The ecology of algal blooms in the Gippsland Lakes

Gippsland Lakes & Catchment Taskforce

2011

The Gippsland Lakes & Catchment Taskforce

Formed by the Victorian Government in 2001, the Taskforce is charged with arresting the decline in water quality in the Lakes (as indicated by an increase in algal blooms). It has adopted an evidence-based and adaptive management approach to the management of the Lakes and their catchment.

The Taskforce has focused on:

- using science to gain a better understanding of the ecology of the Lakes, nutrient sources and management practices to reduce loads;
- taking targeted actions to reduce the nutrient loads entering the Lakes;
- monitoring the ecology of the Lakes to evaluate the success of these actions; and
- taking further action in response to the outcomes of monitoring work.

This report summarises the findings of research into the ecology of algal blooms in the Gippsland Lakes. It outlines the substantial body of knowledge generated which has enabled the Taskforce to focus far more on positive outcomes than was possible less than a decade ago. For copies of the original research reports, visit the Taskforce’s website: www.gippslandlakestaskforce.vic.gov.au/research.htm

Acknowledgements

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Introduction

The Gippsland Lakes are a series of linked waterways in south-eastern Victoria which are fed by streams flowing from the Great Dividing Range. They discharge to the sea via the Cunninghame Arm.

Originally, the estuary discharged intermittently several kilometres east of the current entrance, but this natural outlet was often closed and a man-made channel was constructed in 1889 at Lakes Entrance. The original outlet has now permanently closed.

Figure 1: Map of the Gippsland Lakes (DSE 2011).

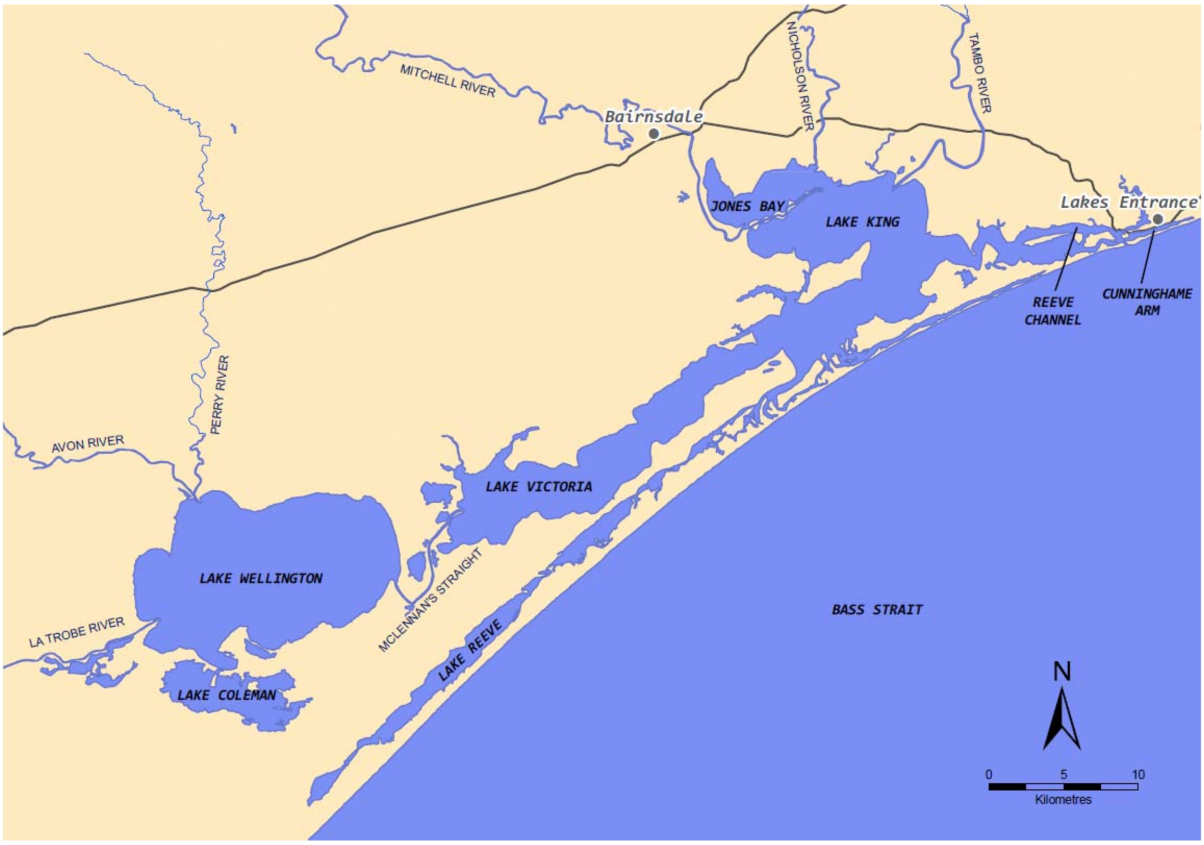
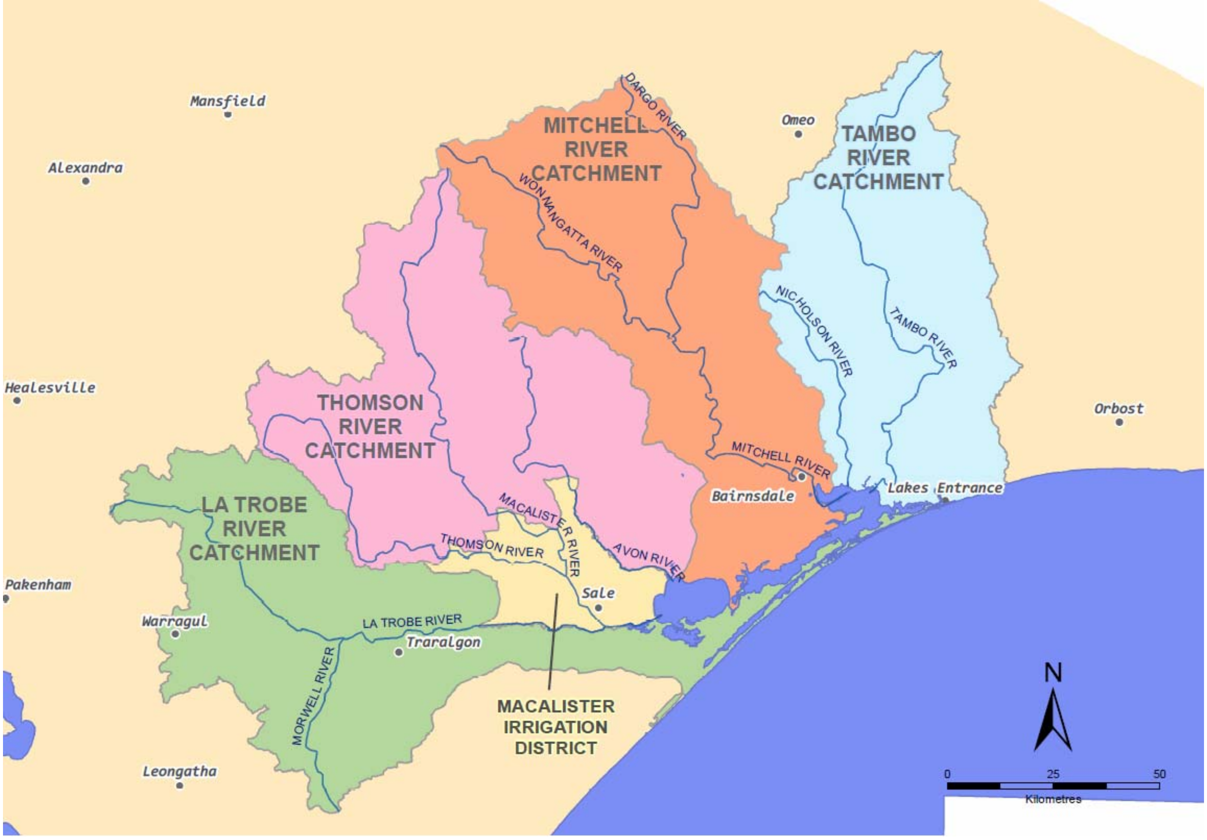


Figure 2: Map of the Gippsland river catchments (DSE 2011).



The lakes receive fresh water from numerous rivers and marine water from tides and storm surges pushing in through the entrance. As a result, the upper lakes (such as Lake Wellington) are brackish, while the lakes closer to the entrance are more saline. Evaporation tends to raise their salinity levels.

The new opening at Lakes Entrance changed the character of the lakes and increased salinity levels. This, in turn, affected the ecology of the lakes, their wildlife and surrounding vegetation.

The condition of the Lakes is now driven by four factors:

- physical characteristics, such as depth and temperature;
- marine inflows through the entrance;
- climate, especially rainfall and summer temperatures; and
- stream inputs, especially nutrients and sediments from the catchments.

Lake characteristics

In this section:

- Water inflows to the Lakes
- Nutrients and sediments
- Physical characteristics – depth, salinity and temperature.

Water inflows to the lake

Lake Wellington is fed by the Latrobe, Thomson and Macallister, Avon and Perry Rivers.

Lake Victoria is fed by Lake Wellington (via the narrow McLennan's Straight) and local creeks. It also receives water from Lake King.

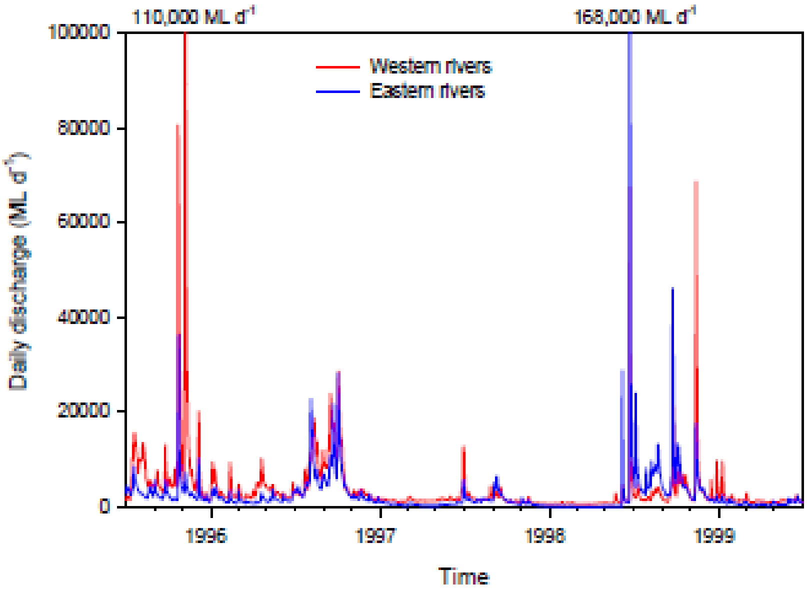
Lake King is fed by Lake Victoria, as well as the Mitchell, Nicholson and Tambo Rivers to the north. Marine inflows from the entrance also reach as far as Lake King.

Lake Reeve lies adjacent and parallel to the coast. It is usually dry at the western end, and is connected to Lake Victoria in the east.

Cunninghame Arm is fed from via Reeve Channel and by marine inflows through the entrance.

Stream flows are seasonal (being highest in winter and spring), and vary considerably from year to year. This variability is due to occasional flood events that provide the greater part of inflows to the lakes. The rivers flowing into Lake Wellington (the western rivers) discharge more water than those entering Lake King (the eastern rivers).

Figure 3: Daily discharges from the eastern and western rivers (Webster et al 2001).



Marine inflows are driven by storms and tides and by relative differences in the height of water in the Lakes and in the ocean. Seasonal changes in sea level (up to 30 cm) are the main driver of marine inflows (Webster et al. 2001, cited by Cook et al. 2008). Strong winds also create local 'tides' in the lakes themselves, pushing water into different areas.

Nutrients and sediments

Around 110,000-190,000 tonnes of sediment are deposited in Lake Wellington each year, although the amount varies with the sediment load in individual flood events and river flows. Sediment cores from the bed of the lake indicate that before European settlement the loads of sediment were far lower, being around 14,000-20,000 tonnes/yr (Hancock and Pietsch 2006). Changes in the sediment inflows indicate that the streams have been 'more energetic' in the past 50-70 years as a result of landscape clearing, drainage, urbanisation and other human activities.

It appears that some of the sediments entering Lake King flow on into Lake Victoria as well – although this may take 10-20 years. Sediments in shallower waters are re-suspended by floods and wind and migrate to deeper areas, where the sediment is re-deposited at the highest rates. The variation in deposition rates across the water bodies makes it difficult to predict total sedimentation with accuracy within those two lakes. Water in the deeper areas tends to have the lowest concentrations of suspended sediments, allowing light to penetrate further (Longmore and Roberts 2006).

Two-thirds of the nutrients entering the Lakes come from the western catchments, into Lake Wellington and thence through to Lake Victoria (Longmore and Roberts 2006). Around 60 tonnes of dissolved inorganic phosphorus (DIP) come from the western catchments per year and 40 tonnes/yr come from rivers entering Lake King. For dissolved inorganic nitrogen (DIN), 1,230 tonnes enter from the western rivers and 1,040 tonnes/yr from the eastern rivers. The system's total annual nutrient loads are considerably higher, due to large additional amounts in organic and particulate forms.

Figure 4: Total nutrient loads entering the Gippsland Lakes (tonnes/yr) (Holland and Cook 2009).

	Total nitrogen	Total phosphorus
Mean 1978 – 2008	1,680	191
Max 1978 – 2008	6,060	869
Min 1978 – 2008	305	32

These nutrients can be re-mobilised from stores in the sediments at the bottom of the lakes to cause outbursts of algal growth. This phenomenon is termed the 'benthic flux'. Scientists now think that nearly all the phosphorus in the top 30 cm of the Lakes' sediments could be available to stimulate algal growth (Longmore and Roberts 2006).

Annual benthic fluxes may range from eight to 35 times the total annual load entering the Lakes via the rivers (Cook et al 2008). It is also becoming clear that more nutrients originate from sediments in deeper water. For example, western Lake Victoria covers barely a tenth of the Lakes’ total area, yet supplies around half the nutrients coming out of the sediments (Longmore and Roberts 2006).

Nutrients are also continually recycled through organisms (plankton and algae) that live within the water column.

Figure 5: Annual nutrient fluxes, including from the top 20 cm of sediments (Longmore and Roberts 2006).

	Phosphorus (DIP – tonnes/yr)			Nitrogen (DIN – tonnes/yr)		
	Influx	Sediments	Recycled	Influx	Sediments	Recycled
Lake Wellington	60	100	310	1,230	440	2,200
Lake Victoria (shallow)		200	240		1,040	1,700
Lake Victoria (deep)		280			1,100	
Lake King (shallow)	40	-60	350	1,038	180	2,500
Lake King (deep)		78			620	

The sediments in the Lakes contain a vast stockpile of nutrients – more than 70 times the annual amount deposited as new influxes. It is estimated it would take from 10-100 years to consume the nutrients stored in the sediments of the Gippsland Lakes (Longmore and Roberts 2006).

Nutrient definitions

DIN = Dissolved Inorganic Nitrogen = nitrite + nitrate + ammonia = forms of nitrogen immediately available for uptake by organisms.

FRP = Filterable Reactive Phosphorus = orthophosphates = forms of phosphate immediately available for uptake by organisms.

TN = Total Nitrogen = nitrite + nitrate + ammonia + organically bound nitrogen.

TP = Total Phosphorus = orthophosphates + condensed phosphates + organically bound phosphorus.

Nitrogen entering the Lakes is partly lost as a gas, through denitrification. This accounts for seven tonnes a year from Lake Wellington, 1,845 tonnes/yr from Lake Victoria, and more than 410 tonnes/yr from Lake King.

Physical characteristics – depth, salinity and temperature

Lake Wellington is shallow, has a relatively flat bottom and is quite fresh. Lakes Victoria and King are deeper but more varied in profile – around half their area is less than 3 m deep, while about one quarter is deeper than 5 m (Hancock and Peisch 2006). Jones Bay, in the north of Lake King, is around 2 m deep (Webster et al 2001).

In calm conditions the deeper waters can 'stratify' into distinct layers. Denser, more saline water lies at the bottom, with fresher water (e.g. from river inflows) resting above. However, strong winds can mix the layers. The boundary between the layers of different salinity is referred to as a halocline.

Figure 6: Lake depths and salinities (Webster et al 2001).

	Lake Wellington	Lake Victoria	Lake King
Area (sq km)	148	75	98
Mean depth (m)	2.6	4.8	5.4
Maximum depth (m)	6	9	10
Salinity ($^o/_{oo}$)	0.5-10	4-17 (surface) 7-25 (bottom)	8-26 (surface) 15-36 (bottom)

$^o/_{oo}$ = parts per thousand; or grams of salt per kilogram of seawater (seawater is about 35 $^o/_{oo}$).

All the lakes except Lake Wellington have large areas where the bottom water is sufficiently saline to support marine life such as seagrasses.

Calm bodies of water may also stratify according to temperature, with colder, denser water lying on the bottom; but this is not thought to be a significant factor in the Gippsland Lakes. The water temperature is highest in summer (around 22°C) and lowest in winter (around 10°C) in all lakes.

The bottom layer of water can also become deprived of oxygen – conditions that are termed hypoxic (very low levels of oxygen) or anoxic (virtually no dissolved oxygen present). This may happen when oxygen-dependant microbes use up all the available oxygen and the lack of mixing means it is not replaced. Anaerobic microbes (organisms that do not rely on gaseous oxygen, but obtain energy from decomposing organic matter) may then thrive.

Lake Wellington used to be dominated by native water plants, such as ribbon weed, but these died out due to an influx of saline water from Lake Victoria during the 1968 drought and have never recovered. Phytoplankton (microalgae) are now the dominant form of vegetation in Lake Wellington (Harris et al 1988; cited in Holland et al 2010).

Catchment characteristics

The Gippsland Lakes are indicators of the health of their catchments and the streams that feed them. Climate, land use and management are key drivers of catchment health. This section considers:

- Climate
- Climate change
- Land use
- Bushfires

Climate

The catchments of the Gippsland Lakes are bounded by the Great Dividing Range to the west and north, and the Strzelecki Ranges to the south, and typically have a relatively wet, temperate climate. Annual rainfalls are commonly around 1500 mm in the ranges (with much of it falling as snow in the west) but decrease to around 900 mm at lower altitudes and less than 600 mm on the plains.

Mean maximum temperatures are usually in the mid-twenties during summer and mid-teens in winter, but are lower in the ranges, where winter brings sub-zero temperatures. Significant rainfall can occur at any time of the year, but peak river flows tend to be in late winter and spring.

Figure 7: Climate statistics – Warragul (BOM 2010).

Statistics	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Mean maximum temperature (°C)	25.9	26.2	23.9	19.7	16.0	13.5	12.9	13.9	16.0	18.9	20.7	23.4	19.2
Mean minimum temperature (°C)	12.5	13.2	11.6	9.0	6.6	4.8	3.8	5.0	6.2	8.0	9.4	10.9	8.4
Mean rainfall (mm)	61.1	51.3	67.8	83.2	93.3	91.4	91.1	102.8	103.9	106.2	88.2	79.2	1019.3

Figure 8: Climate statistics – Bairnsdale (BOM 2010).

Statistics	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Mean maximum temperature (°C)	25.8	26.3	24.1	21.1	17.9	15.0	15.1	16.3	18.3	20.3	21.7	24.3	20.5
Mean minimum temperature (°C)	13.7	14.1	12.3	9.6	6.8	4.9	3.8	4.7	6.4	8.4	10.2	12.0	8.9
Mean rainfall (mm)	64.0	42.8	63.4	62.9	68.5	61.7	36.6	51.5	49.7	59.6	65.0	66.1	693.6

The mean annual evaporation at Bairnsdale is 996 mm – about 50% more than its average rainfall – and it has been estimated that around 340 million cubic metres evaporates from the Lakes per year (Rosengren).

Climate change

Climate predictions indicate that climate change will affect the Gippsland region by:

- increasing average temperatures and the number of hot summer days;
- increasing evaporation rates;
- reducing average rainfall in parts of Gippsland, but uncertain change in others;
- fewer rainy days, but more intense rain events;
- more intense droughts and a possible increase in frequency (especially in the east); and
- increased wind strength and larger storm surges (Cottingham 2008).

For more information about projected future climate visit the Victorian Government's understanding climate change website: www.climatechange.vic.gov.au/regional-projections.

Over time, climate change may result in less total run-off, but storm-driven floods will remain an important feature of the region. There could also be increased risk of bushfires, leading to massive nutrient fluxes from the land if floods occur before burnt areas have had a chance to recover.

Climate change is predicted to also cause rising sea levels due to the melting of ice sheets and glaciers, and the thermal expansion of the upper ocean. Coupled with increasing wind speeds, that will increase the risk of breaches in the current foreshore dune system leading to marine inflows to the Lakes, which would further change the ecology of the Gippsland Lakes.

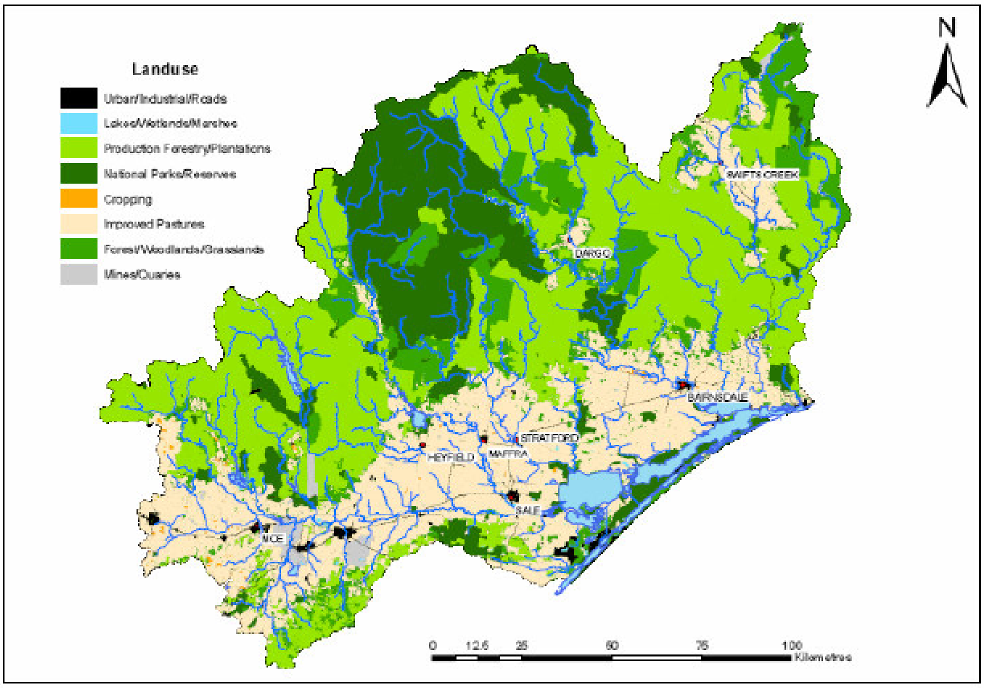
Land use

The biggest land uses in the catchments, and their sediment contributions, are as follows:

Figure 9: Area and sediment contributions from major land uses (Grayson, 2006).

Land use	Area (ha)	Total suspended solids (tonnes/yr)
Forests & Reserves	1,116,592	71,700
Agriculture	796,020	159,931
Residential	8,185	2,173
Mining	19,918	4,840
Other	62,133	9,624

Figure 10: Map of main landuses (Grayson 2006).



Recreation and tourism is a primary economic use of the Lakes. It is based in townships around the Lakes, but uses the entire Lakes system for boating, fishing, camping, bush-walking and bird-watching activities. Recreational fishers spend 1.3 million hours a year in the area and more than 200,000 people visit local parks and reserves a year. An algal bloom in 2008 is estimated to have cost the region $18.2 million, mainly through reduced visitor numbers and business turnover (Connolly and Brain 2009). The Gippsland Lakes are estimated to generate around $250 million in a typical year to the regional economy.

Nature conservation is another major feature of the Lakes. The range of habitats, extensive area and relatively natural condition of many of the wetlands contribute to the region being an internationally important area for conservation. The Gippsland Lakes provide feeding and breeding habitat for 80 bird species, and regularly host 40,000-50,000 waterbirds (West Gippsland CMA 2005).

Bushfires

In the past decade, bushfires have burnt large areas of forest in the Lakes catchments. This damaged 9% of the catchment in 2003 and 34% in 2006/07 (SKM 2008).

A flood in 2007/08 followed the 2006/07 bushfires in the catchments of the Avon, Thomson, Mitchell, Nicholson and Tambo Rivers. This flood brought with it a spike in nutrient loads, in fact the largest loads ever recorded, most of which originated from the burnt catchments (Cook et al 2008). The total nutrient loads entering the Lakes that year were 6,060 tonnes of nitrogen and 870 tonnes of phosphorus (Holland et al 2010). Scientists expect that climate change will increase the frequency, intensity and speed of bushfires (SKM 2009).

Ecological foundations

This section presents information about:

- Nutrient cycles
- Locally occurring algae

Nutrient cycles

Nitrogen and phosphorus ‘cycle’ through the environment, changing form (e.g. from being bound up in organic molecules or liberated in inorganic compounds that may be taken up by living organisms) depending on the action of microbes or chemical reactions, both of which are influenced by changes in the environment (such as oxygen levels).

For nitrogen, key transformations are:

- Nitrification – the conversion by bacteria of nitrogen compounds to more readily available forms (e.g. converting ammonium to nitrite and then nitrate)
- Denitrification – the conversion of nitrates into gaseous nitrogen, nitric oxide and nitrous oxide.

Phosphorus transformations include:

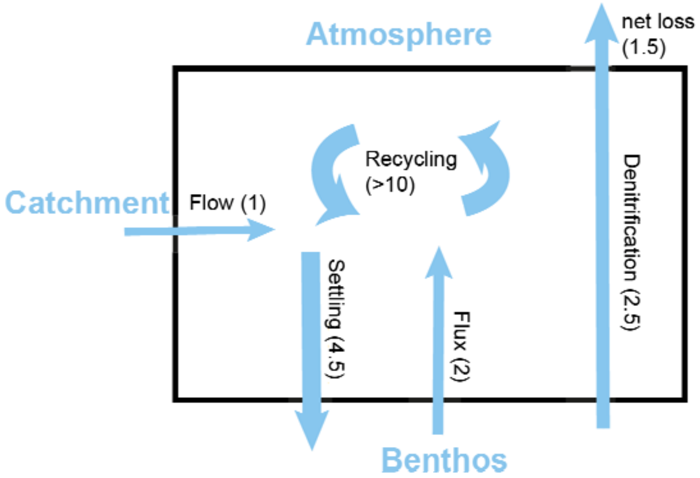
- Sorption – the taking in (absorption) or holding on to (adsorption) of phosphorous by sediments or compounds.
- Reduction – the conversion of iron to iron sulphide (which releases phosphorus to the environment) in hypoxic or anoxic (oxygen deprived) conditions.

Nitrogen and phosphorus may both be subject to:

- Mineralisation – the decomposition of organic matter (often by microbes) into inorganic elements, which may then be available for uptake by other organisms.

Nutrient cycling tends to be much faster for nitrogen than phosphorus. Forms of nitrogen that are available to organisms (known as being ‘bio-available’) are very soluble and do not remain in sediments for long. Phosphorus in sediments is generally in equilibrium with that in the water column above. As water concentrations rise so to do the loads stored in sediments, and if water concentrations decrease, then phosphorus is released from the sediments (Schippers et al 2006; cited by Longmore and Roberts 2006).

Figure 11: Simplified nitrogen cycle (Holland et al 2009).



The numbers in brackets indicate the movement of nitrogen, in mmol/m^2/day

Locally occurring algae

Algae are aquatic organisms powered by sunlight. They include some of the oldest life forms on earth, with ancestors dating back more than three billion years. Algae contain the green pigment chlorophyll, which enables them to use the sun's energy to process carbon dioxide and water into organic compounds and oxygen; known as photosynthesis. This ability, coupled with their abundance, mean that algae play a key role in the environment, generating massive amounts of oxygen and providing the foundation to aquatic food-webs.

Measuring the amount of chlorophyll in water (measured as chlorophyll *a,* the most common light-absorbing pigment involved in photosynthesis) is an easy way to gauge the amount of algae in a water body.

Many micro-algae are single-celled, but some link together to form colonies that range in shape from filaments to spheres or sheets. The main types of algae in the Lakes are:

- Green algae (mainly dinoflagellates) the evolutionary predecessors of flowering plants.
- Diatoms. whose cell walls are made of silica (the same chemical found in sand and glass).
- Blue-green algae (or cyanobacteria) which are really bacteria that contain chlorophyll.

For general information about algae and other life forms, see the Tree of Life website: http://tolweb.org

Dinoflagellates

Dinoflagellates are a diverse, widely spread and important group. They are usually single-celled, but can form filaments. They have two 'flagella' – thin whip-like or ribbon-like threads – that operate at right angles to each other to aid in their movement (and in some, to waft water and food towards a mouth-like opening). They are usually photosynthetic, but not always, and can be significant components of plankton and the food-web that supports other species. Many dinoflagellates are marine, but there are also hundreds of freshwater species.

Their cell walls are divided into plates of cellulose, giving them a distinctive appearance and their cell nucleus and aspects of their DNA are unique. Dinoflagellate blooms sometimes produce 'red tides' containing toxins that are harmful to aquatic life and animals, or people consuming affected fish or shellfish. They have complex lifecycles, some involving a cyst (egg-like) stage that can survive in unfavourable environments.

Important dinoflagellates found in the Gippsland Lakes include:

- *Gymnodinium* – some species are toxin producing; and
- *Noctiluca* – ammonia producing (Cottingham 2009), 'red tides' that are nuisance value but not toxic (Smith pers comm.).

Figure 12: Gymnodinium impudicum.

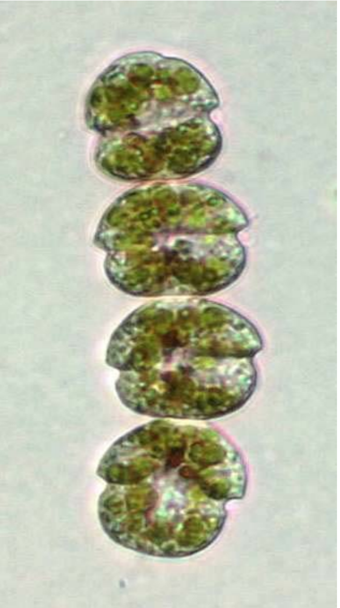
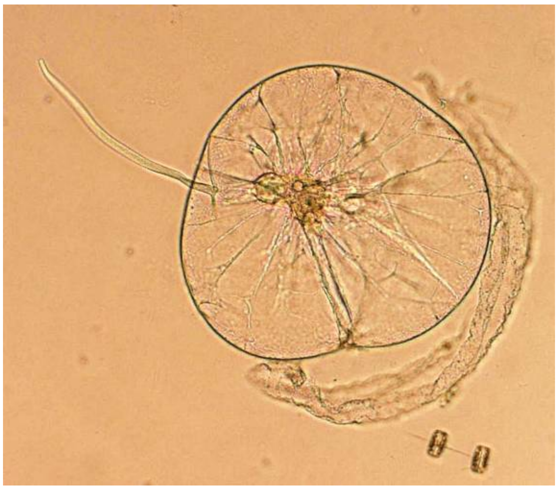


Figure 13: Noctiluca scintillans.



Diatoms

Diatoms are another fundamentally important life form at the base of the food chains that are responsible for 20% of the photosynthesis on Earth. These microscopic algae fix more carbon and generate more oxygen than all the world's tropical rainforests. Diatoms are uni-cellular and their silica-based cell walls form roughly cylindrical shapes with cross sections ranging from circles and ellipses to complex lobed structures. Holes in the cell walls form characteristic patterns and allow water, gases and nutrients through. Diatoms thrive in nutrient-rich environments, with different species found in salt and fresh waters, as well as in sediments and marshes.

Diatoms found in the Gippsland Lakes include:

- Rhizosolenia spp; and
- Ditylum brightwelli.

Figure 14: Rhizosolenia spp.

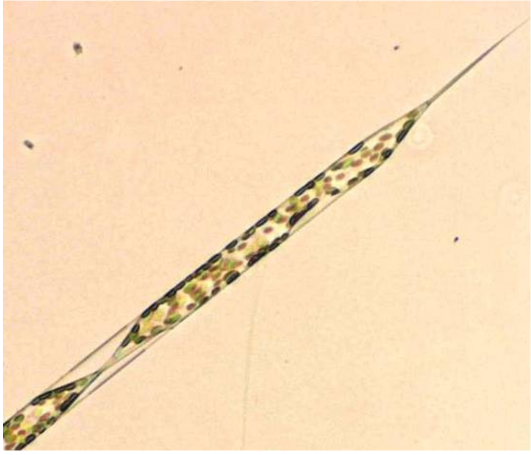


Figure 15: Ditylum brightwelli.

Blue-green algae

Fossil remains of cyanobacteria date back 3.5 billion years. They were the first photosynthetic organisms on Earth and did much to create the oxygen-rich atmosphere that we now take for granted. They are usually uni-cellular, but can come together in colonies to form filaments and sheets. They exist in fresh and marine waters, as well as in soil, and even on some animals. Many species have a hardy spore stage in their lifecycle (known as akinetes) that can survive in harsh environments and 'seed' new populations when circumstances improve.

Numerous forms of cyanobacteria can also fix nitrogen from the water to support their own growth, as well as converting it into forms that are available to other organisms. Many blue-green algae are able to rise and sink due to gas bubbles in their cells or swimming aids, so they can move through stratified layers of water to find the most suitable conditions, for example accumulating near the surface and monopolising the light. This relative advantage is lost in turbulent waters.

The blue-green algae found in the Gippsland Lakes include:

- *Nodularia* – a filamentous, nitrogen-fixing form known to produce thin toxic scums. It can occur in fresh water, but is more common in brackish environments. These are relatively slow growing and can be out-grown by *Synechococcus* which, in favourable conditions, multiplies at twice the rate (Cook et al 2008).
- *Anabaena* – a filamentous, nitrogen-fixing form, known to produce toxic blooms.
- *Microcystis* – forms small irregular, nitrogen-fixing colonies often found in fresh water, where they can also produce toxic blooms.
- *Synechococcus* – unicellular and colonial forms that have a unique (and not well understood) means of movement. These are often marine and, although there are freshwater species, they do better in saline waters. *Synechococcus* may fix some nitrogen, but can use dissolved nitrogen and hence thrive in high nutrient environments (Beardall 2008). They do not produce spores.
- *Calothrix parasitica* – filamentous, non-toxic and bottom dwelling.

Figure 16: Nodularia spumigena.

Figure 17: Calothrix parasitica.

Algal blooms

Triggers

Algal blooms are largely about competition between different alga species, and how competitive advantages change in different conditions. There are always a range of organisms present in the environment, competing for food, nutrients and light. As conditions vary, so to does the competitive advantage of different organisms. Features such as tolerance to salinity or temperature preferences will give one group a temporary advantage over others and, in the right circumstance, their population will explode. In general, warm, still, nutrient-rich conditions can result in an algal bloom of one kind or another.

This section presents information about what triggers an algal bloom. Potential triggers and thresholds include:

- nutrient levels and ratios (especially N:P);
- salinity;
- temperature;
- light;
- oxygen levels; and
- grazing by predatory species.

The stratification and mixing of water is important and contributes (directly and indirectly) to several of the above. It provides a competitive advantage to mobile algae that are able to move between stratified layers that may trap others.

Figure 18: Summary of preferred environments for different algae.

	DIN (uM)	FRP (uM)	N:P	Salinity ($^{0}/_{00}$)	Temperature
Dinoflagellates			>40		
Diatoms					
Nodularia	<0.5	>1.0	<15	15-20	>20
Anabaena			<15	<5	
Microcystis			<15	<5	
Synechococcus	>1.0			>15	>20

Nutrient loads and ratios

The total concentration and relative abundances of the nutrients present are both important to algal growth. All algae require phosphorus for growth, but nitrogen-fixing cyanobacteria can thrive in low nitrogen conditions, whereas non nitrogen-fixing 'green' algae need nitrogen too.

Redfield (C:N:P) Ratio

All marine organisms and oceans have remarkably similar ratios of key elements –
106 carbon : 16 nitrogen : 1 phosphorus.

This is known as the Redfield Ratio, after Alfred Redfield, who first described the phenomenon in 1934.

Aquarium owners monitor the ratio against a 'rule of thumb' that if N:P ratios are more than five or six points above the Redfield Ratio (16) then green algae are likely to thrive, while blue-green algae are favoured at ratios five or six points below.

Studies of the Gippsland Lakes, laboratory experiments and reviews of international literature have provided considerable information about threshold nutrient levels for different algae.

An annual total phosphorus loading of 100 tonnes to the Lakes is apparently the practical threshold for *Nodularia* blooms (Cook et al 2008). No blooms have been observed below that level.

Nodularia blooms have occurred when deeper waters have had low levels of nitrogen (DIN <0.5 uM) and high levels of phosphorus (FRP >1.0 uM). No blooms were observed in 1991-92 and 1993-94, although there had been floods and high levels of phosphorus. It is thought that high nitrogen levels (DIN >0.5 uM) inhibited the growth of *Nodularia* (Cook et al 2008). In 2007-08 there were also very high nitrogen levels following flooding and *Synechococcus* bloomed rather than *Nodularia*.

Synechococcus has been reported to bloom and persist in high nutrient (both nitrogen and phosphorus) environments (Beardall 2008). In the Gippsland Lakes, *Synechococcus* has bloomed when DIN concentrations exceeded 1.0 uM (Cook et al 2008).

Dinoflagellates have bloomed following an influx of nitrogen in flood waters and high ratios of nitrogen to phosphorus (e.g. DIN:FRP >80 and TN:TP >40).

Diatoms require silica concentrations of above 2 uM to dominate, and prefer nitrogen to be available in ratios equal to that of silica. In the Gippsland Lakes, silica is usually abundant and is therefore unlikely to limit the growth of diatoms (Cook et al 2008).

Carbon is usually plentiful in the Gippsland Lakes and is not thought to ever limit algal growth.

Salinity

Different algae prefer different salinity levels:

- *Nodularia* blooms have only been observed at salinity levels between $10^{o}/_{oo}$ and $20^{o}/_{oo}$. For example, nutrient conditions were right for a bloom in February 2005, but high salinities ($>20^{o}/_{oo}$) appear to have precluded it (Cook et al 2008). Low salinities ($<5^{o}/_{oo}$) are also not supportive of *Nodularia* blooms.
- *Microcystis* bloomed at a salinity around $5^{o}/_{oo}$, but are reported to decline at higher salinity levels.
- *Anabaena* is reported to decline at salinities above $5^{o}/_{oo}$.
- *Synechococcus* bloomed at a salinity of $17^{o}/_{oo}$ (Cook et al 2008), but it is usually associated with estuarine or marine conditions (Beardall 2008).

Temperature

Blue-green algae (*cyanobacteria*) tend to only bloom when the air temperature is above 20°C, although there was an exception in July 1989 (Cook et al 2008).

The growth of *Synechococcus* increases with temperature and peaks in the mid-high 20s (Beardall 2008). Populations have been reported to drop at temperatures below 20°C, with no growth occurring at 11°C.

Light

Light energy is the driver of photosynthesis, so hence is an essential requirement for algal growth.

Synechococcus have been reported to follow a circadian rhythm – rising and falling in the water column as light intensity varies during the day. Light increases their growth and they are tolerant of high light conditions (Beardall 2008).

Oxygen levels

The presence (aerobic) or absence of oxygen (hypoxic or anoxic conditions) dictates which forms of microbes survive. It also influences the rate at which mineralisation (the breakdown of organic matter) occurs and the nature of some chemical reactions. Low oxygen levels (and high carbon mineralisation rates) encourage the release of phosphorus from sediments (Cook et al 2008). They also inhibit denitrification, leading to raised levels of ammonia (Webster et al 2010).

Grazing

Synechococcus is reported to be heavily grazed by zooplankton in some parts of the world, which helps to keep populations in check. It has been suggested that blooms occurred when control by grazers 'broke down' (Beardall 2008). However, in the Gippsland Lakes it is thought that algae react more quickly to nutrient influxes than do grazers thus increasing the algal populations (Holland et al 2010).

Recent blooms

Since 1985 there have been seven non-cyanobacterial blooms recorded in the Lakes (usually diatoms or dinoflagellates) and 12 cyanobacterial (blue-green algae) blooms. The latter occurred in Lakes Victoria and King.

Nodularia spumigena is the usual blue-green algae to bloom, with sporadical *A nabaena* and *Microcystis aeruginosa* blooms. However, in November 2007 a bloom of *Synechococcus* occurred for the first time in the Lakes.

Dinoflagellate blooms were recorded in 1988, 1998, 2006 and 2007, and are probably more common than diatom blooms (although records often do not specify). Dinoflagellates are mobile and can move between layers of stratified water (accessing both light-rich surface waters and nutrient-rich deeper waters) giving them an advantage over diatoms, which slowly sink in calm waters (Cook et al 2008).

This section describes:

- A common scenario – a ‘typical’ sequence for algal blooms
- Something new – the first *Synechococcus* bloom in the Gippsland Lakes
- Lessons for the future

A common scenario

A common scenario for algal blooms in the Gippsland Lakes is:

- In autumn, concentrations of bio-available nitrogen and phosphorus are relatively low, as are fluxes of nutrients from the sediments. The ratio of bio-available N:P is around or above 16:1, and algal populations are low.
- Major winter floods dramatically increase nitrogen concentrations, lifting N:P ratios above 40:1. Surface waters are fresh and temperatures are low to mild. In these conditions, non nitrogen-fixing algae (dinoflagellates and diatoms) bloom, using up the available nitrogen before dying out.
- Decaying algae settle on the sediments and are consumed by bacteria, whose respiration uses up the available oxygen, causing the release of phosphorus and nitrogen (significant amounts of which are lost as gas, through denitrification). As phosphorus is released from the sediments in stratified waters with low oxygen levels, the ratio of bio-available N:P drops to around six in the bottom waters.
- As summer approaches and water temperatures rise, the nutrient scene (low nitrogen levels in surface waters and high phosphorus levels in bottom waters) favours a bloom of nitrogen-fixing blue-green algae, usually *Nodularia spumigena*. Mixing of the water and nutrients by strong winds may trigger a bloom, providing water salinities are suitable.

This describes a typical scenario, but the script is not always followed. Conditions may become ripe for a bloom of blue-green algae without a preceding bloom of non-nitrogen fixing algae and there may be years when a winter bloom is not followed by another in summer.

Something new – the first Synechococcus bloom in the Gippsland Lakes

Synechococcus bloomed in the Lakes for the first time in November 2007 and persisted through until early April 2008 (Beardall 2008). This marked the emergence of a new form of algae and a much longer bloom – previously blooms had only lasted a few months.

The bloom appears to have been triggered by high levels of nitrogen introduced by a late season flood following severe bushfires in the catchment. Dinoflagellates and diatoms, and denitrification, did not remove the nitrogen before the onset of warmer temperatures and increased sunlight, resulting in conditions ideal for *Synechococcus* (Holland et al 2008).

Synechococcus are very small and, unlike diatoms that sink readily, appear to remain suspended in the water column upon death. As a result, their nutrients do not enter the sediments (where nitrogen may be removed via denitrification) but remain available and able to sustain subsequent populations of the blue-green algae. Recycling nitrogen in the water column insulates it from the processes that can cause its removal from the Lakes.

The annual nitrogen load leading up to the bloom (6,060 tonnes) was twice the size of the previous biggest and four times the average annual influx. In an average year, denitrification will remove the yearly input of nitrogen, but it was estimated that it would take more than two years to deal with the 2007/08 load, once the bloom had ended. The floods also delivered 870 tonnes of phosphorus to the Lakes – 5½ times the 20-year average. Phosphorus is either lost to the ocean or ultimately buried in deep sediments. Remnants of this load will persist in the Lakes for a long time (Holland et al 2010).

The massive input of nutrients (especially nitrogen) that was introduced by the 2007 floods (and to a lesser extent, their timing) was the driver of the persistent *Synechococcus* bloom. The bloom probably reflects these exceptional circumstances rather than a fundamental shift in the ecology of the Gippsland Lakes.

The 2007/08 bloom was so persistent that there was concern it would shade out light from the lake floor, resulting in a decline of the seagrass beds. Both fish abundance and species richness rely on the existence of seagrass. A survey in September 2008 showed there had been a decline since a 1997 assessment, but a survey in April 2009 showed a subsequent improvement in seagrass condition (Hindell and Warry 2009). By March 2010, the Lakes were considered to be comparable to pre-2007 conditions with regard to nutrient levels and nitrogen as a limiting factor to phytoplankton growth (Holland et al 2010).

Lessons for the future

The Gippsland Lakes are an important and dynamic ecosystem, and their health can be taken as a measure of the health of their catchments. However, it is not possible to manage the Lakes to overcome problems caused by the impacts of activities higher up in the catchments. Better management of the catchments remains the key to the sound health of the Gippsland Lakes.

There will be lags between changes in catchment management and the health of the Lakes, and there are significant risks from the impacts of climate change, but scientific understanding of the ecology of algal blooms shows that benefits will accrue to the Gippsland Lakes and the communities that rely on them if nutrient and sediment inputs can be reduced through better catchment management, and the control of erosion, runoff and nutrient discharges.

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