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SHORT COMMUNICATION

MODELLING SUPPRESSION OF CYANOBACTERIAL BLOOMS BY FLOW MANAGEMENT IN A LOWLAND RIVER

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ABSTRACT

Growth and dominance of the cyanobacterium *Anabaena circinalis* in weir pools of the Barwon–Darling River, Australia, are related to persistent vertical thermal stratification between October and March, when discharge is low. We determined critical velocities and discharges required to suppress bloom formation at three sites, and modelled the occurrence of sub-critical discharges in order to predict the frequency of blooms under different management scenarios. Our model suggests that the frequency of blooms was about double that expected under near-natural flows (without major impoundment or water extraction) for 1990–2000. Flow management, through Environmental Water Provisions that limit water extraction when river levels are low, has been in place since July 2000. Our model suggests that these provisions are unlikely to have had an effect on bloom frequency for 2000–2003. In the longer term, however, they could reduce bloom frequency at some sites by up to one-third. Copyright © 2006 John Wiley & Sons, Ltd.

KEY WORDS: environmental flows; cyanobacteria; *Anabaena circinalis*; flow management

INTRODUCTION

The Barwon–Darling River system in the arid and semi-arid northwest of New South Wales (NSW), Australia, frequently has planktonic blooms of the filamentous toxic cyanobacterium *Anabaena circinalis* (Mitrovic and Gordon, 1998; Oliver *et al*., 2000). Cyanobacterial growth is associated with vertical thermal stratification, which endures for >5 days only under low or zero-flow conditions during the hottest part of the year (October–March) (Oliver *et al.,* 2000; Mitrovic *et al.,* 2003; cf. Webster *et al*., 1995; Sherman *et al*., 1998). During this period, managed flows can prevent stratification and so inhibit bloom development. The system provides water to >250 licensed urban and rural extractors and is regulated by nine headwater dams and 15 weirs. Median annual river flow has been reduced by an estimated 73% of natural flow, with small floods most affected, and the predictability and constancy of discharge have increased markedly (Thoms and Sheldon, 2000).

Allocations of water for environmental purposes such as algal bloom suppression, improved wetland health, and enhanced bird breeding have been provided under state legislation in NSW, Australia (Chessman, 2003). This water is termed an Environmental Water Provision (EWP). In the Barwon–Darling River system, EWPs are designed to limit water extraction when river levels are low, and thereby reduce the frequency and severity of cyanobacterial blooms. The performance of EWPs, however, is not well understood. An existing hydrological model (Simons *et al*., 1996) provides simulated daily discharges (a) with EWPs in place, (b) with extraction but without EWPs, and (c) without extraction (cf. natural discharge). Here, we extend the model to predict the growth to bloom levels of *A. circinalis* (defined as $>15\,000\,\text{cells ml}^{-1}$) under these three flow scenarios at three sites distributed along 600 km of the river. Our aim is to assess the likely effects of the EWPs as a means to suppress bloom development.

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METHODS

Critical discharges and velocities

Sites were selected to represent the upper (Brewarrina), middle (Bourke) and lower (Wilcannia) sections of the Barwon–Darling River (Figure 1). The minimum discharges at which persistent thermal stratification and blooms do not occur (the 'critical' discharges) at Bourke and Wilcannia were estimated from previous studies (Oliver *et al.*, 2000; Mitrovic *et al.*, 2003), and from *Anabaena* cell counts and discharge data over 1992–2003 (Department of Infrastructure, Planning and Natural Resources, unpublished data). Insufficient data were available for Brewarrina; the few blooms recorded there coincided with very low discharges ($< 50\,\mathrm{Ml\,d^{-1}}$) that probably were well below the critical discharge. The cross-sectional profile of the channel at each site was determined at 15 locations at approximately 0.5-km intervals, with the water surface as the vertical reference datum. The bank-to-bank distance at the surface was determined with a range finder (accurate to ± 0.5 m), and depth soundings (± 0.1 m) were made at 1-m intervals across the channel. Average cross-sectional wetted areas were then calculated for river heights equivalent to the critical discharges at Bourke and Wilcannia, and used with critical discharges to estimate mean velocities ($V\,\mathrm{m\,s^{-1}}$) from $V = Q/A$, where Q = discharge ($\mathrm{m^3\,s^{-1}}$) and A = cross-sectional area ($\mathrm{m^2}$). These velocities were then used to estimate the critical discharge at Brewarrina. This process follows Bormans and Webster (1997), who predicted that water velocities necessary to prevent persistent vertical thermal stratification will be equivalent for comparable rivers in similar climatic regions. For a given site, therefore, the critical discharge can be estimated from the relationship between velocity and cross-sectional area or using the critical velocity for similar sites.

Modelling of discharge scenarios

An existing hydrological model (Simons *et al.*, 1996) provided simulated discharge with EWPs (+EWP) and without EWPs (−EWP) for a 3-year period since the current EWPs were implemented (July 2000 to June 2003). Modelled discharges for +EWP were used in preference to measured discharges to increase the comparability of the two scenarios (modelling could not include the effects of minor water extractions, leading to discrepancies between modelled and measured values). Modelled discharges for −EWP were based on the previous (pre-EWP) river pumping rules.

Discharges for +EWP and −EWP were also modelled for 1990–2000, to illustrate the potential effects of EWPs on growth of *A. circinalis* over a longer time with a wider range of climatic conditions. Discharges were also modelled over this period in the absence of major water impoundment and major extraction. These discharges were similar to natural flows, but not identical because the current hydrological models cannot remove the effects of minor impoundment and extraction, changes in runoff patterns caused by clearing of catchment vegetation, or flow changes caused by anthropogenic impacts on the morphology of channels and drainage connections.

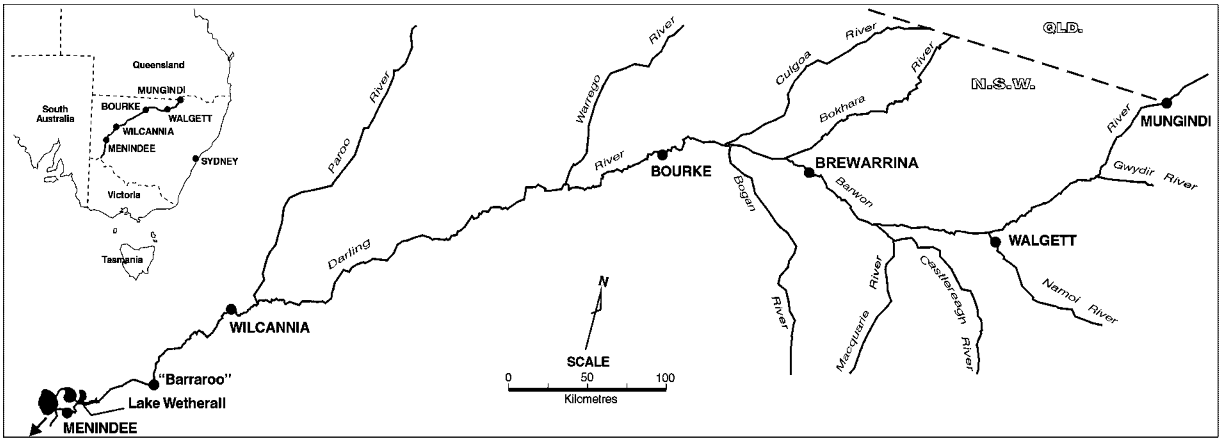

Figure 1. Location of the three study sites on the Barwon–Darling River, NSW, Australia

Modelling of potential bloom frequency

The potential number of blooms (concentrations of over 15 000 cells ml^{-1} of *A. circinalis*) was predicted for the three discharge scenarios, and based on the occurrence of sub-critical discharges for at least 12 days between 15 October and 15 March. Under these conditions, an inoculum of 100 cells ml^{-1} of *A. circinalis* could multiply to over 15 000 cells ml^{-1} (Mitrovic *et al.*, 2003).

RESULTS AND DISCUSSION

Critical discharges and velocities

The critical discharges for Bourke and Wilcannia were determined to be 450 and 350 Ml d^{-1}, respectively (Table I), and the derived critical velocities were almost identical, suggesting that the number of cross-sections measured at each site was sufficient despite channel variability. The average critical velocity of 0.03 m s^{-1} gave a critical discharge of 510 Ml d^{-1} for Brewarrina.

Suppression of A. circinalis by Environmental Water Provisions

Modelled +EWP and −EWP discharges for 2000–2003 fell below critical discharges at the three sites on several occasions (Figure 2). Although there were fewer days of sub-critical discharges under the +EWP scenario at all three sites (Table II), the potential frequencies of blooms were identical. The modelling suggested that the EWP had greater impact on the occurrence of stratification with progression down-river. The differences between modelled discharges with and without EWP were greater at Wilcannia than further upstream (Figure 2), and the difference in the frequency of sub-critical discharges also increased downstream (Table II). This reflects the cumulative effect of pumping restrictions at many places along the river. Modelling of the +EWP and −EWP scenarios for the preceding 10-year period suggested that three fewer *A. circinalis* blooms might have occurred at both Bourke and Wilcannia had the EWP been in place (Table II). The effect of the EWP at Brewarrina was negligible.

Growth of A. circinalis under near-natural discharges

Depending on the site, the potential frequency of *A. circinalis* blooms under the −EWP scenario for 1990–2000 was 1.5–2.2 times the frequency under a near-natural discharge regime. The frequency under the +EWP scenario was 1.0–1.6 times the near-natural frequency (Table II). Thus, the current EWPs are unlikely to restore the natural bloom frequency at all sites, but are likely to move the frequency closer to the natural frequency over the long term.

Implications for management

Large-scale development of irrigation in the Barwon–Darling River basin began in the early 1960s at approximately 50 Gl and expanded until the early 1990s, with approximately 3000 Gl more water extracted in each

Table I. Critical discharges and corresponding velocities to suppress persistent stratification and *Anabaena circinalis* growth, and wetted cross-sectional areas at the critical discharges, for three sites in the Barwon–Darling River

Site	Critical discharge (Ml d^{-1})	Critical velocity (mean ± SD) (m s^{-1})	Cross-sectional area[‡] (mean ± SD) (m^2)
Barwon River at Brewarrina	510*	0.030 ± 0.003[†]	196 ± 23
Darling River at Bourke	450	0.030 ± 0.004	175 ± 21
Darling River at Wilcannia	350	0.031 ± 0.004	132 ± 20

*Estimated from cross-sectional area and critical velocity.

[†] Estimated from critical velocity at other sites.

[‡] $n = 15$.

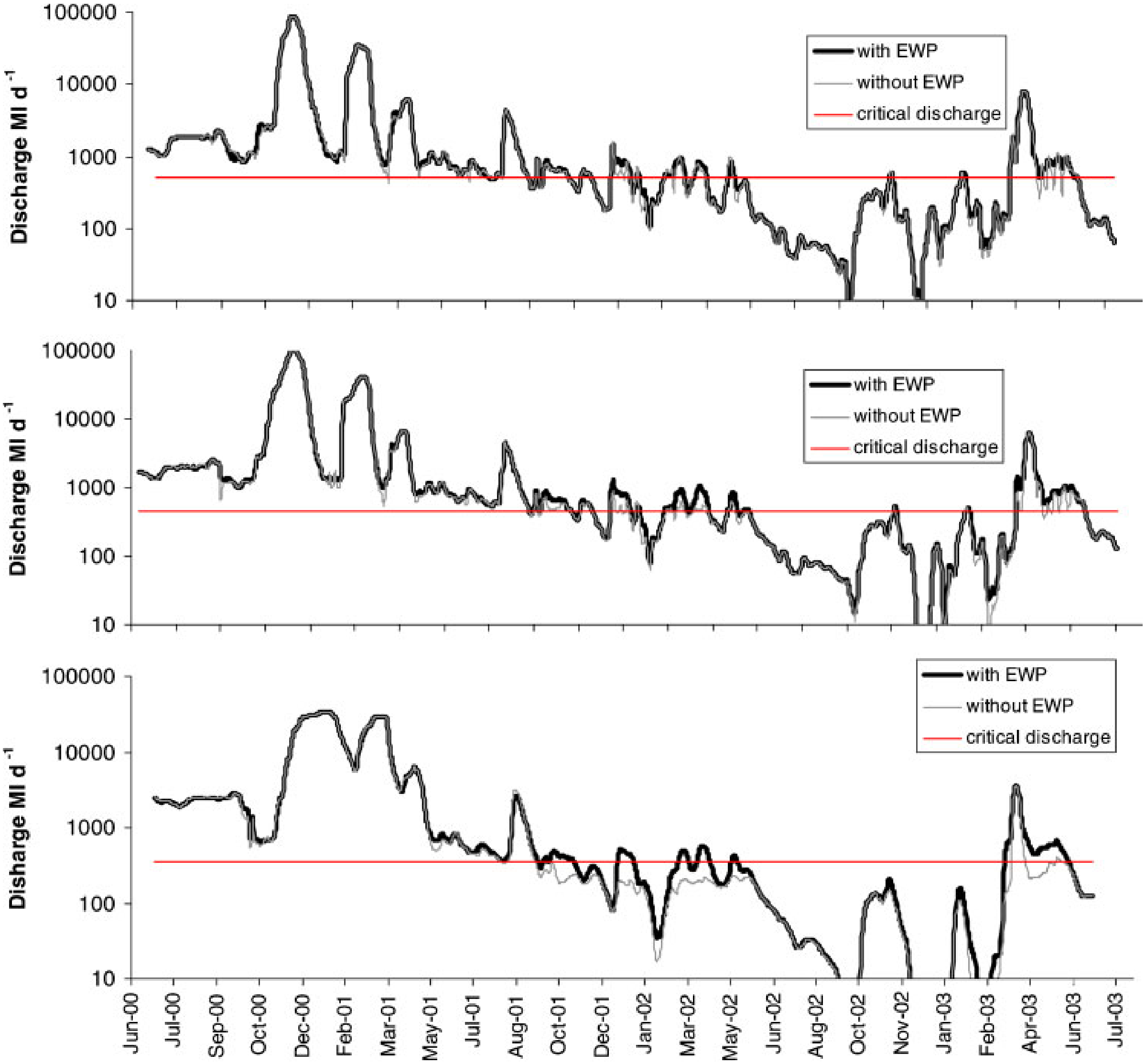

Figure 2. Modelled daily discharges in the Barwon–Darling River at Brewarrina (A), Bourke (B) and Wilcannia (C), for the period July 2000 to June 2003. This figure is available in colour online at www.interscience.wiley.com/journal/rra

Table II. Modelled number of potential blooms of *A. circinalis* and numbers of days below the critical discharge under scenarios without environmental water provisions (−EWP), with these provisions (+EWP) and with near-natural discharge (NN)

Site	Predicted number of blooms					Days of sub-critical discharge				
	2000–2003		1990–2000			2000–2003		1990–2000		
	−EWP	+EWP	−EWP	+EWP	NN	−EWP	+EWP	−EWP	+EWP	NN
Barwon River at Brewarrina	4	4	11	11	7	223	214	519	491	282
Darling River at Bourke	4	4	9	6	6	226	198	367	296	223
Darling River at Wilcannia	2	2	11	8	5	316	253	529	390	209

intervening decade (Bek *et al*., 1994). Although it is widely believed that the frequency of cyanobacterial blooms has been increased by water resource development, there are few supporting data, and simulation modelling may be the only option to evaluate this. Our study suggests that water impoundment and extraction were responsible for approximately half of the blooms in 1990–2000 (Table II). This proportion may have been different in other decades because of the variability of discharge, even under natural conditions (Thoms and Sheldon, 2000).

Our modelling implies that the EWPs in place since mid-2000 are not yet likely to have had much effect on the frequency of blooms of *A. circinalis*. However, modelling of their potential impact, had they been in place from 1990 to 2000, indicates that they could have reduced the frequency by up to one-third at some sites. It thus appears that the EWPs could decrease bloom frequency appreciably over the longer term. We suggest maintenance of flow velocities above $0.04\,\mathrm{m\,s^{-1}}$ from 15 October to 15 March in any year, to minimize the frequency and intensity of blooms. This critical velocity can be converted to a location-specific target discharge where the relationship between cross-sectional wetted area and discharge is known.

The potential frequencies of *A. circinalis* blooms under the three discharge scenarios (Table II) are likely to be overestimates of actual bloom frequencies, as wind action and cool spells may suppress persistent thermal stratification even during summer (Sherman *et al*., 1998). This should affect all three scenarios in a similar manner, and hence the relativity of the predictions is likely to be valid. The absolute values, however, should be regarded with caution. Predictions of persistent stratification could be improved by extending the method to consider other environmental factors such as wind speed, solar radiation, and air and water temperatures, if the data are available (cf. Bormans and Webster, 1997; Maier *et al*., 2004).

Associations between cyanobacterial blooms and low river flow or velocity have been documented worldwide (Lung and Paerl, 1988; Sherman *et al*., 1998; Ha *et al*., 1999). Flow management is a potential amelioration technique for such situations. However, the use of environmental flows to suppress cyanobacterial blooms is a relatively new practice with few documented trials (e.g. Burch *et al*., 1994; Maier *et al*., 2004). The type of model described here might be useful to set environmental flow targets or to assess the suppression of cyanobacterial growth by environmental flows in other river systems.

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