A management response to ecosystem and health risks from estuarine algal blooms

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Globally, increasing human impacts on coastal areas have generally resulted in decreasing water quality (WRI 2003; Codd, et al. 2005). In association with decreasing water quality, increased human exploitation of estuarine resources and habitats has led to detrimental consequences for the trophic structure of estuaries which, in turn has promoted favourable conditions to enable the more frequent occurrence of algal blooms (Lui, et al. 2007). Within the marine and estuarine waters of NSW, reports of algal blooms (recorded since 1890) have increased considerably since 1990 (Ajani, et al. 2001). These enhanced demographic pressures and the associated increased occurrence of algal blooms continue to have important environmental, social and economic implications for sustainable development within estuaries (Tett, et al. 2003; Heisler, et al. 2008).

In most cases, algal blooms do not damage estuarine ecosystems in the long term, however they may be dangerous for human health and deleterious for commercial exploitation of the estuary in the short term (Zingone and Oksfeldt Enevoldsen 2000). Problems arising from algal blooms are diverse and require effective management strategies to mitigate the threat posed to the economic sustainability of estuarine areas and risk to human health (Zingone and Oksfeldt Enevoldsen 2000).

This paper provides a brief overview of current estuarine algal management regimes. These regimes, which provide strategic and operational controls, are dependent upon cost, timely and labour intensive on-site data collection and laboratory quantification. Given the limitations of current monitoring and management of algal blooms a proactive management regime is proposed. This proactive regime is informed by field measurements, telemetric monitoring and predicted data. Different management responses are proposed based on the activity of the algal bloom. Knowledge of impeding algal blooms would enable commercial fishing, aquaculture and recreational users to alter or amend practises that may be detrimental if undertaken during a bloom period.

1 Introduction

Phytoplankton are a natural component of estuarine ecosystems that may proliferate during favourable environmental conditions (e.g. temperature, light, etc) or in response to anthropogenic activities (e.g., nutrient discharge, etc). When particular species dominate a phytoplankton community, they may accumulate and form dense, often visible, biomass films at the surface. When the proliferating species produces toxins (phycotoxins) that threaten both natural and human health the bloom is referred to as a Harmful Algal Bloom (HAB). These HABs have led to fish kills, hypoxia and estuary closure. Current management responses to these events are reactively enacted when a bloom is detected as part of routine monitoring or when it is observed.

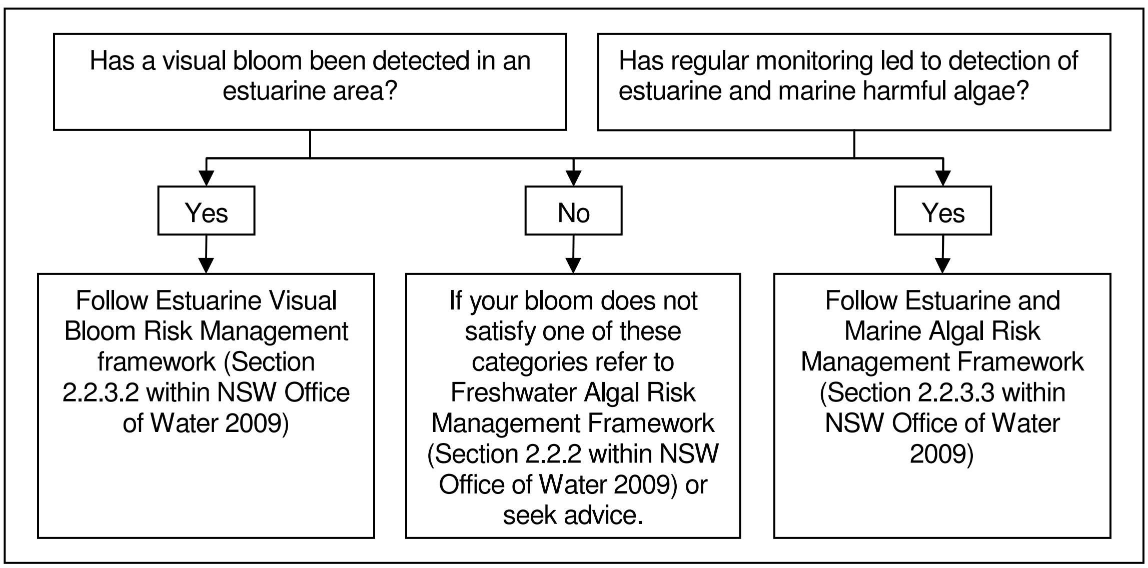
This paper proposes a proactive management response to estuarine algal blooms which is responsive to predicted and observed data that is acquired from a water quality monitoring buoy located within the Berowra Estuary in the Hawkesbury River. This buoy was deployed above uncharacteristic deep holes (-14m AHD) which have been identified as the place from which algal blooms originate (MHL 1998c). Attached to the buoy are probes which continuously monitor (15 minute timestep) changes in Chlorophyll-a (CHLa) fluorescence, temperature, salinity and photosynthetically available radiation. Data collected from the buoy is transmitted and displayed to a publically accessible webpage every 6 hours (www.estuary.hornsby.nsw.gov.au). The probe is routinely calibrated and serviced every 3 and 4 weeks in winter and summer respectively (Coad, et al. 2009).

2 Current management regimes

Current algal bloom management programs require routine (usually weekly to monthly) monitoring and/or reactive monitoring whereby blooms are monitored sporadically and at a greater frequency only when a problematic algae species is detected or a bloom is visually observed (NSW Government 1997b; ANZECC 2000; Haines, et al. 2008; NSW Food Authority 2008; ASQAP 2009; NSW Office of Water 2009). These programs have limited capacity for environmental managers to adequately monitor algal blooms due to logistic constraints such as, (i) problems associated with analytical lag times, (ii) the expense of field monitoring, (iii) staff availability and resources, (iv) safety issues, and (v) large time steps between data collection times. Further, these research and monitoring efforts are episodically intensive and are generally too limited on temporal and spatial scales to adequately investigate environmental conditions that lead to algal blooms or to enable the prediction of algal blooms.

Operational controls currently in place are mainly concerned with providing procedures for *responding* to algal blooms. Current operational responses within NSW to algal blooms are triggered based on observed water discolouration and the potential toxicity and risks of the algal species present (NHMRC 2008; NSW Food Authority 2008; NSW Office of Water 2009). These triggers for bloom response are acted upon as part of a routine monitoring program or following an observed algal event (Table 1).

Table 1 Initiation of the estuarine risk management framework (NSW Office of Water 2009)



3 Proactive management regimes

Including predictive models within current algal bloom management regimes will enable environmental managers to undertake proactive management strategies rather than implementing reactive management regimes, whereby a response to an algal bloom is made only when they occur. Integration of predictive model outputs into proactive management regimes will assist in minimising the impacts of algal blooms by providing adequate warning to public and private sectors of an impending algal bloom. Being able to achieve such an outcome is of local and international importance and is a challenge for modellers worldwide (Recknagel, et al. 1997). If the timing and magnitude of algal blooms could be predicted in the primary stage, then restorative countermeasures could be enacted earlier and at a potentially lower cost to the overall operation (Yabunaka, et al. 1997; Lee, et al. 2003).

Proposed in this paper is a proactive management response to estuarine algal blooms which utilises both real time data collection and predictive modelling. In situ, telemetrically acquired, time series data holds unique information about ecosystem processes and behaviour (Bobbin and Recknagel 2001). Use of this telemetric monitoring system (Coad, et al. 2009) enables the algal dynamics to be represented at a high frequency (e.g. daily update) and consistent time interval, which informs a near to real time management response. When this data is used in conjunction with predicted data, a management response to a predicted algal bloom can be initiated in advance. One, three and seven day forward predictions of estuarine algal blooms are generated from Artificial Neural Networks which have been trained on the high frequency data set from the Berowra Estuary.

4 Algal blooms and thresholds of concern

4.1 Algal bloom definitions

Within Australia's National water quality management strategy, algal blooms are considered to be undesirably high densities of naturally occurring algae (ANZECC 2000). The approach taken for this paper is to define an algal bloom as an increase in the daily CHLa concentrations above the normal annual cycle of CHLa concentrations. These "positive anomalies" can then lead to undesirably high densities of naturally-occurring algae which can then be used as proxies for algae blooms (ANZECC 2000; Carstensen, et al. 2004; Spatharis, et al. 2007). For the Berowra Estuary the normal annual cycle is defined by the seasonal mean concentration of CHLa; which in summer CHLa is the highest, followed by autumn, then spring and lowest in winter (refer to Table 2 with additional seasonal descriptive statistics).

Table 2 Descriptive statistics for seasonal CHLa concentrations within the Berowra estuary (2004-2009)

Season	CHLa_µg/L								
	Mean	Number of observations	Minimum	Maximum	Standard Deviation	Range	25th Percentile	Median	75th Percentile
Summer	8.4	39164	0.0	393.0	15.4	393.0	3.6	5.5	8.5
Autumn	6.2	33523	0.2	86.4	3.9	86.2	3.9	5.3	7.5
Winter	4.0	40190	0.1	30.2	2.1	30.1	2.5	3.4	5.1
Spring	5.5	42930	0.0	347.8	4.6	347.8	3.3	4.7	6.6
All Seasons	6.0	155807	0.0	393.0	8.5	393.0	3.1	4.6	6.8

Given that values of CHLa can vary both temporally and spatially it is recognised that some observed changes in the parameters are likely to be ecologically *trivial*. Hence, it is possible that an exceedence of seasonal means and/or alert thresholds may not be ecologically significant if the exceedence is sustained for a short period of time. Further, it is important that bloom definitions and alert thresholds for an algal bloom are sensitive enough to inform modest, rather than large changes only in CHLa concentrations (ANZECC 2000). Hence, trivial fluctuations in CHLa are arbitrarily defined as being fluctuations that are sustained for less than 3 consecutive days (referred to as a “perturbation”).

The challenge for the management and prediction of algal blooms is to detect *non-trivial* changes in CHLa concentrations with enough time to allow management responses to these changes to be made (ANZECC 2000). For this study, the following perturbation (trivial change) and bloom (non-trivial change) definitions are applied;

- **Perturbation**- is when the mean daily CHLa concentration exceeds the seasonal mean daily concentration for less than three consecutive days.

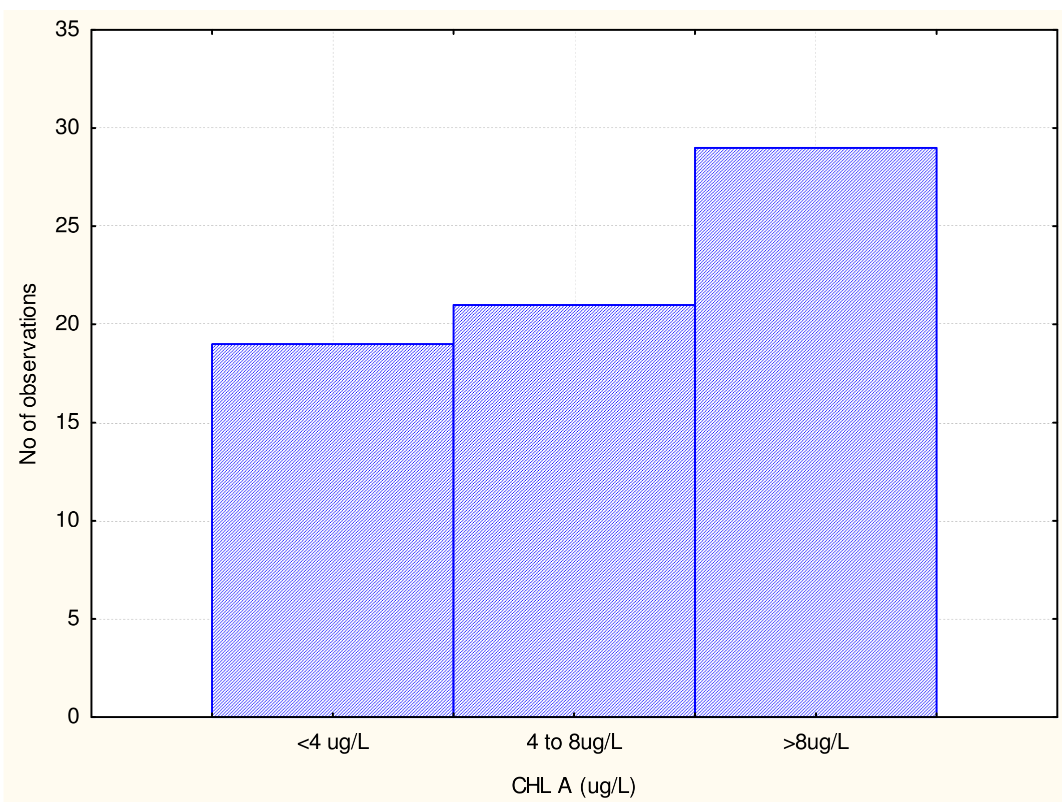
- **Bloom day**- a day where the previous, current and proceeding mean daily CHLa concentration are consecutively above the seasonal mean (Table 2).

- **Algal Bloom**- Three or more consecutive “bloom days”

4.2 Alert thresholds

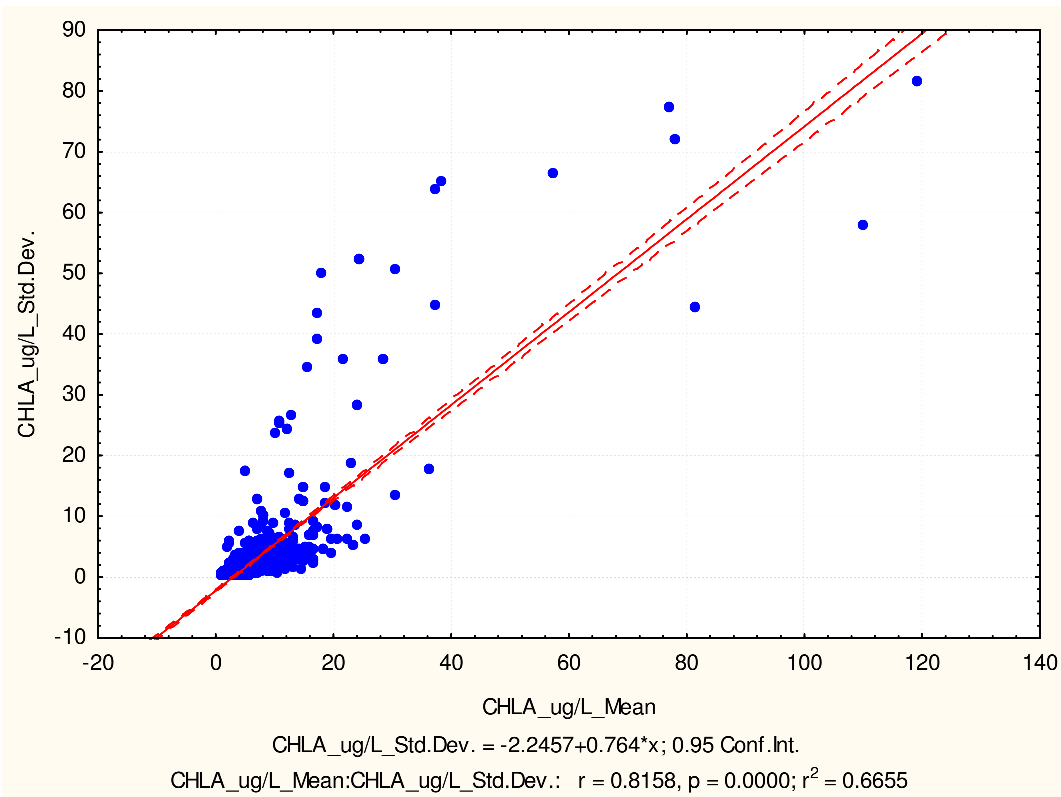
Alert thresholds for algal blooms are required to specify the magnitude of change in CHLa concentrations that are considered to be significant, either ecologically, statistically or both (ANZECC 2000). For the Berowra Estuary, based on documented ecological considerations (HRC 1998; ANZECC 2000), initial CHLa concentrations alert thresholds for ecosystem protection (Table 3) were set at 4μg/L. This initial alert threshold, is also the value, above which further investigation is required for aquatic ecosystem protection of South Eastern Australian estuaries (ANZECC 2000). The next alert level of 8μg/L was based on a localised value for problematic algal levels in the Hawkesbury-Nepean (<8μg/L) as determined by the Healthy Rivers Commission independent inquiry (HRC 1998). Based on this information these initial thresholds are also reasonably comparable with the relative risk of harmful algal being present in high abundance. That is, more harmful algae observations (at concentrations greater than 5000cellsL^{-1}) have occurred at higher CHLa concentrations compared with fewer observations when CHLa concentrations are lower (Figure 1).

Figure 1 Histogram of harmful algae observed at greater than 5000 cellsL^{-1} grouped by CHLa concentrations for the Berowra Estuary between 2004 and 2009



To determine higher alert thresholds, consideration is given to the exponential nature of algal growth, whereby increases in concentrations of CHLa values are exponentially pronounced. When mean daily data is considered, it is apparent that mean daily values of CHLa are correlated (r^2=0.67) with mean daily standard deviations (Figure 2). That is, when high concentrations of CHLa are present they fluctuate more, creating greater data variability as opposed to small concentrations of CHLa where the data variability is reduced over a daily time scale.

Figure 2 Scatterplot of CHLa_µg/L_mean daily vs CHla_µg/L_standard deviation between 2004 and 2009



Given this variability in higher concentrations of CHLa and the exponential nature of algal growth rates, a comparable set of exponential thresholds is proposed (Table 3). In using an exponential approach, these thresholds give recognition to the inherent (and usually large) variability of natural algal populations at high concentrations. These threshold values attempt to represent ecologically important changes and are designed to alert estuary managers to the magnitude of a potential or emerging bloom that should be investigated.

Table 3 CHLa concentration alert thresholds for the Berowra estuary

Threshold CHLa (µg/L)	Seasonal Mean	Descriptor	Reference	Ecosystem Protection Risk	Observed[a,b] (n)	Percent of cases[a,c] (%)
>0 and <4	Winter (4µg/L)	Low	Table 3.3.2 (ANZECC 2000)	Low	551	32.9
>=4 and <8	Summer (8.4µg/L)	Moderate	(HRC 1998)	Moderate	840	50.1
>=8 and <16		Medium		High	214	12.8
>=16 and <32		High			33	2
>=32 and <64		Very High			5	0.3
>=64		Extreme			5	0.3

a- A total of 1677 mean daily results between 2004 and 2009. **b**= 29 results are missing data. **c**= 1.2% of results are missing data

4.3 Management response

The management response to these algal bloom definitions (section 4.1) and alert thresholds (Table 3) is based on a three level monitoring system as follows (adapted from: NHMRC 2008);

- **Surveillance mode** (Non Bloom period)- This mode is enacted when mean daily CHLa is stable or below the seasonal mean. This mode involves routine sampling to monitor phytoplankton biomass and associated environmental variables in conjunction with the real time monitoring to ensure CHLa is maintained under the seasonal mean. An algal bloom management plan is deactivated in this mode.

- **Action mode** (Bloom possible)- This mode is enacted when the mean daily CHLa is increasing through time but is below the seasonal mean. This mode requires action by management authorities to prepare an informative response to estuary users of an impending algal bloom (when using predicted data). An algal bloom management response is enacted when the seasonal mean is exceeded (based on observed data).

- **Alert mode** (Bloom period or perturbation)- This mode requires investigation into the elevated levels of phytoplankton biomass when problematic concentrations occur. That is, when the mean daily CHLa concentration exceeds the seasonal mean. An algal bloom sampling program is enacted with an appropriate frequency and spatial coverage. Toxicity monitoring and assessment maybe warranted based on the species present. “Non-toxic” blooms can be identified during this period when harmful algal cell counts are below phytoplankton alert levels (NSW Office of Water 2009) but mean daily CHLa concentrations are maintained above the seasonal mean. An algal bloom management response is proposed, as part of this paper, to inform users of the level of human contact (i.e. primary and secondary) and when estuary closure is recommended based on mean daily CHLa concentrations (**Error! Reference source not found.**). These responses are cautionary as recommendations for appropriate levels of contact are based specifically on the algal species (rather than the CHLa concentration) present. Currently, there are no guidelines available to inform specific management responses to elevated levels of CHLa concentrations (other than to enact further investigation or algal species diversity and abundance monitoring) (ANZECC 2000).

5 Proposed management response to estuarine algal blooms

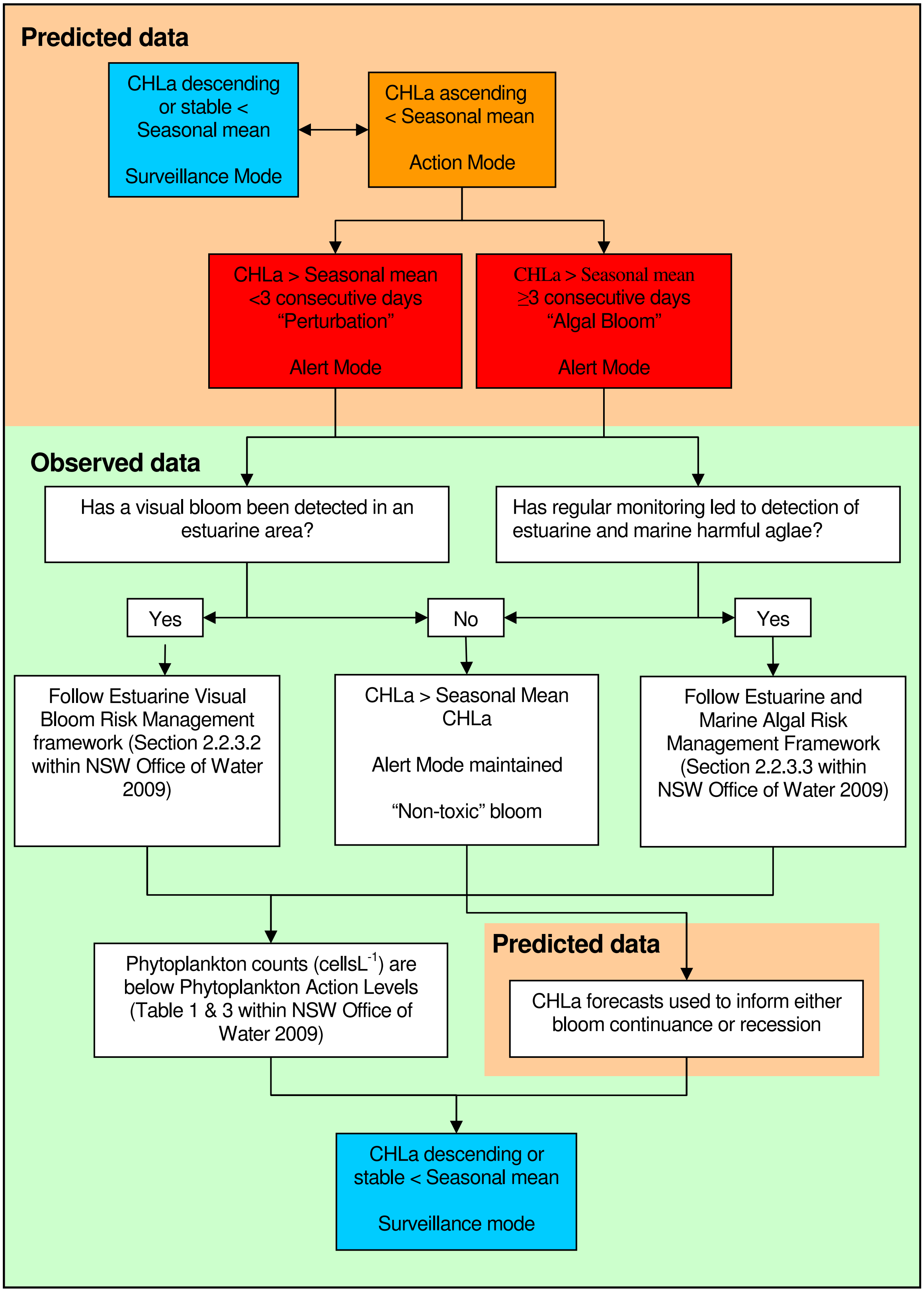
For this paper, an algal management framework is proposed based on daily and predicted CHLa data. This framework is based on (i) definitions of algal blooms, (ii) the alert thresholds and risk to ecosystem protection, and (iii) the management response to these thresholds and bloom definitions. In an operational context, the response to CHLa concentrations present within the estuary would be updated using both current and predicted data. This management framework is described in Table 4.

Table 4 Algal bloom management framework based on mean daily CHLa concentrations for the Berowra estuary

Threshold	CHLa Daily Mean Concentration (ug/L)	Example Bloom Management Response	Ecosystem Protection Risk	Management Mode			Management Mode Key
				Summer	Autumn/ Spring	Winter	
Extreme	64+	Estuary closure recommended	High >8ug/L				**Alert mode** **Bloom**= Seasonal Mean exceeded ≥ 3 consecutive days **Perturbation**= Seasonal Mean exceeded < 3 consecutive days
Very High	32 to 64	Secondary contact cautioned					
High	16 to 32	Primary contact cautioned					
Medium	8 to 16	Community alert					
Moderate	4 to 8	Agency alert	Moderate >4ug/L and < 8ug/L (HRC, 1998)	8ug/L	6ug/L		**Action mode** Increasing CHLa < Seasonal mean
Low	0 to 4	Estuary open	Low <4ug/L (ANZECC, 2000)			4ug/L	**Surveillance Mode** Decreasing or stable CHLa < Seasonal mean

An innovative feature of this management framework is the seasonally adjusted algal bloom threshold and management mode response. Incorporation of this seasonal adjustment gives recognition to the inherent natural seasonal variation within algal populations when defining and investigating an algal bloom. However, it should be noted that the proposed bloom management response is consistent for all seasons. This approach is adopted because an exceedence of 8µg/L is required before community alerts and possible detrimental consequences to the estuary will potentially occur (noted by the "ecosystem protection risk"). For example, this approach recognises that when blooms occur in winter (>4µg/L) an interim "Agency alert" is enacted whilst the bloom is investigated as part of the alert mode response. However, higher proposed bloom management responses (e.g. "Community alert" to "Estuary closure") are not enacted until mean daily CHLa concentrations exceed 8µg/L ≥ 3 consecutive days in winter. Conversely in summer, the "Agency alert" is issued when CHLa concentrations are approaching the seasonal mean (i.e. >4µg/L and < 8µg/L) but when in bloom (i.e. concentrations exceed 8µg/L ≥ 3 consecutive days) the higher proposed bloom management responses are enacted immediately. The combination of the current algal bloom management response (Table 1) and algal bloom management framework (**Error! Reference source not found.**), using both observed and predicted data, creates the opportunity for a proactive algal bloom management regime as described in Figure 3.

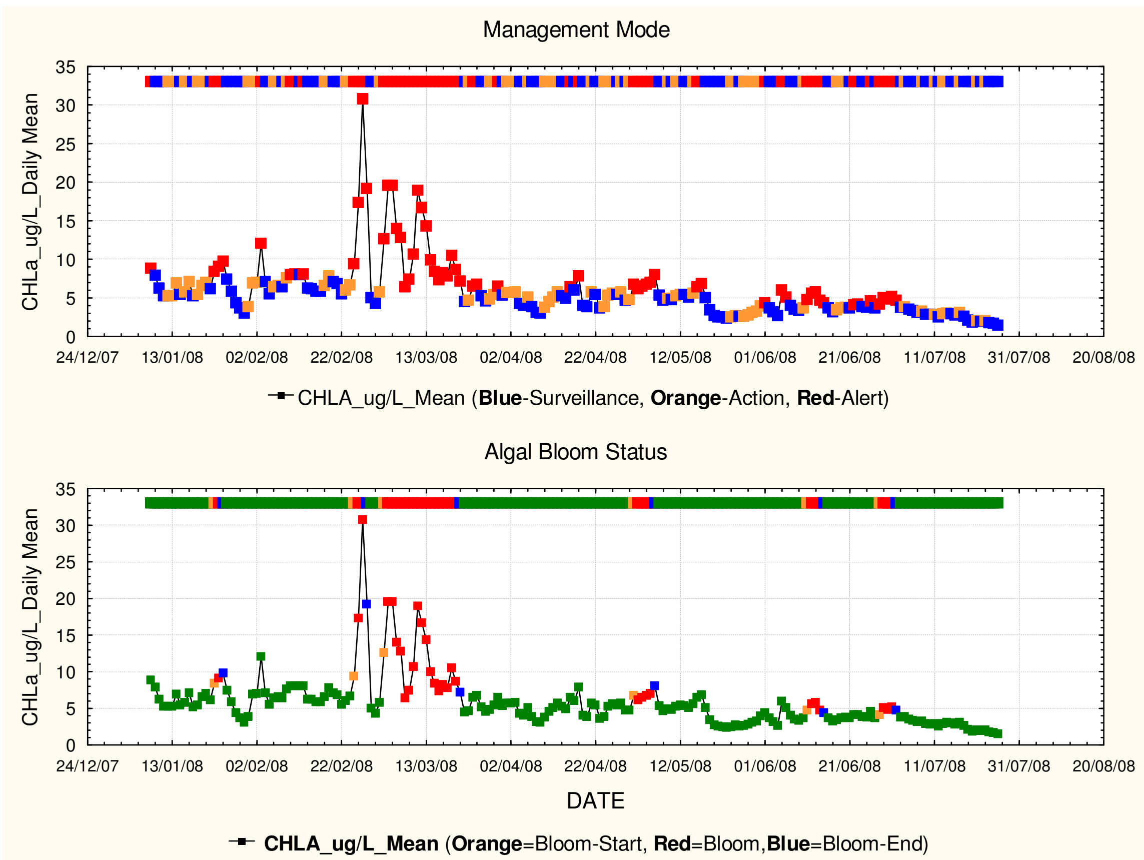
Figure 3 Proactive bloom management regime based on observed and predicted data



6 Case study using January to June 2008 data for the Berowra estuary

For this paper an observed data set (January - June 2008) (Figure 4) has been used to illustrate how both bloom status and the management mode is determined on a daily basis. From the presentation of this data (Figure 4) it is noted that 6 blooms were identified during this period (as denoted by the red colouration on the "Bloom Status" bar). The associated management mode response is also presented as "surveillance", "action" and "alert" modes. The shift between these modes is represented by the "Management Mode" bar with notable periods of the management response being in "alert mode", as corresponding with the bloom periods or perturbations.

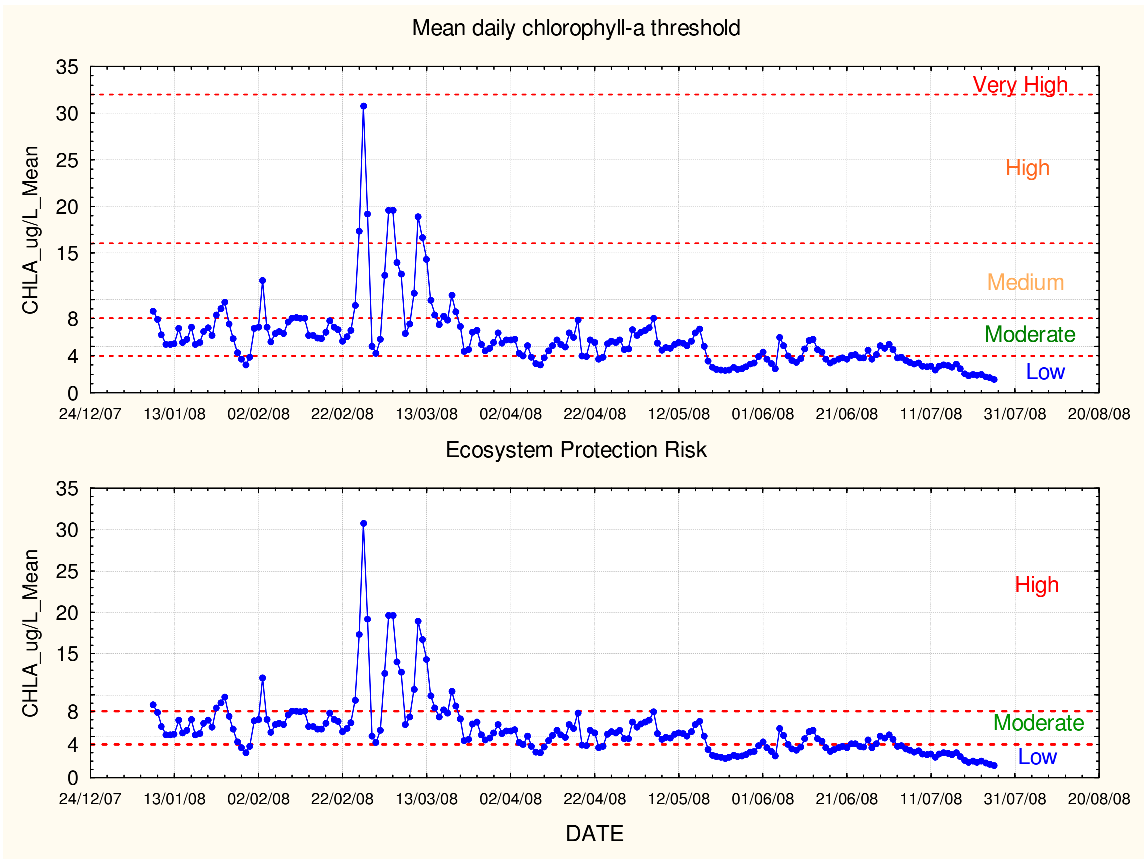
Figure 4 Management response applied to observed data (January to June 2008).



The proposed bloom management response applied during this period (as defined in **Error! Reference source not found.**) varied according to the threshold exceeded by mean daily CHLa concentrations on each day (Figure 5). Concurrently, the risk to ecosystem health is considered (Figure 5) based on mean daily CHLa concentrations with ≤4µg/L being low,

>4µg/L and ≤8µg/L considered moderate and > 8µg/L high risk for the protection of ecosystem functions (as discussed in section- 4.2).

Figure 5 Mean daily chlorophyll-a threshold and ecosystem protection risk



7 Conclusions

Understanding the mechanisms that promote and sustain algal blooms and the provision of accurate algal bloom predictive models is of foremost importance to environmental managers who are required to protect estuarine resources. Hence, it is critical that appropriate water quality monitoring programs, inclusive of experimental and modelling research, are established to inform management programs that mitigate and respond to algal blooms (Sarkar and Chattopadhayay 2003). Without accurate, intensive and long-term data acquisition, the factors that influence estuarine algal blooms cannot be adequately assessed, effective preservation and remediation programs cannot be run, and the success of management programs cannot be properly evaluated (Glasgow, et al. 2004). Being able to distinguish the individual and cumulative effects of physical, chemical and biological controls of algal productivity and composition is the key to understanding, predicting and ultimately managing estuarine algal blooms (Paerl 2006).

A proactive management regime is proposed which is responsive to observed (current conditions) and predicted data (future conditions). This proactive management regime informs a management response which is dependent upon, (i) season and (ii) fluctuations (i.e. increases or decreases) and duration (i.e. perturbations or blooms) of mean daily CHLa concentrations. These management responses are either in "Surveillance mode" (decreasing or stable CHLa concentrations below seasonal mean), "Action mode" (increasing CHLa concentrations below the seasonal mean) and "Alert mode" ("Algal bloom" when CHLa concentrations have exceeded seasonal means ≥3days consecutive days otherwise a "perturbation").

Pivotal to the implementation of such a management regime is (i) a long term monitoring program from which seasonal patterns can be described, (ii) accurate data collection (e.g. rigorous calibration and data quality protocols) and (iii) high resolution (i.e. frequency) data collection to observe temporal trends. Further, these data sets are not limited to informing algal bloom management regimes. Additional, research projects such as understanding environmental flow requirements of the estuary, relationships with prawn catches, oyster condition, health of the estuary, e.t.c. would also benefit from such a data series.

Using both predictive models and continuous in situ environmental monitoring devices provides an opportunity to proactively manage estuarine algal blooms to protect public health, fisheries resources, ecosystem health and estuary aesthetics (Anderson, et al. 2001). An early alert, given with acceptable accuracy and lead-time, means that specific contingency plans could be enacted prior to a bloom occurring. This alert system and associated proactive management will limit potential health problems and economic losses that may arise from the occurrence of an algal bloom.

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