditions needed for such testing.

a) Discharge Volume

The results of our study strongly suggest that provided the water column within the weir pool is mixed on at least a diurnal basis then the growth of *Anabaena* within the weir pool would be curtailed, and *Anabaena* should not reach "bloom" proportions. The minimum (critical) discharge necessary to achieve diurnal mixing in Maude Weir pool is certainly dependent on a series of factors which vary seasonally. These include solar radiation, air temperature, wind speed, humidity, and the temperature of the river discharging into the head of the pool. During the summer season and early autumn, which is when the *Anabaena* are most likely to cause a problem, we suggest that a discharge of 1000 ML d⁻¹ would always be capable of achieving diurnal mixing in the weir pool. We did not observe persistent stratification to occur at greater discharges. It is possible that the necessary discharge may be somewhat lower than 1000 ML d⁻¹ during the times which are most conducive to the formation of stratification. However, there were no periods longer than a few days during the study period when discharges were maintained at levels between 500 and 1000 ML d⁻¹ to allow us to determine more exactly the critical discharge for diurnal mixing from measurements.

Two factors which influence the stratification behaviour of the weir pool are the temperature of

the water flowing into the pool at its upstream end and the water depth within the pool. The surface water temperature in the weir pool is limited by a feedback mechanism to about 30°C. The warmer the surface layer, the faster it loses heat by evaporation, by conduction to the atmosphere, and by the emission of longwave radiation. Under low discharge conditions, cooler water flowing from the river into the weir pool flows under the warmer surface layer. The warmer the incoming water, the less is its temperature contrast with the surface layer and the less is the degree of stratification.

Table 6.1 shows how the model predicts the critical discharge for destratification in the weir pool to vary with inflowing water temperature (T_i) and with water depth (H). For the simulations on which these results are based, we have assumed hypothetical weather conditions which are similar to those of February 1995, a period conducive to the formation of strong stratification. When the temperature of the inflowing water is 21°C and $H = 6$ m, the critical discharge is 1200 ML d⁻¹. At $T_i = 27$ °C, the critical discharge decreases to 900 ML d⁻¹. These temperatures represent the range of those measured for the water flowing into the weir pool during summer.

Water depth has two influences on critical discharges. When the depth of the weir pool is reduced its cross-sectional area is also reduced. Hence the average flow speed for a particular discharge is increased, thereby increasing the production of turbulent kinetic energy responsible for mixing the water column. Also, for a given degree of stratification, whether defined as the mean vertical temperature gradient or the temperature difference between the top and bottom of the water column, less energy is required to homogenise a shallow water column than a deeper one.

The expected reduction of the critical discharge with reduced water depth is shown in the model predictions (Table 6.1). For a full weir pool of 6 m depth, the critical discharge is 1050 ML d⁻¹ when the temperature of the inflow into the pool is 24°C.

Table 6.1 Model predictions of critical discharges as functions of inflowing water temperature and water depth in weir pool

Inflow temperature (°C)	Weir pool depth (m)	Critical discharge (ML d ⁻¹)
21	6	1200
24	6	1050
27	6	900
24	4	650
24	5	800

Reducing the water depth to 4 m, a depth sometimes experienced in Maude Weir pool, reduces the critical discharge to 650 ML d⁻¹. Even though the model predictions for the critical discharge vary substantially with the temperature of the inflow and with water depth, these predictions are all reasonably consistent with the critical discharge of approximately 1000 ML d⁻¹ which we inferred from our measurements of temperature profiles at TC-1.

During the bloom of January 1994, the *Anabaena* took about two weeks to reach problem concentrations. A discharge of 500 ML d⁻¹ provides a bulk residence time of ten days for water in Maude Weir pool when full (Equation 4.1), but we have suggested that stratification may increase this residence time by a factor which is less than two for this discharge. On the basis of preventing the size of an *Anabaena* population from reaching a problem level by constraining the time it has to grow, we suggest that the discharge through Maude Weir should be maintained at a level of 500 ML d⁻¹ at least. Of course, this analysis assumes that the seed population of *Anabaena* within the Murrumbidgee River flowing into the head of the weir pool has a concentration no higher than the concentrations encountered in the weir pool at the start of the bloom of January 1994.

b) Pulsed Discharge

Our study has confirmed that under stratified conditions in Maude Weir pool, *Anabaena* accumulate in the upper part of the water column. We believe that it is this tendency which provides *Anabaena* with its competitive advantage under low

discharge conditions in the weir pool. The maintenance of the discharge at a level sufficient to destroy persistent stratification during the summer may require the release of more water than is available or more than is economically feasible, but it may be possible to minimise near surface *Anabaena* accumulations by pulsing the discharge on a periodic basis. A discharge pulse of sufficient size and duration to cause mixing of the water column from surface to the bottom would also mix the *Anabaena* uniformly. If the pulse is repeated before the cyanobacteria have the opportunity to float back into the euphotic zone, then their growth advantage would be reduced. A second benefit of a pulsed discharge strategy is that it would cause the reoxygenation of bottom waters in the weir pool if they had been significantly depleted in oxygen by respiration processes in the sediments. However, anoxic bottom waters have not been observed in weir pools of the lower Murrumbidgee River (Jones, 1993). This is presumably due to our observation that under stratified conditions, oxygenated water flowing into the weir pool travels along the bottom of the river to the weir.

Two important questions concerning the implementation of such a strategy are: what should be the duration of such pulses; and what should be the frequency of their repetition? Table 6.2 provides the estimated times it took the water column at TC-1 to destratify on those occasions during the study period when an increase in the discharge through Maude Weir appeared to cause destratification. On each day it is assumed that the discharge was increased at 1200 although the actual time of increase could have been four hours earlier

Table 6.2 Measured times to destratification after an increase in discharge through Maude Weir

Date	Maude discharge before (ML d ⁻¹)	Maude discharge after (ML d ⁻¹)	Time for destratification (h)
17 Dec 93	112	3180	8
9 Feb 94	770	1490	15
3 Mar 94	308	926	42
1 Apr 94	657	1910	7
27 Dec 94	476	785	37
18 Jan 95	350	1930	17
30 Mar 95	136	815	14

or later. Destratification was deemed to have occurred when the measured temperature variation through the water column at TC-1 was $< 0.1^{\circ}\text{C}$.

As one would expect, the time to destratification generally decreased as the "Maude discharge after" was increased. For all the occasions shown, the time to destratification was less than 24 hours when the discharge was increased to 1500 ML d⁻¹ or more. It is apparent also that destratification was accomplished by discharge increases to less than 1000 ML d⁻¹ on three occasions. On two of these occasions destratification took longer than 24 hours and on the third occasion destratification took only 14 hours. The third occasion was after the end of summer when the stratification in the weir pool prior to the increase in discharge would have been less strong than during the summer months.

Once the discharge is reduced to a low level, the stratification begins to reset. Vertical mixing between the upper and lower parts of the water column becomes restricted and the *Anabaena* begin to accumulate into the surface layer once again. A time scale for the accumulation of an *Anabaena* population into the surface layer by flotation would be

$$T_f = H/F \quad (6.1)$$

where H is the water depth and F is the flotation speed of the *Anabaena*. If the discharge were pulsed at intervals less than T_f then the accumulation of the population into the surface layer by flotation would be limited. Of course growth of *Anabaena* within

the surface layer will also lead to an apparent surface accumulation of the population. In this case, the time scale for surface accumulation of the population would be

$$T_g = \mu^{-1} \quad (6.2)$$

where μ is the specific growth rate of the population.

We suggest for a cyanobacterial control strategy of pulsed discharges that the interval between pulses should be less than both T_f and T_g . Evaluation of T_f requires knowledge of its flotation speed, but for *Anabaena circinalis*, the dominant *Anabaena* species in Maude Weir pool, measurements of F are rare. Reynolds *et al.* (1987) have reported flotation rates of between -1 (sinking) and 5 m d^{-1} for *Anabaena flos-aquae* a species similar to *A. circinalis*. Brookes (pers. comm) has measured an average floating rate of 0.24 m d^{-1} for a culture of *A. circinalis* obtained from the River Murray. Assuming $F = 0.24 \text{ m d}^{-1}$ and $H = 6 \text{ m}$, we calculate T_f to be 25 days. If F was 1 m d^{-1} then T_f would be 6 days. From our phytoplankton measurements in Maude Weir pool, we have estimated a net specific growth rate for the *Anabaena* population under favourable conditions to be around 0.35 d^{-1} . This growth rate corresponds to a T_g of 3 days. For flotation speeds less than 2 m d^{-1} ($T_f > 3$ days), the required time between discharge pulses to control *Anabaena* blooms would be 3 days. Pulse repetition at longer intervals could still achieve the desired result of reducing population growth to below problem levels.

We suggest that if a pulsed discharge strategy were to be implemented, then the discharges from both Hay and Maude Weirs should be pulsed. Such operation would cause the whole of the weir pool to destratify, not just its downstream end as would occur if only Maude Weir's discharge were pulsed. To maintain an increased discharge requires an increase in the hydraulic gradient through the river section and the weir pool. This necessitates water levels changing between Hay and Maude Weirs which may be undesirable from the point of view of bank erosion. If we suppose that the discharge was increased from a base flow of 350 ML d^{-1} to 1500 ML d^{-1} then our model predicts that water levels will change by a maximum of 15 cm along the weir pool, assuming that the water level at Maude is held constant. After the discharge is reduced again water levels would return to their base flow values. If a pulsed discharge strategy is to be invoked it would be desirable to check the water level predictions from POM against measurements.

c) Discharge Height

We investigate whether Maude Weir, being an underflow weir, exacerbates the potential for cyanobacterial blooms in its weir pool. Figure 6.1 compares the modelled (using POM) stratification and flow patterns through the weir pool for an underflow and an overflow weir. For these simulations, we have assumed that the discharge is 150 ML d^{-1} and that hypothetical weather conditions conducive to stratification prevail (section 6a). For both simulations, the temperature of the water flowing into the weir pool is set to 24°C and the water depth at the weir is 6 m. Water is discharged through the weir uniformly with depth from either the bottom half (underflow weir) or the top half (overflow weir) of the water column. We recognise that the actual pattern of discharge is influenced by stratification (section 4b) and that our assumed depth distribution is only an approximation.

The simulations shown in Figure 6.1 are the temperatures averaged over a 24 hour period; the contour lines on each plot are the flow streamlines similarly averaged. The closer together the adjacent streamlines, the stronger the flow velocity between

them. Through most of the length of the weir pool the water column stratifies strongly and in a similar way for the two types of weir discharges, suggesting that if *Anabaena* was present in either case it would find conditions conducive to growth. However, for the underflow weir most of the flow through the weir pool occurs at depth whereas for the overflow weir the throughflow occurs in the upper part of the water column. Consequently, the predicted residence times of an *Anabaena* population concentrated in the surface layer would be quite different in the two cases. For the overflow weir the predicted residence time of the top 2 m of the water column is 30 days compared to 51 days for the underflow weir. The bulk residence time for the weir pool calculated using Equation 4.1 is 33 days.

We also obtained model predictions for a discharge of 350 ML d^{-1} . In contrast to the case of a 150 ML d^{-1} discharge, the model predictions for the 350 ML d^{-1} case show that only within a few kilometres of the weir are there significant differences in the temperature structures and the flow fields in the weir pool between underflow and overflow weirs. Through most of the body of the weir pool for both types of weir discharge, the flow velocities are fairly uniform with depth except near the bottom where there is retardation due to bottom friction. If we calculate a residence time for the upper 2 m of the water column based on the average flow velocity in this layer, we obtain 12.3 days for the underflow weir versus 11.9 days for the overflow weir, a difference of only 3%. For a 350 ML d^{-1} discharge, POM predicts that surface flow speeds reduce as the main flow dives towards the bottom within a few kilometres of the underflow weir. The surface stagnation zone near the weir which results has the potential to accumulate buoyant phytoplankton. The overflow weir has an analogous stagnant region extending along the bottom upstream from the weir. Such a zone would be prone to suffer oxygen depletion due to consumption in bottom sediments and possibly exacerbate sediment nutrient release. A discharge of about 300 ML d^{-1} represents the transition between regimes where POM would predict that the type of weir discharge has a major or a minor effect on the flow through the weir pool. It also happens that the modelling of selective withdrawal described in

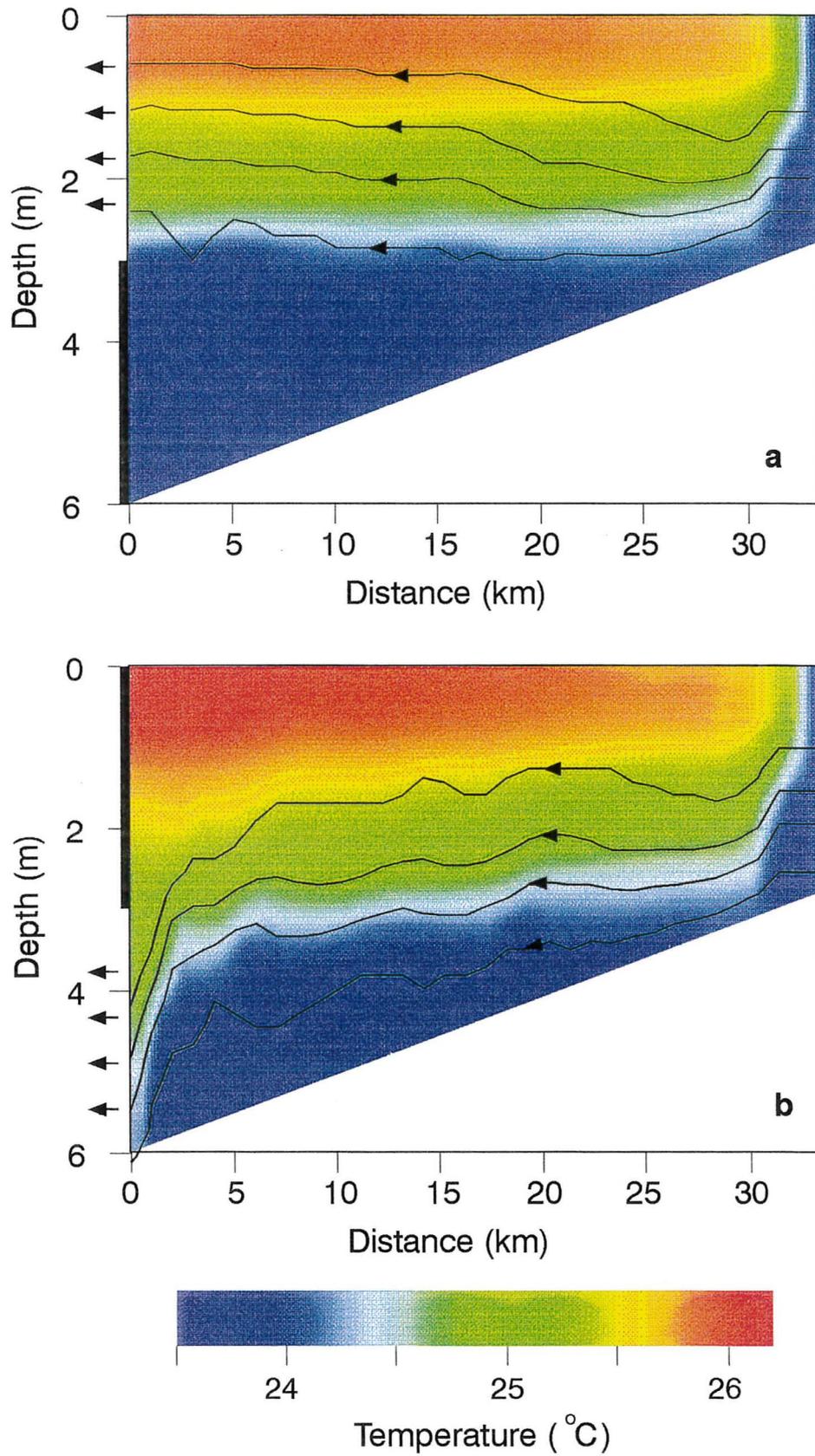


Figure 6.1 Modelled temperature and flow streamlines in the weir pool behind a) an overflow weir, and b) an underflow weir. The weir discharge is 150 ML d^{-1}

section 4b indicates that a discharge of about 300 ML d^{-1} separates regimes in which the weir throughflow is drawn mainly from the lower parts of the water column and one in which it is drawn more evenly from the surface to the bottom. Thus both models suggest that the relative benefit of using an overflow release strategy to reduce the residence time of the surface layer in Maude Weir pool cuts in for discharges less than about 300 ML d^{-1} . The simulations of POM indicate that the discharge required to destratify the weir pool is marginally different for overflow and underflow weirs.

Siphons on the walls of underflow weirs have been suggested as a possible method for minimising *Anabaena* blooms in weir pools (Jones, 1993). The siphons would be operated to draw off the surface layer of the weir pool and thereby remove the buoyant cyanobacteria or perhaps reduce the tendency of the weir pool to stratify. In effect, the system allows some of the discharge past the weir to be an overflow. Our model simulations comparing overflow and underflow weirs have demonstrated that siphons are likely to reduce the tendency of the weir pool to stratify only marginally, but they do have the potential for significantly reducing the residence time of the surface layer when the discharge is less than about 300 ML d^{-1} . Of course, to achieve a significant benefit through the length of the weir pool, the majority of the water passing the weir would have to flow through the siphons. Siphons would diminish any localised buildup of *Anabaena* in the stagnant zone near an underflow weir.

Siphons were installed on Maude Weir for a twenty-five day period in March 1995 for testing purposes. The total discharge through the three siphons was estimated to be 74 ML d^{-1} ; the discharge past the weir was generally 200 to 300 ML d^{-1} during this time. Unfortunately for the siphon testing, prior to the installation of the siphons the stratification was not well established and *Anabaena* abundance was low, conditions which continued during the testing period. Examination of the thermistor chain and the ADCP records from TC-1 revealed no change to the stratification of the water column or in the currents at this site which could be attributed to the

operation of the siphons. Consequently, the extent to which siphons represent an effective tool for cyanobacterial management remains equivocal.

d) Withdrawal Depth

Figure 4.13a shows how the *Anabaena* population was strongly concentrated in the surface layer during times of persistent stratification. On this particular day (January 19, 1994), the average concentration decreased from $34\,000 \text{ cells mL}^{-1}$ near the water surface to about $1000 \text{ cells mL}^{-1}$ at 3.8 m depth. For another set of profiles taken later during the same period of persistent stratification on January 26, 1994, the concentrations decreased by a factor of about ten between the surface and 3 m depth at two stations within 6 km of Maude Weir.

A simple strategy for minimising the impact of an *Anabaena* bloom on water quality once it has been established under conditions of persistent stratification is to remove water for domestic consumption from near the bottom of the weir pool where *Anabaena* concentrations are likely to be much lower than they would be at the water surface. Of course such a strategy would not be appropriate if other strategies involving mixing of the water column had been implemented. Potential hypolimnetic water quality problems (high colour due to manganese, bad odours due to hydrogen sulphide) are not expected as no bottom anoxia has been noted with this underflow weir, as discussed above.

e) Artificial Destratification

Artificial destratification is a strategy which has been employed in Australian reservoirs with the aim of reducing cyanobacterial growth (McAuliffe and Rosich, 1989). Destratification is usually accomplished with bottom mounted bubblers or by mechanical mixers. We use POM to evaluate the potential benefits of artificial destratification in Maude Weir pool. We model the stratification and flow within the weir pool with an idealised destratification device sited 8 km upstream from the weir. The destratification device causes the water column to be completely mixed from the surface to the bottom, a situation which can only be

approximated by real destratification systems. Figure 6.2a shows the modelled stratification and flow streamlines within the weir pool for a discharge through the pool of 150 ML d^{-1} , with an inflowing water temperature of 24°C , and with the hypothetical weather conditions conducive to stratification prevailing. This simulation can be compared directly to that shown in Figure 6.1b which does not have a destratification device.

It is apparent that the destratification device does not limit the formation of stratification except in the vicinity of the device itself. With destratification the surface layer is deeper and perhaps a little warmer over most of the length of the pool. Except in the vicinity of the device, destratification appears to cause the flow speeds of the surface layer to be retarded; that is destratification has a blocking effect on this layer. Figure 6.2b shows the effect of three destratification devices spread along the length of the weir pool. The degree of blocking of the surface layer and the strength of stratification are reduced from what they are with one device, particularly through the upstream half of the weir pool.

The effects of artificial destratification on *Anabaena* concentrations are likely to be significant. The increase in residence time of the surface layer would allow the *Anabaena* population to grow to a greater size potentially, but at a discharge of 150 ML d^{-1} the residence time of the surface layer is already long enough without destratification (50 days) that it is not likely to be

the limiting factor for the size of the population. By increasing the thickness of the surface layer and by thereby spreading the distribution of *Anabaena* to a greater depth, artificial destratification would potentially reduce the growth rate of *Anabaena* due to light limitation. Also, in the vicinity of the artificial destratification devices, the *Anabaena* would be mixed from the surface to the bottom—a condition which is not conducive to its growth. The stratification model predicts that with three destratification devices, the critical discharge necessary to induce diurnal mixing throughout the weir pool is 850 ML d^{-1} compared to 1050 ML d^{-1} without artificial destratification. A further benefit of artificial stratification is that it would minimise the likelihood of bottom waters in the weir pool becoming anoxic.

Artificial destratification can be accomplished at a relatively low cost. We estimate that less than 100 W of power is needed for the continuous destratification of the water column in Maude Weir pool at one location. A well designed mechanical mixer having a destratification efficiency of 10% would therefore require a maximum of 1 kW to operate it. Such power can be easily provided through the normal electrical power grid assuming that it exists in suitable locations. Artificial destratification needs only be undertaken during periods when its application is likely to be beneficial. The technique would appear to offer considerable promise as a cost-effective strategy for minimising cyanobacterial blooms.

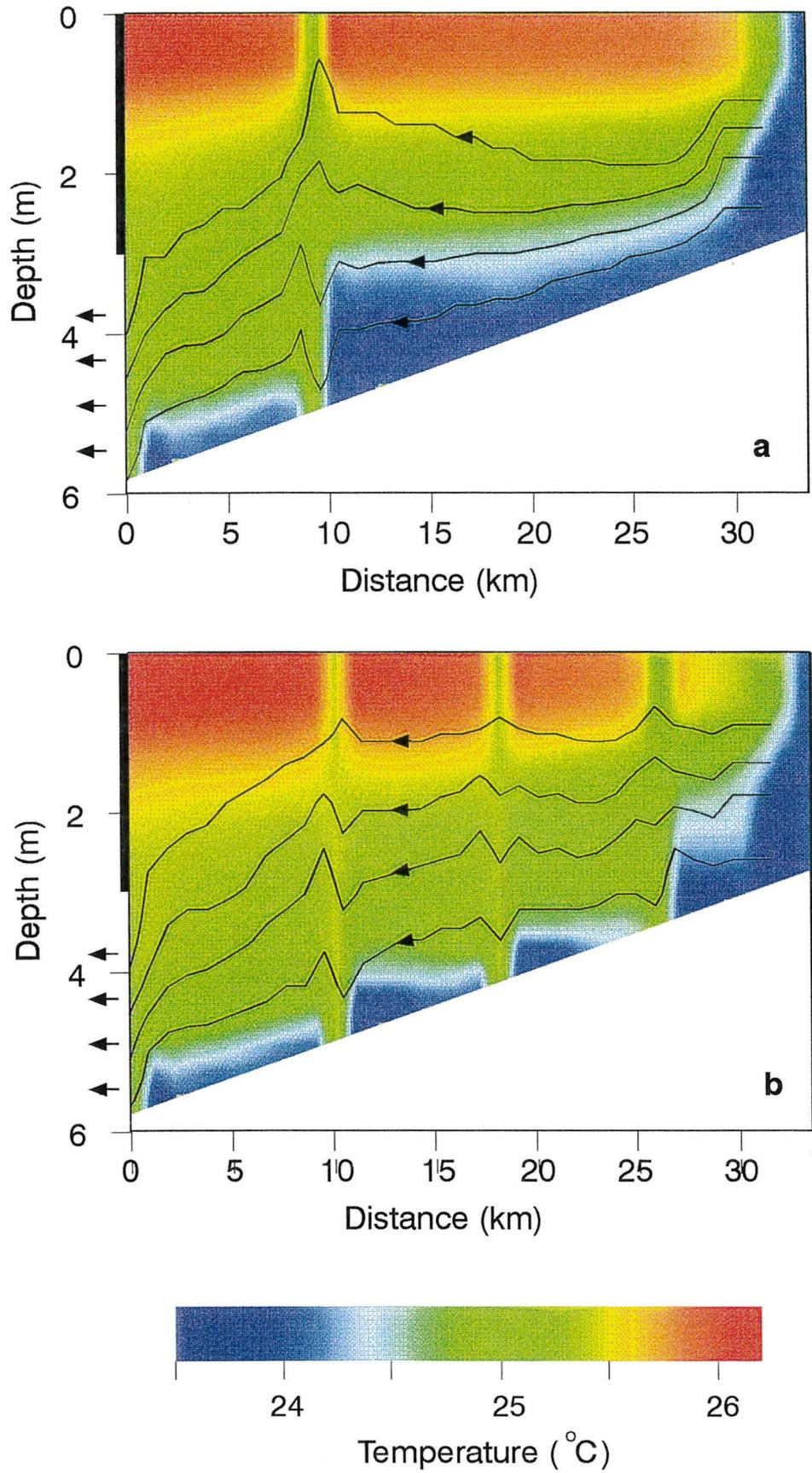


Figure 6.2 Modelled temperatures and flow streamlines in the weir pool behind an underflow weir with a) one mixer, and b) three mixers. The weir discharge is 150 ML d⁻¹.

7. Conclusions and Recommendations

a) Principal Findings

- i) Based on measurements from this study in Maude Weir pool and on measurements made in previous years in Hay Weir pool it would appear that a necessary condition for the development of *Anabaena* blooms in these two weir pools is that discharge through the weirs be less than about 1000 ML d^{-1} . Blooms are likely to occur only when discharge is less than 1000 ML d^{-1} for more than fourteen days. Growth of the *Anabaena* population occurred for discharges less than 500 ML d^{-1} , but there were no prolonged periods of discharge between 500 and 1000 ML d^{-1} during the study so the limiting discharge for *Anabaena* growth is not known more precisely. Concentrations of the dominant river phytoplankter, the diatom *Melosira (Aulacoseira) granulata*, were reduced under low discharge conditions, but this species dominated the summertime phytoplankton assemblage when the discharges exceeded 1000 ML d^{-1} .
- ii) A discharge of around 1000 ML d^{-1} represents the transition of the water column within the Maude Weir pool between it being persistently stratified and diurnally mixed during the summer.
- iii) When the water column was persistently stratified, we observed the *Anabaena* population to have accumulated in the surface layer and the *Melosira* population to be more strongly concentrated towards the bottom. These distributions are consistent with *Anabaena* being positively buoyant and *Melosira* being negatively buoyant.
- iv) We hypothesise that it is the separation of the populations within the water column under persistently stratified conditions which allows the *Anabaena* population to thrive and which causes the *Melosira* population to

decline. The *Anabaena* population in the surface layer would have ample access to the light necessary for growth, whereas the *Melosira* population would experience darkness as well as losses due to sedimentation.

v) Whether an *Anabaena* population can grow to problem proportions also depends on its residence time in the weir pool. For discharges above 1000 ML d^{-1} , water moves through the weir pool approximately as a plug flow. Residence time of phytoplankton within the pool is simply the volume of the weir pool divided by the discharge. At low discharges, when the weir pool is strongly stratified, the river flow into the upstream end of the pool flows along the pool at depth and out through the underflow weir. Consequently, under these conditions, a surface layer containing an *Anabaena* population would have a very long residence time.

vi) Although low discharge and persistent stratification would seem to be necessary conditions for an *Anabaena* bloom in Maude Weir pool, they were not always sufficient conditions. It is unknown why blooms were not always observed to occur under favourable discharge and stratification conditions. Possible explanations are nutrient limitation, predation by zooplankton, and advection away from the phytoplankton measurement site by westerly winds.

vii) The best example of an *Anabaena* bloom during this study in Maude Weir pool occurred during a five week period of persistent stratification in January–February 1994. The *Anabaena* concentration near Maude Weir increased exponentially with time with a net specific growth rate of 0.37 d^{-1} for the first three weeks, then the concentration remained relatively constant

for the next two weeks. It is probable that 0.37 d^{-1} is similar to the true *in situ* growth rate for *Anabaena*, since the discharge was low and the advection of *Anabaena* along the weir pool would have been small. This growth rate is consistent with *Anabaena* growth rates which have been reported elsewhere, and those we have observed in cultured strains.

viii) Nutrient bioassay measurements were made on a regular basis during the summer of 1993/1994. Only once during the *Anabaena* bloom of January–February 1994 was there a weak suggestion of phosphorus limitation of phytoplankton function. Nitrogen limitation was indicated during times of *Melosira* dominance before and after the *Anabaena* bloom. Unfortunately, the nutrient bioassays were not repeated the following summer to establish whether or not nutrient limitation played a role in the failure of the *Anabaena* population to bloom during that time.

b) Management Strategies

The following summarise our assessments of the efficacies of the management strategies we have considered for controlling cyanobacterial blooms in weir pools.

i) Maintaining the discharge through Hay and Maude Weirs at 1000 ML d^{-1} would almost certainly eliminate the problem of *Anabaena* blooms in Maude Weir pool in summer. This conclusion is based primarily on measurements from this study. The critical discharge for *Anabaena* control in Maude Weir pool may be as low as 500 ML d^{-1} . Factors which affect the critical discharge include the temperature of the inflowing river water, the water level in the weir pool, and the weather. Maintaining a suitable discharge would be an effective strategy in other weir pools as well, but we would expect the discharge required for cyanobacterial control would differ from that for Maude.

ii) Pulsing the discharge through the weir pool represents a promising method for controlling *Anabaena* population growth at times when the average discharge (over time) must be restricted. For Maude, we suggest that a 1500 ML d^{-1} pulse of a day's duration would easily be sufficient to mix the water column and restrain cyanobacterial growth. The pulse would be repeated at a regular interval. Ideally, the repetition interval would equal the inverse of the specific growth rate of the *Anabaena* population, which we infer to be about three days in Maude Weir pool, but repetition at longer intervals could still achieve the desired result of reducing population growth to below problem levels.

iii) Based on predictions from models of weir pool stratification and withdrawal, it would seem that the degree of stratification within the weir pool would be similar if Maude Weir were an overflow weir rather than an underflow weir. However, the residence time of the surface layer in the weir pool and hence the time available for the growth of an *Anabaena* population would be substantially less than for an underflow weir for discharges less than about 300 ML d^{-1} . This model derived value of 300 ML d^{-1} for the upper limit of the effectiveness of an overflow discharge for minimising blooms should be regarded as indicative only; models are only approximations to real phenomena. Siphons on the weir are a means of obtaining an overflow discharge through an underflow weir. They therefore represent a promising technique for minimising cyanobacterial blooms provided that they carry the major part of the discharge. Alteration of weir gate structure to allow overflows during low flow periods may be beneficial.

iv) Under stratified conditions, *Anabaena* concentrations at depth within Maude Weir pool were measured to be at least a factor of ten less than those measured in the surface layer. Consequently, the strategy of

withdrawing water for domestic consumption from the bottom of a stratified weir pool would be effective for minimising the concentrations of *Anabaena* in the water supply.

v) As a potential cost effective strategy for minimising *Anabaena* blooms, artificial destratification deserves serious consideration. Based on our model simulations we expect that the technique would reduce *Anabaena* growth rates by increasing the thickness of the surface layer and by mixing the *Anabaena* through the water column in the vicinity of the destratification devices. Artificial destratification has the potential for significantly reducing the discharge required to maintain diurnal mixing in the weir pool. It would also ensure bottom waters remain oxygenated.

c) Further work

The following are recommendations for further work deriving from this study.

i) Pulsing the discharge, operating overflow weir structures such as siphons, and artificial destratification are all promising strategies for controlling cyanobacterial blooms which should be tested. We need to test the impact of a discharge pulse during a period of low discharge on the distributions and population changes of *Anabaena* in a weir pool. Such a test would provide information on growth rates of *Anabaena* and on their flotation rates. This information is necessary for the optimisation of a pulsed discharge strategy.

The field tests of the siphons during the Maude study were equivocal, primarily due to less than ideal conditions of *Anabaena* growth and stratification. Our modelling of weir pool stratification and flow suggests that siphons should have some benefit, particularly when the weir discharge is less than about 300 ML d⁻¹. The siphons need to

be tested during low discharge conditions when the *Anabaena* are actively growing.

We need to verify the model predictions of the effects of artificial destratification on both the stratification and the flows using an actual destratification device installed in Maude Weir pool. Further modelling studies are required to estimate the impact of the technique on cyanobacterial distributions and growth rates and to determine whether combinations of artificial destratification and other strategies, such as pulsing the discharge, might be optimal for minimising cyanobacterial blooms.

ii) Laboratory investigations into the growth response of *Anabaena* to nutrients and light need to continue. We also need to investigate the buoyancy characteristics of this cyanobacterium and to determine how these characteristics might be affected by physiological state. Successful modelling of cyanobacterial distributions and growth requires quantitative information on how individual cells or colonies respond to their physical and chemical environments. Such modelling is crucial to the optimisation of pulsed discharges and artificial destratification as management strategies.

iii) In order to model the population changes of cyanobacteria within weir pools we need to know how the population is being seeded. The time it takes a population to reach bloom proportions will depend on the cyanobacterial concentration at the beginning of the growth period. Our data indicate that a "subsistence" population of *Anabaena* (1–10 cells mL⁻¹) is present in the weir pool throughout most, if not all, of the year. Exponential growth phases mostly appear to arise from this "endogenous" population. Nonetheless, it would be valuable to unequivocally determine whether other seed sources of *Anabaena* are important. Possible seed sources are the river flowing into the end of the weir pool, populations which have been trapped in

backwaters or behind logs ("dead zones") or akinete germination from the sediments.

A related question is what happens to *Anabaena* cells when they are flushed from a weir pool into a well mixed river section? Are they transported intact to cause a problem in the next weir pool downstream, or are they ruptured by the shear forces encountered as they pass under the weir?

iv) We need to know more about the loss mechanisms of *Anabaena* and what limits the size of the maximum population. To what extent are cyanobacteria which float to the water surface killed by overexposure to the sun? Is predation by zooplankton a major loss factor? Is the size of an *Anabaena* bloom in Maude Weir pool limited by nutrient availability? The answers to these questions have implications for the choice of the optimal management strategy.

v) Ultimately, we need to test a model for *Anabaena* growth in a suitable weir pool. Such a test would need to account for the nutrient dynamics in the weir pool and could very well be conducted in conjunction with tests of a cyanobacterial management strategy such as pulsing the discharge.

vi) Most of the cyanobacterial control strategies proposed here have potential impacts on other elements of weir pool and river ecology. Cycles of stratification and destratification may expose sediments to wide fluctuations in water oxygen content—a markedly different situation to the stable (and possibly zero) oxygen contents in a seasonally stratified pool or river. The sediment temperature is likely to be higher also. These changes are likely to affect nutrient cycling within the sediments for N, P, and S especially; cycling between the sediments and water column; and the water column N to P ratio.

8. Communication Activities

The following communications activities relate directly to this study.

a) Workshops, Seminars, and Conference Presentations

Presentation of "Cyanobacterial blooms: A 'natural' feature of impounded Australian waters?" by G. J. Jones to the Australian Society for Limnology Congress, Rottneest Island, January, 1994.

Attendance by Bormans, Jones, Murray, Oliver, Sherman and Webster at LWRRDC/MDBC workshop on controlling algal blooms through nutrients and flow, Canberra, June 1994.

Attendance by Webster, Sherman, and Bormans at AWWA Environmental Flows Seminar, Canberra, August 1994. The following two presentations have been published in the proceedings of the meeting:

i) "Flow, stratification and the growth of algae and cyanobacteria in Maude Weir pool on the Murrumbidgee River", B. S. Sherman, G. J. Jones, and I. T. Webster.

ii) "Effects of flow on algal growth in well mixed rivers", M. Bormans and I. T. Webster

Presentation of "Control strategies for cyanobacterial blooms in weir pools" by G. J. Jones and I. T. Webster to the NSW State Algal Coordinating Committee, Sydney, January 31, 1995.

Presentation of "Fluorescence transients in response to nutrient enrichment of N- and P- limited *Microcystis aeruginosa* cultures and natural phytoplankton populations: a measure of nutrient limitation" by R. L. Oliver and M. D. Wood to the Robertson Symposium on Chlorophyll Fluorescence, ANU, May 1994. The presentation has been published in the proceedings of the meeting.

Sherman, B. S., Jones, G. J., and Webster, I. T., 1994. Flow, stratification and the growth of algae and cyanobacteria in Maude Weir pool on the Murrumbidgee River. Poster presentation, IAWQ-SIL Conference on selection mechanisms controlling biomass distribution, Noordwijkerhout, The Netherlands, December 1995.

Sherman, B. S., Jones, G. J., and Webster, I. T., 1994. Flow, stratification and the growth of algae and cyanobacteria in Maude Weir pool on the Murrumbidgee River. Poster presentation, ASLO Conference, Reno, Nevada, U.S.A., June 1995.

Presentation of "Cyanobacterial blooms in the Murrumbidgee River" by G. J. Jones to the Riverina Academy of Sciences meeting, Charles Sturt University, June 1995.

Presentation of "Flow, stratification, and the growth of phytoplankton in a river impoundment" by I. T. Webster to the SIL Congress, Sao Paulo, Brazil, July 1995. The presentation is to be published in the proceedings of the meeting.

Presentation of the following talks to the Australian Society for Limnology Congress, Jenolan Caves, September 1995:

i) "A technique for assessing nutrient limitation in field populations of phytoplankton using chlorophyll a transients" by M. Fink and R. Oliver.

ii) "Why flow controls phytoplankton growth in the Murrumbidgee River" by B. S. Sherman, G. J. Jones, and I. T. Webster.

iii) "Modelling the relationship between stratification and discharge in rivers" by M. Bormans and I. T. Webster.

Presentation of "Control strategies for cyanobacterial blooms in weir pools" by B. Sherman to the Riverine Environment Research Forum, MDBC-NRMS, Melbourne, October 1995.

Presentation of "Control strategies for cyanobacterial blooms in weir pools" by I. T. Webster to the Nutrient Reduction Targets Working Group of the Murray-Darling Basin Commission, October 12, 1995.

Presentation of "Modelling the relationship between flow and stratification in a weir pool on the Murrumbidgee River" by M. Bormans, Centre for Environmental Mechanics, Canberra, Dec. 4 1995.

Presentation of "Control Strategies for Cyanobacterial Blooms in Weir Pools" by I. T. Webster to the CSIRO Blue-Green Algae Program Meeting, Hobart, March 5, 1996.

Presentation of "Control Strategies for Cyanobacterial Blooms in Weir Pools" by I. T. Webster at the Centre for Environmental Mechanics, Canberra, March 21, 1996.

Presentation of "Control Strategies for Cyanobacterial Blooms in Weir Pools" by M. Bormans to the Queensland Department of Natural Resources, Rockhampton, July 18, 1996.

b) Newspaper, Magazine and Radio Articles

Results of last years research (Griffith Laboratory) have been widely disseminated to stakeholders across Australia in the form of a CSIRO Division of Water Resources "Seeking Solutions" information sheet entitled "River flow and blue-green algal blooms".

A similar article to that appearing in the Seeking Solutions sheet was widely circulated in the Queensland Algal Blooms newsletter—"The Water Column"—and in the MDFRC monthly newsletter "Ripples" in May, which also is circulated to all major stakeholders.

Article by Julian Cribb in The Australian newspaper, October 26, 1994 "Science sabotages river menace".

Article by Sean Murphy in The Border Mail newspaper, January 5, 1995 "Algae experiment to kick off".

Article by David Mussared in the magazine ECOS summer 1995–1996 (page 5) "River algae go with the flow".

Article by Julian Cribb in The Weekend Australian newspaper, March 9–10, 1996 "Strategy found to eradicate toxic algae".

Twenty radio interviews including Countrywide.

c) Publications

Bormans, B. and Webster, I. T., 1994. Effects of flow on algal growth in well mixed rivers. *Proceedings of the Environmental Flows Seminar*, AWWA, Canberra, 29–35.

Oliver, R. L. and Wood, M. D., 1994. Fluorescence transients in response to nutrient enrichment of N- and P- limited *Microcystis aeruginosa* cultures and natural phytoplankton populations: a measure of nutrient limitation. *Aust. J. Plant Phys.*, 22 (2): 331–340.

Sherman, B. S., Jones, G. J., and Webster, I. T., 1994. Flow, stratification and the growth of algae and cyanobacteria in Maude Weir pool on the Murrumbidgee River. *Proceedings of the Environmental Flows Seminar*, AWWA, Canberra, 170–177.

Appendix A

Data Collection Methods

1. Physical Monitoring Instrumentation

Physical monitoring instrumentation was installed at the study site for periods ranging from weeks to months to continuously measure a variety of environmental parameters. This instrumentation included thermistor chains which measured profiles of water temperature through the water column, weather stations which measured a number of important meteorological parameters including wind speed and radiation, Hobo™ temperature recorders which measured the temperatures of the

weir discharges, and the Acoustic Doppler Current Profiler (ADCP) which we used to measure vertical profiles of current velocity as well as bathymetric determinations. Details of the measured parameters, the frequencies of data recording, and the measurement accuracies of the physical monitoring instrumentation used in the study are presented in Table A.1. In all cases the measurement resolution was equal to or exceeded the measurement accuracy.

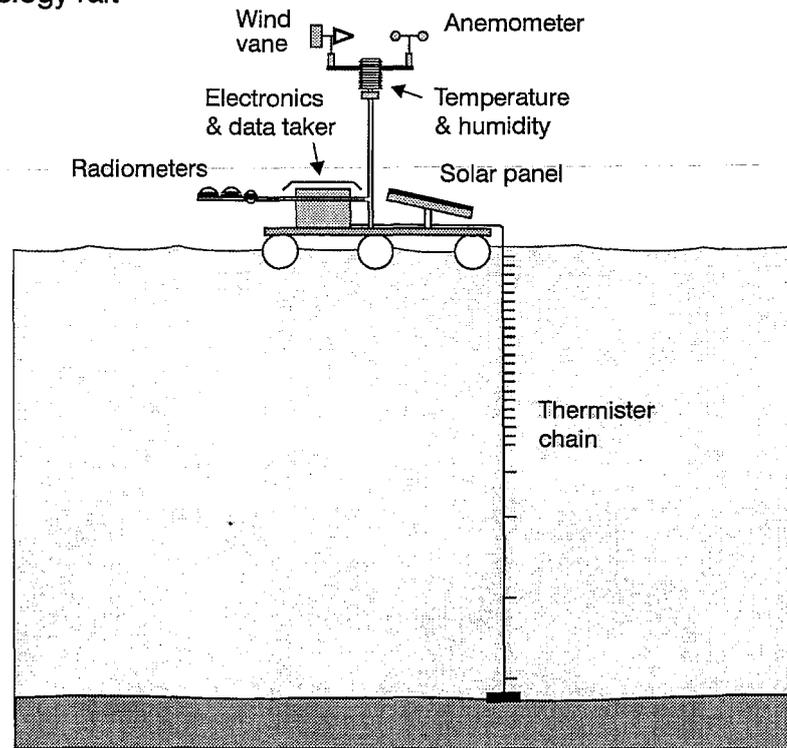
Table A.1 Physical Monitoring Instrumentation

Instrumentation	Measurement Parameter	Recording Interval*	Measurement Accuracy
Thermistor Chain	Water temperatures (°C) at depths of 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0, 1.2, 1.4, 1.6, 1.8, 2.0, 2.5, 3.0, 4.0, 5.0 m	10 min.	±0.02°C
Met. Station Raft (TC-1)	Wind speed (m s ⁻¹)	1 min.	±0.1 m s ⁻¹
	Wind direction (°)	1 min.	±15° **
	Air temperature (°C)	10 min.	±0.2°C
	Relative humidity (%)	10 min.	±2%
	Upwelling and downwelling shortwave radiation (W m ⁻²) between 0.4 and 0.8 µm	10 min.	±5%
	Upwelling and downwelling longwave radiation (W m ⁻²) between 0.8 and 80 µm	10 min.	±10%
Met. Station Paddock	Wind speed (m s ⁻¹)	2 min.	±0.1 m s ⁻¹
	Wind direction (°)	2 min.	±3°
Hobo Temperature Recorder	Water temperature (°C)	24 min.	±0.14°C
ADCP	Current velocity (m s ⁻¹) at depth intervals of 0.5 m	30 min.	

* Most instrumentation measured at finer time intervals, so that recorded data generally represent averages of many more closely spaced measurements.

** The loss of accuracy in the raft wind directions is due to the raft being able to swing on its mooring.

a TC-1 Meteorology raft



b TC-2, TC-3

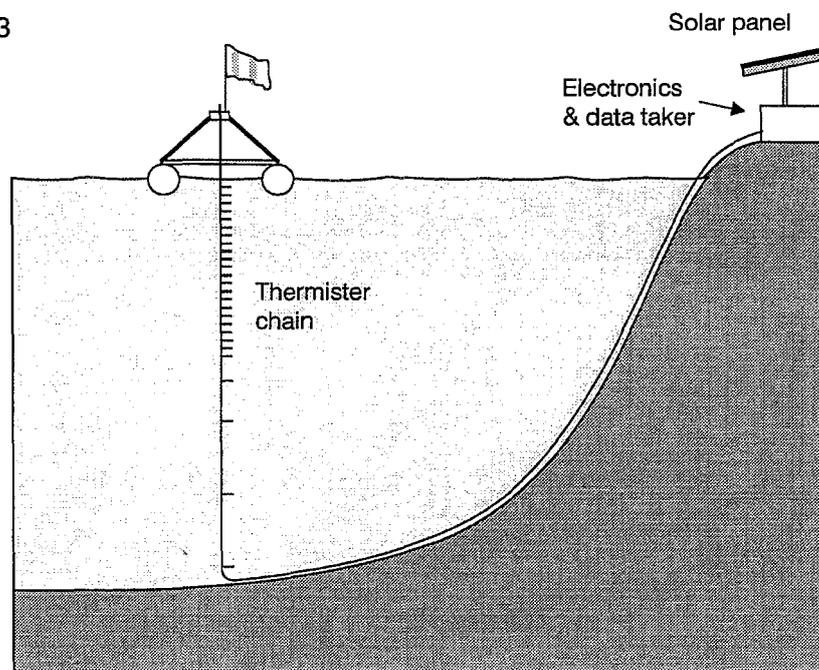


Figure A1 Schematic showing the thermistor chain installations.

a) Thermistor Chains

A thermistor chain consists of a string of temperature sensors (thermistors) which is hung vertically in the water column to allow the measurement of temperature at a series of depths. We used three identical thermistor chains in our study which each incorporated nineteen thermistors (Thermometrics Inc.). One of the thermistor chains, TC-1, was hung from the raft near the weir which also supported our main meteorological station (Fig. A.1a), whereas the other two thermistor chains TC-2 and TC-3 were supported by much smaller rafts at sites further upstream (Fig. A.1b). The spacing of the thermistors through the water column was adjusted to provide finer resolution near the water surface than near the bottom (Table A.1). Thermistors at depths greater than the water depth would lie on the bottom of the weir pool. This occurred from time to time as the pool level was raised or lowered. Data were recorded using Datataker™ model 505 data loggers which were mounted in cabinets on the shore for TC-2 and TC-3 and on the raft for TC-1. The data logging systems were powered by 12 VDC batteries that were kept charged by photovoltaic panels. The data collection system on the raft was connected by modem to the telephone system. This permitted the remote downloading of the thermistor chain and meteorological station data from the raft at TC-1.

b) Meteorological Stations

The meteorological station on the raft comprised an anemometer and wind vane for measuring wind speed and direction, an air temperature sensor, a humidity sensor, and radiometers for measuring the up- and downwelling from and to the water surface. In order to measure wind velocities at a site removed from the sheltering effects of the trees lining the weir pool we installed an additional anemometer and wind vane in an open paddock about 0.5 km away from the river. The meteorological data from the raft were recorded and transmitted via telephone link using the system already described for the thermistor chains. Recording of the paddock meteorological measurements was accomplished using a Datataker™ model 500 data logger.

i) Wind Measurements

The anemometers and wind vanes used to measure wind speed and direction on the raft at TC-1 and in the paddock were of the same type. Wind speeds were measured using a triple cup anemometer manufactured by Vaisala Pty. Ltd. (model WAA15), whereas wind direction was measured using a vane manufactured by the same company (model WAV15). The height of the raft wind sensors above the water surface was 2.1 m. In the paddock the wind sensors were fitted to a mast at a height of 3.5 m above the ground.

ii) Air Temperature and Humidity

Relative humidity was measured on the raft at TC-1 using a Vaisala model HMD30Y solid-state humidity probe which also measured air temperature. This probe was mounted within a radiation shield at a height of 1.8 m above the water surface.

iii) Radiometers

We employed three radiometers extending from the side of the raft at TC-1 to measure the radiation impinging on and reflected/emitted from the water surface. A Kipp and Zonen™ model CM14 pyranometer was used to make measurements of the downward and reflected fluxes of shortwave radiation to and from the water surface. The longwave radiative flux impinging the water surface and the longwave flux emitted from the water surface were measured using a Kipp and Zonen model CG2 pyrgeometer. Subtracting the upward from the downward flux for each radiation type provides the net radiative fluxes which are required as input to the stratification model for the weir pool. The two radiometers were mounted at a height of 0.5 m above the water surface.

c) Hobo Temperature Logger

The Hobo™ temperature logger is a self-contained temperature logger about the size of a matchbox. We placed these devices inside waterproof brass housings which we hung by wire rope in the outflows from Hay and Maude Weirs. Deployed in

this way the Hobos provided time series of the temperature of the discharges from the two weirs.

d) Acoustic Doppler Current Profiler

The Acoustic Doppler Current Profiler (ADCP) measures current velocities through the water column. The instrument we used is a model BBADCP manufactured by RD Instruments. We deployed it in a frame on the bottom pointing upwards at a location near the raft at TC-1. The device transmits acoustic pulses at a frequency of 1200 kHz in four cones inclined at an angle of 20° to the vertical. Some of the acoustic energy is reflected by water density variations or by debris in the water back towards the ADCP where it is received by acoustic transducers. By analysing the Doppler shifts of the reflected pulses, the ADCP determines the velocity of the water at the depth of reflection. Since some acoustic reflection occurs from all depths between the top of the device and the water surface, a profile of velocity can be measured through the water column. We operated the ADCP in a mode which measured velocities at a vertical resolution of 0.5 m. Each measurement represents an average velocity through a 0.5 m bin.

At the beginning of the study, we operated the ADCP attached to the front of our boat in downward looking mode to measure the bathymetry of the weir pool. In this configuration the time of flight of the acoustic reflection off the bottom is taken to be a measure of the water depth in exactly the same way as for a conventional echo sounder. By analysing the Doppler shift of the bottom reflection, the speed and direction of the boat can be measured directly. Integration of the speed and direction with time from a known starting position provides a continuous estimate of the boat's position which is recorded alongside the water depth. The use of the ADCP in this way provided a very convenient method for obtaining the bathymetric data we required.

Table A.2 The TFD profiler

Measurement Parameter	Accuracy	Resolution
Temperature	±0.1°C	0.015°C
Fluorescence	N/A	1% of range
Depth	±2% of depth	6 mm

2. Temperature-Fluorescence-Depth (TFD) Profiler

During our more intensive field studies, we measured vertical profiles of temperature and fluorescence at a series of stations located along extended sections of the weir pool using our TFD profiler. This is a device lowered and raised through the water column by a hand-operated winch on our boat. Temperature was measured using two fast response thermistors (Thermometrics™ model FP07), fluorescence was measured using a Sea Tech Inc. fluorometer, and depth was measured using a Keller™ model PAA-2 (Table A.2). Conductivity, pH, and dissolved oxygen sensors were also mounted on the profiler, but the measurements obtained from these were not considered to be reliable and so are not reported. Data from the TFD profiler were recorded by computer on the boat as the device was being lowered or raised. With a nominal lowering/raising rate of 0.25 m s⁻¹ for the profiler and a data recording rate of 42.8 Hz the nominal spatial resolution (vertical) of the measurements from the profiler is 6 mm.

We use fluorescence as a surrogate for chlorophyll-a concentration. For a particular phytoplankton species, the chlorophyll-a concentration is approximately proportional to fluorescence at least at those times or those depths where fluorescence is not diminished by photoinhibition or severe environmental stress. The fluorescence emitted per unit chlorophyll concentration decreases with increasing exposure to irradiance greater than about 100 μmol quanta m⁻² s⁻¹. This irradiance occurred at a depth of about 1 m in the weir pool during daylight hours. For calculating chlorophyll from fluorescence, we used the manufacturer's calibration. During the study at Maude we had the opportunity to check this calibration using samples of water analysed for chlorophyll chemically. We found the manufacturer's calibration underestimated measured chlorophyll by about 10% only.

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