Impacts of climate variability on riverine algal blooms

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Abstract: This paper presents results from a project to model algal bloom occurrence in weir pools in the lower Murrumbidgee River, Australia. The IQQM model (Integrated Quality-Quantity Model) is used to simulate streamflows, irrigation demand and diversions, dam water storage and releases, and decision-making by both irrigators and managers. A simple model of *Anabaena* algal bloom occurrence has been coupled to IQQM. Long-term climate data is obtained from a climate downscaling algorithm, which, when applied to GCM predictions can provide climate data suitable for driving IQQM under a variety of climatic scenarios. The coupled model is used to assess the impact of climate variability and possible climate change on the frequency, duration and magnitude of *Anabaena* blooms. The impact of two management strategies for bloom control are also assessed and it is shown that even quite simple, resource-neutral, adaptive management strategies have the potential to substantially reduce the occurrence and impact of algal blooms and to more than compensate for the deleterious impacts of climate change.

Keywords: *algal blooms; stream flow; thermal stratification; climate variability; adaptive management*

1. INTRODUCTION

1.1. Background

Increasing agricultural development in inland regions of Australia has required substantial diversion of water resources to provide for irrigation in areas where rainfall is low or unreliable. As a result, the flow regimes in inland rivers have changed considerably from their natural state. Not only is there less flow overall, but there also tend to be fewer and less prolonged flooding events than in the past. These changes have had considerable impact on water quality. Increased nutrient fluxes, coupled with generally low flows and enhanced stratification, have led to recent increases in the prevalence and persistence of blue-green algae outbreaks.

Observations of phytoplankton abundance and succession in a weir pool on the Murrumbidgee River indicate that the positively-buoyant cyanobacterium *Anabaena circinalis* dominates when thermal stratification is strong (Sherman et al., 1998, Webster et al., 2000). In general, this occurs when solar heating of the surface is high and flow rates are low. *Anabaena* blooms require about 14 days of persistent stratification to reach concentration levels that pose a risk to livestock or human health (Sherman et al., 1998). Observations also suggest that nutrient availability is not a limiting factor for *Anabaena* occurrence and development at that site (Sherman et al., 1998).

Bormans and Webster (1997) proposed an objective criterion for the transition between mixed and stratified conditions in a lowland river. Their non-dimensional mixing index depends primarily on flow velocity, water depth, net surface heat flux into the water column, net shortwave radiation and turbidity. Comparison with thermistor measurements in a weir pool indicates the existence of a critical value of the mixing criterion, below which stratified conditions occur in the pool. Bormans et al. (1997) used this criterion to predict diurnal persistence of stratification.

Given the nature of its input variables, the Bormans and Webster criterion is not readily usable with downscaled meteorological data. In Section 3, we propose a simplified stratification index which can be used to predict the occurrence of diurnal stratification using readily observed or downscaled data. Section 4 describes a method for downscaling climate data to provide multi-site realisations of current and future climates. In Section 5 we use the stratification index, together with discharge predictions from the IQQM model to predict the long-term variability of *Anabaena* blooms in a weir pool. Section 5 also analyses the impact of potential future climatic conditions on bloom occurrence and tests a simple management adaptation strategy for reducing the occurrence and severity of blooms. Thus, this paper brings together hydrology, climate, hydrodynamics, phytoplankton dynamics and river management to predict an important indicator of river health in a large lowland river.

2. STUDY AREA AND DATA COLLECTION

The Murrumbidgee River drains about 84000 km^2 of New South Wales and the Australian Capital Territory. Large-scale irrigated agriculture in the catchment is supplied by major impoundments at Burrinjuck Dam and Blowering Dam. There are also several gated weirs, one of which is Maude Weir, located at Maude, 60 km upstream of the confluence with the Lachlan River and 75 km downstream of Hay Weir.

During the summers of 1993–94 and 1994–95, an intensive campaign of field measurement of physical, chemical and biological data was undertaken at Maude Weir (Sherman et al., 1998). The data collected included observations of the pool's thermal stratification, which was measured by thermistor chains at 10-minute intervals. Phytoplankton abundance was sampled three times weekly during the summers 1991–92 to 1994–95.

3. MODEL OF BLOOM OCCURRENCE

3.1. Model Development

In the light of the observations of Sherman et al. (1998) and the difficulties of using Bormans and Webster's (1997) criterion with downscaled data, we propose a new, simplified stratification index,

$$S = q/(T_{max})^a$$

where q is the weir discharge rate (ML d^{-1}), T_{max} is the daily maximum air temperature (ºC) and a is a model parameter. The maximum daily temperature is included as a readily observable surrogate for solar heating. The effects of variations in turbidity are not included.

This criterion will indicate persistent diurnal stratification whenever S is less than some critical value, S_c. We then make the assumption that an *Anabaena* bloom will occur after 14 consecutive days of persistent stratification, and that any bloom will be destroyed whenever S exceeds S_c.

3.2. Model validation

Stratification index

The model parameters, a and S_c, were calibrated by comparison of S against the observed occurrence of thermal stratification in Maude Weir pool. This process made use of observations during the summers of 1993–94 and 1994–95 of water temperature at a sequence of depths between 0.1 m and 5.0 m averaged over 10-minute intervals (Sherman et al., 1998). The stratification state of the weir pool was assessed in terms of two variables, $(\Delta T)_{min}$ and $(\Delta T)_{max}$, respectively the daily minimum and maximum temperature differences between the upper and lower thermistors. For days with $(\Delta T)_{min} \geq 0$, the weir pool was considered to be persistently stratified. A value of $(\Delta T)_{min} < 0$ indicates that the pool was fully mixed for at least part of the day. Furthermore, for the latter category, we can use the maximum daily temperature difference to discriminate between days with persistent mixing ($(\Delta T)_{max} \leq 0.35$) and days with occasional mixing ($(\Delta T)_{max} > 0.35$). The threshhold value of 0.35 is obtained from analysis of a change of slope in a plot of exceedence probability for $(\Delta T)_{max}$.

It was found that the parameter values $a = 1.67$ and $S_c = 2.5$ allowed for good identification of days with persistent stratification (Figure 1). Of 150 days with observed persistent stratification, S misidentified only two as partially mixed. Of 108 days with observed mixing, only 11 were misidentified as persistently stratified. All 11 were stratified for at least part of the day. Most misidentifications occurred either at the beginning or end of sequences of days with persistent stratification. That is, they occurred during periods of transition to and from persistent stratification.

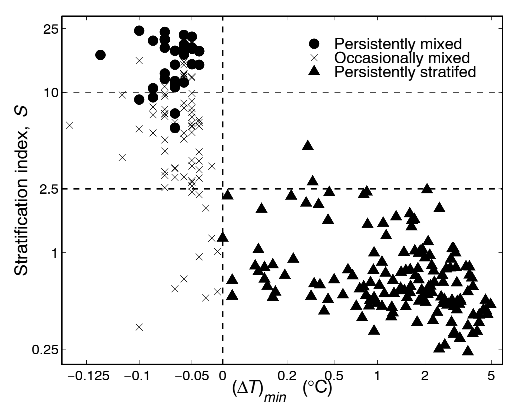

Figure 1. Comparison of observed stratification, expressed in terms of $(\Delta T)_{min}$, and the predicted daily stratification index for 258 days in the summers of 1993–1994 and 1994–1995. The vertical broken line discriminates between days with persistent observed stratification and those without. The horizontal broken lines are at the critical values of S at 2.5 and 10.

Figure 1 also suggests that a critical S value of about 10 can be used to distinguish days with persistent mixing from days with occasional mixing, although the delineation is not as good as for stratification at $S_c = 2.5$.

Anabaena blooms

A time series of the stratification index, S, was generated from observed records of daily weir discharge and daily maximum air temperature (Figure 2) and indicates that S remained at less than S_c for periods of 14 days or more on three occasions during the summer of 1991–92.

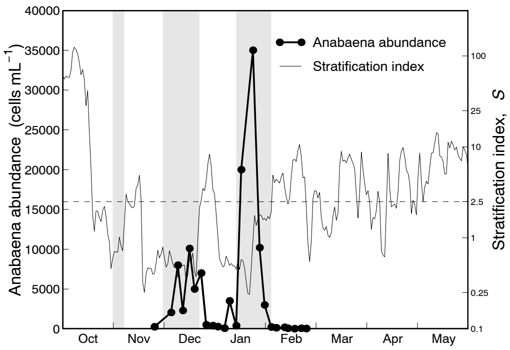

Figure 2. Observed *Anabaena* concentrations in Maude Weir pool compared with predicted stratification index, 1991–92. The shaded regions show periods of predicted *Anabaena* blooms. The broken line is the critical value of $S = 2.5$.

The first of these periods of prolonged, persistent stratification lasted for 21 days in late October and early November. Given that *Anabaena* requires about 14 days of persistent stratification to reach serious concentration levels, a serious bloom of 7 days duration is predicted for early November. Unfortunately, no concentration samples were taken during this period to confirm the presence of a bloom. The two subsequent periods of persistent stratification are suggestive of *Anabaena* blooms of 22 days duration in early December and 21 days duration in late January. In both cases, these coincide extremely well with observed blooms, which reach respective peaks of 10000 cells mL^{-1} and 35000 cells mL^{-1}.

The January bloom dissipated when S returned to levels above S_c at the beginning of February. Thereafter, except for some periods of persistent stratification that were too brief to generate blooms, S remained above S_c throughout the remainder of summer and autumn. No further *Anabaena* blooms were either predicted or observed.

4. DOWNSCALING AND CLIMATE CHANGE PROJECTION

4.1. Statistical downscaling

The Nonhomogeneous Hidden Markov Model (NHMM) of Hughes et al. (1999) models multi-site patterns of daily precipitation occurrence as a finite number of 'hidden' (i.e., unobserved) weather states. The temporal evolution of these daily states is modelled as a first-order Markov process with transition probabilities conditioned on a small number of synoptic-scale, atmospheric predictors such as sea level pressure. By determining distinct multi-site daily precipitation occurrence patterns, rather than atmospheric circulation patterns, the NHMM captures much of the spatial and temporal variability of daily, multi-site precipitation occurrence records.

At each site, daily precipitation amounts, for each weather state of a selected NHMM, are modelled by regressions of transformed amounts on precipitation occurrence at key neighbouring sites. This approach captures both the means and variabilities of the daily precipitation amounts data (Charles et al., 1999).

The model for generating multi-site daily temperatures (maximum and minimum) is fitted after NHMM selection, with parameters conditional on the weather states. Temperature is modelled as a multivariate normal process with specified between-site covariance (for each weather state) and at-site lag-1 correlation. In this way, the generated series maintain the spatial and temporal characteristics of daily temperature trends.

The process of fitting NHMMs for 30 sites across the Murrumbidgee River Basin is described by Charles et al. (2003). The sites were chosen to include Maude and the sites used in the IQQM flow prediction model. Fitting was on a seasonal basis, for winter (April–September) and summer (October–March). The selected model for summer has six weather states and four atmospheric predictors. The selected model for winter has five weather states and five atmospheric predictors.

4.2. Downscaled climate change projections

GCM predictions used in this study were obtained from the Mark 3 version of the CSIRO coupled model (Gordon et al., 2002). Two 30-year time-slices of daily data were saved from a transient run (climate change forcing IPCC scenario A2), for current (centred on 1990) and projected future (centred on 2050) climates. The 2050 scenario represents a climate with 1.7 times the CO_2 concentration of the 1990 climate.

By driving the NHMMs fitted to observed data with predictors extracted from the two GCM time-slices, 99 year sequences of daily weather were generated for each of the 30 sites for both summer and winter climates.

The sequence corresponding to the future climate typically has at-site rainfall totals that range from 4.6 % to 11.2 % less than the current sequence (mean 8.2 %), and maximum air temperatures that are on average 0.9 °C greater. The at-site potential evaporation calculated for the future climate scenario ranges from 5.9 % to 6.8 % greater than for the current climate (mean 6.5 %).

5. LONG-TERM VARIABILITY IN ALGAL BLOOM OCCURRENCE

5.1. Generation of weir discharge data

The New South Wales Department of Land and Water Conservation has developed a modelling tool, IQQM, for use in planning and evaluating management policies. IQQM includes modules for simulating streamflow generation and transport, irrigation demand and decision-making by both managers and irrigators.

The Murrumbidgee IQQM model used in this paper is calibrated to 1993–94 conditions. That is, it is conditioned on the legislation, cropping types, areas and practices, water usage regimes and supply management protocols that prevailed in the catchment in 1993–94. As such, its flow predictions do not purport to reproduce historical flows (except for the years around 1993–94), but instead, predict the flows that would have occurred had the 1993–94 conditions been in effect. Nonetheless, we can still use these predictions to gain some insight into the long-term variability of river health, and in particular into the way this variability is affected by resource management procedures.

The particular flow prediction used in this paper is the daily discharge of water from Maude Weir. In practice, this discharge is controlled by daily gate adjustments, and is thus at the whim of human decision-making, as well as of the incoming flows.

Comparison of the discharges predicted by IQQM with those observed indicates that IQQM is a reasonably good predictor of Maude Weir discharges. Over the period 1990 to 1999, the efficiency of daily predictions is 0.83, while the efficiency of monthly predictions is 0.91.

5.2. Bloom variability

Simulation of *Anabaena* bloom occurrence at Maude Weir was carried out using synthetic data corresponding to the current climate. Results showed that for a 99-year simulation period, a total of 257 serious blooms were predicted (the thick, solid line in Figure 3), an average of 2.6 blooms per year. These blooms had a median duration of 12 days, while the most persistent lasted for 122 days. The total number of days per year (July to June) with serious blooms shows a nearly linear distribution (Figure 4), with a median of 56 days and a maximum of 124 days. At least one serious bloom occurred in each year.

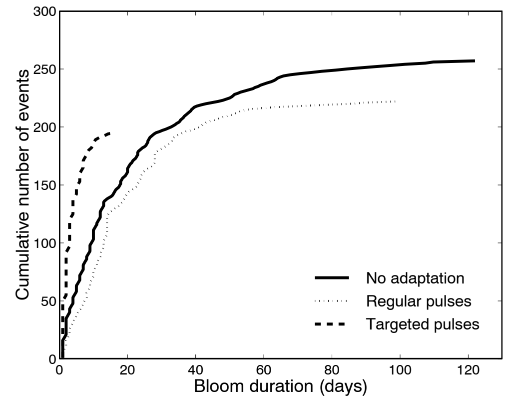

Figure 3. Predicted *Anabaena* bloom durations at Maude Weir pool under three management options for a 99-year sequence of current climate.

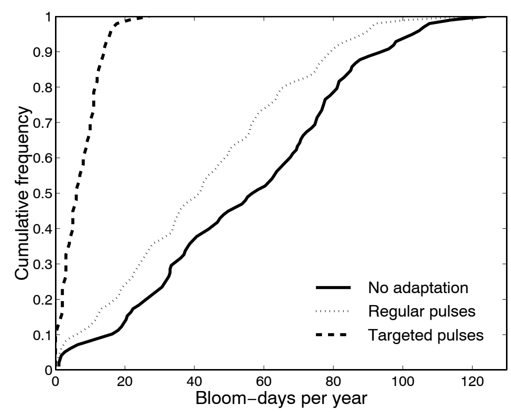

Figure 4. Predicted annual number of days with *Anabaena* blooms at Maude Weir pool under three management options for the current climate.

5.3. Management adaptation

Webster et al. (2000) suggested four strategies for minimising the occurrence or impacts of *Anabaena* blooms. One of the most promising was to use pulsed discharges to periodically increase flow rates through the weir pool and thus break up the thermal stratification. Unlike the suggestion of Webster at al. (2000), in which the pulse is resourced from an upstream reservoir, we analyse the situation whereby the pulse is sourced from within Maude Weir pool. We assume that on any day with $S < S_c$ (i.e., persistent stratification) an amount equal to 5 % of the normal discharge is retained in the pool and that this accumulated excess is discharged in a single pulse every 14 days. If the normal discharge rate exceeds 10000 ML d^{-1}, then any excess is discharged with it. This management strategy has the advantage that it is resource-neutral for all upstream users, although there is a small cost (a delay of up to 14 days) to downstream users.

The simulation results with this regular pulsing of water through the weir are shown in Figures 3 and 4. There is a modest reduction in the number of events (to 222, or 2.2 per year), in the maximum bloom durations (99 days) and in the median (42 days) and maximum (119 days) annual number of bloom days, but an increase in the median duration to 16 days. There are now two years out of 99 with no blooms at all.

A second management strategy was also tested. In this strategy, pulses were not released on a regular 14 day cycle, but the excess (5 % of daily flow) was retained in the weir until such time as its release (when combined with the normal discharge) was sufficient to raise S above S_c. In other words, release of the excess was targeted to the days yielding maximum advantage.

Again the results appear in Figures 3 and 4, and show a substantial impact in ameliorating bloom durations. The total number of events has reduced slightly to 195 (2.0 per year), but their median and maximum durations are now only 3 days and 16 days, respectively. The median and maximum annual number of bloom days are reduced to just 6 and 27, respectively, and a total of 11 years have no blooms at all.

5.4. Impacts of climate change

The future climate scenario was characterised by small, but variable reductions in precipitation and increases in both maximum air temperature and potential evaporation. When this climate data was used as input to IQQM, tributary inflows were about 25 % less than for the current climate. The resulting discharge from Maude Weir showed a substantial reduction of 52 %, mostly at the high end of the flow distribution. For the lowest 50 % of flows, a reduction of only 7 % was predicted.

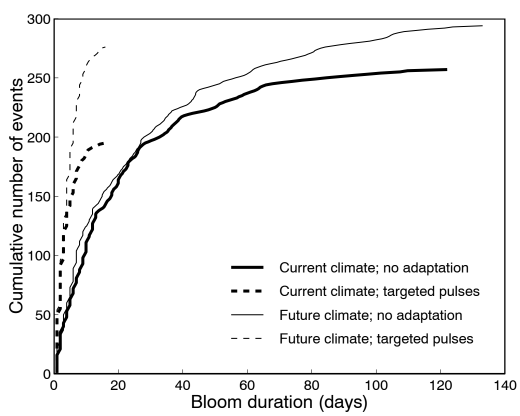

Figure 5. Predicted *Anabaena* bloom durations at Maude Weir pool under two management options for 99-year series of current and future climate.

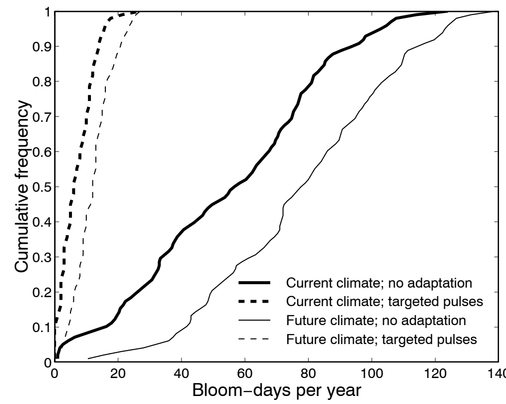

Figure 6. Predicted annual number of days with *Anabaena* blooms at Maude Weir under two management options for current and future climates.

The decrease in discharge and increase in temperature give rise to increases in *Anabaena* bloom occurrence and duration (Figures 5 and 6). The average number of bloom events is expected to rise to 3.0 per year, and the median and maximum durations are expected to be 14 days and 133 days, respectively. The median and maximum number of bloom days per year are expected to rise to 78 and 139 days, respectively. Also noticeable in Figure 6 is the relative rarity of years with fewer than 40 bloom days.

If the targeted pulse management option is applied, the duration of individual events is reduced to similar levels as the current climate case, with a median of 4 days and a maximum of 16 days, but the number of events is greater (2.8 per year). As a consequence, the median number of bloom days per year doubles (to 12), but the maximum remains at 27 days.

6. DISCUSSION

Despite being based on daily discharge and daily maximum air temperature, the stratification index, S, appears to be a good predictor of persistent diurnal stratification. Most of its prediction errors are during periods of transition between persistent stratification and partial mixing. It is also clear from observations that prolonged persistent stratification is a necessary condition for *Anabaena* blooms to occur. We can be less certain, however, that blooms will continue so long as the stratification persists. Although most observational evidence points to the conclusion that blooms at Maude Weir are not limited by nutrient availability, no blooms were observed during 1991 to 1995 that lasted as long as some of those predicted in this paper. It is conceivable, that nutrient limitation may become more critical as bloom duration increases. It is also possible that some other mechanism (e.g., predation) may make the blooms self-limiting. Clearly, more study on bloom dynamics is required. As more evidence comes to hand we may need to revisit our assumption that an *Anabaena* bloom will not abate until mixing of the water column occurs.

The adaptive management strategy tested in this paper targets pulses to the times when they will have maximum effect in destroying stratification. The impact of this strategy on long-term bloom occurrence and persistence trends is substantial. In particular, the durations of blooms are greatly reduced in comparison with the unmanaged case. Since bloom duration, at least during the initial stages of a bloom, is an indicator of cell abundance (Sherman et al., 1998), it is also clear that this targeted pulsing of discharge will also have a significant impact in lessening the severity of *Anabaena* blooms. This makes it an attractive option for bloom management, especially given that the water used for pulsing is sourced from within the weir pool itself.

Despite the predicted weir discharge reducing by 52 % under the climate change scenario, the impact on bloom occurrence is relatively minor. During summer, when discharges are at their lowest and, as a consequence, blooms are most prevalent, the water resources of the catchment are managed in such a way as to provide relatively similar flows at Maude Weir under both climate scenarios. Of particular interest to system managers will be the observation that despite the predicted bloom occurrences and durations increasing for the changed climate, judicious management of the resource can still ameliorate their impact to levels much less than at present.

7. CONCLUSIONS

This paper has brought together hydrology, climate, hydrodynamics, river management and phytoplankton dynamics to predict an important indicator of river health in a large lowland river: occurrence and duration of blooms of the blue-green algae, *Anabaena circinalis*. A simple stratification index, based on weir discharge and daily maximum air temperature only, has been developed to predict the occurrence of days with persistent diurnal stratification at Maude Weir pool. This index can also be used to predict the occurrence and duration of *Anabaena* blooms in the pool. Simulations of the Murrumbidgee water supply system with synthetic climate data obtained from downscaled GCM runs indicates that slight increases in bloom occurrence and duration can be expected in the future as the climate becomes drier and hotter. A simple adaptive management strategy has been shown to provide significant reductions in bloom severity, and has the potential to overcome the effects of climate change on algal blooms.

8. ACKNOWLEDGEMENTS

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