Three-Dimensional Modelling of a Microcystis bloom event in a Western Australian Estuary

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Abstract: In January 2000, there was a record maximum rainfall throughout much of the watershed of the Swan River estuary, leading to the first reported *Microcystis aeruginosa* bloom in the estuary. Peak cell counts reached over 100,000 cells mL^{-1}. A coupled three-dimensional hydrodynamic-ecological model, ELCOM-CAEDYM, is applied to the period of development and subsequent decline of the bloom. The model, previously calibrated for a more typical year (1995), accurately reproduced the unusual hydrodynamic circumstances and predicted the magnitude and timing of the *Microcystis* bloom. Salinity and temperature were the primary factors controlling the growth of *Microcystis* during the period of interest. The simulations described provide further validation of the model and its potential as a predictive tool.

Keywords: Swan River Estuary; Cyanobacteria; *Microcystis aeruginosa*; Nuisance Algae; Modelling

1. INTRODUCTION

Freshwater cyanobacteria are not generally associated with estuarine environments because of their limited tolerance to salinity [Kirst, 1990] and, in freshwater reaches, because of constraints due to turbulence or high rates of flushing [Chan and Hamilton, 2001]. In the Swan River estuary in Western Australia, cyanobacterial cell densities have rarely exceeded 5,000 cells mL^{-1}. Higher densities have been linked to rainfall events transporting cyanobacteria from adjoining wetlands into the estuary rather than to growth within the estuary [John, 1994]. Freshwater cyanobacterial cells that enter the estuary are likely to be adversely affected by high salinity (>20 ‰) in summer and autumn [Kurup et al., 1998] and by sub-optimal growing conditions in winter and spring, when water temperature and ambient light levels are relatively low, and freshwater discharge and flushing rates are high [Chan and Hamilton, 2001].

Here, we describe and model the unusual circumstances of January-February (summer) 2000 that triggered a large, toxic bloom of *Microcystis aeruginosa* in the Swan River estuary.

2. STUDY SITE

The Swan River estuary (Fig. 1) is located on the Swan Coastal Plain, Western Australia. It flows through the city of Perth and covers an area of approximately 52 km^2, with a mean depth of 6 m and a watershed area of 121,000 km^2 [Viney and Sivapalan, 2001]. The estuary is subject to moderate to high nutrient loads associated with urban and agricultural runoff [Peters and Donohue, 2001].

Mean annual rainfall varies from ~ 870 mm in Perth to < 300 mm in the furthest inland region of the watershed. Approximately two-thirds of the annual rainfall occurs in winter-spring, between June and September. In summer and autumn, runoff events from watersheds contributing to the Swan River estuary are infrequent and are usually confined almost exclusively to smaller watersheds within 50 km of the coast [Stephens and Imberger, 1996]. The Avon River watershed, which constitutes 99.5 % of the total watershed area of the Swan River, is dry for around 7-8 months of the year [Donohue et al., 2001].
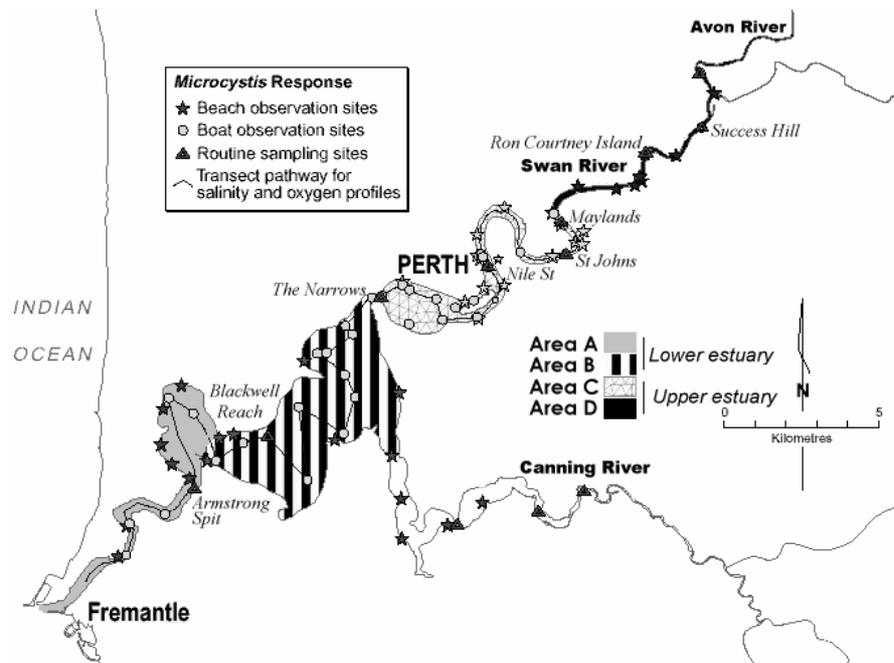
Figure 1. The Swan River Estuary, showing sampling sites.

4. METHODS

4.1 Monitoring

The Western Australian Department of Environment, Water and Catchment Protection conducts regular monitoring of the Swan River estuary. Weekly profiles of temperature and salinity are taken at 10 stations (Fig. 1), together with water samples for analysis of chlorophyll *a* and nutrients. Depth-integrated cell counts are performed at each station every two weeks. During the bloom period described here, the frequency of monitoring was increased, with cell counts taken at additional sites (Fig. 1) on 6, 10, 14-18 and 20-22 February 2000.

4.2 Model Description

Simulations of the bloom event were conducted with a coupled hydrodynamic (Estuarine and Lake Computer Model, or ELCOM) and ecological (Computational Aquatic Ecosystem Dynamics Model, or CAEDYM) model. ELCOM solves the unsteady hydrostatic, Navier-Stokes, Boussinesq, Reynolds-averaged and scalar transport equations, and is described in detail by Hodges et al. [2000]. CAEDYM has been described previously by Chan et al. [in press]. CAEDYM simulates up to five phytoplankton groups as well as nitrogen, phosphorus and oxygen dynamics. For the present application, the major phytoplankton groups observed in the Swan River estuary, i.e. *Microcystis aeruginosa*, chlorophytes, marine diatoms, freshwater diatoms, chlorophytes and dinoflagellates, were included to allow accurate simulations of resource competition between *Microcystis* and other groups.

The model domain covered the region from Fremantle to 16 km upstream of Success Hill (Fig. 1), with a 2 km ocean buffer at the downstream boundary. Canning River was not included. The bathymetry was 'straightened' [Hodges and Imberger, 2001] to allow the river to be simulated with a uniform 1000 m x 100 m horizontal grid by 0.5 m vertical grid, with a 600 s timestep.

Parameter values used to describe *Microcystis* are given in Table 1; parameter values for other groups were as determined for the simulations described by Chan et al. [in press].

Table 1. Parameter values used to describe *Microcystis aeruginosa*.

Parameter	Description	Value
μ_{max}	Maximum specific growth rate at 20°C (day^{-1})	1.2[1]
R	Loss rate coefficient (day^{-1})	0.1[2]
K_P	Half-saturation constant for phosphorus uptake (mg L^{-1})	0.006[3]
K_N	Half-saturation constant for nitrogen uptake (mg L^{-1})	0.03
S_{opt}	Maximum salinity for optimal growth (‰)	4[4]

S_{max}	Upper bound of salinity tolerance (‰)	25^4
T_{opt}	Temperature for maximal growth (°C)	30^5
T_{max}	Upper bound of temperature tolerance (°C)	35^5
θ	Non-dimensional temperature multiplier.	1.08^6

[1] Maximum rate observed in laboratory cultures of *Microcystis aerugunosa* taken from the Swan River during the bloom [unpublished data].

[2] Scavia et al. [1976] give a range for loss rates of cyanobacteria of 0.05 to 0.25 day^{-1}.

[3] Holm and Armstrong [1981].

[4] Value that gave the best fit of CAEDYM's salinity response function to the observed salinity response in of *Microcystis* in laboratory trials [unpublished data].

[5] For *Microcystis* spp., Krüger and Eloff [1978] give a range for T_{opt} of 28.8 to 30.5°C.

[6] Robarts and Zohary [1987] cite a literature range of 1.4 to 5.0 for Q_{10} for *Microcystis aeruginosa*, corresponding to θ of 1.03 to 1.17.

4. RESULTS AND DISCUSSION

4.1 Rainfall, river inflow and salinity

In January 2000, a total rainfall of 138 mm was recorded at Perth Airport, most of which occurred on a single day, 22 January (day 22). Similar rainfall was recorded at gauging stations throughout the Swan River watershed. Runoff peaked the following day and combined inflows from the two major tributaries to the Swan River peaked at a daily mean value of 350 m^3s^{-1}. This pattern contrasts sharply with typical summer rainfall and discharge for the region, which are usually negligible at this time of year (Fig. 2).
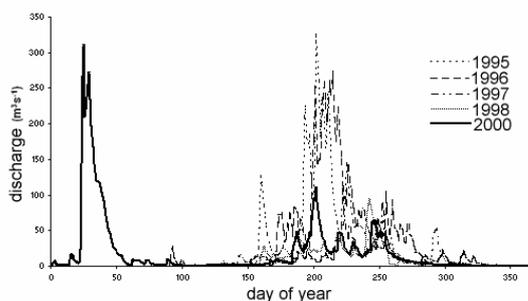

Figure 2. Comparison of watershed inflow to the Swan River in 2000 with more typical years.

Salinity in the estuary before the inflow event varied from 35 ‰ near the coast to 25 ‰ upstream. *Microcystis* was absent from estuary water samples in this period, with the phytoplankton assemblage dominated by dinoflagellates. Discharge to the Swan River following the rainfall event on day 22 completely flushed brackish and marine water (defined here as salinity, S > 10 ‰) from the upper estuary by day 31 (Fig 3). In the lower estuary it produced a surface water layer of ~ 4m that had relatively low salinity (S < 7 ‰).

By mid-February, river discharge had decreased substantially (Fig. 2). Salinity had increased to above 10 ‰ in most of the estuary (Fig 4) as brackish water re-entered the system, driven as a gravity current under the influence of reduced resistance from discharge of freshwater and the passage of a low-pressure barometric pressure front that increased ocean water levels substantially above the mean tidal amplitude.

Typical profiles of field and model salinity during the simulation are given in Figs 3 and 4. In general, ELCOM reproduced observed salinities very well (ΔS < 4 ‰), although predicted bottom salinity near Maylands was at times too high. This may be due to local variations in bathymetry that are not captured by the resolution used for the model. These effects appear more pronounced near the edge of the salt-wedge.

4.2 Water Quality

Levels of inorganic nitrogen and phosphorus were high in the river inflows (e.g. [PO4] > 0.4 mg L^{-1} and [NO3] > 2 mg L^{-1}) immediately following the river inflow event. At this time water temperatures were high (> 25°C), saline water was mostly flushed from the estuary, and irradiance was high.

Figure 5 shows the mean depth-integrated daily cyanophyte cell count per square metre in each region (Fig. 1) in January-February 2000. Cell densities (cells mL^{-1}) from surface samples taken in the morning are shown in Fig. 6. Model output, which included growth rates and growth limiting factors, confirmed that *Microcystis* was able to grow strongly within in the high-temperature, high-nutrient, low-salinity conditions that followed the heavy inflow, although seeding from tributaries was also significant (the bloom could not be replicated if it was assumed that cell counts in inflows were low).
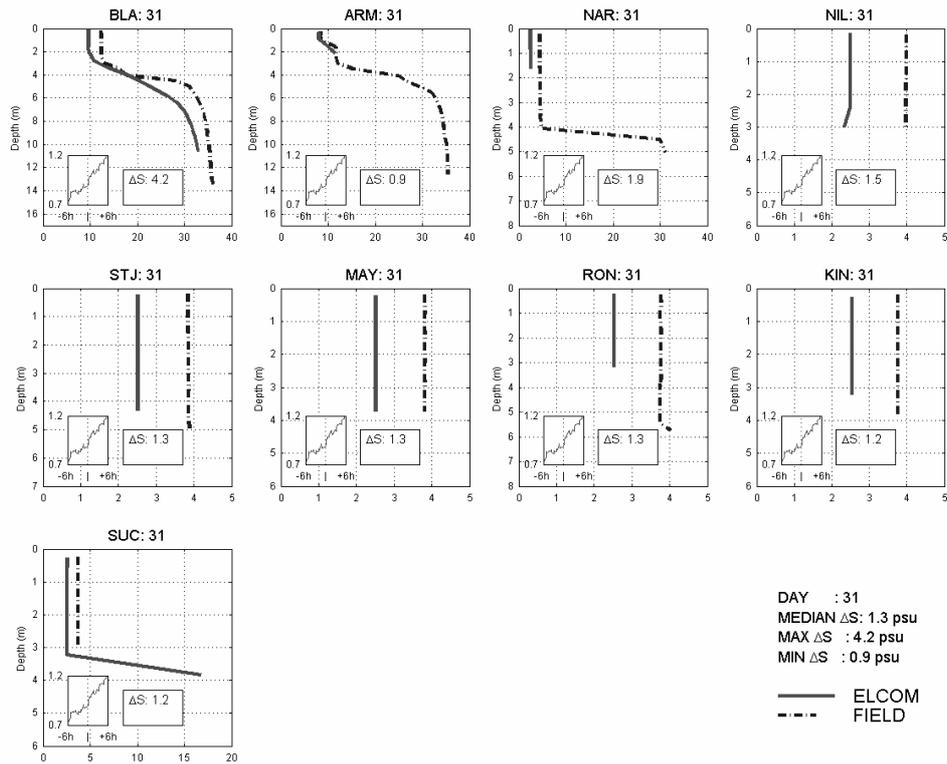
Figure 3. Field versus model (ELCOM) salinity profiles, day 31 (31 January 2000). BLA = Blackwell Reach; ARM = Armstrong; NAR = Narrows; NILE = Nile St; STJ = St Johns; MAY = Maylands; RON = Ron Courtney Island; SUC = Success Hill (see Fig. 1). Insets show tidal height at Fremantle around the time of the measurements. ΔS is the sum of the squares of the difference between field and model values.
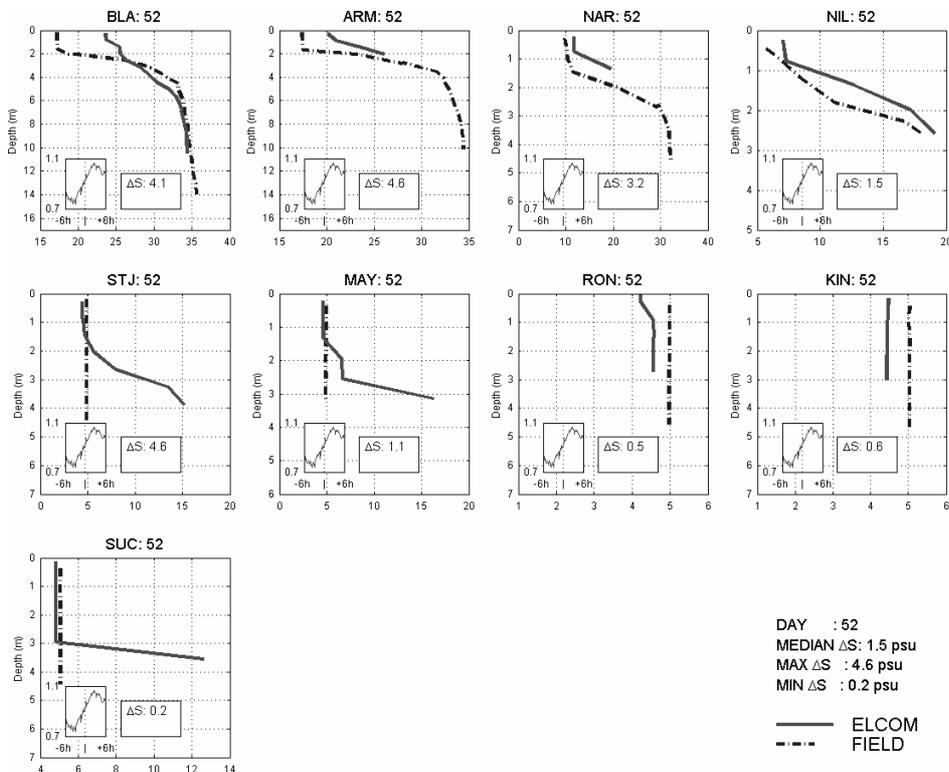

Figure 4. Field versus model (ELCOM) salinity profiles, day 52 (21 February 2000). Insets and key as for Figure 3.

Wind-induced advection in the model was important in creating patches of very high *Microcystis* concentrations near shorelines. Such patchiness was also observed in the field.

Microcystis cell counts peaked on day 47, approximately three weeks after the maximum river discharge, with measurements exceeding 1,000,000 cells mL^{-1} at some stations but declining rapidly after day 48. Exponential trend lines for observations during the growth phase of the bloom (days 38 to 47) gave $R^2 = 0.61$ ($P < 0.01$) and $R^2 = 0.24$ ($P < 0.05$) for the decline (Fig. 5). The relatively poor fit in the decay phase largely reflects along-river variation. Two outliers (a data point in region A on day 38 where no cyanobacteria were observed and a single observation of cyanobacteria in excess of 1.1 x 10^{12} cells m^{-2} near the shore in region B on day 43) were excluded from the regression analysis. The regressions indicate net cell growth rates of 0.35 d^{-1} between day 36 and day 45, and loss rates of 0.25 d^{-1} after day 45.
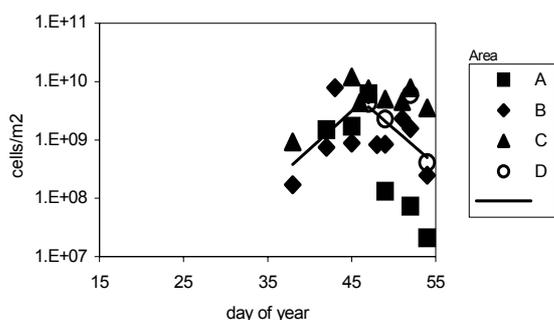

Figure 5. Cyanobacteria cell counts in the estuary. Observations are grouped by area (see Fig. 1).
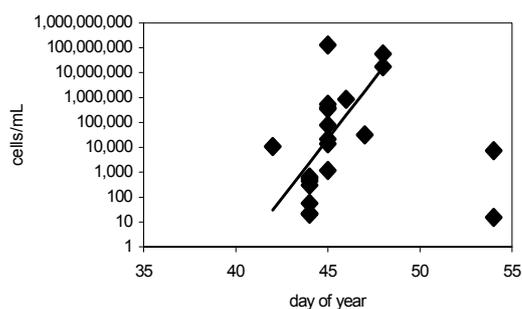

Figure 6. Surface cyanobacteria density (cells mL^{-1}) at beach and boat observation sites (Fig. 1) in the Swan River estuary during February 2000.

Surface cell counts (Fig. 6), which reflect dense scum formation due to cell buoyancy and surface advection, particularly in the latter stages of the bloom, increased at a rate of 9.0 day^{-1} ($R^2 = 0.44$, $P < 0.01$). Qualitatively, Fig. 5 suggests that the decline in *Microcystis* cells was considerably more rapid near the mouth of the estuary (region A in

Fig. 1) than in the middle reaches (B and C). This is consistent with a decline due to increasing salinity as the salt wedge propagated upstream. Tidal incursions raised the surface salinity in the lower reaches of the estuary above 10 ‰ by day 52, while salinity in the upper reaches was still low (< 10 ‰) at day 59.

Figure 7 shows the spatially averaged depth-integrated *Microcystis* cell count simulated with ELCOM-CAEDYM as a time series over the period of the simulation. The modelled doubling rate during the exponential growth period is approximately 0.30 d^{-1} (cf. 0.35 d^{-1} from the regression fit) and peak cell counts are also comparable with those observed in the field.
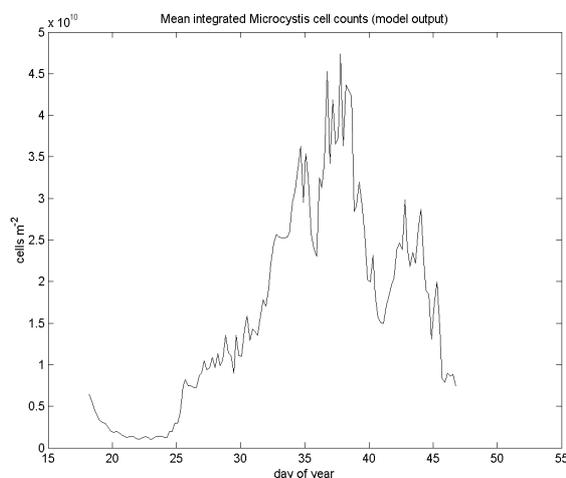

Figure 7. Mean *Microcystis* concentrations in the surface layer of the model. Chlorophyll *a* output has been converted to cell counts using a conversion factor of 0.0039 mg chl *a* cell^{-1} for comparison with Figure 7.

The bloom peaks a few days earlier in the model than was observed. Examination of the distribution of *Microcystis* cells in the model showed that cells were quickly flushed from the upper estuary into the lower domain in the model, but not in the field. As a consequence, the modelled bloom declined where tidal flushing raised salinities in the lower estuary, rather than continuing to grow until the salt wedge had propagated into the upper estuary, a few days later. This may reflect the low temporal resolution of boundary condition data. Fortnightly cell counts were converted to chlorophyll *a* (assuming 0.0039 mg chl *a* cell^{-1}) and used to set inflow concentrations of *Microcystis*. This frequency does not encompass the very dynamic nature of the bloom in the estuary. It is considered to be a potential source of error, particularly in the volumetrically smaller upper estuary, where tributary inputs exert a greater influence.

5. CONCLUSIONS

Lower salinities associated with an influx of freshwater following a rare summer storm, combined with favourable nutrient, temperature and light conditions, resulted in the first *Microcystis* bloom observed in the Swan River estuary. The conditions leading to this bloom were extraordinary under present climatic conditions. Most recent climate models, however, predict that such extreme rainfall events will recur with greater frequency in Australia in the future, due to global warming [Whetton, 2001]. If these predictions are accurate for southwestern Australia, conditions suitable for the development of *Microcystis* blooms in the Swan River estuary may recur.

The ability of a model developed and calibrated for conditions typical of the Swan River estuary to reproduce a bloom event under highly anomalous environmental conditions, supports the general applicability of this model and its potential as a predictive management tool.

6. ACKNOWLEDGEMENTS

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