1. INTRODUCTION

Planktonic algal blooms are a major feature of the biological activity in the Gippsland Lakes and toxic blue-green algal blooms, in particular, are of ongoing concern due to their deleterious effects on fish and other marine life, water quality for swimming and flow-on impacts on local businesses and tourism. There are other groups of plankton that have the potential to be toxic and/or disrupt ecosystem function, however little attention has been paid to these in the past.

In August 1998 regular EPA “fixed site” water quality sampling and real-time spatial monitoring techniques detected extremely high levels of Chlorophyll $a$ due to a significant dinoflagellate bloom. The bloom covered much of Lake Victoria and Lake King and followed a drought-breaking flood. Subsequent sampling by EPA followed the course of the bloom and the ensuing development of a bloom of the blue/green alga *Nodularia spumigena*.

The dinoflagellate bloom went largely unnoticed by the wider community, as there were no bright green surface scums that are a feature of blue/green *Nodularia* blooms which have occurred in the area. During the dinoflagellate bloom the water was a dark olive green progressing to a turbid chocolate brown at the height of the bloom.

Water quality conditions for the Gippsland Lakes before and after the flood are presented in this report together with information on the identification of the main dinoflagellate bloom species. A linked sequence of events over a 17 month period is described that progresses from drought to flood to dinoflagellate bloom and ultimately a bloom of the toxic blue/green alga *Nodularia spumigena*. The results of this study support the proposition that major rain events drive the cycle of algal blooms in the estuarine Gippsland Lakes system.

2. METHODS

EPA regularly assesses the Gippsland Lakes at five sites as part of its fixed site monitoring program which has provided a temporal sequence of water quality data since 1986. In addition to this program, EPA has developed and trialed a system to map the patterns of surface water quality parameters over open water areas. This provides more spatially intensive data that can lead to a better understanding of the dynamics of significant environmental events.
Sampling for this report was conducted over a seventeen-month period from January 1998 to May 1999. Fixed sites and open water transects were sampled on eleven occasions mostly at 2 monthly intervals, although more frequent sampling was carried out at the peak of the dinoflagellate bloom.

2.1 Study Area

The Gippsland Lakes, 200km east of Melbourne, is an estuarine coastal lagoon system separated by sand barriers from oceanic Bass Strait (Fig. 1). From west to east, the system comprises Lake Wellington, which connects to Lake Victoria via the narrow McLennan Strait, Lake King that merges with the eastern end of Lake Victoria near Raymond Island, and Reeves Channel which links the system to Cunningham and North Arms at Lakes Entrance. A narrow channel linking the lakes with the sea is maintained through the sand barrier at Lakes Entrance. The surface area of the lakes system is approximately 360 km² and the catchment about 20,000 km² (Bird 1978).

2.2 Fixed Site Monitoring

At the five EPA water quality monitoring sites (Fig. 1), unfiltered water samples for laboratory analysis are taken. Surface waters are sampled at 0.5 metres and bottom waters at 0.5 metres from the bottom. Nutrients are analysed by the Marine and Freshwater Resources Institute, Queenscliff. Ammonium, nitrate and nitrite nitrogen is analysed using colorimetry by segmented flow analyser, and total phosphorus with acid digestion and colorimetry by segmented flow
analyser. Chlorophyll pigments are analysed by solvent extraction followed by spectrophotometry.

2.3 Vertical Profiles

In addition to the water samples at the five fixed sites, vertical profiles of water quality parameters including salinity, turbidity and dissolved oxygen combined with depth are measured with a Yeo-Kal Model 611 water quality meter logging directly to computer.

2.4 Water Quality Mapping System

Using a water pick-up tube suspended below a moving boat, water is directed through a Turner Model 10-005R fluorometer (for chlorophyll a) and through a flow-through cell housing a Yeo-Kal Model 611 multi-parameter water quality meter measuring salinity, temperature, pH, dissolved oxygen and turbidity. By utilising GPS position fixing in conjunction with a laptop computer logging system based on ‘TerraScan’ (Resource Industry Associates) and ‘Excel’ (Microsoft) software, these water quality parameters are measured, recorded and displayed in real time every 4 seconds at boat speeds in excess of 30 knots. This allows spatial coverage across the lakes system together with the fixed site sampling within a day.

In each transect, a number of samples are taken for laboratory spectrophotometric chlorophyll a analysis to establish a correlation with fluorescence as measured in the field by the fluorometer.

Generalised spatially interpolated contour plots of chlorophyll a are created in the surface mapping system “Surfer” (Golden Software Inc.) using kriging as the interpolation method and a grid dimension of approximately 1200 metres. As the contour boundaries are software derived, the final result is dependent on the interpolation method, settings and data density. They do however, give a useful indication of spatial chlorophyll a patterns. Settings have been chosen to achieve an intuitively sensible result and areas that are well away from the sampling zone have been masked.

3. RESULTS

3.1 Sequence of Events

Results of spatial and fixed site water quality sampling prior to, during and after a major flood, combined with rainfall and river flow data, show the development and demise of subsequent algal blooms.

Drought

The Gippsland region experienced a drought throughout 1997 to June 1998. From April 1997 to June 1998, phytoplankton levels in the lakes system, as indicated by chlorophyll a, were relatively low (eg Jan – May, Fig. 4). Salinities were high, stratification was usually weak and dissolved oxygen levels in bottom waters were generally good (eg. 14 May, Fig. 6).

Flood

In late June 1998, a major rain event in the Gippsland Lakes catchment (Fig. 2) led to flooding on the Mitchell, Nicholson and Tambo Rivers which combined to cause flooding in the Gippsland Lakes. At that time the Latrobe River was not significantly affected however the Avon and Perry Rivers were the
source of elevated flows into Lake Wellington (Fig. 3).

When sampling was conducted on 1-2 July 1998, salinities in surface waters of the lakes had reduced markedly. However, the floodwaters were restricted to the upper 3 to 4 metres of the water column, passing over the more saline water below (Fig. 6). It is interesting to note that, even in such an extreme flood event, the incoming waters did not mix significantly with the deeper layers. This situation created strong salinity stratification of the water column.

![Figure 2. Indicative 24 hour Rainfall for the Gippsland Lakes Catchment](image)
During the July 1998 sampling, phytoplankton levels were relatively low in Lake King and most of Lake Victoria. However, an area of elevated chlorophyll $a$ was detected in the southwest corner of Lake Wellington due to a localised bloom of the non-toxic dinoflagellate *Heterocapsa triquetra*. A small bloom of this species had been detected previously off the eastern entrance to McLennan Strait on 14 May 1998.

**Dinoflagellate Bloom**

By the next sampling time on 5 August, salinities in surface waters at the Lake King North site had risen back to about 16 practical salinity units (psu) from about 4 psu immediately after the flood. A dinoflagellate bloom had developed over much of Lake King and Lake Victoria (Figure 4). The main bloom species were *Heterocapsa triquetra* and to a lesser extent *Gymnodinium cf aureolum*, and significant numbers of the small diatom *Skeletonema costatum* also were recorded. However, at the next sampling time on 20 August, *G. cf aureolum* was by far the most dominant organism and chlorophyll $a$ levels exceeded 1000 $\mu$g/l at some locations.
Decline of the Dinoflagellate Bloom

The bloom had started to diminish by 24 September with chlorophyll a levels in Lake King below 40 µg/l. Numbers of *G. cf aureolum* and *Skeletonema costatum* had decreased substantially although large numbers of nano and picoplanktonic organisms were present. Another rain event occurred in late September 1998 leading to flooding on the Mitchell River (BoM September 1998) and elevated flows in the Latrobe River (Figure 3). The September sampling was conducted just prior to any impact from this event.

By the next sampling time on 25-26 November chlorophyll a levels in Lake King and the eastern end of Lake Victoria had returned to near pre-flood levels. However, levels in Lake Wellington and western Lake Victoria were declining at a slower rate and remained elevated.

It should be noted that from previous observations chlorophyll a levels in the shallow and turbid Lake Wellington are typically higher than in the other lakes. The plankton in Lake Wellington are usually of mixed groups and species with a high proportion of nano and picoplankton making identification difficult.
Figure 4. Spatially Interpolated Chlorophyll a Contours – 1998
Blue/Green Algal Bloom

In mid January 1999, the first sighting of a bloom of the blue/green alga *Nodularia spumagena* was reported. Lake King and Bancroft Bay and Reeves Channel near Metung were the areas most affected. Extremely high cell counts were recorded at localised sites particularly near Metung (K. Thomas pers. comm.) but by April 1999 no sign of the *Nodularia* bloom was apparent.

Figure 5. Spatially Interpolated Chlorophyll $a$ Contours Feb to May 1999
3.2 Water Quality Conditions

3.3 Vertical Profiles of Physico-chemical Water Quality Indicators at Lake King North

Differences in the vertical profiles of selected physico-chemical parameters over time illustrate the impact of the flood on water quality. The Lake King North site was selected to demonstrate the changes in water quality in terms of turbidity, salinity and dissolved oxygen in the bloom area over time. These patterns are illustrated in Figure 6. This site is relatively deep at around 7 metres, and is more central to Lake King and thus not as affected by shoreline or tidal influences as other sites in the bloom area.

14 May 1998 – Six weeks prior to the flood

The vertical profile of salinity showed the lake to be very saline (around 32 psu) and well mixed showing no stratification. Dissolved oxygen levels were about 100% saturated through most of the water column with only a slight depression close to the bottom. Turbidity was close to zero throughout the water column.

1 July 1998 – One week into the flood

A distinct freshwater layer (salinity of 4 psu) extended down to about 3 metres and overlayed quite saline bottom waters at 28 psu. Although the water column was now stratified, dissolved oxygen levels were still relatively high, generally above 80% saturation, in the bottom layer. Turbidity was very high in the surface layer due to the turbid floodwaters. However, the lower saline layer was significantly clearer demonstrating the lack of mixing between the two layers.

5 August 1998 – Early stages of the bloom

Strong stratification continued. Salinity increased to 16 psu in the surface layer and increased only slightly to about 30 psu in the lower layer. Turbidity had dropped significantly in the surface layer down to 3 ntu and the lower layer still close to 0 ntu. Dissolved oxygen in the surface layer was supersaturated probably reflecting the very high productivity of the dense dinoflagellate bloom. This contrasts with severe oxygen depletion in the lower layer where saturation levels were less than 10%.

24 September 1998 – Later stages of the bloom

The salinity profile for September was similar to that in August except that the transition between the upper, fresher layer and the lower, more saline layer was much sharper indicating strong stratification and stable conditions. The turbidity profile was also similar to the August sampling. Oxygen levels in the surface layer still showed a degree of supersaturation but not as extreme as in August, which suggests a reduction in bloom productivity. However, the bottom layer was anoxic with the oxygen saturation level passing from 110% at the surface to 0% at about 2 metres above the bottom.
Figure 6. Vertical Profiles of Turbidity, Salinity and Dissolved Oxygen
Lake King North Site, May to September 1998
3.2.2 Nutrients

On 1 July, one week after the start of the flood, dissolved inorganic nitrogen (DIN) levels were extremely elevated at Lake King North, Lake King South and Metung, the sites most affected by the flood (Fig. 7). However by 5 August, levels in surface waters were down to near pre-flood levels. The other sites sampled showed a similar pattern of change but at lower DIN levels. Lake Wellington, least affected by the flood, showed the smallest pulse of nitrogen. At the Lake King sites, DIN in bottom waters remained elevated after the flood.

Total phosphorus (PTOT) levels in the lakes appeared not to rise as an immediate result of the flood (Fig. 7). PTOT levels in bottom waters at the Lake King sites did rise significantly towards the end of the bloom about three months after the flood. At the Lake Wellington and Lake Victoria sites, phosphorus levels also increased well after the flood event but were similar in the surface and bottom waters, probably due to less pronounced salinity stratification (Fig. 7).

The phosphorus pattern at the Metung site shows higher levels in surface waters for the July to November 1998 period. This is most probably due to the bottom waters at this site being more directly influenced by oceanic tidal water from Bass Strait.

3.2.3 Chlorophyll a

Over the July to August period, phytoplankton biomass increased dramatically in Lakes King and Victoria as indicated by chlorophyll a levels (Fig. 7). By November 1998 chlorophyll a levels had reduced significantly, but then rose again slightly in Lake King in January and at Metung in February due to the Nodularia bloom. Lake Wellington and most of Lake Victoria were not affected by the Nodularia bloom.

The bloom density varied significantly across the study area. From the spatial mapping data on 20 August 1998, chlorophyll a levels ranged from 10 to 1300µg/l over the area affected by the dinoflagellate bloom. No fixed site sampling was conducted on this date. The highest chlorophyll a level recorded in the fixed site sampling program was 115 µg/l at Metung on 5 August, when spatially mapped chlorophyll a measurements ranged from 25 to 250 µg/l.

The highest chlorophyll a concentrations due to the Nodularia bloom were recorded on 18 March 1999 by spatial mapping. Levels ranged from 10 to 400 µg/l over the affected area compared with the highest measurement from the fixed site program of 19 µg/l at the Metung site on the same date. The highest fixed site chlorophyll a result due to the Nodularia bloom was 26 µg/l on 17 February at the Lake King North site when the spatially mapped results ranged from 3 to 62µg/l.

The differences between these results highlight the value of the spatially intensive mapping system to better characterise water quality parameters that can be highly variable. Traditional water sampling at discrete fixed sites that are often far apart can miss much of the detail of events such as algal blooms and floods.
Figure 7. Nutrient, Chlorophyll a and Salinity data for the Lake Wellington, Lake Victoria, Lake King and Metung Sites

EPA Victoria
3.3 Identification of Species

There were two distinct dinoflagellates that dominated the phytoplankton during the study. Detailed examination and identification of the dinoflagellates was necessary to determine if either of these organisms was known to be toxic, and to enable accurate comparisons should future blooms occur.

The most abundant dinoflagellate, a non-chain-forming gymnodinioid cell, reached levels in excess of $3 \times 10^7$ cells /L. The cells, which were 24-34 µm in length and 22-30 µm wide, contained numerous golden-brown chloroplasts and a central to posterior nucleus. Scanning Electron Microscopy (SEM) revealed the presence of a loop (or horseshoe) shaped apical groove, a feature common to a range of Gymnodinium species (egs. Bolch & Hallegraeff 1990, Bolch et al. in press, Ellegaard et al 1993, Ellegaard & Yoshima 1998) including the Paralytic Shellfish Poison (PSP) producing Gymnodinium catenatum. The overall features and dimensions of the dinoflagellate fit within the description of Gymnodinium aureolum (see Hansen et al) so we have ascribed the name Gymnodinium cf. aureolum to the organism in this study. Knowledge of the toxicity of G. aureolum is somewhat confused as G. mikimotoi, a known fish killer, has often been misidentified as G. aureolum (Hansen et al). G. cf aureolum from this study may well prove not to be toxic as no fishkills were reported at the time of the bloom however, in light of its close affinity with known toxic species, further investigation into its toxicity is warranted.

Figure 8. Scanning electron micrographs of Gymnodinium cf. aureolum from this study
The other important dinoflagellate dominated during the early stages of the bloom, reaching densities in excess of $9 \times 10^6$ cells/L. Cells were between 22 and 30µm in length and possessed a distinctive antapical horn, characteristic of *Heterocapsa triquetra*. Thecal plate arrangement and scale morphology were examined with Transmission Electron Microscopy (TEM) and SEM to verify the identification of this organism. *Heterocapsa triquetra* has a worldwide distribution and is not known to be toxic.

Figure 9. Scanning electron micrograph of *Heterocapsa triquetra*
4. DISCUSSION

4.1 Factors Influencing Dinoflagellate Bloom Formation and Dynamics

4.1.1 Catchment run-off

A review of algal blooms in Australian coastal waters indicated that dense algal concentrations are most strongly developed under stratified stable conditions, at high temperatures and following high organic input from land run-off after heavy rains (Hallegraeff, 1995). These conditions were apparent in this study, except temperatures were not at a maximum in August 1998 when the bloom was detected. Previous reports (Longmore, 1994, Norman, 1988) indicate that blooms in the Gippsland Lakes can happen at any time of year suggesting that temperature may not necessarily be a critical factor as to whether a bloom develops.

Longmore (1994) reported a dinoflagellate/diatom bloom in the Gippsland Lakes following heavy rains in November 1988 with the dominant organism being an “unknown” dinoflagellate. It is interesting to note that this bloom preceded a blue/green algal Nodularia bloom in July 1989.

The relationship between other flood events and algal blooms in the Gippsland Lakes further highlights the potential link with catchment run-off. Table 1 outlines these events from 1965 to 1997 and although some blooms may have gone unreported the list covers most of the major blooms for the period. Dates of blooms in the table reflect when blooms were reported, not necessarily when they started.

There have been floods to the Gippsland Lakes that did not appear to be followed by major algal blooms (Chessman 1988). For example, chlorophyll data held by EPA and that reported in Arnott and McKinnon (1983) suggests that no major bloom occurred in the spring or summer of 1978/79 following the major floods of June 1978.

The nature of antecedent conditions and river flows appears to be important in promoting algal blooms in the Gippsland Lakes. Long dry periods with low river flows during autumn and winter, followed by major rainfall events and flood flows in spring, appear to be typical conditions associated with algal blooms.
Table 1. Reports of Blooms and Flood Events in the Gippsland Lakes - 1965 to 1997

<table>
<thead>
<tr>
<th>Year</th>
<th>Month</th>
<th>Event Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1965</td>
<td>July</td>
<td>Nodularia bloom in Lake Wellington after bushfires and heavy rain (Solly 1966)</td>
</tr>
<tr>
<td>1971</td>
<td>Jan/Feb</td>
<td>major flood in Gippsland Lakes (Bird 1972)</td>
</tr>
<tr>
<td></td>
<td>March</td>
<td>Microcystis bloom in Lake Wellington (F&amp;WD 1971)</td>
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<tr>
<td></td>
<td>May</td>
<td>Lake King, dinoflagellate dominated</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Lake Victoria, mainly diatom dominated - Nodularia present</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Lake Wellington, Nodularia/diatom dominated</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Nodularia dominant in Bunga Arm (Powling and Wan)</td>
</tr>
<tr>
<td>1973/74</td>
<td>Aug</td>
<td>major flooding on Latrobe, Macalister and Mitchell Rivers (BoM)</td>
</tr>
<tr>
<td></td>
<td>Feb</td>
<td>Nodularia bloom Lakes King and Victoria (EPA 1974)</td>
</tr>
<tr>
<td>1984</td>
<td>July</td>
<td>moderate flooding on Mitchell, Tambo and Latrobe Rivers Floods (BoM)</td>
</tr>
<tr>
<td></td>
<td>Oct</td>
<td>minor non-specified bloom in Lakes Victoria and Wellington (chlorophyll data in Longmore et al 1988)</td>
</tr>
<tr>
<td>1985/86</td>
<td>Sept/Oct</td>
<td>floods on Latrobe and Mitchell Rivers (BoM)</td>
</tr>
<tr>
<td></td>
<td>Dec</td>
<td>major flooding on Tambo river and moderate on Latrobe and Mitchell rivers (BoM)</td>
</tr>
<tr>
<td></td>
<td>Jan</td>
<td>Anabaena bloom in Lake King (Norman 1988)</td>
</tr>
<tr>
<td>1986/87</td>
<td>Oct</td>
<td>minor flooding on Macalister and Mitchell Rivers (BoM)</td>
</tr>
<tr>
<td></td>
<td>Feb</td>
<td>Nodularia bloom in Lake King (Norman 1988)</td>
</tr>
<tr>
<td>1987</td>
<td>July</td>
<td>minor flooding on Mitchell and Thompson Rivers (BoM)</td>
</tr>
<tr>
<td></td>
<td>Aug</td>
<td>non-specified bloom in Lake Victoria (Norman 1988)</td>
</tr>
<tr>
<td></td>
<td>Dec/April</td>
<td>Nodularia bloom in Lake Victoria (Norman 1988)</td>
</tr>
<tr>
<td>Year</td>
<td>Month</td>
<td>Event Description</td>
</tr>
<tr>
<td>----------</td>
<td>--------</td>
<td>-----------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>1988/89</td>
<td>Nov 1988</td>
<td>East Gippsland has wettest November on record, moderate flooding on the Mitchell River (BoM)</td>
</tr>
<tr>
<td></td>
<td>Dec 1988</td>
<td>Dinoflagellate bloom in Lake Victoria (Longmore 1994)</td>
</tr>
<tr>
<td></td>
<td>July 1989</td>
<td>Nodularia bloom in lakes (Longmore 1994)</td>
</tr>
<tr>
<td>1989</td>
<td>July 1989</td>
<td>Minor flooding on Latrobe River (BoM)</td>
</tr>
<tr>
<td></td>
<td>Dec 1989</td>
<td>Nodularia bloom in east Lake Victoria and south Lake King (Longmore 1994)</td>
</tr>
<tr>
<td>1990</td>
<td>April 1990</td>
<td>Major flooding on Mitchell, Avon and Thompson Rivers, minor to moderate flooding on other rivers (RWC 1991)</td>
</tr>
<tr>
<td></td>
<td>July 1990</td>
<td>Unspecified bloom in Lake King North (EPA chlorophyll data)</td>
</tr>
<tr>
<td></td>
<td>Sept 1990</td>
<td>Unspecified bloom in lakes King South and Victoria (EPA chlorophyll data)</td>
</tr>
<tr>
<td>1992/93</td>
<td>Sept 1992</td>
<td>Record breaking rains and many floods across Victoria (BoM)</td>
</tr>
<tr>
<td></td>
<td>Dec 1992</td>
<td>Major flooding on the Macalister River (BoM)</td>
</tr>
<tr>
<td></td>
<td>Jan 1993</td>
<td>Microcystis bloom in Jones Bay/Lake King (P Marwood pers. com.)</td>
</tr>
<tr>
<td>1995/6</td>
<td>October 1995</td>
<td>Major flooding on the Latrobe River (BoM)</td>
</tr>
<tr>
<td></td>
<td>January 1996</td>
<td>Unspecified bloom (not blue/green) in Lake Victoria (EPA chlorophyll data)</td>
</tr>
<tr>
<td></td>
<td>May 1996</td>
<td>Nodularia bloom in Lake King (EPA data)</td>
</tr>
<tr>
<td>1996/7</td>
<td>July-Oct 1996</td>
<td>Minor flooding on the Latrobe and moderate flooding on Mitchell Rivers (BoM)</td>
</tr>
<tr>
<td></td>
<td>Feb 1997</td>
<td>Nodularia bloom in Lake King (EPA chlorophyll data)</td>
</tr>
</tbody>
</table>
4.1.2 Nitrogen and Phosphorus

Phytoplankton productivity in the Gippsland Lakes is considered to be primarily nitrogen limited (Axelrad and Bulthuis 1977, Smith 1975). The levels of nitrogen measured in the first half of 1998 were at the lower end of the normal range. When sampling was conducted on 1 July, one week after the rain event, dissolved inorganic nitrogen (DIN) levels were extremely elevated. However, by the next sampling time on 5 August, levels in surface waters were down to near pre-flood levels. This was particularly evident at the Lake King North, Lake King South and Metung sites. The other sites showed similar patterns (Fig. 7) with Lake Wellington, which was least affected by the flood, showing the smallest pulse of nitrogen.

Over this period, phytoplankton biomass increased dramatically in Lakes King and Victoria as indicated by chlorophyll a levels (Figs. 4&7). Rapid assimilation of DIN from the water column by phytoplankton most likely accounted for the lowering of DIN concentrations. This pattern is consistent with observations from other Australian estuaries (eg. O'Donohue and Dennison 1997).

In contrast to DIN, total phosphorus (PTOT) levels appeared not to rise as an immediate result of the flood. However, PTOT levels did rise significantly, particularly in bottom waters, towards the end of the bloom about three months later. (Fig. 7). Two factors could explain this rise in phosphorus - firstly, enhanced phosphorus release from the sediments due to oxygen depletion in bottom waters and secondly, release of phosphorus from decaying bloom organisms.

It has been reported elsewhere that phosphorus did not increase as a result of a flood event. Scanes et al. (1999) found that after input into Tuggerah Lakes, New South Wales, from a major rain event, there was little change in phosphorus concentrations but an increase in dissolved nitrogen and a rapid increase in chlorophyll a concentrations.

4.1.3 Organic Matter

Phytoplankton blooms often occur after significant rain events and river discharge which introduce large quantities of humic substances (dissolved organic matter) to estuarine and coastal systems (Heil, 1996). Nitrogen in combination with humic substances from soils, rivers, sediments and decomposing vegetation can stimulate the growth of dinoflagellates to the point of out competing diatoms (Graneli et al. 1989). Doblin (1999) found that the input of dissolved organic matter into Tasmanian coastal waters after rainfall events played a critical role in the development of blooms of Gymnodinium catenatum a potentially closely related species to the Gymnodinium sp. of this study.

Although humic substances are not analysed in the current Gippsland Lakes monitoring program it is most probable that elevated levels would have been associated with the flood. As a result of low river flows prior to the June rain event, organic matter would be retained in the catchment. A "first flush" from the major rain event is likely to be particularly high in dissolved organic matter and could play a part in bloom initiation and maintenance.

4.1.4 Other Micro-nutrients and Trace Elements

Levels of some trace elements can be critical for determining the cell densities that phytoplankton bloom species can achieve. Iron (Fe) and Selenium...
(Se) are two such elements although it is unlikely that iron is limiting in an estuarine system such as the Gippsland Lakes.

Selenium has been identified as an important trace element for the growth of certain phytoplankton species such as the dinoflagellates *Gymnodinium catenatum* (Doblin et al. 1999) and *Gymnodinium nagasakiense* (*mikimotoi*) (Ishimaru et al. 1989). These species are closely related to *Gymnodinium cf auroleum* found in this study so it is possible that selenium plays a role in the growth of dinoflagellates in the Gippsland Lakes.

Doblin et al. (1999) conclude that the riverine input of inorganic selenium and its interaction with dissolved inorganic matter may be a critical factor in the development of *G. catenatum* blooms after rain. The level of selenium in the lakes is not known, however, Glover et al. (1980) reported elevated levels in fish. An assessment of the significance of selenium to algal blooms in the Gippsland Lakes may be warranted.

It is reported in the scientific literature that blooms of dinoflagellates can be related to levels of cobalamin (vitamin B₁₂) that is washed from soils and marsh areas where it is produced by both bacteria and blue-green algae (Round 1965). Once again, the significance of this substance to bloom dynamics in the Gippsland Lakes is not known but could be a useful avenue for future study.

### 4.1.5 Stratification

A surprising aspect of the flood event was that the huge quantities of fresh water discharging into the lakes did not push out the deeper saline waters. The floodwater was restricted to the top 3 to 4 metres thus stratifying the previously well-mixed water column. Salinity stratification, in combination with the increased organic sediment load from the bloom, led to severe oxygen depletion in the lower layer and by 24 September at the Lake King North site the lower 1.5 metres of the water column was anoxic. This was towards the later stages of the bloom and appears to have led to a significant release of phosphorus from the sediments.

### 4.1.6 Species Identification

Particular attention was paid to the identification of the bloom species to determine whether they were known to be toxic and also to enable comparisons to be made should such blooms continue to be a regular occurrence in the Gippsland Lakes.

Identification of plankton species, especially unarmoured dinoflagellates, can be difficult. Because of the delicacy of many species, the cells do not usually retain their morphology when preserved by normal means and identification generally requires careful observations of live cells (Larson 1994). With some species electron microscopy may be necessary to reveal the fine detail necessary for identification.

The taxonomic resolution of previous studies in the Gippsland Lakes (e.g. Smith 1975, Ducker et al 1977, Longmore 1994) were often limited to genus level and did not include detailed descriptions of organisms. Consequently it is not known whether the bloom species in this study have been a feature of previous blooms.
4.2 Development of the blue/green algal bloom

Blue-green algal blooms are usually associated with freshwater systems where phosphorus is generally the limiting nutrient. In the Baltic Sea, where *Nodularia* blooms are a persistent problem, bloom development is initiated through phosphorus enrichment of warm, stratified surface waters low in nitrogen (Sellner 1997).

In the Western Australian Peel-Harvey estuarine system winter and spring diatom blooms developed following nutrient loading from significant river inflow (Lukatelich and McComb 1986). After the collapse of the diatom blooms, recycling of nutrients supported summer blooms of *Nodularia*. Similar processes could be occurring in the Gippsland Lakes.

It seems likely that the dinoflagellate bloom reported in this study modified conditions in the Lakes in such a way as to favour the later development of the *Nodularia* bloom. The following sequence of events is hypothesised to have led ultimately to the *Nodularia* bloom that started in January 1999.

- Prolonged drought resulted in lakes relatively saline and well mixed.
- Major rain event in June 1998 (especially in lower catchment and eastern end of Lakes).
- Pulse of nitrogen and possibly other growth promoters from rivers and catchment.
- Major dinoflagellate/diatom bloom in July/August 1998
- Nitrogen and possibly other growth promoters depleted.
- Dinoflagellate bloom diminishes.
- A second, smaller rain event in late September 1998 added more fresh water to the system
- Salinity stratification resulting from freshwater pulse, and increased organic load on sediments from senesing dinoflagellate/diatom bloom, led to anoxia in bottom waters.
- Phosphorus released from sediments during anoxic conditions, and additional phosphorus released from the senesing dinoflagellate bloom.
- Strong winds late in December 1998 (Grayson et al. 1999) caused mixing of nutrient rich bottom waters with warmer surface water in the euphotic zone.
- Low N and high P coupled with warmer water and favourable salinity led to serious *Nodularia* bloom - January/March 1999.

Preliminary monitoring for this study suggests that a similar scenario may have preceded a previous *Nodularia* bloom in the Gippsland Lakes. Heavy spring rains in October 1995 and major flooding in the Latrobe River followed a winter of below average rainfall. A large area of elevated chlorophyll *a*, possibly due to a dinoflagellate/diatom bloom, was detected in Lake Victoria in January 1996 and a *Nodularia* bloom was well established by May 1996. As discussed previously, Longmore (1994) also reported a *Nodularia* bloom in July 1989 that followed a dinoflagellate bloom in December 1988 and heavy November rains.
It appears that it can take a lag of six months or more for a rain event to lead to a major blue/green algae bloom in the Gippsland Lakes. The development of such blooms may be dependent on the progress of other types of blooms such as, in this case, the dinoflagellates. There may well be other scenarios that result in blue/green algal blooms but further regular monitoring and special investigations are required to fully understand this large and complex system.

5. CONCLUSIONS

A major rain episode in June 1998 and consequent flooding of the Gippsland Lakes initiated a sequence of events that included a significant dinoflagellate bloom and culminated in a bloom of the toxic blue/green alga *Nodularia spumigena*.

Elevated nitrogen levels associated with the flood appeared to initiate the dinoflagellate bloom, the result of which was to modify conditions that favoured the development of the blue/green algal bloom.

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7. REFERENCES


Ellegaard, M., Christensen, N.F. and Moestrup, O. (1993). Temperature and salinity effects on growth of a non-chain-forming strain of Gymnodinium catenatum (Dinophyceae) established from a cyst from recent sediments in The Sound (Oeresund), Denmark. J. PHYCOL. vol. 29, no. 4, pp. 418-426


