

APPLIED ISSUES

# Critical flow velocities for the growth and dominance of *Anabaena circinalis* in some turbid freshwater rivers

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## SUMMARY

1. From measurements at several weir pool sites along the turbid and freshwater Barwon-Darling River, Australia, the development of persistent stratification (for periods of >5 days) was related to river discharge. For the sites examined, the required discharge to allow the development of persistent stratification was between 100 and 450 ML day<sup>-1</sup> during the hotter months. High discharge during the hotter months did not allow the formation of persistent stratification, although diel stratification did occur. Low discharge through the cooler months resulted in diel stratification, although persistent stratification lasting for a few days could occur at times.

2. The growth and dominance of *Anabaena circinalis* at these sites was closely related to the establishment and maintenance of persistent and strong thermal stratification. **Growth only occurred during extended periods (>5 days) of persistent stratification.** These conditions not only restrict the displacement of *A. circinalis* downstream, they also allowed the alga to accumulate in surface waters.

3. The discharge levels required to suppress the formation of persistent stratification at the study sites were variable because of large differences in channel cross-sectional area. To compensate for this variation, the discharges were converted to flow velocities. **A critical velocity of 0.05 ms<sup>-1</sup> was sufficient for the suppression of persistent thermal stratification and concurrent *A. circinalis* growth for all sites.** The turbulent velocity ( $u^*$ ) under weak wind mixing at the study locations varied between  $2.66 \times 10^{-3}$  and  $2.91 \times 10^{-3}$  ms<sup>-1</sup> at the critical flow velocities. These values may have potential to be applied to other rivers in similar climatic zones to suppress nuisance cyanobacterial growth.

*Keywords:* *Anabaena*, cyanobacteria, flow velocity, river discharge, thermal stratification

## Introduction

In turbid Australian rivers such as the Murray (Bormans *et al.*, 1997), the lower Darling (Hötzel & Croome, 1994; Oliver *et al.*, 2000) and the Murrumbidgee (Webster *et al.*, 1995; Sherman *et al.*, 1998), the growth of *Anabaena* and other cyanobacteria has been

linked to low discharge. Weir pools are particularly susceptible to the effects of reduced discharge and are known to be susceptible to blooms of cyanobacteria (Hötzel & Croome, 1994). Discharge (Marshall & Burchardt, 1998; Ha *et al.*, 1999), flow velocity (Lung & Paerl, 1988) and turbulence (Steinberg & Hartman, 1988; Eldridge & Sieracki, 1993) have been identified as important factors influencing the development of cyanobacterial blooms. Determining discharge levels that suppress cyanobacterial growth is useful at a river reach or site scale for river management. However, as discharge values are site-specific, being

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influenced by cross-sectional area, they cannot be extrapolated to other river reaches and systems.

Discharge influences the downstream translocation of phytoplankton, the mixing of phytoplankton cells through the vertical light gradient and can also affect the physicochemical environment within a river, such as by influencing the development of thermal stratification. Recently, the development of persistent stratification has been linked to the growth of *Anabaena* in an Australian river (Sherman *et al.*, 1998), and the authors suggest site specific discharge levels to suppress the formation of persistent stratification and concurrent *Anabaena* growth at this site. Manipulating discharge to change flow rate, and indirectly how this affects stratification, is one of only a few ways that phytoplankton growth may be controlled in a river (Webster *et al.*, 1995). The use of a 'critical flow velocity' or 'critical turbulent velocity' ( $u^*$ ) would be more useful, as it can be applied more widely as a flow target for reducing cyanobacterial growth in rivers. Bormans & Webster (1997) developed a model that predicts, for similar climatic conditions, the flow velocity necessary to disperse persistent thermal stratification will be comparable. Such a critical velocity should be transferable to other rivers in similar climatic zones, and may be of use to water resource managers trying to determine effective flows for reducing cyanobacterial growth.

The Barwon-Darling River, New South Wales, Australia came to worldwide prominence during November and December 1991 with the onset of a massive 1000 km bloom of the filamentous toxic cyanobacterium *Anabaena circinalis* Rabenhorst (Bowling & Baker, 1996). The Barwon-Darling is the only major

river system in this large, semi-arid region that has high reliance on surface water for drinking and domestic water supply, stock watering and irrigation. Historically the rivers of the Murray–Darling system have been managed for agricultural purposes so that maximising water storage and minimising discharges have been key considerations (Ebsary, 1994). As a result, many weirs with large volumes of water stored behind them (resembling a series of linked impoundments) have been built along the river.

Although the underlying limnological conditions occurring in the Darling River at the time of the 1991 bloom were reported (Bowling & Baker, 1996), the conditions triggering *Anabaena* growth in this river are still unclear. The present paper uses data from several study locations along the Darling River to illustrate links between discharge and the development of persistent stratification, and consequently how this affects the development of *Anabaena* growth. As channel morphology differs among sites, discharge levels are converted to flow velocity to determine a consistent 'critical velocity' for the suppression of *A. circinalis* growth that can be applied more generally across river systems in similar climatic zones.

## Methods

### Study sites

The study was focused predominantly on a site in the Bourke Weir pool, located on the Darling River (Fig. 1) where data were collected for 3 years (1995–98). In addition, 2 years' data were collected from the Namoi River at Walgett near its confluence with the

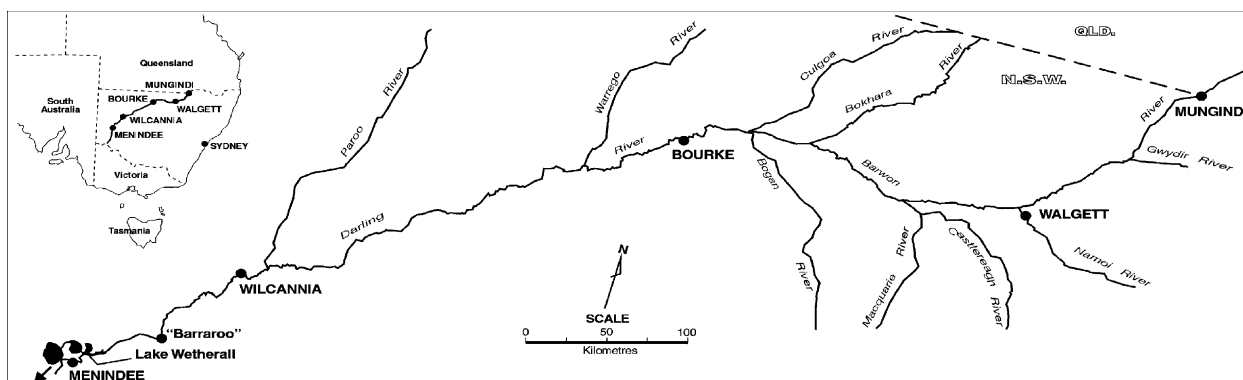


Fig. 1 Location of the Namoi River at Walgett, Darling River at Bourke, Darling River at Wilcannia and Darling River at Barraroo study sites.

Barwon-Darling (1996–98), and from the Darling River at Wilcannia (1996–98). Short-term sampling was also performed on the Darling River at Barraroo during a bloom event. All sites are shown in Fig. 1.

The Bourke, Walgett and Wilcannia sites are within weir pools that discharge by overflow. The weirs are simple walls that impound a volume of water and cannot be used to regulate flow rates downstream. The weirs are relatively small and store water within the confines of the river channel, forming weir pools that stretch for approximately 30–50 km upstream.

### *Sampling and analysis*

Discharge data were available for the sites from routine records of the New South Wales Department of Land and Water Conservation. Readings are presented as mean daily discharge.

Samples for algal enumeration were taken twice weekly during summer and weekly otherwise, at approximately 9 a.m., from a boat anchored in mid-stream. A 1.5-m long hosepipe was used to integrate the top of the water column. Each sample was mixed in a bucket, decanted into a sample bottle and preserved with Lugol's iodine solution. These samples were subsequently counted using a calibrated Lund cell and compound microscope after concentration by sedimentation in a measuring cylinder. Counting precision was to  $\pm 20\%$  (Hötzel & Croome, 1999). Phytoplankton were identified to genus level using the keys of Prescott (1978), except for the cyanobacterium *Anabaena*, which was identified to species level (Baker, 1990).

Samples for turbidity were also taken from 25 cm below the water surface, and stored cool (4 °C) until laboratory analysis using a calibrated HACH nephelometer (HACH, Loveland, CO, USA). Samples were collected in the same way for total suspended solids (TSS) which was determined gravimetrically. Water temperature and dissolved oxygen were measured *in situ* using a Yeokal Electronics Pty Ltd 603 temperature/dissolved oxygen meter (YEOKAL Electronics, Brookvale, Australia). Surface water pH and conductivity were recorded using a TPS Pty Ltd digital pH meter and conductivity meter (TPS, Brisbane, Australia), respectively. Water transparency was measured using a white 20 cm diameter Secchi disc lowered on the unshaded side of a boat. Light penetration and euphotic depth ( $Z_{eu}$ ) were determined using a

Licor LI-185B quantameter (Li-cor, Lincoln, NB, USA) coupled to an underwater quantum sensor and reference sensor in air. Measurements of downwelling and upwelling irradiance were recorded at 10-cm intervals down the water column. The euphotic depth was determined as 1% of the incident surface irradiance ( $I_0$ ). A chain of recording thermistors (HOBO™, Onset Computer Corporation, Bourne, MA, USA) were placed in the river at Bourke and Walgett for the duration of the study and recorded temperature (0.2 °C detection limit) at approximate depths of 0, 0.25, 0.5, 0.75, 1, 1.5, 2, 2.5 and 3.5 m at hourly intervals.

At the Barraroo site, discrete water samples for algal enumeration were taken at depths of 0, 0.5, 1, 2 and 3 m using a horizontal trap sampler from a boat anchored midstream in the Darling River. Sampling was performed three times per day over a 24-h period (6:00, 14:00 and 24:00 hours) to examine phytoplankton vertical distributions. Samples were preserved with Lugol's solution and counted as previously described.

### *Data analysis*

Correlation analysis (Spearman) was applied to the physicochemical and phytoplankton abundance data. Significant correlations ( $P < 0.05$ ) were analysed by regression to find the line of best fit. If two or more relationships were evident for a phytoplankton group or species, multiple regression was applied to examine the combined effect of the environmental variables.

## **Results**

### *Discharge and the development of persistent stratification in the Darling River at Bourke*

Persistent stratification occurred in the Darling River at Bourke when discharge was low, and only then during the hotter months (Fig. 2). Two periods when persistent stratification was observed are discussed below. The first period is discussed in greater detail and occurred early in the study (October to November 1995) when discharge was zero as summer approached. Low discharge in the river continued as air and water temperatures increased during November and December 1995. Persistent thermal stratification (defined as temperature between top and bottom

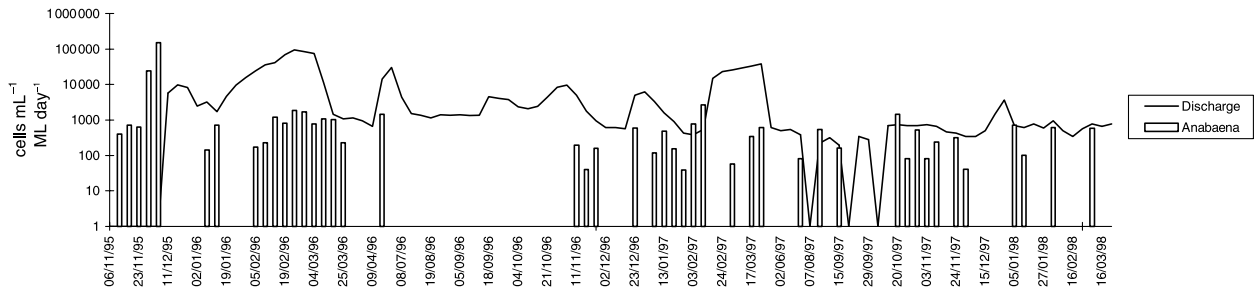


Fig. 2 *Anabaena circinalis* numbers and discharge in the Darling River at Bourke over 1995–98.

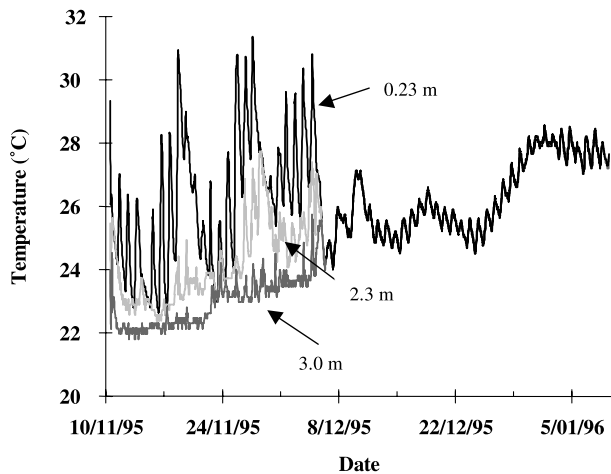


Fig. 3 Thermal stratification measured for three thermistors at depths of 0.23, 2.3, and 3 m from 30 November until 25 December 1995 at Bourke. After the 26 December 1995 the depths were 1.3, 3.4 and 4.1 m, respectively.

waters constantly  $>0.5$  °C for more than 5 days) had occurred in the weir pool by 10 November. The temperature data obtained from three of the thermistor chain sensors over 60 days between November 1995 and January 1996 provide an overview of the typical patterns in temperature stratification that occurred during this period (Fig. 3). Initially, and up until 6 December, temperature stratification was observed in the water column, with differences in temperature between depths of 0.23, 2.3 and 3.0 m as indicated by the separation between the temperature lines. Higher temperatures are nearer to the water surface. The water column appeared to mix briefly on 24 November, but stratification became more pronounced after this date and minimum vertical temperature differences were usually maintained at greater than 1 °C over the entire 24 h.

During November and early December 1995 when discharge was zero, the maximum and minimum air

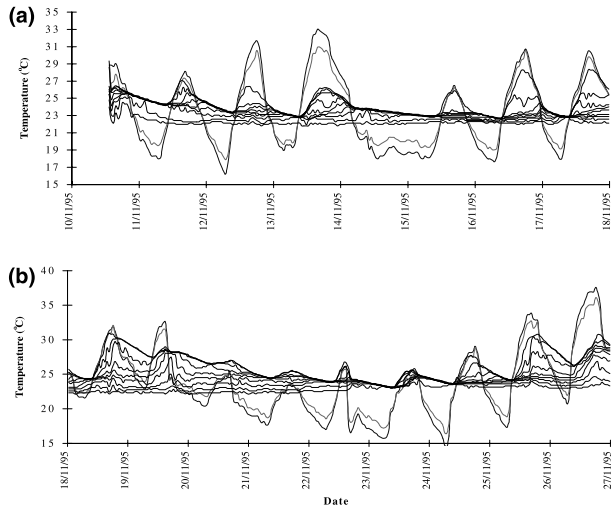


Fig. 4 Water temperature profiles in the Darling River and air temperature at Bourke (a) and (b) from 10 November until 27 November 1995. Two sensors measured air temperatures at 0.14 and 0.5 m above the water surface (traces showing the largest oscillations). Water temperatures were measured at depths of 0.23, 0.58, 0.93, 1.28, 1.63, 2.0, 2.3, 2.7 and 3.0 m with higher temperatures at shallower depths.

temperatures varied considerably between days and influenced temperature stratification in the water column. Air temperatures showed large oscillations (Fig. 4), with minimum and maximum temperatures of 15 and 38 °C, and large diurnal fluctuations (up to 16 °C). High daytime temperatures resulted in intense stratification, but were often followed by low temperatures at night that led to convective mixing of the surface layers to depths of 2–3 m (Fig. 4). On occasions when night-time temperatures did not drop much below water temperatures, thermal stratification was maintained throughout the night, as occurred between 18 and 20 November (Fig. 4). On days when air temperatures were relatively low (25 °C maximum) the degree of stratification in the weir pool decreased. Changes in mixing for the period prior to the high

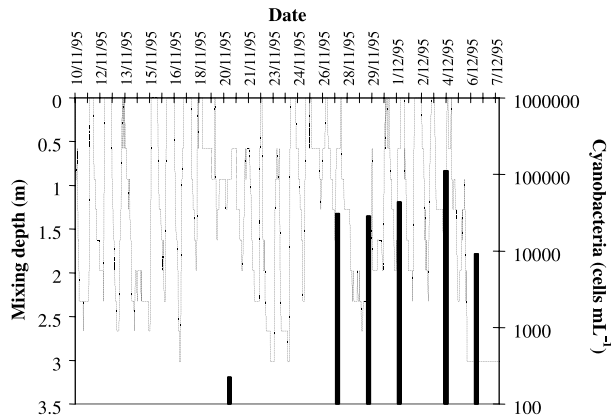


Fig. 5 Mixing depth (continuous line) and concentration of cyanobacteria (bars) in the Darling River at Bourke from 11 November until 7 December 1995.

discharge event on 6 December are shown in Fig. 5. Early in the period, mixing depths generally approached the surface during the day (i.e. temperature stratification occurred throughout the monitored depth) and extended to between 2.3 and 3 m depth during the night (Fig. 5). On occasions, when overnight air temperatures were not much lower than water temperatures, the overnight mixing depths were reduced. This occurred between 18 and 20 November and again between 26 and 27 November when maximum mixing depths did not greatly exceed 1.0 m (Figs 4 and 5). On 6 December 1995, the rapidly rising river (Fig. 2) fully mixed the water column so that temperatures were uniform from top to bottom, as indicated by the superimposed temperature lines in Fig. 3.

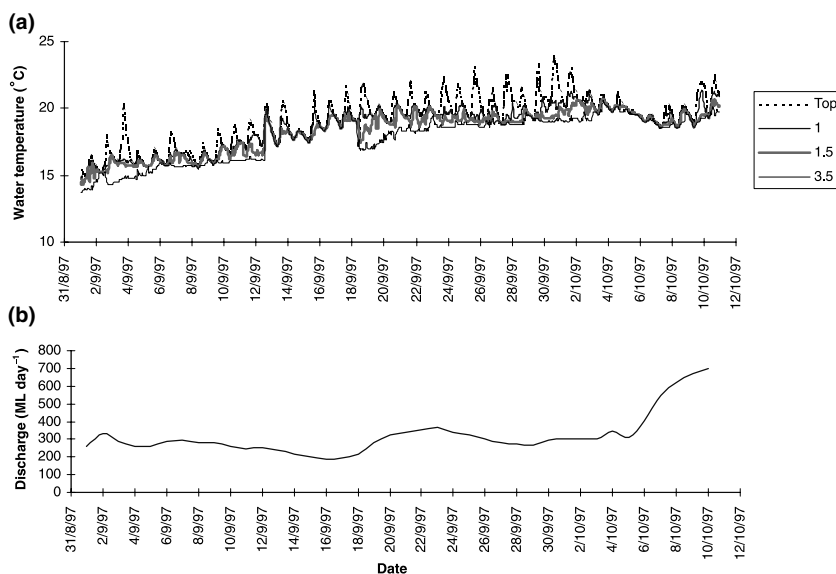


Fig. 6 Thermal stratification (a) and discharge (b) in the Darling River at Bourke from 1 September until 11 October 1997.

On one occasion during October 1997, persistent stratification occurred in the river (Fig. 6). Discharge was low in August ( $<300 \text{ ML day}^{-1}$ ), but persistent stratification did not occur for more than a few days at a time. Not until September, under a similar discharge regime ( $<400 \text{ ML day}^{-1}$ ), was stratification able to persist for extended periods. It is likely that thermal energy was insufficient to keep the water column persistently stratified until mid-September. Persistent stratification occurred from 19 September and was maintained until discharge disrupted stratification and growth in mid-October (Fig. 6).

Figure 7 shows the thermal conditions in the Bourke weir pool during the time period in 1996 equivalent to that when the 1995 bloom took place. In 1996, discharge dropped gradually from  $1500 \text{ ML day}^{-1}$  in mid-November to  $500 \text{ ML day}^{-1}$  by mid-December. As discharge decreased, diel stratification became stronger and average water temperature increased, but thermal stratification did not develop for more than a few days at a time without overnight mixing of the water column (Fig. 7).

A significant linear relationship ( $P < 0.0001$ ,  $r^2 = 0.79$ ) between discharge and maximum stratification (greatest temperature difference between the surface and the bottom over a 24-h period) was determined for Bourke weir pool over the study. With little wind mixing and typical summer temperatures, persistent stratification (defined as minimum change in temperature between top and bottom waters  $>0.5 \text{ }^\circ\text{C}$  for more than 5 days) usually started once

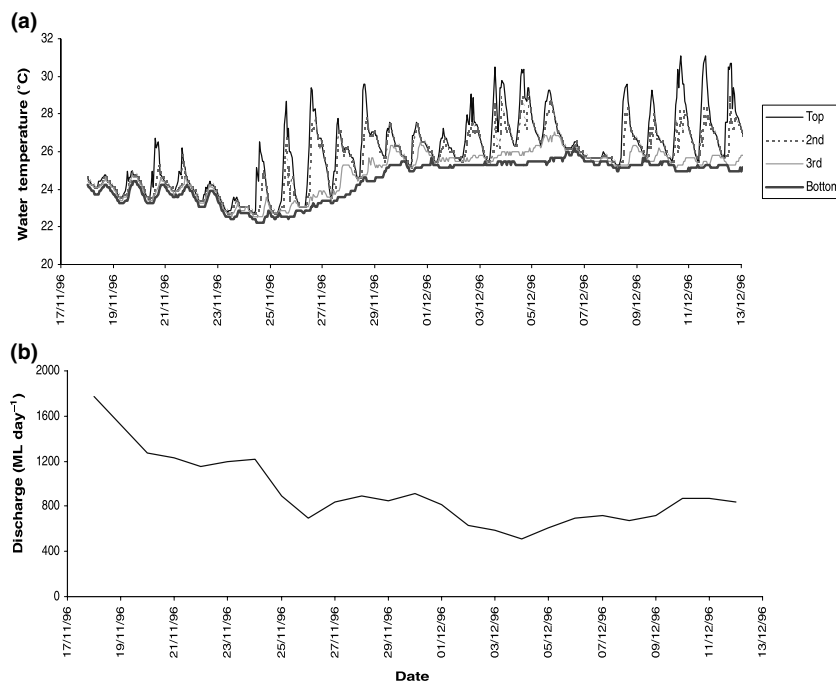


Fig. 7 Thermal stratification (a) and discharge (b) in the Darling River at Bourke from 17 November until 13 December 1996.

discharges were  $<450 \text{ ML day}^{-1}$  and the maximum daily temperature differential approached  $5 \text{ }^{\circ}\text{C}$ .

#### Discharge, persistent stratification and the growth of *A. circinalis* at Bourke

Figure 8 shows large *Anabaena* growth has historically (1992–96) occurred only during periods of low discharge, usually less than approximately  $500 \text{ ML day}^{-1}$ . This seems consistent with the occurrence of persistent stratification during flows below  $450 \text{ ML day}^{-1}$  in the hotter periods of the year. In this study, only one substantial bloom and two minor growths of *A. circinalis* occurred at Bourke during the

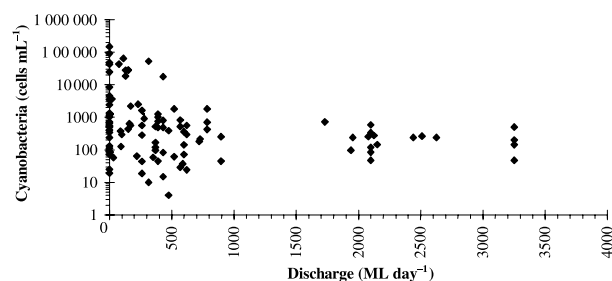


Fig. 8 Scatter plot between the concentration of cyanobacteria and discharge rate for the Darling River at Bourke from the period September 1992 to February 1996.

3-year study (Fig. 2). The largest bloom occurred during November and December 1995 (early summer), when cell numbers reached over  $100\,000 \text{ cells ML}^{-1}$ . The period prior to the 1995 bloom of *A. circinalis* was characterised by low discharge (no flow actually entering the weir pool or discharging from it), reduced turbidity ( $10\text{--}25 \text{ NTU}$ ), high water temperatures and low cyanobacterial numbers ( $<200 \text{ cells ML}^{-1}$ ). Despite the extended period of zero discharge at this time (Fig. 2), a significant population of cyanobacteria was not observed until 20 November, when a concentration of approximately  $200 \text{ cells ML}^{-1}$  of *A. circinalis* was recorded (Fig. 5). This coincided with a period of several days when diurnal mixing was curtailed. During this time, reduced mixing depths occurred more frequently and the *A. circinalis* population increased at a specific growth rate of approximately  $0.4 \text{ day}^{-1}$ , which is equivalent to a population doubling time of 1.7 days. Although a number of other phytoplankton taxa were present during the peak of the *A. circinalis* bloom, no one group predominated and the total counts were around  $3000 \text{ cells ML}^{-1}$ .

*Anabaena circinalis* reached a population concentration of over  $100\,000 \text{ cells ML}^{-1}$  before increased discharge in December to over  $1000 \text{ ML day}^{-1}$  (Fig. 2) mixed the weir pool, destroyed the thermal

stratification and removed the cyanobacterial population (Fig. 5). Samples taken on 11 December lacked *A. circinalis* cells, the speed of the population decline probably indicating downstream translocation of the cells. Other phytoplankton taxa also declined with the increased discharge.

On one occasion in 1997 during February, *A. circinalis* concentrations increased to 2671 cells mL<sup>-1</sup> (Fig. 2). At this time discharge had decreased to 348 ML day<sup>-1</sup>. The thermistor data through January and February were lost, but temperature stratification was probably persistent, as witnessed at similar times in other years at this discharge rate. *Anabaena circinalis* growth was disrupted by increased discharge to over 10 000 ML day<sup>-1</sup> in mid-February (Fig. 2). Another small peak in the *A. circinalis* population also occurred in October 1997, reaching 1450 cells mL<sup>-1</sup>. Discharge was low in August, September and October (<300 ML day<sup>-1</sup>) and from 19 September persistent stratification was maintained (Fig. 6). Increased discharge disrupted stratification and *A. circinalis* growth in mid-October.

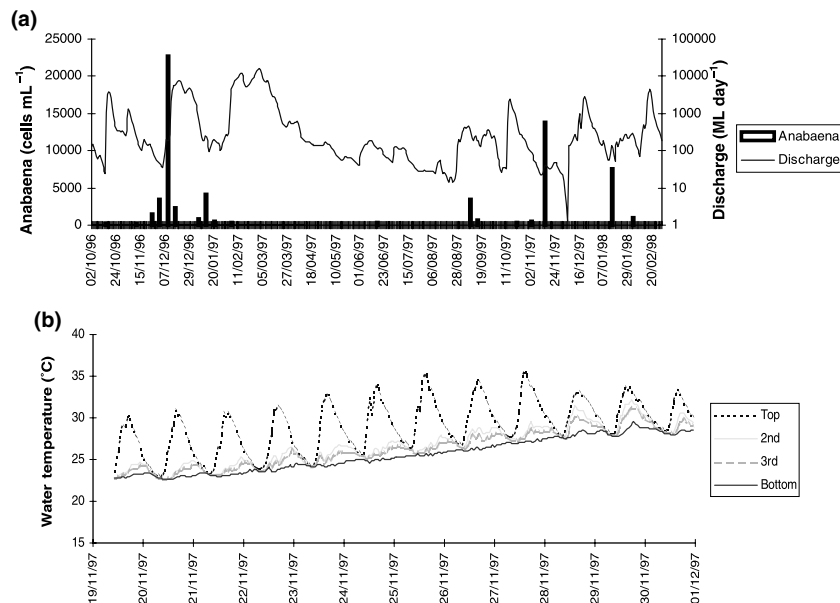
Growths of *A. circinalis* only occurred during periods of extended persistent stratification. Periods of low discharge that occurred without persistent stratification, even during the hottest months of summer, did not result in cyanobacterial blooms. Discharge dropped from 1500 to 500 ML day<sup>-1</sup> during summer in 1996 and stratification did not persist for

more than a few days at a time (Fig. 7). Throughout this period *A. circinalis* cell concentrations remained low (cf. <1000 cells ML<sup>-1</sup>).

#### Other sites examined

Growths of *A. circinalis* occurred in the Namoi River at Walgett during December 1996, reaching a maximum of 22 000 cells ML<sup>-1</sup> (Fig. 10). Two weeks prior to the growth, discharge dropped from 100 to <50 ML day<sup>-1</sup>. The bloom was eventually suppressed and flushed downstream when discharge increased to over 1000 ML day<sup>-1</sup>. The only other substantial growth occurred during December 1997, reaching over 13 000 cells ML<sup>-1</sup>. Discharge again dropped to <50 ML day<sup>-1</sup> prior to growth, and thermal stratification became stronger and more persistent (Fig. 9). Discharges below 100 ML day<sup>-1</sup> in the hotter months allowed the development of *A. circinalis* growths in the Namoi River at Walgett. Discharges required for *A. circinalis* growths to occur were lower than at Bourke, probably because the channel is narrower and river shallower at low discharge.

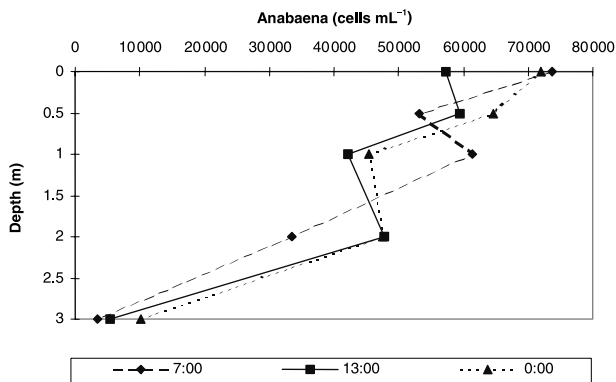
Several *A. circinalis* blooms occurred elsewhere along the Barwon-Darling River during the study. These were examined over short periods to determine whether associated environmental conditions were consistent with those at the other sites. Growths of *Anabaena* sp. in the Darling River at Wilcannia, during



**Fig. 9** *Anabaena* numbers and discharge (top), and thermal stratification during late November 1997 leading up to a bloom of *Anabaena* (bottom) in the Namoi River at Walgett.

1997, coincided with persistent stratification. Discharges gradually decreased from 400 to <100 ML day<sup>-1</sup> and the euphotic depth was 1.7 m. *Anabaena* sp. numbers rose concurrently to over 50 000 cells ML<sup>-1</sup>. Discharges increased to over 1000 ML day<sup>-1</sup> in early January and *Anabaena* numbers decreased to below 1000 cells mL<sup>-1</sup>. Discharges above 200 ML day<sup>-1</sup> appear sufficient to stop the formation of persistent stratification and excessive *Anabaena* growth.

In the Darling River at Barraroo, in November 1997, *Anabaena* sp. cell numbers reached over 70 000 cells mL<sup>-1</sup> when discharges were consistently below 300 ML day<sup>-1</sup>. During the bloom, the euphotic depth was 2.5 m, with the thermocline at a similar depth. Samples were taken at various depths over a 24-h period to determine whether *Anabaena* sp. were able to disentrain from the vertical mixing forces of the water column, and accumulating at the surface, spent greater amounts of time in the euphotic zone (Fig. 10). The profiles showed accumulation of *Anabaena* towards the surface throughout the 24-h period (especially in the early morning and at midnight). Afternoon samples showed lower surface concentrations. Total cell numbers of *Anabaena* in the three



**Fig. 10** Vertical patterns in *Anabaena* sp. cell concentration (cell mL<sup>-1</sup>) in the Darling River at Barraroo on 23 November 1997 at three times (7:00, 13:00 and 0:00 hours).

profiles were quite similar ( $233\,200 \pm 16\,500$  cells ML<sup>-1</sup>) indicating total biomass between the profiles had not changed greatly over the period of study. Concentrations of *Anabaena* were less than a fifth as high in bottom waters and most of the population maintained position within the euphotic zone (2.5 m). Non-cyanobacterial phytoplankton showed a relatively even distribution throughout the water column and were usually between 1000 and 3000 cells ML<sup>-1</sup>.

#### Flow velocity and the development of persistent stratification

To standardise the relationships between discharge and the development of persistent stratification at different sites, flow velocities were determined (ratio of discharge to channel cross-sectional area) at the discharge levels identified for persistent stratification to occur. Channel capacities, depths and cross-sectional areas varied at each of the sites at the identified discharge levels. Table 1 shows the values determined for discharge, cross-sectional area and determined critical flow velocities to suppress stratification. Critical flow velocities for the sites were found to be similar despite large differences in cross-sectional area. A critical flow velocity that suppressed the development of persistent stratification during the hotter months at all sites was 0.05 ms<sup>-1</sup>. Under weak wind mixing (<20 ms<sup>-1</sup>), the turbulent velocity (or friction velocity), is also important in determining when transitions between the mixed and stratified water column may occur. Wind mixing is likely to play a small role in this river system as summer wind conditions are usually calm and short reaches and high banks minimise wind effects. The turbulent velocity ( $u^*$ ) under turbulently mixed conditions (defined by Reynolds Number) was calculated using the equation  $u^* = \hat{u} [2.5 \ln (12 H/r_p)]^{-1}$ , where  $\hat{u}$  is the average velocity of flow,  $H$  is the full water depth and  $r_p$  is the roughness of the bed channel (Reynolds,

**Table 1** Summary of variables used to determine the critical flow velocities required to suppress the development of persistent stratification at the study sites. The determined turbulent velocities ( $u^*$ ) required are also presented for each site

Study site	Discharge (ML d <sup>-1</sup> )	Discharge Q (m <sup>3</sup> s <sup>-1</sup> )	Average cross-sectional area (m <sup>2</sup> )	Critical velocity (ms <sup>-1</sup> )	Turbulent ( $u^*$ ) velocity (ms <sup>-1</sup> )
Darling River at Bourke	450	5.2	97	0.053	$2.91 \times 10^{-3}$
Namoi River at Walgett	100	1.2	28	0.041	$2.66 \times 10^{-3}$
Darling River at Wilcannia	200	2.3	50	0.046	$2.79 \times 10^{-3}$



1994). First, the water column at the critical discharge was, as expected, determined to be turbulently mixed (Reynolds Number > 100 000). For a flow velocity of  $0.05 \text{ ms}^{-1}$ , an  $r_p$  of 0.05 m and a water depth of 4 m (such as at Bourke), the turbulent velocity was found to be  $2.91 \times 10^{-3} \text{ ms}^{-1}$ , which approximates with Reynolds (1994) model. The turbulent velocities determined for all sites are shown in Table 1 and ranged between  $2.66 \times 10^{-3}$  and  $2.91 \times 10^{-3} \text{ ms}^{-1}$ .

## Discussion

### *Discharge, persistent stratification and the growth of A. circinalis*

Although discharge is an important factor determining cyanobacterial growth in river systems (Lung & Paerl, 1988; Hötzel & Croome, 1994), it is the establishment of persistent thermal stratification when discharges are low that appears to be the critical factor triggering the development of blooms of *A. circinalis* in the Darling River. Substantial growth occurred only when stratification was persistent. A similar influence was noted at Maude weir pool on the Murrumbidgee River, Australia (Sherman *et al.*, 1998), where transitions between *Anabaena* spp. and *Aulacoseira* spp. were dependent upon the establishment and breakdown of persistent stratification.

An increase in the concentration of *A. circinalis* coincided with several days of moderate night-time temperatures when stratification was not extensively disrupted by convective cooling and maximum mixing depths were restricted to between 0.5 and 1.0 m. In the following 2 weeks, the maximum mixing depths did not often penetrate below 2 m and the minimum temperature differences between the upper and lower thermistors varied between 1 and 8 °C (Fig. 4). The overall reduction in mixing and increase in intensity of the stratification was associated with an increase in the concentration of *A. circinalis*. The close association between the reduction in mixing depth and the increase in concentration of *A. circinalis* suggests a causal link.

If prolonged stratification is a prerequisite for the growth of *A. circinalis* at Bourke, then the data relating thermal stratification to discharge can be used to identify discharge levels conducive to its growth. It appears that as discharge falls below  $3000 \text{ ML day}^{-1}$ , diurnal thermal stratification appears (i.e. stratified

during the day and mixed during the night). As discharge continues to fall between 450 and  $2000 \text{ ML day}^{-1}$ , stratification intensifies, although still frequently dissipated at night. Discharge rates  $<450 \text{ ML day}^{-1}$  during the hotter months appear necessary for prolonged stratification. The actual discharge level needed to mix the weir pool and remove stratification will depend on the prevailing meteorological conditions and also on the depth and volume of the weir pool at the time. Cool spells can increase convective mixing that impacts the mixing depth (Bormans *et al.*, 1997; Sherman *et al.*, 1998). However, these estimates are probably typical for summer conditions. Even at zero discharge, extensive convective mixing appeared to be sufficient to curtail persistent thermal stratification on occasions. Persistent stratification did not occur during the cooler months (May to early September) even at very low discharges.

### *Critical flow velocities for the growth of A. circinalis*

The discharge levels identified as impacting on the growth of *Anabaena* at Bourke are similar to those identified at Maude Weir, on the Murrumbidgee River, Australia which is similar in size and length (Sherman *et al.*, 1998). This similarity is perhaps surprising given the notable differences in climate between Bourke and Maude (surface waters at Bourke are 5 °C higher during persistent stratification) and the differences in water quality, especially turbidity, between the rivers (Sherman *et al.*, 1998; Oliver *et al.*, 2000). These comparisons suggest that the physical dimensions of the weir pool are more important than the regional climatic differences in determining the critical discharge rates controlling cyanobacterial blooms. If this is the case then these findings could be generalised across weir pools of comparable size elsewhere. The data provided in this paper for several different sites allows an opportunity to test this.

Bormans & Webster (1997) developed a mixing criterion for turbid rivers based on the balance between the relative supply rates of stratifying thermal energy and destratifying turbulent kinetic energy. Flow over the river bottom was assumed to be the only source of turbulent kinetic energy. When these two competing processes are equal, marking the transition between mixed and stratified conditions,

their ratio ( $R$ ) was found to be relatively constant. The equation derived was:

$$R = U^3 / [H(\alpha g / \rho C_p)(Q_{\text{net}} - 2Q_1 / K_d H)]$$

where  $U$  is the depth averaged velocity,  $H$  is the depth,  $\alpha$  is the thermal expansion coefficient,  $g$  is the gravity acceleration,  $\rho$  is the density of water,  $C_p$  is the specific heat capacity of water,  $Q_{\text{net}}$  is the net surface heat flux,  $Q_1$  is the net short wave radiation and  $K_d$  is the attenuation coefficient. Within a similar climatic region, at a particular time of the year, the net surface heat flux will be comparable. When  $K_d H$  is large, variations in it have only a small effect on the rate of change of potential energy and consequently, in a restricted climatic zone, the change of potential energy at different sites will be similar and  $R$  will be largely a function of  $U^3/H$ . Assuming  $R$  to be constant, the water velocity at the transition between stratified and mixed conditions will also be relatively constant, varying only with the cube root of depth.

The three weir pools in this study for which data were available to identify the water velocity required to dissipate persistent thermal stratification (Namoi River at Walgett, Darling River at Bourke and Darling River at Wilcannia) are in a similar climatic zone, although separated by large distances. They have similar depths (2.0, 4.0 and 3.8 m, respectively) and are turbid such that  $K_d H$  is relatively large. It is expected from the model that, although different discharge levels are required to dissipate the thermal stratification (100, 450 and 200 ML day<sup>-1</sup> for Walgett, Bourke and Wilcannia, respectively), the water velocity required should be similar between sites. This occurs because turbulence is a balance between the stratifying influence of thermal stratification and the turbulent kinetic energy from the flow over the bottom. If the average stratifying conditions are similar (i.e. similar climatic zone), then similar turbulent kinetic energy is required to disperse stratification. From our data, the model seems reliable with similar critical flow velocities calculated for the three sites. From our measurements we suggest that a critical flow velocity of around 0.05 ms<sup>-1</sup> is required to prevent the development of persistent stratification during warmer periods. A turbulent velocity of above  $3.0 \times 10^{-3}$  ms<sup>-1</sup> is also suggested to prevent persistent stratification occurring. These values may be useful to water managers in similar climatic zones who require flow velocity values to suppress the development of

cyanobacterial blooms in rivers. Flow velocity can be reasonably easily measured or related to discharge through cross-sectional area measurements and so could be applied relatively easily by river managers. For rivers in other climatic zones, the relationship should still hold but the critical flow will be different.

#### *Reasons for A. circinalis dominance during persistent stratification*

Although the higher water temperatures occurring during persistent stratification favour cyanobacterial growth through enhanced metabolic rates (Robarts & Zohary, 1987), the dominance of *Anabaena* is more likely the result of the physical and chemical state of the water column. The lack of water column mixing under persistent stratification can allow buoyant *Anabaena* to accumulate in surface waters (Fig. 10). By being positioned within the surface waters for periods greater than those of entrained phytoplankton *Anabaena* can receive a considerable growth advantage (Ibelings, Mur & Walsby, 1991; Walsby *et al.*, 1997). This was found to be fivefold (daily integral of productivity) compared with an evenly dispersed population in the Darling River at Trevallyn (Mitrovic *et al.*, 2001).

#### Conclusion

From measurements at several weir pool sites along the turbid and freshwater Barwon-Darling River, Australia, the development of persistent stratification (for periods of >5 days) was related to river discharge. The growth and dominance of *A. circinalis* at these sites was closely related to the establishment and maintenance of persistent and strong thermal stratification. A flow velocity of 0.05 ms<sup>-1</sup> and a turbulent velocity of  $3.0 \times 10^{-3}$  ms<sup>-1</sup> appear sufficient to prevent the development of persistent thermal stratification and concurrent *A. circinalis* growth for all sites. These values may potentially be applied to other rivers in similar climatic zones to suppress nuisance cyanobacterial growth.

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