

Sydney Catchment Authority
Cyanobacteria Risk Profile
2010



Executive summary

This Cyanobacteria Risk Profile provides a comprehensive reference and planning document for the identification and management of risks from cyanobacteria blooms in all SCA reservoirs. It builds on the 2005 Cyanobacteria Management Strategy (SCA, 2005a) and the Warragamba Dam Blue Green Algal Action Plan (SCA, 2008). The document includes:

- a cyanobacteria risk profile for each reservoir based on trophic status, algal history, and trends in nutrients and algae
- a summary of the key nutrient sources in each catchment
- a description of cyanobacteria species recorded in SCA reservoirs and associated problems including toxins, taste and odour, and filter clogging
- an explanation of the causes of cyanobacteria blooms in SCA reservoirs
- the current standards and guidelines for cyanobacteria
- a review of the current monitoring arrangements
- a description of the management options, both implemented and considered.

An assessment of algal risk status of each of the SCA's reservoirs is an essential prerequisite of a meaningful risk management strategy. The cyanobacteria risk profiles of the reservoirs in the Sydney water supply system have been assessed using a trophic index (an international scale based on chlorophyll-*a*: an index of algal activity) the historical record of algal blooms, and the occurrence of problem species.

Most of the SCA's reservoirs were found to currently have a low to moderate chlorophyll-*a* status:

- Woronora and Blue Mountains were assessed as oligotrophic (low nutrient content and low algal production)
- Warragamba, Avon, Nepean, Cordeaux, Cataract, Prospect and Tallowa (Shoalhaven Arm) were assessed as mesotrophic (medium level of nutrients and intermediate level of algal production)
- Wingecarribee, Fitzroy Falls, Tallowa (Kangaroo Arm) were assessed as eutrophic (waters frequently rich in nutrients that promote algal growth)
- No reservoirs were found to be hypertrophic (very nutrient rich lakes characterised by frequent and severe nutrient blooms).

Only four reservoirs (Wingecarribee, Fitzroy Falls, Tallowa (Kangaroo Arm) and Warragamba) have recorded major algal blooms (chlorophyll-*a* exceeding 20µg/L) over the nine years since July 2000, while five others have not recorded a notable algal bloom at all over that period.

Customer taste and odour complaints have frequently been associated with elevated counts of the cyanobacteria species *Anabaena*. Since year 2000 (Table 2.1) only the Wingecarribee, Tallowa (Kangaroo arm), and Warragamba (Coxs arm) reservoirs exceeded the SCA's taste and odour high risk threshold (cell counts exceeding the 2000 cells/mL) each in one season.

Since July 2000, these reservoirs have exceeded the SCA's alert level threshold for potential cyanobacteria toxins (cell counts exceeding 6,500 cells/mL):

- Wingecarribee and Tallowa - Kangaroo arm exceeded in four or more seasons
- Warragamba exceeded in two to three seasons
- Tallowa (Shoalhaven arm) exceeded in one season.

The SCA's alert levels are based on counts of all potentially toxin producing genera, such as *Anabaena* and *Microcystis*, whereas the National Health and Medical Research Council (NHMRC) guidelines are based only on specifically identified potentially toxin producing species such as *Microcystis aeruginosa* and *Anabaena circinalis*. Under NHMRC guidelines the number of alerts and therefore the perceived risk would have been significantly lower, particularly in Warragamba Reservoir.

The water quality data suggests that chlorophyll-*a* was increasing in eight of the reservoirs at a rate of between approximately 1% and 6% a year between 2000 and 2009. This may have been due in part to the influence of algal blooms which occurred in some of the storages in 2006-07 as a result of significant rainfall events.

As a general rule, trends in nutrients would be expected to match the trends in chlorophyll-*a*, but this has not been the case in SCA reservoirs. Of the eight reservoirs showing significant increases in chlorophyll-*a*, seven recorded decreases in nitrogen over the same period. In Australia, water bodies are typically phosphorus limited which means chlorophyll-*a* is likely to be more closely aligned to phosphorus than nitrogen. Unfortunately the phosphorus data for most SCA reservoirs is not suitable for long term trend analysis but there is some evidence that phosphorus levels have been declining in most reservoirs since 2005. The apparent discrepancy between the trends on chlorophyll-*a* and nutrients was not investigated for this Risk Profile, but may partly be due to the fact that algal production in SCA reservoirs is more responsive to short duration increases in nutrient availability resulting from wet weather events than it is to any gradual prolonged build-up of nutrients. This issue is worthy of further investigation.

The risk profiling has identified a useful pattern in the status of the reservoirs as they cluster into four groups as discussed below.

Group A

Wingecarribee Reservoir, Fitzroy Falls Reservoir, Tallowa Reservoir (Lake Yarrunga - Kangaroo arm), and possibly Bendeela Pondage

- high risk - eutrophic status with strong increasing trajectories
- all reservoirs are interconnected through water transfers.

Group B

Warragamba Reservoir– all zones

- moderately high risk - mesotrophic status with increasing trajectories
- 40-60% probability of cyanobacteria blooms developing in a year
- dominated by *Microcystis*
- cyanobacteria blooms are primarily event driven.

Group C

Tallowa Reservoir (Lake Yarrunga) - Shoalhaven arm, Prospect Reservoir, Nepean Reservoir, Avon Reservoir, Cataract Reservoir and Cordeaux Reservoir

- moderate risk - mesotrophic and (except Tallowa Reservoir - Shoalhaven arm) with weak trajectories
- less than 10% probability of cyanobacteria bloom developing in a year.

Group D

Woronora Reservoir and the Blue Mountains reservoirs

- Low risk - low trophic status and decreasing trajectories
- Nearly 0% probability of cyanobacteria blooms based on last 10 years.

Since its implementation, work under the Warragamba Dam Blue-Green Algae Action Plan (WDBGAAP) (SCA, 2008f) has delivered significant outcomes which support the SCA and Sydney Water Corporation (SWC) to better manage the risk of algal blooms developing, and improve their ability to manage the potential impacts in the event of algal blooms. By risk profiling all SCA reservoirs, this document provides a basis for focusing and prioritising actions and identifying knowledge gaps and management needs. This information allows the SCA to effectively build on past research and management initiatives.

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Abbreviations

ADWG	Australian Drinking Water Guidelines
AWT	Australian Water Technologies
CDSS	Catchment Decision Support System
CMA	Catchment Management Authority
CRMF	Corporate Risk Management Framework
HCP	Healthy Catchments Program
LEP	Local Environment Plan
MSCRACC	Metropolitan South Coast Regional Algae Coordinating Committee
NHMRC	National Health and Medical Research Council
NorBE	Neutral or Beneficial Effects
RWQIRP	Raw Water Quality Incident Response Plan
SAAG	State Algal Advisory Group
SAWC	South Australian Water Corporation
SCA	Sydney Catchment Authority
SEPP	State Environment Planning Policy
SLWCA	Strategic Land and Water Capability Assessment
STP	Sewage Treatment Plant
SWC	Sydney Water Corporation
TN	Total Nitrogen
TP	Total Phosphorus
WDBGAAP	Warragamba Dam Blue-Green Algae Action Plan
WHO	World Health Organization
WQRA	Water Quality Research Australia

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1 Introduction

1.1 Purpose

This document sets out the Cyanobacteria Risk Profile 2010 for Sydney's drinking water catchments. The strategy is an initiative of the SCA and has been developed in consultation with SWC. It seeks to identify and address the risks posed by cyanobacteria in SCA reservoirs to ensure that the SCA and SWC continue to supply water that meets ADWG.

The purpose of this document is to identify:

- the trophic status of the SCA reservoirs
- recent trends in the algal and nutrient conditions of each storage
- the nature of cyanobacteria blooms and their associated risks
- relevant targets, standards and guidelines
- the linkages with other NSW agencies responsible for managing cyanobacteria
- current SCA practices relating to cyanobacteria management in the SCA reservoirs
- the broad operational, planning, communication and research activities required in the short, medium and long-terms to manage the risks now and in the future.

The Risk Profile will be reviewed and supplementary notes prepared each year in June. This ongoing work will allow the ratings to be updated, taking into account new information and changed circumstances. The Risk Profile will be subject to a comprehensive review after five years in June 2015. Responsibility for ensuring the completion of the annual review and five year revision of the Risk Profile resides with the General Manager Corporate Development.

A research and development program will be implemented through a detailed action plan that will scope projects and actions, and outline delivery times, roles and responsibilities and budgets (Cyanobacteria Management Strategy and Action Plan, SCA 2010).

1.2 Context

The Risk Profile builds upon an earlier Cyanobacteria Risk Management Strategy developed in 2005 (SCA, 2005a) and the Warragamba Dam Blue-Green Algae Action Plan (WDBGAAP) (SCA, 2008f). The 2005 Strategy outlined the potential risks that cyanobacteria posed to raw water quality for drinking and recreational access in the SCA's reservoirs and identified management strategies to control those risks. The WDBGAAP was developed in consultation with SWC and NSW Health in response to the 2007 cyanobacteria bloom in Warragamba Reservoir (Lake Burragorang).

The WDBGAAP had 53 actions organised in sections covering operational responses, catchment and reservoir management actions, treatment strategies, targeted research, monitoring, and communication.

The Cyanobacteria Risk Profile links with a range of other plans that relate to the management of cyanobacteria in the SCA’s storages:

- Corporate Risk Management Framework (SCA, 2010c)
- Cyanobacteria (Blue-Green Algae) Response Plan (SCA, 2010b) which outlines how the SCA should respond to cyanobacteria blooms as they occur. The processes are focussed upon the requirements of the SCA customers, stakeholders and regulators being met
- Relevant requirements outlined in the Bulk Water Supply agreement between SCA and SWC
- SCA Cyanobacteria Management Strategy and Action Plan (SCA, 2010a)
- Precinct plans currently being developed which will provide an overview of the key issues in the SCA storages based upon nine precinct areas
- SCA communication plan.

In managing cyanobacteria the SCA will work with other agencies involved in cyanobacteria management in NSW. The interaction between the various initiatives of the SCA and other agencies is outlined in Figure 1.1.

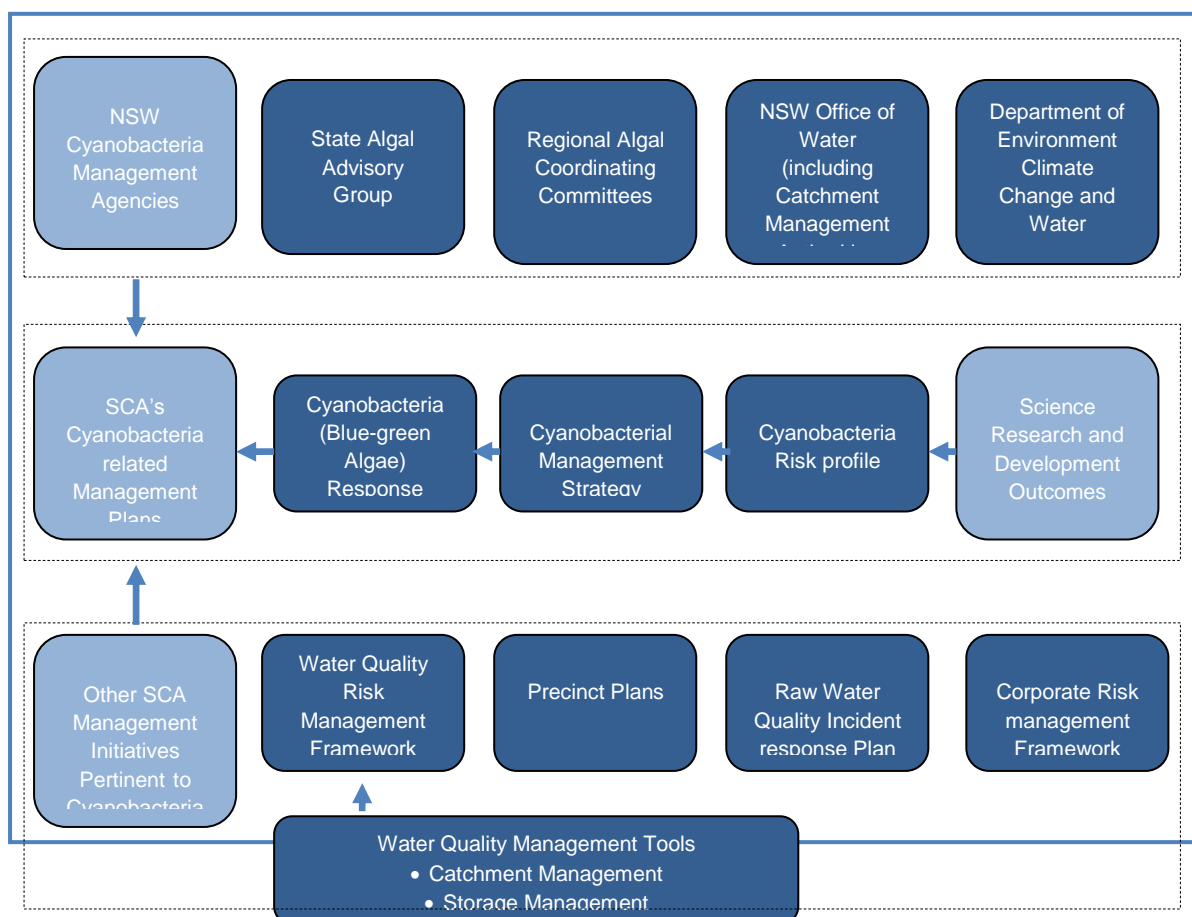


Figure 1.1 Relationship between the Cyanobacteria Risk Profile and other plans and initiatives relevant to the management of cyanobacteria

1.3 The SCA water supply system

The SCA manages 21 storage dams (11 major dams) that hold more than 2.5 million megalitres of water (Figure 1.2). Water for these dams is collected from five primary catchment areas, occupying 16,000 square kilometres. The water storages vary substantially in depth, shape and volume. They receive water from catchments of very different sizes and landuse characteristics. Water is transferred between storages either via the run of river or through artificial canals, tunnels and pipelines. The most significant transfer route is from Tallowa Reservoir to the Warragamba and Nepean reservoirs via Bendeela Pondage, and the Fitzroy Falls and Wingecarribee reservoirs.

THE WATER SUPPLY SYSTEM

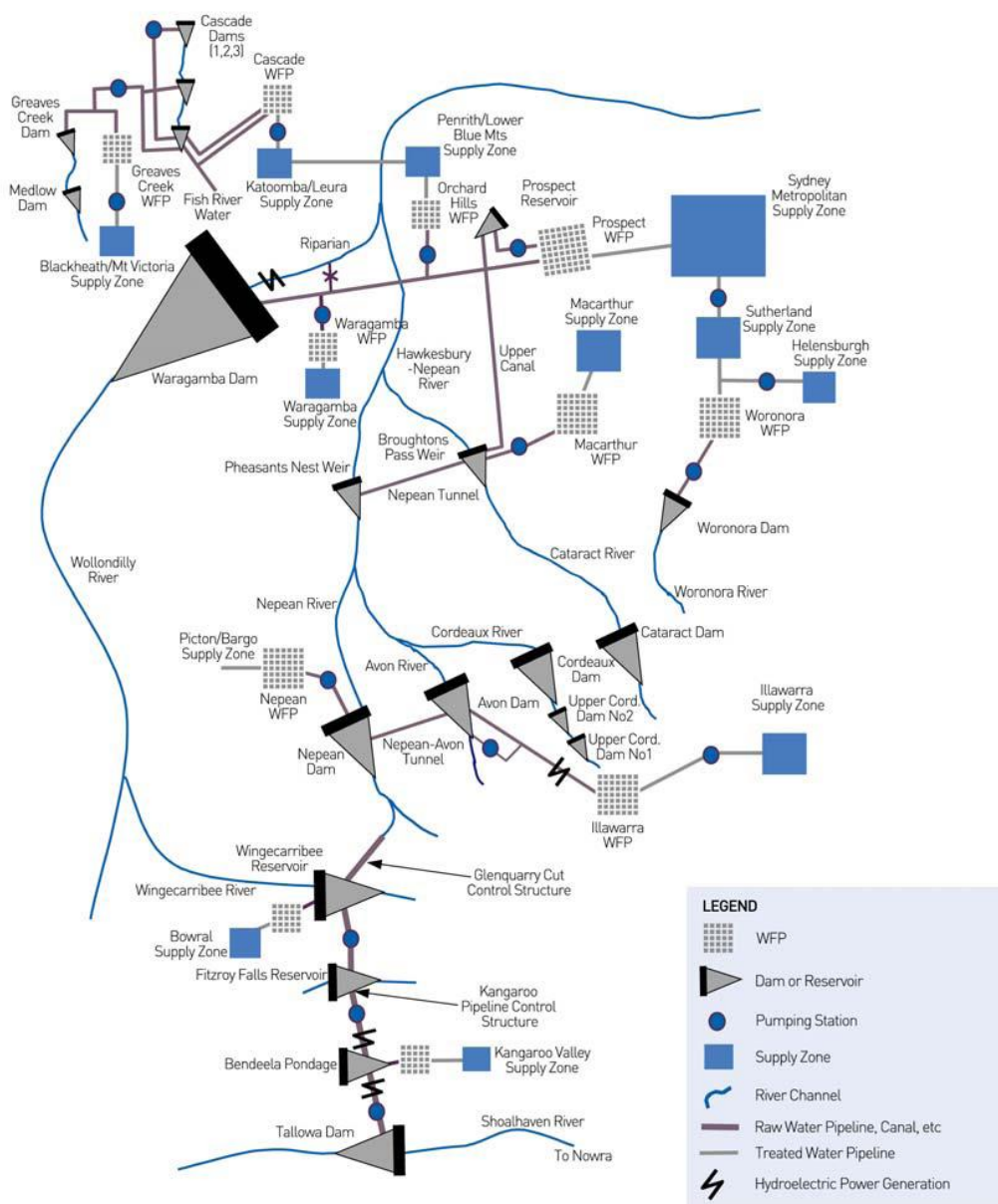


Figure 1.2 Schematic of Sydney's reservoirs and water supply

Cyanobacteria, commonly referred to as blue-green algae, are common in all water bodies (both natural and man-made) and co-exist with green algal plant communities. In order for a cyanobacteria bloom to develop, there must be high nutrient concentrations in the surface waters, high light intensity, suitable water temperature and pH. These conditions allow for dominance of cyanobacteria over other algae. Nutrients can be delivered to the zone of light penetration by either:

- resuspension of settled nutrients, which is typically associated with destratification or overturn and is likely to be a significant source of nutrients in the shallower reservoirs or
- inflows, which can transport significant quantities of nutrients from diverse catchment sources with the nutrient loads increasing with increasing discharge volume and the length of dry period before the inflow. Transfers can also deliver additional nutrients although not generally in the same quantities as inflows.

All water storages have a background level of algae. The shallower reservoirs, such as Fitzroy Falls and Wingecarribee, are more likely to have seasonal algal blooms subject to weather and lake chemistry. The most likely time for a cyanobacteria bloom in the larger reservoirs such as Warragamba and Tallowa is after significant inflows which deliver significant quantities of nutrients to the reservoir.

The SCA is responsible for the supply of bulk raw water to SWC as defined in the Bulk Water Supply Agreement. SWC is responsible for the treatment of raw water to meet ADWG and the delivery of treated water to consumers. The SCA and SWC have a number of established options for configuring and operating the system in order to supply the best quality water available.

To ensure the best quality raw water is selected from its storages, the SCA uses a number of quality management processes including:

- selecting water from different reservoirs
- selecting water from different levels in the storages
- destratifying reservoirs
- monitoring water quality and analysing trends.

The SCA's Bulk Raw Water Quality Incident Response Plan, developed in consultation with SWC and endorsed by NSW Health, defines how the agencies respond to water quality incidents, in particular liaison and consultation with stakeholders.

2 Cyanobacteria risk profiles for SCA reservoirs

2.1 Overview

The SCA operates 21 reservoirs as part of its water supply system (Figure 1.2) which supply raw drinking water for treatment to Sydney and a number of rural communities. The reservoirs vary considerably in location, exposure to wind and light, size and depth and consequently their vulnerability to cyanobacteria blooms also varies considerably. Table 2.1 provides an overview of the algal/cyanobacteria risk profile of each reservoir, specifically the:

- trophic status
- history of algal blooms and trends in chlorophyll-*a* and nutrients
- history of when taste and odour and health alert thresholds were exceeded
- catchment nutrient sources (identified by the SCA's Catchment Decision Support System (CDSS)) and associated actions under the SCA's Health Catchments Program (HCP).

Two large reservoirs, Tallowa and Warragamba, are subdivided into two and four sub-areas respectively as these reservoirs are quite complex and there are distinct differences between the component areas. Conversely, the five small reservoirs which make up the Blue Mountains systems have been combined.

2.2 Current trophic status

Trophic state indices use chlorophyll-*a*, total phosphorus (TP), and total nitrogen (TN) to describe the biotic potential of a reservoir. The Carlson Index has been used to describe the SCA storages because it:

- can be calculated using data collected by routine monitoring
- is internationally recognised
- provides a result that can be used to define biotic trends both within a single lake/reservoir and between lakes/reservoirs.

Carlson's chlorophyll-*a* Index describes the reservoirs as being in four possible states:

Oligotrophic – having low primary production, the result of low nutrient content. These lakes have low algal production, and consequently, often have very clear waters, with high drinking-water quality.

Mesotrophic – having an intermediate level of productivity, greater than oligotrophic lakes, but less than eutrophic lakes. These lakes are commonly clear water lakes and ponds with beds of submerged aquatic plants and medium levels of nutrients.

Eutrophic - having waters rich in mineral and organic nutrients that promote a proliferation of plant life, especially algae.

Hypereutrophic – very nutrient-rich lakes characterised by frequent and severe nuisance algal blooms and low transparency. Hypereutrophic lakes are the most biologically productive lakes, and support large amounts of plants, fish and other animals.

Indices for chlorophyll-*a* and TP were derived using the Carlson Method (Carlson, 1977). The TN index was calculated using a derivative of the Carlson Method (Kratzer and Brevonik, 1981). Both methods were used to align with previous assessments of trophy in SCA storages (Hassan and Hawkins, 2001). Trend analysis was calculated using the ‘percentage annual change’ method of Burns et al (2000), also aligning with previous work (Hassan and Hawkins, 2001). All details of data treatment and ‘within method’ variation are available from Appendix D of this document.

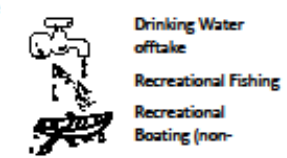
Table 2.1 Summary of cyanobacteria risk profiles across SCA storages

Storage	Current Trophic Status ¹	1990 - 1999 Trend	2000-2009 Trend		Nine Season Algal Statistics (2000-2009)								Priority Catchment Sources of TP & TN (✓ action under Healthy Catchment Strategy 2009/10 and/or 2010/11)								Storage Uses ⁵	
		% change per year				% of bloom years ^{3,4} expressed in terms of chlorophyll a		Maximum recorded chlorophyll a (µg/L)	% of years ^{3,4} levels associated with taste & odour exceeded (Anabaena)		% of years ^{3,4} levels associated with health problems exceeded (Anabaena + Microcystis)		Grazing	Int. Animal Ind.	Urban runoff	STP	Sewer	On-Site Sew. Disp.	Hort./ Crops	Transfers from other catchments		
		Chlorophyll a	Chlorophyll a	TP ²	TN	(> 10 µg/L - moderate)	(> 20 µg/L - significant)		(> 1000 cells/mL - medium alert)	(> 2000 cells/mL - high alert)	(> 2000 cells/mL - medium alert)	(> 6500 cells/mL - high alert)										
Wingecarribee Reservoir	High	1.8 ↑	6.3 ↑	2.7 ↑	2.3 ↓	78	22	50 (Dec 06)	22	11	89	67	✓	✓							Tallowa & Fitzroy	WSC
Fitzroy Falls Reservoir	High	4 ↓	5 ↑	3 ↓	3.7 ↓	100 ³	22	34 (Dec 06)	0	0	78	33	✓								Tallowa	SCC
Bendeels Pondage	No data	No data	No data	No data	No data	No data	No data	No data	0	0	56	22	No catchment of its own								Tallowa	SCC
Tallowa Reservoir - Shoalhaven Arm	Moderate	5.2 ↑	6.1 ↑	7.5 ↓	1.3 ↓	22	0	16 (Feb 07)	0	0	11	0									N/A	
Tallowa Reservoir - Kangaroo Arm	High	5.9 ↑	3.6 ↑	8.9 ↓	0.7 ↓	100	33	36 (Dec 06)	11	0	67	44	✓	✓							N/A	
Warragamba (Cox's Arm)	Moderate	2.3 ↑	1.5 ↑	0.8 ↓	1.5 ↑	88	33	33 (Jan 03)	22	11	56	33				✓					N/A	
Warragamba (Wollondilly Arm)	Moderate	12.9 ↑	2.2 ↑	10.6 ↓	2.6 ↓	44	0	17 (Sep 07)	11	0	44	33	✓				✓	✓			Wingecarribee, Fitzroy & Tallowa	
Warragamba (The Junction (DWA12, DWA27 & DWA9))	Moderate	4.8 ↑	5.5 ↑	1.7 ↓	0.9 ↑	11	0	24 (Oct 07)	11	11	44	22	✓				✓	✓				
Warragamba (The Gorge (DWA2))	Moderate	5.3 ↑	5.2 ↑	7.5 ↓	1.8 ↑	22	11	65 (Sep 07)	11	0	56	22	✓				✓	✓			Wingecarribee, Fitzroy & Tallowa	SW
Nepean Reservoir	Moderate	5.4 ↑	1.6 ↑	12.5 ↓	0 →	0	0	8 (Mar 07)	0	0	0	0	✓	✓							Wingecarribee, Fitzroy & Tallowa	SW
Avon Reservoir	Moderate	3.9 ↓	2.7 ↑	8.4 ↓	0.1 ↑	0	0	14 (May 07)	0	0	0	0									Wingecarribee, Fitzroy & Tallowa	SW
Cataract Reservoir	Moderate	0.5 ↓	2.5 ↑	5.9 ↓	0.4 ↓	0	0	9 (Dec 05)	0	0	0	0									N/A	
Cordeaux Reservoir	Moderate	0.8 ↑	1.3 ↑	6.4 ↑	0.5 ↑	11	0	12 (Feb 02)	0	0	0	0									N/A	
Woronora Reservoir	Moderate	1.7 ↑	3.3 ↓	11.4 ↓	0.8 ↑	0	0	5 (Oct 02)	0	0	0	0									N/A	SW
Blue Mtns Reservoirs	Moderate	8.2 ↑	4.5 ↓	7.7 ↓	5 ↓	33	0	18 (Mar 05)	0	0	0	0									Fish River	SW
Prospect Reservoir	Moderate	5.2 ↑	2.1 ↑	7 ↓	2.6 ↓	0	0	8 (Jun 03)	0	0	0	0	No catchment of its own								Warra, Wingecarribee, Nepean, Fitzroy & Tallowa	SW

1 Two year average 2008/09
 2 Phosphorus data is based upon the period 2006 to 2009 as the data over the ten year period is considered unsuitable for the calculation of trends
 3 only 9 years of data available

4 Based upon years running from 1 July to 30 June
 5 SW = Sydney Water Corporation
 SCC = Shoalhaven City Council
 WSC = Wingecarribee Shire Council

Trophic Status	Nutrient Status
Eutrophic	High
Mesotrophic	Moderate
Oligotrophic	Low



For numerical resolution, the year was represented as a fraction of one year (July 1st = 1, June 30 = 365). The 'year' was chosen to be represented in this way to resolve numerical discrepancies in values between the beginning of the 'year' (1) and the end (365) and to represent annual biotic cycles within each reservoir. The de-seasonalisation values were subtracted from the actual data. The residuals were plotted and a linear regression of the residuals obtained. The slope of this regression is a daily value, which in turn was converted to yearly (to provide an annual change value) and an annual percentage was derived by dividing this yearly value by the long term average of the dataset. This was compared to the trophic indices as verification of the method.

'Potentially toxin-producing' cyanobacteria risk profiles for each SCA reservoir are shown in Figures 2.1 and 2.2. The first profile, Figure 2.1, assesses the frequency of 'known' potentially toxin-producing cyanobacteria events of greater than 2,000 cells/mL on a seasonal basis in the last nine algal seasons. The National Health and Medical Research Council Guidelines (ADWG) (NHRMC, 2010) are based on the individual cell populations of *Anabaena circinalis*, *Microcystis aureginosa* and other known toxin-producing species (details in Appendix C). Figure 2.1 incorporates the known toxin-producing species of *Anabaena circinalis* and *Microcystis aureginosa*.

Using this assessment, the SCA reservoirs fall under three broad groups:

- The highest risk group has a significant frequency of potentially toxin-producing cyanobacteria growth on a seasonal basis. Events of this size occur almost yearly, reflecting the trophic status of these reservoirs.
- Potentially toxin-producing blooms are infrequent for reservoirs in the second group (one in five to one in 10 years), reflecting their relatively lower trophic status.
- The third group is considered the lowest risk, where there are no reports of potentially toxin-producing blooms, reflecting a substantially lower trophic status.

The second risk profile assesses SCA reservoirs based on a wider description of potentially toxin-producing cyanobacteria (Figure 2.2). The SCA Cyanobacteria Response Plan includes all *Microcystis* species as being potentially toxin-producing, and is consistent with the description provided by the analytical labs used by the SCA for algal analysis. Whether all *Microcystis* species are potentially toxin-producing (in particular, the *Microcystis* unknown species that dominated the 2007 Warragamba bloom) is an area of research that is being undertaken by the SCA.

Comparison of Figure 2.1 and Figure 2.2 demonstrates that including all potentially toxin-producing cyanobacteria into the risk profile does not influence the majority of SCA reservoirs. However it changes the risk profile of Warragamba Reservoir significantly. There are now four groupings of SCA reservoirs within the second risk profile (Figure 2.2). The highest group (Group A) has a high frequency of bloom events and have been increasing substantially in yearly trajectory of trophic status since 2000. Group B is composed of the Warragamba Reservoir sites where blooms occur twice a year. Unusually, the trophic trajectories of the Junction and Gorge sites of Warragamba Reservoir appear to be larger than the corresponding trajectories of the Wollondilly and Coxs arms. Group C is composed of reservoirs with a substantial degree of trophy which develops infrequently into a potentially toxin-producing cyanobacteria bloom. All storages in this group show a low

trophic trajectory with the exception of Yarrunga - Shoalhaven River, which shows a trajectory of a similar scale to Group A Reservoirs. The last group, Group D, as previously appears (Figure 2.2) a group of low trophic and an insignificant risk of a potentially toxin-producing cyanobacteria bloom event.

2.3 Trends in chlorophyll-a

Chlorophyll-a is an index of algal activity. Interpretation of the apparent trends in chlorophyll-a should be undertaken carefully as individual major events (cyanobacteria blooms) can skew the results. Therefore, while chlorophyll-a concentrations have been increasing in eight of the storages at a rate of between 1.3% and 6.3% per year over the last nine years (2000-2009), this may be due in part at least to the influence of drought breaking rains in 2006 and 2007 which triggered algal blooms in some of the storages. The highest rates of increase were recorded in Wingecarribee Reservoir (6.3% per year), Fitzroy Falls Reservoir (5% per year), Tallowa Reservoir - Shoalhaven arm (6.1% per year) and Warragamba Reservoir - Junction and Gorge (5.5 and 5.2% per year respectively).

These trends are generally consistent with the previous 10 years (1990-1999) which was similarly influenced by major inflows in 1998. The reservoirs which have demonstrated the strongest trends are:

- Wingecarribee Reservoir where the rate of increase has accelerated since 2000 (1.8% to 6.3% per year)
- Fitzroy Falls Reservoir where chlorophyll-a levels were decreasing between 1990 and 2000, but increasing after 2000
- Warragamba Reservoir - Wollondilly arm where chlorophyll-a was increasing at a rate of 12.9% per year between 1990 and 2000 but has subsequently slowed to 2.2% per year
- Prospect reservoir where the rate of increase has noticeably reduced from 5.2% per year (1990-2000) to 2.1% per year (2000-2009).

The rates of increase in the other reservoirs have remained relatively stable over the last 20 years.

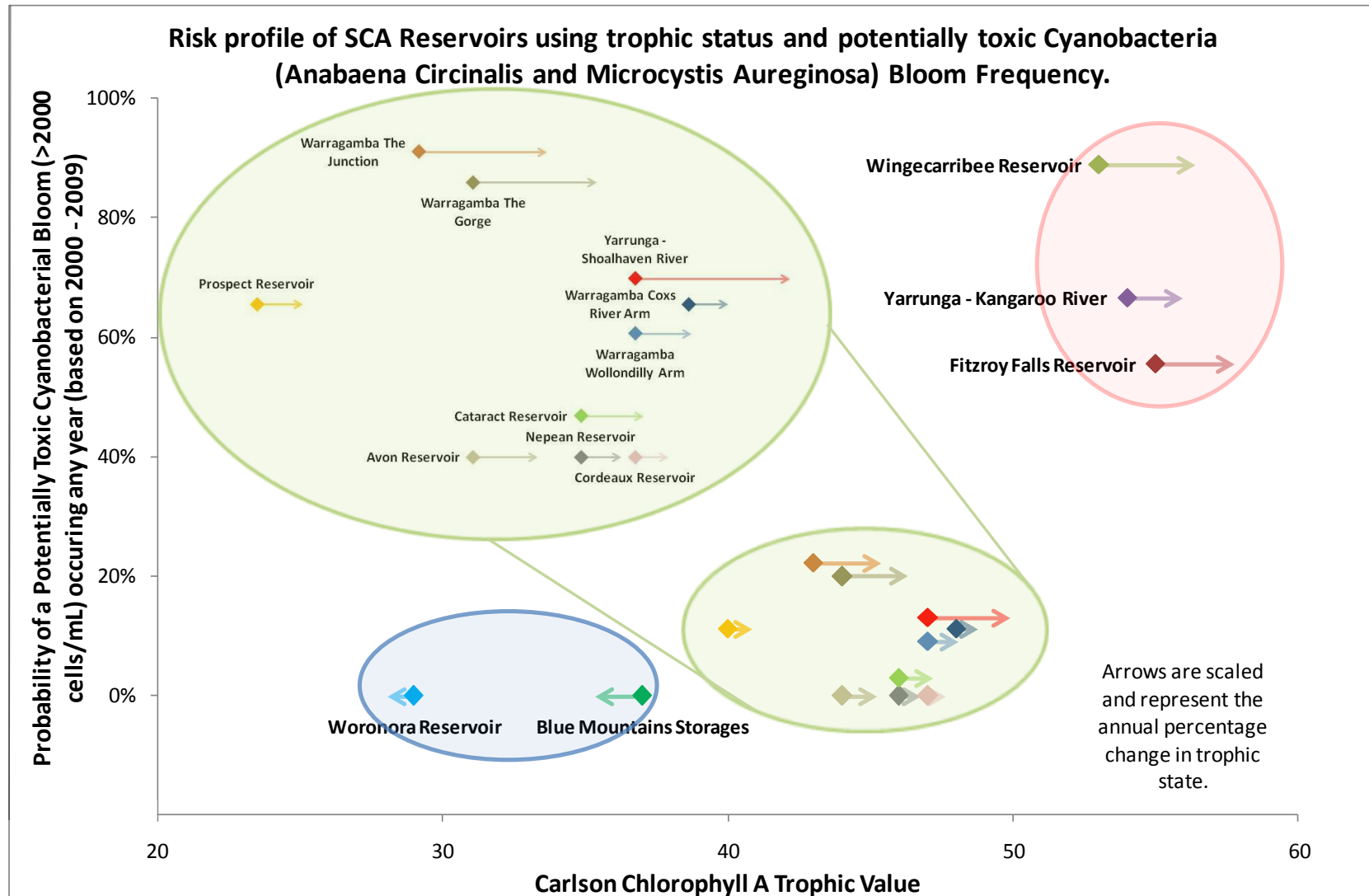


Figure 2.1 Grouping of SCA reservoirs on the basis of chlorophyll-a concentrations, the trajectories of these concentrations over nine years since 2000, and the risk of blooms of potentially toxin-producing cyanobacteria (in terms of *Microcystis aeruginosa* and *Anabaena circinalis*)

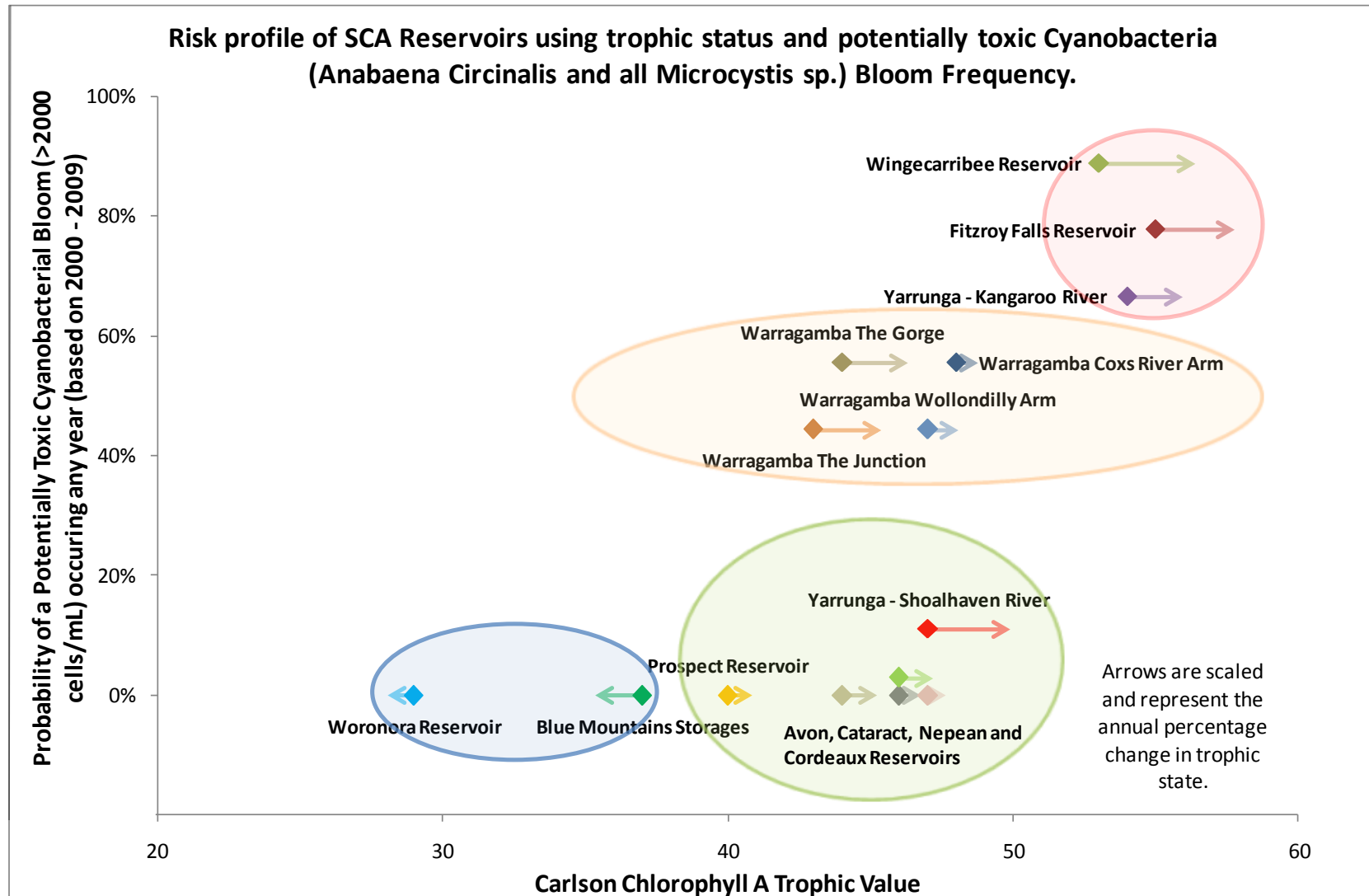


Figure 2.2 Grouping of the SCA reservoirs on the basis of chlorophyll-a concentrations, the trajectories of these concentrations over nine years since 2000, and the risk of blooms of potentially toxin-producing cyanobacteria (in terms of total *Microcystis* and *Anabaena*)

2.4 Trends in nutrient levels

Chlorophyll-a trends are generally expected to follow the trends in TN and TP as these nutrients are necessary to support changes in biotic loadings. However, since 2000 trends in chlorophyll-a have not been matched by the apparent trends in the nutrients in the SCA reservoirs. Of the eight reservoirs showing a significant increase in chlorophyll-a concentrations, seven indicate decreases in TN over the same period. The notable exception is Warragamba Reservoir where TN has been generally increasing since 2000.

It is expected that algal production would be more closely aligned to phosphorus availability than nitrogen as most Australian lakes are phosphorus limited. Unfortunately the use of TP data to validate the chlorophyll-a trends is difficult. A review of TP measurements at all major reservoir sampling locations over the last 20 years indicates that there have been two dramatic shifts in TP concentrations at most of the reservoir sampling locations:

- After 2000, the baseline of TP measurements appears to have doubled (from ~10µg/L to 15-25µg/L).
- After 2005, the TP measurement baseline appears to have decreased by more than 200% (from 15-25µg/L to 5-10µg/L).

Each change appears to have occurred in periods of less than six months. These changes do not coincide with any known environmental conditions that could explain them, rather they coincide with alterations in analytical process (within method), analytical laboratory and/or changes in sampling frequency, depth, type (discrete vs. composite) and/or limits of reporting. While all the analytical methods used over this period were standardised, validated and fully accredited, it has not been possible to source any research that compares before and after results from these alterations in methodologies. Without a better understanding of what is causing the changes in the data, trend analysis of the TP data since 2000 has not been considered possible. However, the analytical methods have been stable since 2005 and therefore the trends observed in TP since 2005 have been included in Table 2.1. Unfortunately trend analysis on a relatively short data set is problematic as it is very sensitive to short term variability. Nevertheless, the data does suggest that TP concentrations in most of the reservoirs have been declining since 2005 and increasing in only two reservoirs (Wingecarribee and Cordeaux).

While it is not easy to explain the discrepancy between trends in nutrients and chlorophyll-a levels observed in most SCA reservoirs, it could indicate that algal production is more responsive to short term increases in nutrient concentrations (eg as a result of wet weather inflows) than to the long term nutrient status of these storages. Further investigation would be required to clarify this.

2.5 History of algal blooms

Algal blooms can be defined by chlorophyll-a levels exceeding 10 µg/L for a moderate bloom and 20µg/L for a major bloom (Haskins et al 1994). In the nine years since 2000 only four SCA storages have recorded blooms exceeding 20µg/L (Table 2.1):

- Warragamba (Coxs arm) and Tallowa (Kangaroo arm) on three occasions
- Wingecarribee and Fitzroy Falls on two occasions
- Warragamba (Gorge) on one occasion.

The frequency of moderate blooms, with chlorophyll-a exceeding 10 µg/L, has been relatively low outside of the above reservoirs, with the Nepean, Avon, Cataract, Woronora, and Prospect reservoirs not recording an algal bloom since 2000.

2.6 Frequency of taste and odour risks

Taste and odour complaints have been generally associated with elevated counts of *Anabaena*, and therefore two risk thresholds have been adopted:

- 1,000 cells/mL (indicating moderate risk)
- 2,000 cells/mL (indicating high risk).

Only three reservoirs have reported cell counts exceeding the 2,000 cells/mL threshold since 2000 (Table 2.1), each on one occasion:

- Wingecarribee
- Tallowa (Kangaroo arm)
- Warragamba (Coxs arm).

2.7 Frequency of health associated risks

The National Health and Medical Research Council (NHMRC) recommends cyanobacteria health alert levels (Appendix C) based on *Microcystis aeruginosa* and/or *Anabaena circinalis* populations. A medium alert level is set at populations between 2,000 and 6,500 cells/mL, and high alert is set at populations over 6,500 cells/mL. A population of *Microcystis aeruginosa* and/or *Anabaena circinalis* exceeding 50,000 cells/mL is characterised as an extreme alert level. However, the SCA adopted a risk level framework (Cyanobacteria Response Plan, SCA 2010) based on all species of *Microcystis* and *Anabaena* genera for its incident management. The following reservoirs have reported cell counts exceeding the 6,500 cells/mL threshold since July 2000:

- Wingecarribee and Tallowa(Kangaroo arm) exceeded in four or more seasons
- Warragamba exceeded in two to three seasons
- Tallowa (Shoalhaven arm) exceeded in one season.

Microcystis species (*Microcystis* unknown) with smaller cell sizes, which dominated the major bloom in 2007, have been detected at high population in all sections of Warragamba Reservoir.

2.8 Catchment nutrient sources

In 2008, the SCA completed the Catchment Decision Support System (CDSS) which rates the relative hazard posed by different pollution sources across the catchments based on landscape characteristics, land management practices and rainfall statistics. The CDSS calculates a weighted hazard index depending on the potential for pollutants to be available, mobilised and transported from source to stream. These pollutant source hazard ratings allow the SCA's Healthy Catchments Program (HCP) to focus its incentives, grants and education programs in the areas of highest hazard. The CDSS has assessed the highest hazard source areas for nutrients as follows:

- Grazing and intensive animal enterprises in the Tallowa, Warragamba, Wingecarribee, Fitzroy, and Nepean catchments
- Horticulture and cropping in the Tallowa (Shoalhaven) and Warragamba catchments
- On-site sewage disposal in the Wingecarribee and Warragamba catchments
- Sewage treatment plants (STPs), sewer overflows and urban runoff in the Warragamba catchment.

The HCP is currently targeting grazing, intensive animal enterprises, on-site sewage disposal, and STPs and sewers in the Warragamba catchment to reduce nutrient exports.

It should be noted that in section 2.8.1 to 2.8.4 reference to *Microcystis* means *Microcystis aeruginosa* and *Anabaena* means *Anabaena circinalis*. This contrasts with the general usage in the SCA where *Microcystis* and *Anabaena* represent the total of all *Microcystis* species and of all *Anabaena* species respectively.

2.8.1 Wingecarribee Reservoir

Wingecarribee Reservoir (Figure 2.3) is currently a shallow eutrophic lake which experiences an algal bloom almost every year.

Over the last 20 years, the chlorophyll-*a* index has fluctuated between mesotrophic (waters having moderate levels of mineral and organic nutrients and/or plant life, especially algae) and eutrophic (Figure 2.4). This is consistent with the earlier findings of a study undertaken by Australian Water Technologies (AWT, 2000).



Figure 2.3 Wingecarribee Reservoir

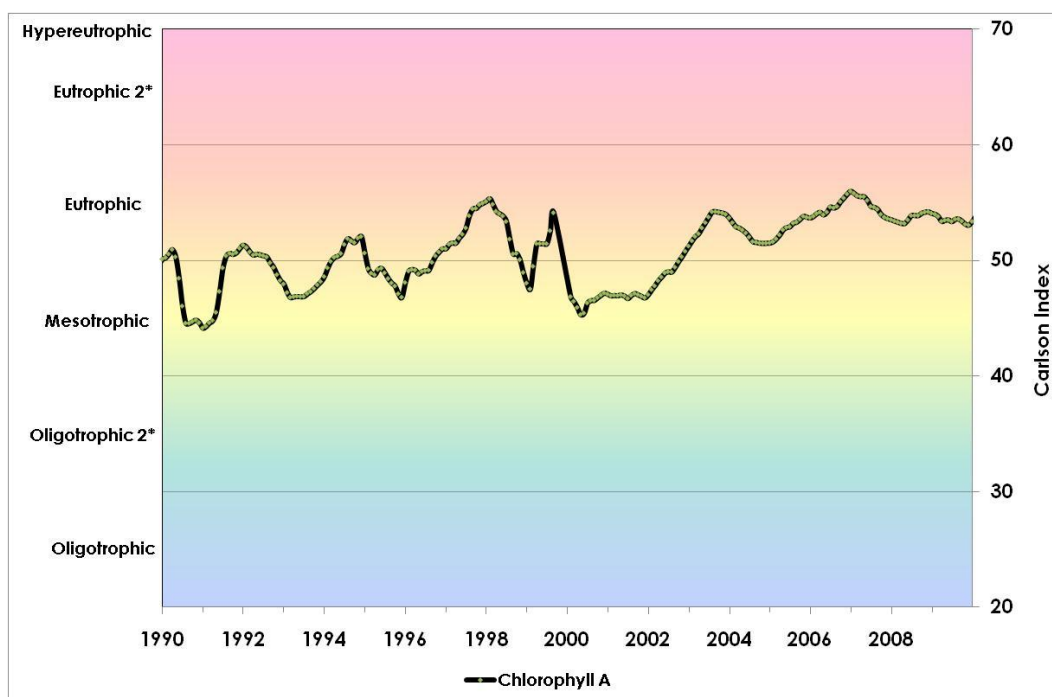


Figure 2.4 Carlson Trophic Index of chlorophyll-a in Wingecarribee Reservoir from January 1990 to December 2009

Moderate levels of algae have been recorded in Wingecarribee Reservoir throughout the last 20 years with detections typically in the 5-10 µg/L range (Figure 2.5) with only five events recording in excess of 20 µg/L. Green algae have been the most common species, while potentially toxin-producing or taste/odour species have been infrequently detected. In each of the five highest chlorophyll events on record, less than 10.5% of the biovolume was the potentially toxin-producing cyanobacteria (*Microcystis* or *Anabaena*). Cyanotoxin detections (exceeding 0.3 µg/L) have been reported in Wingecarribee Reservoir most summers and have exceeded the ADWG of 1.3 µg/L during three summers since 2000.

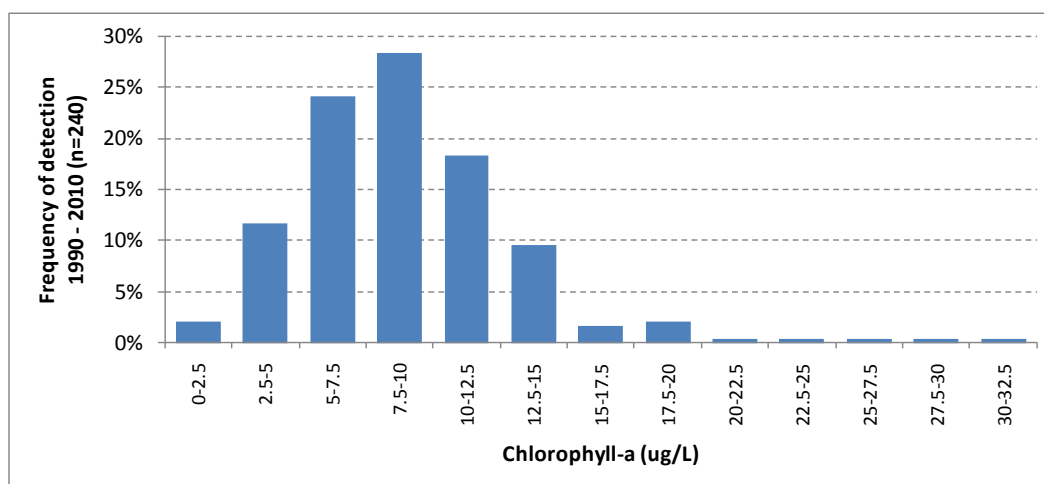


Figure 2.5 Frequency of chlorophyll-a detection in Wingecarribee Reservoir between 1990 and 2010 (DWI1)

The tiny cells of *Aphanocapsa*, *Cyanonephron* and *Cyanodictyon* dominate the populations. These species have persisted throughout the years, and cell densities of over 10,000 cells/mL are often present in winter. Maximum cyanobacteria biovolume in each summer is typically around 0.3 mm³/L. While this biovolume was dominated by *Aphanocapsa* in the early 2000s, by the mid to late 2000s the potentially toxin-producing *Microcystis* and *Anabaena* were starting to dominate. *Anabaena* cell counts reached levels associated with a moderate risk for taste and odour (1,000 cells/L) in two of the last nine years, while the combined cell numbers of *Anabaena* and *Microcystis* exceeded the high health alert level (6,500 cells/L) in four of those years. Wingecarribee Reservoir does not feed directly into the Sydney drinking water supply as it routed first through either Warragamba or Nepean reservoir. However, the reservoir is used as a potable water supply in the Wingecarribee Shire after filtration and chlorine dosing. In response to this risk, the Wingecarribee Shire Council installed a dissolved air flotation and powder activated carbon treatment system, which is very effective at removing the algae and cyanobacteria, and any associated toxins.

The trends in chlorophyll-a indicate an ongoing decline in the condition of this storage with chlorophyll a increasing at a rate of 6.3% per year since 2000. This has accelerated from the 1990-2000 rate of 1.8% per year. Over the last 10 years however, TN has been decreasing by 2.3% per year. The TP data is not reliable prior to 2005 but indicates a 2.7% per year increase since then. It is probable that the elevated cyanobacteria cell numbers reflect a

subtle change in the environmental conditions which favour the growth of these species. Factors that could be contributing to the increase in algal activity may include the:

- unique chemical and biotic interactions with the peat swamp
- water transfers which commenced in 2003.

Further investigation is required to clarify the causes of increased algae in Wingecarribee Reservoir.

Wingecarribee Reservoir was treated with copper sulphate after a reported major algal bloom occurred in early 1998. This treatment caused large mortalities of fish and macroinvertebrates, including the disappearance of molluscs, but the results with respect to cyanobacteria were uncertain. No chemical treatment of the reservoir has been attempted since then.

The catchment of Wingecarribee Reservoir is relatively small. It includes protected swamplands adjacent to the reservoir, grazing lands and the small town of Robertson. The CDSS was used to assess grazing, dairies and on-site sewage disposal systems in the unsewered town as priority sources of nutrients. The HCP is currently targeting all three with incentives, grants and education programs for reductions in nutrient export.

2.8.2 Fitzroy Falls Reservoir

Fitzroy Falls Reservoir (Figure 2.6) frequently supports algal blooms which are typically smaller than those experienced in Wingecarribee Reservoir. During the last nine years, Fitzroy Falls Reservoir has recorded moderate algal blooms (10 – 20 µg/L) in eight summers but major blooms (>20 µg/L) in only two summers. Chlorophyll-a levels have been increasing steadily over the last nine years at a rate of more than 5% per year, which is a concerning reversal from the previous nine years when it was decreasing at 4% per year as shown in Figure 2.7. TN has been decreasing at 3.7% per year since 2000, while TP has decreased at 3% per year since 2005. Similarities with Wingecarribee Reservoir are not surprising as they are both shallow reservoirs directly connected through the Shoalhaven transfer route.



but major blooms (>20 µg/L) in only two summers. Chlorophyll-a levels have been increasing steadily over the last nine years at a rate of more than 5% per year, which is a concerning reversal from the previous nine years when it was decreasing at 4% per year as shown in Figure 2.7. TN has been decreasing at 3.7% per year since 2000, while TP has decreased at 3% per year since 2005. Similarities with Wingecarribee Reservoir are not surprising as they are both shallow reservoirs directly connected through the Shoalhaven transfer route.

Figure 2.6 Fitzroy Falls Reservoir

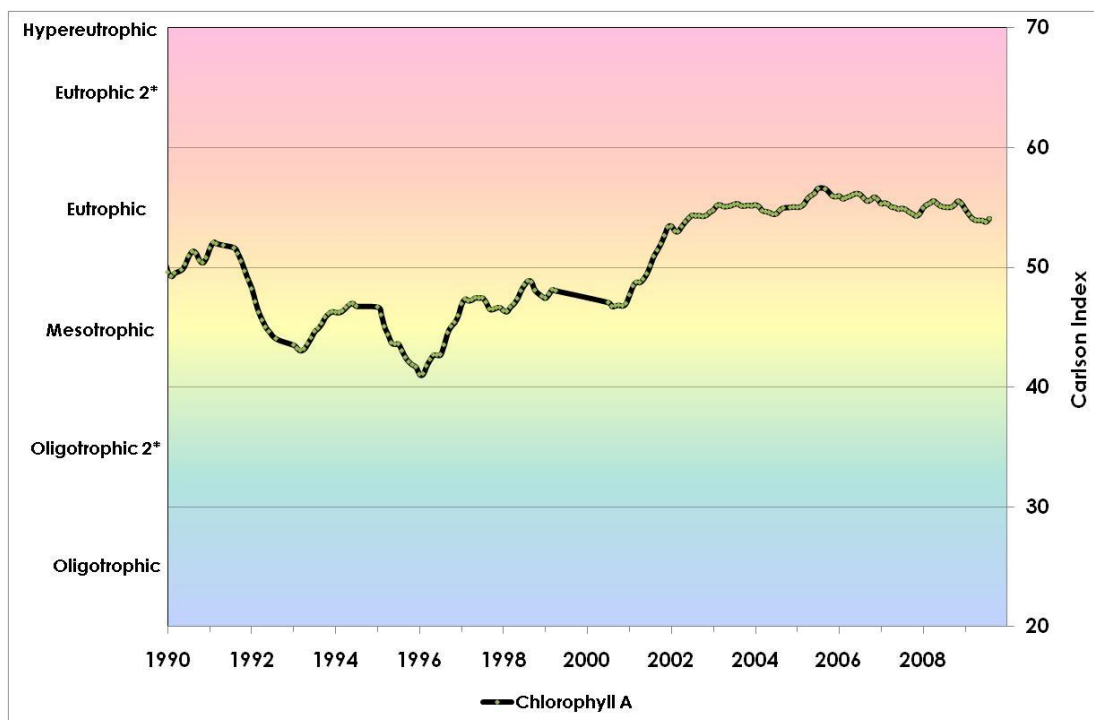


Figure 2.7 Carlson Trophic Index of chlorophyll-a in Fitzroy Falls Reservoir from January 1990 to December 2009

Aphanocapsa, *Cyanonephron* and *Cyanodictyon* dominate cell numbers during blooms. *Anabaena* is less evident than in Wingecarribee Reservoir and cell counts did not reach levels associated with taste and odour risks in the last 10 years. *Microcystis* is more common, such that cell counts for the two species combined exceeded the high health alert level (6,500 cells/L) in three of the last 10 years. Risks to water supplies are nevertheless low from Fitzroy Falls Reservoir as it does not feed directly into the Sydney drinking water supply as it is routed first through Wingecarribee Reservoir and then through either Warragamba or Nepean reservoir. Return water reaching Bendeela Pondage during hydro-electric power generation is treated at the Kangaroo Valley water filtration plant.

Actions are ongoing under the HCP to address the main sources of nutrients within the small catchment. It is likely that significant nutrients loads and possibly algal biovolume are entering the storage through water transfers from Tallowa Reservoir.

2.8.3 Tallowa Reservoir (Lake Yarrunga)

Tallowa Reservoir (Lake Yarrunga) is made up of two distinct arms, the southern Shoalhaven arm and the northern Kangaroo arm (Figure 2.8). There are very notable differences between them. The Shoalhaven arm is in relatively good condition being mesotrophic, and has not recorded over 20 µg/L chlorophyll-*a* in the last 10 years. *Anabaena* has never exceeded 1,000 cells/mL while the medium health alert for the potentially toxin-producing species of *Anabaena* and *Microcystis* (2,000 cells/mL) has only been exceeded once in the past 10 years. While this situation is encouraging, chlorophyll-*a* levels have been increasing over the past 20 years at a rate of 5-6% per year (Figure 2.9). The trend is not matched by increases in nutrients with TN decreasing over the last 10 years by 1.3% per year, and TP decreasing by 7.5% per year since 2005.

The large southern catchment of the Shoalhaven drains to the Shoalhaven arm and is dominated by steep slopes of native vegetation close to the storage and agriculture further south. The large size of the catchment means that even at moderate rates of nutrient export (per unit area), the cumulative loads will be high during major runoff events. The CDSS identified horticultural and cropping areas as priority nutrient sources which deserve targeted action.



Figure 2.8 Tallowa Reservoir (Lake Yarrunga)

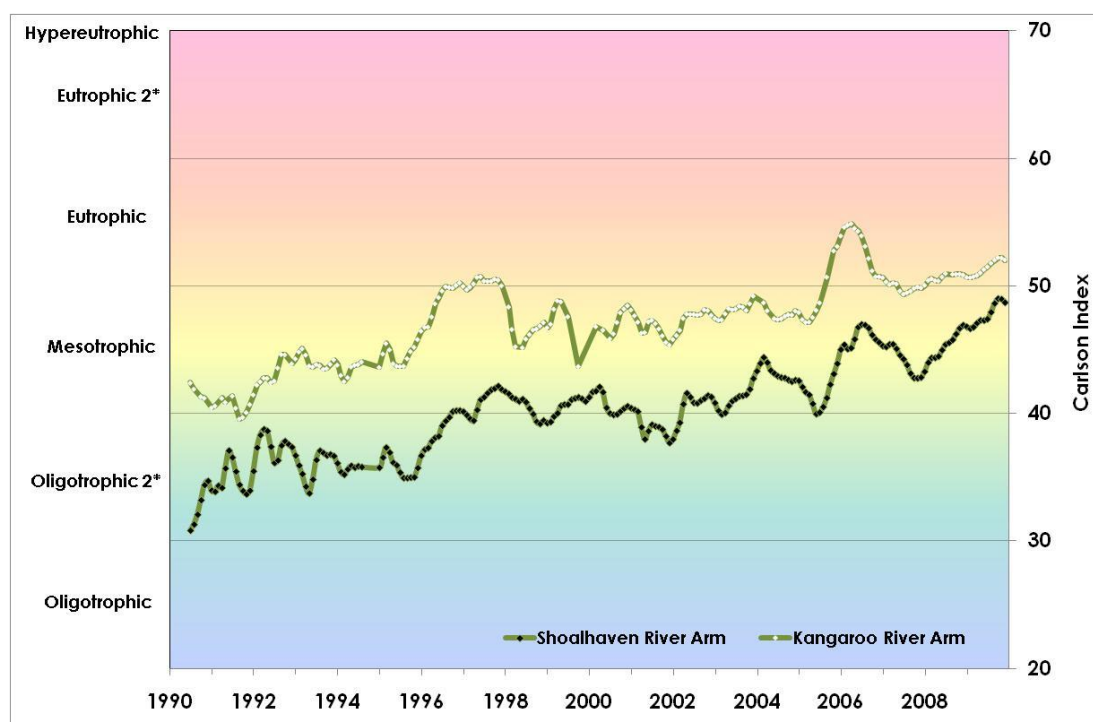


Figure 2.9 Carlson Trophic Index of chlorophyll-a in Tallowa Reservoir (Lake Yarrunga) from January 1990 to December 2009

The Kangaroo arm of the reservoir is significantly more problematic as it is eutrophic and is the source of water transferred to Bendeela Pondage. The Shoalhaven Shire Council water supply is diverted from Bendeela Pondage to the water filtration plant, while water is also transferred on through Fitzroy Falls and Wingecarribee reservoirs to Sydney's drinking water supply.

Over the last nine years, the Kangaroo arm has recorded algal blooms every year with chlorophyll-a levels in excess of 20 µg/L in three of those years. *Anabaena* and *Microcystis* have both been recorded in sufficiently high numbers to exceed the taste and odour risk threshold of 1,000 cells/L of *Anabaena* in two of the nine years, and the threshold of 2,000 cells/L in one year. The medium health alert level (2,000 cells/L of *Anabaena* and *Microcystis* combined) was exceeded in six of the years while the high health alert level (6,500 cells/L) was exceeded twice over the nine years.

As shown in Figure 2.9 the rate of increase in the chlorophyll-a levels in the Kangaroo arm has slowed from 5.9% per year (1990-2000) to 3.6% per year (2000-2010). TN and TP have been declining at 0.7% per year (since 2000) and 8.9% per year (since 2005) respectively.

2.8.4 Warragamba Reservoir (Lake Burragorang)

Warragamba Reservoir (Lake Burragorang) is the SCA's largest and most complex reservoir (Figure 2.10). While the whole reservoir rates as mesotrophic, there are four quite distinctive sub areas within the reservoir which are considered separately:

- the Coxs arm to the north-west
- the Wollondilly arm to the south-west
- the Warragamba junction
- the Gorge to the dam wall in the north-east.



Figure 2.10 Warragamba Reservoir (Lake Burragorang)

Coxs arm

The Coxs arm has historically exhibited the most algal activity, particularly close to the inflows of the Kedumba and Coxs rivers. Although these blooms often exceeded the guidelines for the recreational use of water, they were confined to a small area of the upper reaches and have had little consequence for the overall water quality of the storage. In the mid-1990s actions were taken to address this issue through the construction of a sewage tunnel through the Blue Mountains and the consequent transfer of the STP discharges away from Kedumba River.

Chlorophyll-a levels have been increasing in the Coxs arm at a moderate rate of around 2% per year since 1990 (Figure 2.11). Since 2000, TN has increased by 1.5% per year. TP has decreased by 0.8% per year since 2005. Nevertheless, of the last nine years, chlorophyll-a levels between 10 and 20 ug/L were recorded in six years, while levels exceeded 20µg/L in three years.

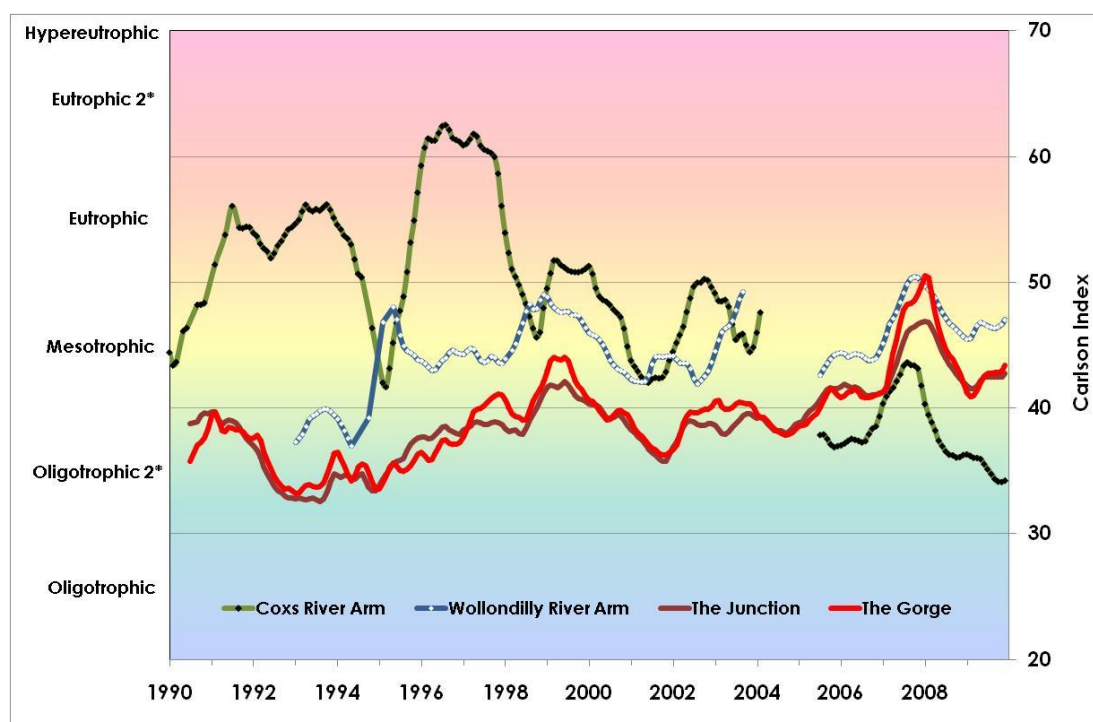


Figure 2.11 Carlson Trophic Index of chlorophyll-a in Warragamba Reservoir from January 1990 to December 2009

The Coxs arm is mainly influenced by the catchments of the Coxs, Kedumba and Kowmung rivers. These catchments support diverse landuses and are large enough to contribute significant wet weather nutrient loads. The CDSS has identified urban runoff, STP discharges and sewer overflows as the primary sources of nutrients. STPs in the Upper Coxs catchment are being upgraded under the HCP. Lake Lyell, Lake Wallace and Thompsons Creek Dam, which are significant enroute storages and owned and operated by Delta Electricity, buffer much of the nutrient loads coming from the Upper Coxs catchment. Lake Lyell has not spilled for over 10 years. When it does, it could potentially release a substantial load of nutrients and/or algal biomass. Studies into the dynamics of these lakes are needed to better understand the role they play in trapping, transforming and subsequently remobilising nutrients and any associated algae.

Wollondilly arm

The Wollondilly arm of the storage recorded a more rapid increase in chlorophyll-a levels of 12.9% per year between 1990 and 2000 than occurred in the Coxs arm. This rate of increase has slowed to 2.2% per year since 2000 (Figure 2.11). TN has been decreasing by 2.6% per year since 2000 while TP has been decreasing by 10.6% per year since 2005. There have been no instances of chlorophyll-a exceeding 20 µg/L in the last nine years and just four years when it has exceeded 10 µg/L.

The large catchment draining into this arm of the reservoir supports diverse landuses and some significant population centres in the Southern Highlands and Goulburn areas. The CDSS identified a number of significant nutrient sources including grazing lands, intensive

animals, horticulture and cropping, urban stormwater runoff, on-site wastewater systems and sewer overflows. The HCP is currently focusing on education and incentive programs on grazing land, sewer modelling and refurbishment, and on-site inspections and maintenance.

The Junction:

The Warragamba junction is where the waters from the Wollondilly and Coxs tributaries converge. The relative influence of the two tributaries depends on the amount of flow from each tributary (with the Wollondilly typically dominating during the autumn/winter period), and the order in which water reaches the confluence. Local runoff from the steep forested slopes of the special areas adjacent to the reservoir also contributes to the mix in wet weather events. The junction has been relatively free of algal blooms with only one year (2007) recording chlorophyll-*a* levels in excess of 20 µg/L. However, chlorophyll-*a* has been steadily increasing at a rate of around 5% per year. This has remained relatively stable over the past 20 years (Figure 2.11). Since 2000 TN has been increasing at a rate of 3.3% per year, while TP has been decreasing at a rate of 1.7% per year since 2005.

The Gorge

The Gorge is the most critical part of the lake for water supply as the drinking water offtake draws directly from it. Historically the Gorge has avoided serious algal activity with only two years recording chlorophyll-*a* concentrations over 10 µg/L in the last nine years. Following a series of rainfall events in June 2007, a cyanobacteria bloom developed in Warragamba Reservoir in August of that year. By September the cell count of *Microcystis* exceeded 100,000 cells/mL in the Gorge (with chlorophyll-*a* peaking at 65 µg/L) and persisted until November with a peak population of 800,000 cells/mL. A cyanobacterial bloom of this proportion in the Gorge was unprecedented. Prior to this event, *Microcystis* populations had exceeded 30,000 cells/mL on only two occasions, in October/November 1983 (43,000 cells/mL) and in October 2006 (36,000 cells/mL).

Australian Water Technologies (AWT 1994) investigated historical data on algal densities in Warragamba Reservoir and found that major algal blooms were typically preceded by floods between April and August. The SCA investigations of the 2007 event concluded that the bloom event was the result of an unusual combination of factors which were unprecedented in Warragamba Reservoir prior to 2007:

- A moderate-sized inflow which entered the storage as an underflow.
- Inflow occurring during the seasonal cooling cycle (April –July) which caused the post-inflow stratification to progressively weaken and move deeper into the water profile as a result of continued surface cooling. This allowed the advective transport of nutrients from the nutrient rich underflow into the epilimnion.
- High levels of nutrients reaching the dam wall during the inflow event due to the combination of high catchment contributions, the remobilisation of nutrients from lake bed deposits within the storage, and the efficient transport of these nutrient rich waters to the dam wall.
- Low initial storage volume and low storage volume to inflow volume ratio, which meant the old water was readily displaced upwards by the inflows into a relatively thin layer. This resulted in the nutrient rich inflow water lying close to the surface and being subjected to surface cooling and wind forcing.

Over the past 20 years chlorophyll-*a* has been steadily increasing in the Gorge at a rate of over 5% per year (Figure 2.11). Since 2000 TN has also been increasing at a rate of 1.8% per year, while TP has been decreasing at a rate of 7.5% per year since 2005. Nutrients are transported into the Gorge during high flow events from all tributaries and should therefore benefit from any reduction in loads from its catchments which result from actions under the HCP.

In October 2008, four Solarbee water recirculation units were installed in the Gorge area as part of the WDBGAAP. A preliminary investigation of their performance found that there was no evidence that the units were either disrupting cyanobacteria populations directly or altering water quality/habitat in a way that might discourage cyanobacteria growth.

3 Cyanobacteria species

3.1 Overview

Cyanobacteria, commonly known as blue-green algae, are in all water bodies and co-exist with algal plant communities. Collectively, cyanobacteria (prokaryotes) and “green algae” (chlorophytes) form the photosynthetic communities found either within the water column (pelagic) or attached to surfaces (benthic). Although cyanobacteria are also called blue-green algae, they are closer to bacteria than algae in their cell structure. They vary in colour from green through blue-green to red. The term ‘algae’ refers to both cyanobacteria and green algae.

The term algal bloom (high-density populations often floating on or near the water surface) can be characterised as the proliferation of planktonic algae in aquatic habitats up to millions of cells per litre (Carmichael, 1994). Blooms are also defined in terms of chlorophyll-*a* concentration. Chlorophyll-*a* is a pigment required for photosynthesis and can be used as a general measure of all photosynthetic organisms present, which includes both green algae and cyanobacteria species.

Floating cyanobacteria have important physiological and morphological features that allow them to successfully compete with other algae to reach bloom proportions under certain environmental conditions. Most genera of cyanobacteria contain gas vesicles (Table 3.1). The buoyancy of cyanobacteria that contain gas vesicles is known to fluctuate as a result of ambient light, temperature, nutrient concentrations and their metabolic activity (Brooks and Ganf, 2001) and appears to give them some advantages over other species competing for light and food. However, the popular belief that ‘buoyancy regulation’ allows cyanobacteria to exploit light-nutrient gradients has not been demonstrated in the field (Bormans et al, 1999). During photosynthesis, carbohydrates accumulate in the cells, and this accumulation induces sinking of the assemblage of cells. Away from the surface photosynthesis ceases, during respiration and metabolic activity, gas vesicles fill up and cell becomes lighter, and the assemblage floats back towards the surface. The frequency and rate of the sinking/floating cycle is a function of the number of cells in the assemblage. Often, single cells or smaller assemblages continue to stay at the surface due to inadequate force differential to move them down. The species common in SCA reservoirs are most likely to be found almost exclusively within the diurnal mixing surface layer.

Cyanobacteria occur in a broad range of shapes and sizes (Appendix A). They are found in water as either single cells floating free within the water column, or assembled into groups as colonies or filaments. Filaments can be straight, coiled, or twisted. Colony-forming cyanobacteria can be found both in colonies of up to many thousands cells, and as individual cells. Dimension of these formations are generally in the millimetre range. Further, filaments and colonies can aggregate to form much larger structures to become visible to the naked eye.

Table 3.1 Properties of cyanobacteria commonly found in SCA waterways

Species	Typical shape	Typical volume of one cell (μm^3)		Nitrogen fixer	Gas vesicles	Potentially toxin producing in Australia
		SW	Burch			
<i>Anabaena affinis</i>	Sphere	106	76	Yes	Yes	Yes
<i>Anabaena bergii</i>	Cylinder	60	85	Yes	Yes	Yes
<i>Anabaena circinalis</i>	Sphere	168	250	Yes	Yes	Yes
<i>Anabaena crassa</i>	Ellipsoid	213	330	Yes	Yes	Yes
<i>Anabaena flos-aquae</i>	Sphere	-	56	Yes	Yes	No
<i>Anabaena spiroides</i>	Sphere	-	270	Yes	Yes	No
<i>Anabaenopsis elenkinii</i>	Ellipsoid	127	133	Yes	Yes	No
<i>Aphanizomenon issatschenkoi</i>	Cylinder	-	57	Yes	Yes	No
<i>Aphanizomenon ovalisporum</i>	Cylinder	-	52	Yes	Yes	Yes
<i>Aphanizomenon sp.</i>	Cylinder	47	-	Yes	Yes	No
<i>Aphanocapsa incerta</i>	Sphere	5.7	1.8	No	No	No
<i>Aphanocapsa sp.</i>	Sphere	0.5	-	No	No	No
<i>Aphanothece clathrata</i>	Rod	1	2.1	No	No	No
<i>Aphanothece sp.</i>	Rod	0.7	-	No	No	No
<i>Chroococcus sp.</i>	Sphere	-	28	No	No	No
<i>Coelosphaerium sp.</i>	Sphere	11	2.3	No	Yes	No
<i>Cyanodictyon sp.</i>	Sphere	0.5	0.1	No	No	No
<i>Cyanonephron sp.</i>	Rod	0.4	5.4	No	No	No
<i>Cylindrospermopsis raciborskii</i>	Cylinder	100	42	Yes	Yes	Yes
<i>Gloetrichia echinulata</i>	Ellipsoid	-	-	Yes	Yes	Yes
<i>Limnothrix sp.</i>	Cylinder	27	12	No	Yes	No
<i>Lyngbya limnetica</i>	Cylinder	-	-	No	No	No
<i>Merismopedia sp.</i>	Sphere	0.2	0.9	No	No	No
<i>Microcystis aeruginosa</i>	Sphere	48	87	No	Yes	Yes
<i>Microcystis flos-aquae</i>	Sphere	32	22	No	Yes	Yes
<i>Microcystis wesenbergii</i>	Sphere	156	113	No	Yes	No
<i>Nostoc linckia</i>	Sphere	-	40	Yes	No	Yes
<i>Oscillatoria /Planktothrix</i>	Cylinder	500	-	No	Yes	No
<i>Phormidium sp.</i>	Cylinder	20	-	No	No	Yes
<i>Planktolyngbya subtilis</i>	Cylinder	5.4	5.9	No	No	No
<i>Pseudoanabaena galeata</i>	Cylinder	5.3	14	No	?	?
<i>Pseudoanabaena limnetica</i>	Cylinder	10	11	No	Yes	No
<i>Raphidiopsis sp.</i>	Cylinder	25	-	No	No	Yes
<i>Rhabdoderma sp.</i>	Cylinder	3.2	-	No	No	No
<i>Rhabdogloea sp.</i>	Cone	0.8	-	No	No	No
<i>Romeria sp.</i>	Rod	6	-	No	No	No
<i>Snowella lacustris</i>	Ellipsoid	27	8.2	No	No	No
<i>Spirulina sp.</i>		5.1	-	No	No	No

SW = Sydney Water Corporation Algae Laboratory; Burch = Burch et al. (2010)

In addition to their ability to photosynthesise, some cyanobacteria (eg *Anabaena*) can fix nitrogen from the atmosphere which gives them further advantages when nitrogen levels limit the growth of other algae. Some freshwater cyanobacteria are known to produce potent toxins while other cyanobacteria species produce compounds causing unpleasant taste and odour.

The common problematic cyanobacteria genera in Australian freshwaters are *Microcystis*, *Anabaena*, *Cylindrospermopsis*, *Aphanizomenon*, *Anabaenopsis*, and benthic *Phormidium* and *Planktothrix*. Potentially toxin-producing cyanobacteria recorded within Sydney's drinking water catchments include *Anabaena*, *Microcystis*, *Cylindrospermopsis* and *Aphanizomenon*.

3.2 Cyanobacteria species found in the SCA storages, lakes and catchments

Overviews of the history of cyanobacteria presence in SCA reservoirs have been undertaken since 1994, such as Hassan et al (1994), Hassan and Hawkins (2001), Sherman and Orr (2003), and the 2005 Cyanobacteria Risk Management Strategy (SCA, 2005).

Following the 2007 cyanobacteria bloom in Warragamba Reservoir, the SCA prepared a series of reports on the nature of the bloom (SCA, 2008a; SCA, 2008b; Vigneswaran and Charan, 2008), and cyanobacteria species in Wingecarribee and Fitzroy Fall reservoirs (Vigneswaran and Bales, 2010; SCA, 2008d).

In the past 12 years major cyanobacteria incidents were declared at Wingecarribee Reservoir (1998, 2003 and 2005) and at Warragamba Reservoir in 2007. Significant detections of cyanobacteria toxins were reported at Wingecarribee Reservoir in 1998, 2003 and 2005, and at Fitzroy Falls Reservoir in 2003.

The regular occurrence of *Microcystis aeruginosa* and *Anabaena circinalis* in Wingecarribee and Fitzroy Falls reservoirs has been of concern, especially after the commencement of inter-basin transfers in 2003. An unnamed species of the potentially toxin producing genus, *Microcystis*, dominated the cyanobacteria bloom with visible surface accumulation of scum near the dam wall of Warragamba Reservoir in 2007.

Traditionally, cyanobacteria and algae populations were reported and analysed in terms of number of cells in a unit volume of water (generally mL). Due to the limited understanding of the toxic properties of cyanobacteria, total cyanobacteria population per unit volume was used as a measure in declaring water quality incidents. The new alert framework (see Section 6 and Appendix C) uses cell populations of selected species of cyanobacteria known to have the potential to produce toxins.

As cell sizes can vary enormously between different algal species, it is important to be aware of the species size when comparing cell numbers. Biovolume is an estimation of the volume taken up by each species to account for differences in cell size, and provides a more comparable reference of population dominance. However, with large differences in cell size, analysis by comparing biovolumes alone can overshadow increasing numbers of smaller

species. Biovolume of each species can be calculated by multiplying the volume of a single cell by the cell count. Total biovolume is reported generally in mm^3/L .

A large number and variety of cyanobacteria species have been detected in SCA reservoirs. Many are only ever present in relatively small numbers while others have periodically reached bloom proportions. Table 3.1 lists most of the recorded species and their key characteristics including shape, volume, and whether they are nitrogen fixers, contain gas vesicles and are potentially toxin producers. Table 3.2 sets out some of the most notable cyanobacteria occurrences in SCA reservoirs.

A detailed description of the key species is included at Appendix A.

Table 3.2 Notable occurrences of cyanobacteria in SCA reservoirs

Cyanobacteria	Locations	Year
<i>Microcystis aeruginosa</i>	Fitzroy Falls	01/02, 02/03, 03/04
	Tallowa	05/06, 07/08
	Warragamba	05/06, 07/08
	Wingecarribee	03/04, 06/07, 07/08, 08/09
	Prospect	00/01
<i>Microcystis species</i>	Fitzroy Falls	09/10
	Tallowa	04/05, 07/08, 08/09
	Warragamba	07/08, 08/09, 09/10
	Wingecarribee	04/05, 05/06, 06/07, 07/08, 08/09
	Bendeela	04/05, 07/08, 09/10
<i>Anabaena circinalis</i>	Fitzroy Falls	06/07, 09/10
	Tallowa	06/07, 09/10
	Warragamba	07/08
	Wingecarribee	06/07, 07/08
	Prospect	04/05, 07/08, 09/10
<i>Aphanocapsa incerta</i>	Wingecarribee	97/98, 98/99
Cyanotoxin	Locations	Year
Microcystin toxin	Fitzroy Falls	02/03 ^a ; 03/04 ^b
	Bendeela Pondage	01/02 ^b ; 02/03 ^a
	Tallowa	05/06 ^b
	Wingecarribee	03/04 ^a , 06/07 ^a , 07/08 ^a ; 08/09 ^a

^a – exceeding 1.3 $\mu\text{g}/\text{L}$ ^b – exceeding 0.7 $\mu\text{g}/\text{L}$

4 Causes of cyanobacteria blooms

4.1 Overview

The presence of algae in water is not a single-issue water quality problem with a unique cause or solution. Under usual conditions, all water storages have a background level of algae. Cyanobacteria are common in all water bodies and co-exist with other algal communities. The appearance of large blooms is however unusual and generally occurs in response to a change in reservoir conditions such that large populations of cyanobacteria are able to proliferate. Such conditions may include the availability of nutrients such as nitrogen and phosphorus at a location where adequate light and space for growth are available.

In order for a cyanobacteria bloom to form, the following factors are required:

- high nutrient concentrations
- high light intensity, temperature and pH (allowing dominance of cyanobacteria over other algae)
- conditions that lead to large-scale flotation of much of the algal biomass (high population of cells with gas-vesicles and a stable water column).

A bloom will generally develop in water that contains adequate levels of essential inorganic nutrients, water temperatures generally between 15°C and 30°C, and pH levels between six and nine (Chorus and Bartram, 1999) coupled with suitable light intensity. The factors and causes that are likely to promote the development of a cyanobacterial bloom, and the effects that may result from these blooms, are summarised in Figure 4.1. The manner in which these factors influence the growth of cyanobacteria is outlined in sections 4.2 to 4.5.

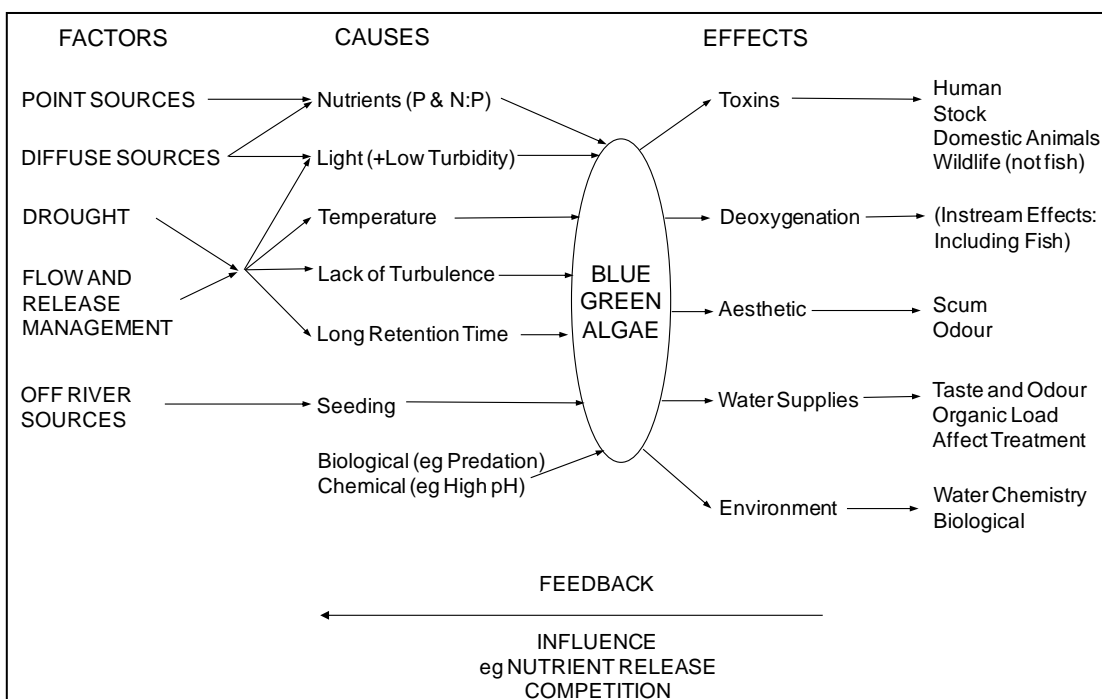


Figure 4.1 Cyanobacteria blooms – major causes and effects (adapted from SACC, 1996)

4.2 Nutrients

Phosphorus and nitrogen are the two primary nutrients required by cyanobacteria. The nutrient supply influences cyanobacteria growth in a number of ways including:

- species composition (selectivity)
- magnitude (concentration)
- duration of the bloom.

Broadly, phosphorus and nitrogen loads determine the rate and the magnitude of cyanobacteria growth. The greater the nutrient supply, then the greater the potential for algal growth to develop to bloom proportions. The importance of phosphorus and nitrogen concentrations in algal growth is reflected in the fact that there has been a worldwide focus on programs to achieve targeted reductions in catchment loads of nitrogen and phosphorus into water storages, and has been identified as a key to reducing the risk of cyanobacteria blooms (Wetzel, 2001).

The concentrations of phosphorus and nitrogen that are required to promote a bloom are specific to a species. Cyanobacteria have been reported to have a higher affinity for nitrogen and phosphorus compared to other phytoplankton, indicating that cyanobacteria will dominate over green algae at lower nitrogen to phosphorus ratios (cyanobacteria 10-16N:1P versus green at 16-23N:1P) (Mur et al, 1999). This finding cannot be used to determine the potential for a cyanobacteria bloom, as nutrients would not be in the bio-available form in the water column required to initiate and sustain a bloom, and some cyanobacteria species can fix atmospheric nitrogen (Table 3.1). Further, cyanobacteria cells have a capacity for intracellular phosphorus storage (known as luxury uptake) under conditions of high phosphorus availability. This internal storage can be significant and cells can store enough phosphorus for an additional three or four cell divisions. Effectively, this means that one cell can become eight to 16 cells, without requiring any further phosphorous uptake (Chorus and Mur, 1999).

In order to build cells, phytoplankton requires macro-nutrients in approximately the following ratio by mass (Chorus and Mur, 1999):

Carbon	Hydrogen	Oxygen	Nitrogen	Phosphorus
42	8.5	57	7	1

This ratio is highly generalised and specific requirements are likely to vary significantly with species. Carbon is provided by carbon dioxide and sunlight via photosynthesis and is not likely to be critically limiting relative to other nutrients. Hydrogen and oxygen are obtained from water which is abundantly available. Nitrogen and phosphorus however are required in the reservoir waters in order for growth to occur. Given that nitrogen is typically available in SCA reservoirs at concentrations around 300 µg/L, the background concentrations for phosphorus are typically around 5-10 µg/L making phosphorus more likely to be the limiting factor to algal growth.

In a natural ecosystem a rough estimation of the carrying capacity of a reservoir can be made, with 1 µg of phosphorus producing 100 µg of biomass, equating to roughly 1 µg of chlorophyll-a (Chorus and Mur, 1999). This suggests that the 2007 Warragamba bloom, for example, which peaked at 46 µg/L chlorophyll-a, could have been supported by as little as 46 µg/L of phosphorus. This is supported by the monitoring data which shows that the *Microcystis* sp. bloom began to develop when concentrations near the dam wall of TN rose above 600µg/L and TP rose above 30µg/L.

The availability of nutrients indicates that algae can grow. However nutrients alone do not explain the dominance of cyanobacteria over green algae and other phytoplankton. Cyanobacteria will dominate over other types of algae under certain physical and chemical conditions. Generally, desmids are typical of low-nutrient waters, while colonial cyanobacteria, green algae and centric diatoms are more characteristic of mesotrophic to eutrophic conditions (Sigeo, 2005).

The growth rate of cyanobacteria (0.3-1.4 doublings per day) is much lower than other green algae (1.3-2.3 doublings per day) (Mur et al, 1999). This indicates that under unlimited conditions, green algae will dominate over cyanobacteria because they can grow faster and better compete for nutrients. For cyanobacteria to out-compete green algae, some aspect of the reservoir must have been more favourable to cyanobacteria at the time of the bloom.

Phosphorus and nitrogen can be found in the water column in many forms such as dissolved, solid, and bound to organic. Increased nutrients generate excessive cyanobacteria growth, however some types of phosphorus and nitrogen promote certain species over others. A simple example is that nitrogen fixing algae (Table 3.1) can use atmospheric nitrogen and may not solely depend on nitrogen in the water column. In a nitrogen-limited environment which has excess phosphorus available, a nitrogen-fixing cyanobacteria species has a competitive advantage over a species which is solely dependent on aqueous nitrogen (unable to fix atmospheric nitrogen) and is potentially more likely to bloom. Alternatively, if aqueous nitrogen is available, this competitive advantage is minimised and other factors probably become more critical in defining which cyanobacteria (if any) become dominant. Understanding the relationship between phosphorus and nitrogen chemistries and the influence on cyanobacterial growth is generally limited by the difficulty in accurately measuring the different types of phosphorus and nitrogen in the water column.

The duration of a bloom is also determined by the ongoing availability of nutrients to fuel growth. The three avenues for nutrient provision are the initial supply, additional supply (which may be inflow or hydrodynamically related) and reuse of nutrients from degraded algal cells. If there is an adequate supply of nutrients cyanobacteria growth rates will be exponential. As the cells degrade, some nutrients are released back into the water column. Part of this nutrient load settles and does not influence further growth and part is re-accumulated by the bloom which maintains biotic mass. If additional nutrients are supplied, growth rates can be maintained until a non-nutrient dynamic limits growth.

Other nutrients may also be significant to growth, bloom development and potentially even toxin production. Micro-nutrients such as magnesium, iron, cobalt, and nickel have been suggested as cyanobacteria growth factors in many cultured laboratory experiments. However the micro-nutrient concentrations required by cyanobacteria are generally very low

and may be highly specific. There is relatively little known about the micro-nutrient requirements for the different species of cyanobacteria. For this reason, phosphorus and nitrogen concentrations are typically used as indicators for the potential of cyanobacteria growth and an excess of these nutrients is a key indicator of increased risk of bloom development.

4.3 Temperature and pH

Cyanobacteria require a number of favourable environmental factors to promote growth. As cyanobacteria are photosynthetic organisms, solar radiation is required for energy. The quality of radiation appears to be critical in describing the initiation of cyanobacteria growth, but its influence on growth limitation or decline is uncertain. The depth of penetration of radiation into the water column describes the habitat available to harbour cyanobacteria growth. With increased penetration, there is more habitat available for growth and thereby more growth potential. Therefore, when nutrients are in excess and the water is clear, cyanobacteria growth potential increases. Secchi disk depth and turbidity are good surrogate measurements for describing the light penetration capacity.

Water temperatures greater than 15°C are often observed with cyanobacteria bloom development with maximum growth rates achieved above 25°C (Mur et al, 1999). Previous analyses in SCA storages suggest that (total) solar radiation provision above 600 watts per square metre is sufficient to facilitate cyanobacteria growth (Faulkner, 2009), which typically occurs between August and April/May on a yearly basis. This suggests that if a cyanobacteria species became dominant early in the warm season, with an adequate supply of nutrients, the species would remain dominant through to April the following year. Observations show that in most SCA reservoirs there is typically a change in cyanobacteria species dominance around December/January and again in approximately February/March. However, there have been examples of cyanobacteria cell densities in excess of 10,000 cells/mL during winter in Wingecarribee and Fitzroy Falls reservoirs, suggesting that while solar radiation is important, it is secondary to nutrient requirements.

There is a growing body of evidence that suggests that thermal warming of surface layers of the water column (the surface mixed layer) defines the capacity for vertical migration of cyanobacteria and may be a selection or decline mechanism (Moreno-Ostos et al, 2009). Warming of the water surface creates a difference in density of the water which has a number of possible influences including:

- limiting the ability of algae to both reach nutrients at depth and to rise and reach sunlight
- locking nutrient loads into a thin layer where they are more concentrated and more readily available
- creating density differentials which prevent cyanobacteria from vertically migrating out of the surface layer with the result that they can become over-irradiated and stop growing.

These influences are highly dependent on the type of cyanobacteria and its ecology. Therefore, while they are known to be significant, it is probably only part of the environmental conditions that define a cyanobacteria response.

During the growth period of the 2007 Warragamba *Microcystis* bloom, the epilimnion water temperature ranged between 11°C and 17°C, and initial pH immediately prior to the bloom was about 7.7. Cyanobacteria tend to be better competitors at alkaline pH levels but an initial pH of 7.7 is insufficient to provide any significant initial advantage. Once in bloom proportions, cyanobacteria will self-generate a competitive pH advantage via high CO₂ uptake for photosynthesis and this condition favours cyanobacteria over other phytoplankton (Reynolds, 2006). However in order to raise pH, high levels of photosynthetic activity are required so numbers of cells must already be significant. Neither of these initial conditions would particularly favour the proliferation of cyanobacteria over green algae and other species.

4.4 Inflows, storage levels and transfers

The SCA manages a wide variety of storages which vary in depth, catchment types and connectivity (whether a direct water transfer route exists). Cyanobacteria are found in all SCA storages yet they vary in species, concentration and frequency of a significant response. As mentioned above, providing the environmental conditions such as solar radiation are appropriate, the availability of nutrients determines many attributes of a cyanobacterial response. There are three main mechanisms for delivering nutrients to the zone of light penetration (the water surface) to promote cyanobacteria growth. These are:

- catchment derived inflows
- anthropogenic derived inflows (transfers)
- resuspension of sedimented nutrients.

Catchment derived inflows move a nutrient load from agricultural, urban and forested lands via runoff and into the water column. Typically, inflow events provide a nutrient load that relates to the size of the inflow, although prior conditions are significant as they influence both the accumulation of nutrients on the land and the potential for mobilisation (eg erosion). Nutrients delivered by an inflow event are often adsorbed onto turbid particles and settle according to size fractionation (large particles quickly, smaller particles slower) and density. This nutrient load is then trapped in the lake bed sediments and unless disturbed is unlikely to influence future cyanobacteria growth in the water column (SCA, 2008e).

SCA reviews indicate that transfers are unlikely to have a major influence on cyanobacteria bloom development in most reasonably sized storages (SCA, 2008d). While nutrient loads can be transferred between storages, such transfers generally occur during naturally low flow periods when nutrient loads into the storages are relatively low and the additions brought in by the transfers once diluted in the storage will not significantly increase nutrient availability on the surface waters. Water transfers can also potentially transfer cyanobacteria cells from one storage to another. There is no evidence to suggest that a cyanobacteria bloom has been transferred between SCA storages however there may be some potential for cyanobacteria seeding to occur via transfers (SCA, 2008a).

Resuspension of settled nutrients is potentially a significant nutrient source in most SCA reservoirs. Resuspension or disturbance of nutrients can result from physical forcing during destratification (overturns), shear generated by flowing water (in shallow areas) from transfers, shallow water disturbance (littoral zones) and chemical transformations caused by

oxygen deficit (anoxia) in the water column. Chemical transformations and shallow water disturbance are probably yearly phenomena in most storages. While they no doubt influence the overall biotic response, this is likely to be small and not a dominant cause of bloom formation. Sediment disturbance in shallower reservoirs that exhibit little stratification is likely to be significant source of nutrients.

4.5 Biological factors

There are a number of identified organisms that have the potential to limit cyanobacteria growth or influence species selection. Zooplankton are filter feeders which consume a wide range of aquatic micro-organisms including cyanobacteria. The level of zooplankton predation on either cyanobacteria or other competing species in the SCA storages has not been investigated and is therefore not well established. Research has suggested that zooplankton communities are unable to clear a cyanobacteria bloom, which might indicate that cyanobacteria are poor food quality for reasons of toxicity, nutrient inadequacies, and physical inhibitions (Haney, 1987; Lampert, 1987).

Little is understood of the natural ecology of other organisms such as bacterial pathogens, cyanophages (viruses), protozoa and aquatic fungi (Wetzel, 2001), however all are thought to influence algal populations. There is little evidence in SCA storages or worldwide of these factors influencing bloom development or decline. The perceived prevalence of these organisms suggests that they are part of the natural mortality system of cyanobacteria and are probably not limiting to the degree that they would prevent the formation of a cyanobacteria bloom.

Some bacteria have been identified that live in the mucilage of certain species of cyanobacteria. It is believed they metabolise waste from the algae while providing a small amount of nutrient availability for the algal cell (Ho, Pers.comm.), yet it is unlikely that bacteria can provide enough nutrients to support the formation of a bloom. This relationship is probably akin to mutualism in that the bacteria are taking advantage of an ecological niche in a way that also advantages the cyanobacteria cell. Otherwise, there is little information concerning how other microbiota influence populations of cyanobacteria in SCA storages.

Nutrient availability for algae may also be influenced by the extent of microbial activity in the sediments. Microbial communities can have a significant role in nitrogen reduction (denitrification - the removal of organic nitrogen from the system and conversion to nitrogen gas) providing sufficient carbon is available for microbial growth. Normal microbial activity is likely to have been affected by the nutrient inflows however the extent to which this may have occurred was not measured and is unknown. While there is little that can be done to control this activity, investigations could provide significant information to aid understanding of nutrient loading.

5 The risks posed by cyanobacteria to water supplies

5.1 Overview

Water quality and treatment concerns typically associated with cyanobacteria include the presence of harmful toxins, offensive tastes and odours, and filter clogging. Historically, there is well documented and anecdotal evidence of animal and human poisonings from drinking water contaminated with cyanobacteria blooms (Newcombe et al, 2010). In extreme circumstances, cyanobacteria toxins can cause stock (Negri et al, 1995) and human (Jochimsen et al, 1998) deaths. Contact by humans can cause skin, eye or respiratory irritation, while ingestion can cause hepato-enteritis and pneumonia.

Cyanobacteria blooms and their impact on stock are often reported in newspapers and government warnings, which would not necessarily be captured by the scientific literature. Hence the literature is likely to underestimate the frequency and impact of blooms. The published records of stock deaths caused by cyanobacteria toxicity in Australia were summarised by Steffensen et al (1999).

5.1.1 Toxins

Cyanobacteria may cause serious problems in drinking and recreational water sources through their actual or potential for the release of toxins. About one third of freshwater cyanobacteria exhibit toxic properties but no simple method exists for distinguishing the toxin-producing from the non-toxin-producing. Researchers generally agree that many of the bloom forming species are potentially toxin producing (Yoo et al, 1995; Chorus and Bartram, 1999).

Cyanobacteria species that are known to produce toxins generally contain the toxins internally until the cells begin to die or the cell walls are ruptured. Few cyanobacteria species release toxins throughout their life cycle (Yoo et al, 1995). The toxins released to the aquatic environment may persist for a few days and as long as several weeks or months, depending on the type of toxin and environmental conditions. Despite the increasing worldwide interest in the risks associated with algal toxins, there have been relatively few practical solutions to remove the cyanobacteria toxins in situ from water bodies.

Toxins are produced by cyanobacteria that contain the appropriate genes for toxin production. However, two different strains of the same species of cyanobacteria can differ in the nature and extent of toxin production and, even when strains that do contain toxin-producing genes are present, the conditions that trigger toxin formation can vary. Furthermore, where a non-toxigenic strain is found to occur, the conditions that enable proliferation of a non-toxigenic strain could also be favourable to a toxin-producing strain of the same species. Therefore, in general, the precautionary principle is adopted.

In fresh water, cyanobacteria belonging to the genera *Anabaena* and *Microcystis* are responsible for almost all cases of algal poisoning in Australia. *Microcystis* produces a liver poison that has long-term effects while *Anabaena circinalis* produces a suite of potent nerve poisons. Both groups of algae may cause skin lesions as well. *Cylindrospermopsis* produces

a toxin termed cylindrospermopsin known to have caused significant health problems on Palm Island in the 1970s. *Aphanocapsa incerta*, a common species in the SCA's catchment and formerly classified as a species of *Microcystis*, has never been shown to be capable of producing toxins.

Cyanobacteria in Australia have been shown to produce four classes of toxins which are of potential concern for public health (CRCWQT, 2002). Extensive information on cyanotoxins can be found elsewhere (Nicholson and Burch, 2001; Chorus and Bartram, 1999; Yoo et al, 1995; Deere, 2009). These four classes are:

- cyclic peptide hepatotoxins which includes the microcystins and nodularin
- neurotoxic alkaloids include the saxitoxins which are also referred to as paralytic shellfish poisons (PSPs)
- hepatotoxic alkaloid, such as cylindrospermopsin
- endotoxins, which although not toxic in their own right, are allergenic compounds.

Table 5.1 gives a brief overview of these toxins. Further information is provided in sections 5.2.1 to 5.2.5.

Table 5.1 Summary of selected cyanobacteria toxins

Toxin	Organism ^a	Class	Mode of action	Mouse toxicity LD ₅₀ ^b (µg kg ⁻¹)	Persistence in surface waters
Microcystin	<i>Microcystis aeruginosa</i> <i>Anabaena circinalis</i>	Peptide	Hepatotoxin Tumour promotion	50 – 300 < 50	Days - weeks (moderate stability to heat)
Nodularin	<i>Nodularia spumigena</i>	Peptide	Hepatotoxin Carcinogen	30 – 50 < 30	Days - weeks (moderate stability to heat)
Saxitoxins	<i>Anabaena circinalis</i> <i>Cylindrospermopsis raciborskii</i>	Alkaloid	Neurotoxin	10 (STX) 1700 (C1)	weeks - months (stable)
Cylindrospermopsin	<i>Cylindrospermopsis raciborskii</i> <i>Aphanizomenon ovalisporum</i>	Alkaloid	Hepatotoxin	2100 (24 h) 200 (5 d)	Days - weeks (moderate stability to sunlight)

a - In different parts of the world, different species create different toxins. This summary focuses on Australian context.

b - Dose (range) required to kill 50 % of mice treated by intraperitoneal injection. Values based on Jones and Orr (2000)

Note: Cyanobacteria literature generally includes another potent toxin, anatoxin. This neurotoxin is generally widespread in cyanobacteria in the northern hemisphere (Newcombe *et al.*, 2010)

5.2 Microcystin

Microcystin is a generic term used to describe a suite of about 70 cyclic peptide hepatotoxins. Because of the wealth of toxicological and histological information relating to microcystin-LR intoxication, it is the *de facto* standard by which toxicity of the other microcystins are measured. Microcystins have both acute and chronic effects. Acute effects including death due to liver damage if the dose is high enough can occur within a few hours.

The drinking water guidelines are derived from the long-term chronic effects of toxins as potent tumour promoters that can result from exposure to sub-acute doses. Microcystins are presently not considered carcinogenic in their own right but this is still inconclusive. In Australia, microcystins are known to be produced only by *Microcystis* sp., primarily *Microcystis aeruginosa*. Relative potency of various strains of microcystin can be found elsewhere (Deere, 2009).

5.2.1 Nodularin

Nodularin is a hepatotoxin produced by *Nodularia spumigena*. Nodularin is structurally similar to microcystin and exerts similar toxicity to microcystin-LR. *Nodularia spumigena* is primarily regarded as a brackish water species and is known to form blooms in estuarine lakes in Australia. It can also occur in brackish inland lakes in Australia. In addition to saline environments, blooms of *Nodularia spumigena* have been reported in freshwater lakes of the lower River Murray, South Australia. Lower numbers of *Nodularia spumigena* have been recorded in other river systems of the Murray-Darling Basin. The limited geographic scope for blooms of this organism in freshwater in Australia makes the occurrence of nodularin a relatively minor health threat with respect to Sydney's drinking water.

5.2.2 Saxitoxins / Paralytic shellfish poisons

The terms saxitoxins (STX) and paralytic shellfish poisons (PSPs) are used to refer to the whole suite of related neurotoxic alkaloids which are usually co-produced with saxitoxins. Saxitoxins include gonyautoxins (GTX) and C-toxins. Of the saxitoxins, STX and the GTXs are the most toxic. Degradation of the relative non-toxic C-toxin results in very toxic decarbonyl-GTXs and C-toxins (Negri et al, 1997). In Australia, saxitoxin is produced by *Anabaena circinalis*.

5.2.3 Cylindrospermopsin

Cylindrospermopsin is a hepatotoxic alkaloid produced by *Cylindrospermopsis raciborskii* and *Aphanizomenon ovalisporum* in Australia. *Cylindrospermopsis raciborskii* forms dense subsurface bands in stratified reservoirs. *Aphanizomenon ovalisporum* forms dense brown surface scums. Both are predominantly tropical or sub-tropical species with most blooms occurring in Queensland, however these species are considered invasive. *Cylindrospermopsis* has been found in the Hunter Valley and at Kiama. Significant detections of certain species of *Cylindrospermopsis raciborskii* have been reported in NSW in the Murray River and Penrith Lakes. Certain species of *Cylindrospermopsis* were reported at moderate numbers in Hawkesbury–Nepean River system and Shoalhaven waterways in

the recent past. *Aphanizomenon ovalisporum* has caused problems in Murrurundi town water supply (Hunter Valley) in 2002. *Cylindrospermopsis raciborskii* has been recorded from the Murray River in South Australia (Baker and Humpage, 1994).

5.2.4 Endotoxins

The outer walls of cyanobacteria contain lipopolysaccharides. These are mainly contact irritants and may cause dermatitis and conjunctivitis in people coming into contact with the algae through swimming and showering. They may also cause stomach cramps, nausea, fever and headaches, and may cause irritation to airways and breathing difficulties if swallowed. Gastroenteritis may result from accidentally ingesting the water. Allergenic response to endotoxins in humans seems to be genetically based or idiosyncratic, as some react and others do not for the same exposure (Pilotto et al, 2002).

5.3 Taste and odour

Some algae and cyanobacteria release compounds that have objectionable tastes and odours. These may be 'grassy', 'musty' or 'earthy' (Table 5.2). Geosmin and 2-methylisoborneol (MIB) are two such compounds produced by cyanobacteria, particularly *Anabaena*. Because these compounds are in solution, they are not generally removed by filtration and pass into the reticulation system causing customer complaints. Human sense of smell is extremely sensitive to these compounds, detectable in the order of 10-15 ng/L. Chlorination may destroy some of these compounds under optimum conditions. Activated carbon is the most effective method for the removal of most of such odorous compounds, but is not routinely available at most of the water treatment plants in Sydney and is an expensive and complex option. Extensive information on taste and odour caused by cyanobacteria can be found elsewhere (Palmer, 1980; Lanciotti et al, 2003; MWH and PB, 2008; Mallevaille and Suffet, 1987; Suffet et al, 1995; Suffet et al, 1999; Hobson et al, 2010).

Table 5.2 Cyanobacteria sources of taste and odour in water* (Newcombe et al 2010)

Odour	Compound	Source
Earthy	Geosmin	Cyanobacteria (<i>Anabaena</i> , <i>Oscillatoria</i>)
		<i>Actinomyces</i> bacteria
Musty	2-Methylisoborneol (MIB)	Cyanobacteria (<i>Phormidium</i> , <i>Planktothrix</i> , <i>Anabaena</i>)
		<i>Actinomyces</i> bacteria
Grassy	B-Cyclocitral	Cyanobacteria
		Green algae
		Diatoms
Sulphurous	Mercaptans	Cyanobacteria

*This is not an exhaustive list on taste and odour compounds found in water. More information can be found at Palmer (1980) and Suffet et al (1996 and 1999).

5.4 Filter clogging

Algae cause significant filter clogging, especially when there is no clarification (flotation or sedimentation) step. This is particularly severe in the case of some algal diatom species that have siliceous recalcitrant skeletons. The potential for blockage during filtration is indicated by calculating the total cross-sectional area (Area Standard Unit or ASU), which is derived from cell count and average size for each species present. Extensive information on the sizes of various algal and cyanobacteria species can be found elsewhere (AWT, 2002).

Although most of the larger cyanobacteria species (Table 3.1) are readily removed during filtration by optimising coagulation, certain cells can still go through the conventional filter units. Increasing cell populations lead to shortened filter runs. Further, contacts among algal cells and filter media cause cell damage, and lead to the release of toxins, nutrients and organic matter into drinking water. Organic matter in water results in taste and odour problems, increases chlorine demand and causes organochlorine disinfection by-products. Nutrients cause bacterial growth in the distribution system, leading to bacteriological non-compliance and increased biofilm activity.

5.5 Secondary effects

There are secondary effects of algal blooms. It is likely that cyanobacteria cells may die off suddenly and cause deoxygenation of water due to the decay of organic matter. Lack of dissolved oxygen in water leads to fish kill, and increased levels of iron, manganese and ammonia. Further, blooms cause wide fluctuations in pH.

6 Cyanobacteria guidelines and standards

6.1 Overview

The risks of exposure to cyanobacteria and cyanotoxins for the consumers of Sydney's water supply, the users of water in SCA reservoirs and SCA staff can occur through:

- Ingestion - the primary risk to consumers from cyanobacteria intoxication is from direct consumption (drinking) and accidental ingestion (during showering and bathing).
- Recreational exposure - includes all water-related activities such as swimming or canoeing where direct contact and immersion in water is intended or a probable outcome.
- Occupational exposure - field workers may be exposed to risk by direct contact with cyanotoxins in water and aerosols while carrying out duties.

The primary use for water stored in SCA reservoirs is to supply raw water to SWC, Shoalhaven City Council and Wingecarribee Shire Council for treatment and reticulation. Eraring Energy circulates water between the reservoirs in the Shoalhaven System for hydro-electric generation. Each of these customers operates under a bulk water licence or agreement. The SCA also supplies water to the residents and users of picnic sites, a scout camp at Cataract Reservoir and the National Parks and Wildlife Service at Fitzroy Falls Reservoir. It is the responsibility of users to assess suitability and safety of the water for their own particular requirements.

The 1996 Australian Drinking Water Guidelines (ADWG) (NHMRC, 1996) did not provide any guideline values for cyanobacteria in drinking water. The first detailed framework for the response to cyanobacteria blooms was developed by the Metropolitan/South Coast Regional Algal Coordinating Committee. This provided two separate guidelines for drinking water and freshwater in terms of cell numbers (RACC, 2000).

The 2004 ADWG (NHMRC, 2004) recommend that total microcystins in drinking water should not exceed 1.3 $\mu\text{g/L}$ expressed as microcystin-LR toxicity equivalent. There is no guideline value for other major toxin-producing cyanobacteria species or toxins at present (Appendix C). The SCA bases its guidelines and alert framework on the current ADWG (NHMRC, 2004).

The NHMRC has proposed revised maximum guidelines and alert levels (NHMRC, 2010). Further details on the guideline and framework development can be found in Appendix C.

6.2 Drinking water exposure

The primary risk to consumers from cyanobacteria intoxication is from drinking, or accidentally ingesting (eg while showering and bathing) untreated or partially treated water which is contaminated with cyanotoxins.

International guidelines formulated by the World Health Organization (WHO) for potable use of water contaminated by cyanotoxins have been derived only for microcystins. The maximum guideline level for drinking water as recommended by WHO is 1 µg (total microcystin-LR equivalents) / L (Chorus and Bartram, 1999). This guideline level is equivalent to approximately 5,000 cells mL⁻¹ in water and is based on a microcystin-LR cell quota of 200 fg / cell which making it one of the most potent strains of *Microcystis aeruginosa* found to date.

The SCA is using the current ADWG (NHMRC, 2004) and an Alert Level Framework for *Cyanobacteria* in drinking water sources with respect to public health (Table 6.1). Although the cell numbers were designated in the alert framework based on the potential toxin production by *Microcystis aeruginosa*, the SCA uses all potentially toxin-producing cyanobacteria in its alert framework. The public health concern is directly related to the actual and potential presence of toxins in water. Hence, a robust knowledge of the effect of toxins is critical. The proposed modifications to ADWG address individual species of potentially toxin producing cyanobacteria with specific alert framework for each species. For further information on this see Appendix C.

The Detection Level covers the early stages of bloom development when cyanobacteria are detected first at low levels in the water storage. Alert Level 1 represents the level at which the cyanobacteria population is established and localised high numbers may occur. Alert Level 2 characterises the presence of moderate and slightly higher cell numbers of potentially toxin-producing cyanobacteria with a potential for occurrences of toxins above the guideline values. Conditions in Alert Level 3 are indicative of a significant increase in the risk of adverse human health effects from the supply of water.

Where a cyanobacteria effect exceeds the threshold levels for the issue of an advisory, local health authorities are informed. A formal advisory is issued only if the second sample exceeds the threshold. The advisory is withdrawn following two consecutive readings below the advisory threshold and only after consultation with state and local health authorities.

A standard health advisory is issued directly to customers on the authority of the General Manager, Water Supply Division. Advisory levels at state and national levels are currently under review and in all cases the SCA consults with health authorities for advice on the currency and applicability of the cyanobacteria advisory levels proposed in this report.

Sampling protocols have been adopted to maintain a high quality and reliable sampling program capable of informing the process and are discussed in Chapter 7.

Table 6.1 SCA Alert Level Framework (SCA, 2010b) for cyanobacteria in drinking water sources with respect to public health

Alert level	Total Potentially toxin producing cyanobacteria Cells/mL	Total cyanobacteria biovolume equivalent	Total Microcystin-LR toxicity equivalents	Actions	Notifications
Alert	500 - <2000	N/A		<ul style="list-style-type: none"> Routine monitoring and surveillance for scum and odours 	<ul style="list-style-type: none"> SWC and councils
Minor Incident	2000 - 6500	N/A		<ul style="list-style-type: none"> Operations manager to raise incident and send notification forms to GM Water Supply Implement weekly sampling for cell counts Increase surveillance for scum and odours Seek advice from NSW Health regarding toxicity monitoring Obtain information on Water Filtration Plant performance 	<ul style="list-style-type: none"> NSW Health (cell count and toxin levels if monitored) SWC and councils
Major Incident	>6500	N/A	1.3 µg/L	<ul style="list-style-type: none"> Seek advice from NSW Health on actions/warnings Implement twice weekly sampling and surveillance 	<ul style="list-style-type: none"> NSW Health (cell count & toxin levels), MSCRACC and affected customers
Emergency	Two or more consecutive instances of major incident levels	N/A		<ul style="list-style-type: none"> As per Major Incident and as agreed by NSW Health and affected customers 	

6.3 Recreational exposure

Primary recreational contact includes all water-related activities where direct contact and immersion in water is the intended action or a probable outcome of the activity. Primary contact includes swimming, water and jet skiing, dinghy and catamaran sailing, wind surfing, kayaking and canoeing. These activities have a risk of accidental oral ingestion of cyanotoxins from untreated raw water, and a risk of skin irritation due to contact with the water. Primary contact recreation activities are not allowed in most of the SCA reservoirs. Controlled activities are allowed at Fitzroy Falls and Lake Yarrunga.

Based on the risk of accidental cyanotoxin ingestion, restrictions on bathing are recommended when cyanobacteria cell concentrations equal or exceed 100,000 cells / mL (Chorus and Bartram, 1999). Based largely on an Australian epidemiological study by Pilotto et al (1997), it is recognised that cell concentrations of 20,000 cells (total cyanobacteria) / mL may increase the incidence of skin irritations and other symptoms in a small, susceptible percentage of the population.

Skin irritations can be caused by allergic response to compounds other than the cyanotoxins. The allergens (called endotoxins) are primarily lipopolysaccharide compounds found within the cyanobacterial cell wall, and are present in all cyanobacteria, irrespective of whether they test positive for toxins or not.

A study jointly undertaken by the SCA (Burch et al, 2002) found that skin irritation was evident only for a small percentage of individuals when exposed to water containing cyanobacteria. As the response was idiosyncratic and not dose-related, it was not possible to determine the exposure level to prevent skin irritation problems during bathing and recreational activities.

Irrespective of the cell counts reported from laboratory analyses of collected samples, if cyanobacteria surface scums are observed during routine site inspections, then bathing and other forms of direct contact are not recommended. Cell concentrations in these scums are concentrated at the water surface and can exceed 10 million cells / mL. Ingestion of surface scum material is potentially fatal.

WHO has derived a three-tiered guideline system for bathing waters. Based on this, the New South Wales Algal Advisory Group recommends a three-stage Interim Guidelines for recreation waters (Appendix C). These recreational guidelines are similar to the drinking water management with a colour alert scale. Green alert implies low cyanobacteria concentrations but requires monitoring, and amber level being a heightened level of alert, with increased sampling and surveillance. The red alert characterises a state of action where waters are unsuitable for recreation.

The SCA's recreational water response plan (Table 6.2) is applicable to Fitzroy Falls Reservoir and Lake Yarrunga, as the two storages are used for recreational purposes. Alert levels for recreational waters are triggered by the concentration of algal cells in the sample, the total biovolume equivalent, the toxin concentration or the presence of scum.

Table 6.2 SCA Monitoring and response framework (SCA, 2010b) for cyanobacteria in recreational water sources

Alert level	Total potentially toxin producing cyanobacteria cells/mL	Total cyanobacteria biovolume equivalent	Total Microcystin-LR toxicity equivalents OR Visible algal scum	Actions	Notifications
Green	500 – 5,000	0.04 – 0.4 mm ³ /L		<ul style="list-style-type: none"> • Implement weekly sampling for cell counts and surveillance for scum & odours 	<ul style="list-style-type: none"> • Forward sample results to SCC and EE
Amber (Minor Incident)	5,000 – 50,000	0.4 – 4 mm ³ /L		<ul style="list-style-type: none"> • Operations Manager to raise incident and send notification forms to GMWS • Implement twice weekly sampling for cell counts and biovolume • Increase surveillance for scum and odours 	<ul style="list-style-type: none"> • NSW Health (cell count and toxin levels if monitored) • SCC & EE (cell count) • Consult with EE on status of transfers, refer to operating protocols
Red (Major Incident)	>50,000	> 4 mm ³ /L	10 µg/L <ul style="list-style-type: none"> • Visible scums persist in the area 	<ul style="list-style-type: none"> • Seek advice from NSW Health on actions/ warnings • Continue twice weekly monitoring including toxins • Erect signage in response to algal alerts issued by MSCRACC 	<ul style="list-style-type: none"> • NSW Health (cell count and toxin levels) • NOW, MSRACC, EE • Direct customers • Stakeholders including downstream residents and recreational groups
Emergency	Two or more consecutive instances of major incident levels	Two or more consecutive instances of major incident levels		<ul style="list-style-type: none"> • As per Major Incident and as agreed by NSW Health and affected customers 	<ul style="list-style-type: none"> • As per Major Incident and as agreed by NSW Health and affected customers

6.4 Toxin guidelines

The NHMRC reviews the ADWG (NHMRC, 2004) for cyanotoxins. Currently, formal recommendations for maximum cyanotoxins concentrations in drinking water in Australia only apply to microcystins.

6.4.1 Microcystin

The Tolerable Daily Intake (TDI) adopted by WHO for human consumption of microcystins is 2.2 μg microcystin-LR toxicity equivalents / kg (body weight) with a factor of 80% of the TDI being attributed to the consumption of water. Based on a 60 kg human with an average daily drinking water consumption of 2 L, WHO derived a microcystin concentration 0.96 μg / L that was rounded up to 1 μg / L for convenience.

Whilst retaining the TDI set by the WHO, a modified guideline limit of 1.3 μg / L was recommended by NHMRC for Australian drinking water. This reflects a larger average adult size of 70 kg, and a higher percentage allocation of the TDI to drinking water (90 %). This value is expected to be maintained in the revised guidelines.

For a highly potent toxin-producing strain of *Microcystis aeruginosa* with microcystin cell quota of 0.2 pg microcystin-LR cell⁻¹, 1.3 μg /L has been assessed as being equivalent to a cell count of 6,500 cells/mL. In accordance with recommendations in the ADWG, an advisory is issued if *Microcystis aeruginosa* cell concentrations exceed 6,500 cells/ mL in two successive counts (Table 6.1).

6.4.2 Saxitoxins (Paralytic Shellfish Poisons)

Formal guideline concentrations for maximum contamination of drinking water by saxitoxins have not yet been determined in Australia or internationally due to the lack of adequate data, but are currently under development. Based on the relative molecular toxicities of saxitoxin and microcystin-LR and observations of acute exposure effects by Fitzgerald et al (1999), the South Australian Health Department nominally applies a provisional health guideline for total saxitoxins of 3 μg / L. The same value has been recommended for the revised ADWG (NHMRC, 2010).

For a highly potent toxin-producing bloom of *Anabaena circinalis* the 3 μg / L level currently used in South Australia is equivalent to a cell concentration of approximately 20,000 cells / mL in raw untreated water. An alert level of 6,500 cells/mL at 30% of the density equivalent has been adopted. An advisory is therefore issued if *Anabaena circinalis* cell concentrations exceed 20,000 cells / mL. Further details can be found in Appendix C.

6.4.3 Cylindrospermopsin

Formal guideline concentrations for cylindrospermopsin have not yet been determined in Australia or internationally due to the lack of adequate data, but are currently under development. The state health authority in Queensland informally applies a provisional health guideline for cylindrospermopsin of 1 µg / L (Orr and Schnieder, 2006). The same value has been recommended for the proposed revision of ADWG (NHMRC, 2010).

Unlike microcystins and saxitoxins, extracellular cylindrospermopsin can exceed intracellular concentrations by more than 100-fold (Chiswell et al, 2000). It is therefore not possible to predict accurately the total dissolved cylindrospermopsin concentration on the basis of cell concentration.

Where untreated water is supplied by the SCA at reservoirs for drinking and *Cylindrospermopsis raciborskii* cells are present at concentrations exceeding 1,500 cells / mL, the water should be tested for cylindrospermopsin (see Appendix C). A level of 4,500 cells/mL is at 30% of the density equivalent (0.3 µg / L), which is a suitable alert level for the SCA reservoirs. If the total concentration of cylindrospermopsin (intracellular plus extracellular) exceeds 1 µg / L (or the *Cylindrospermopsis raciborskii* population exceeds 15,000 cells/mL) an advisory should be issued, and either an alternative water supply is made available or the raw water is treated to remove algal cells and toxins.

7. Monitoring and analysis review

7.1 Overview

Water quality monitoring is the systematic collection and analysis of water samples using appropriate quality controls. It is a critical element of an effective management plan of water storages, streams and the catchment. An effective monitoring program is carefully designed to measure and report on a set of indicators which provide understanding about a particular situation and/or current or emerging risks.

The current algae – cyanobacteria monitoring program in SCA reservoirs aims to fulfil a number of objectives, including:

- identifying potential public health incidents
- measuring compliance against water quality criteria
- identifying and predicting changes and trends in water quality
- investigating the causes of blooms and measuring the success of management programs.

The SCA's water quality monitoring program consists of routine and non-routine components. Monitoring locations are noted in Figures 7.1, 7.2 and 7.3. Routine sampling is undertaken as described in the SCA's Water Quality Management Program (2010-2015) (SCA 2009) to assess the quality of catchment waters and the occurrence of changes in water quality. Non-routine monitoring is carried out to meet a number of objectives including increased event/incident surveillance, special investigations, research and evaluation. Non-routine monitoring also helps describe the influence of floods, bushfires, contamination incidents, spills, assessment of the impacts of catchment activities and/or interventions on water quantity or quality.

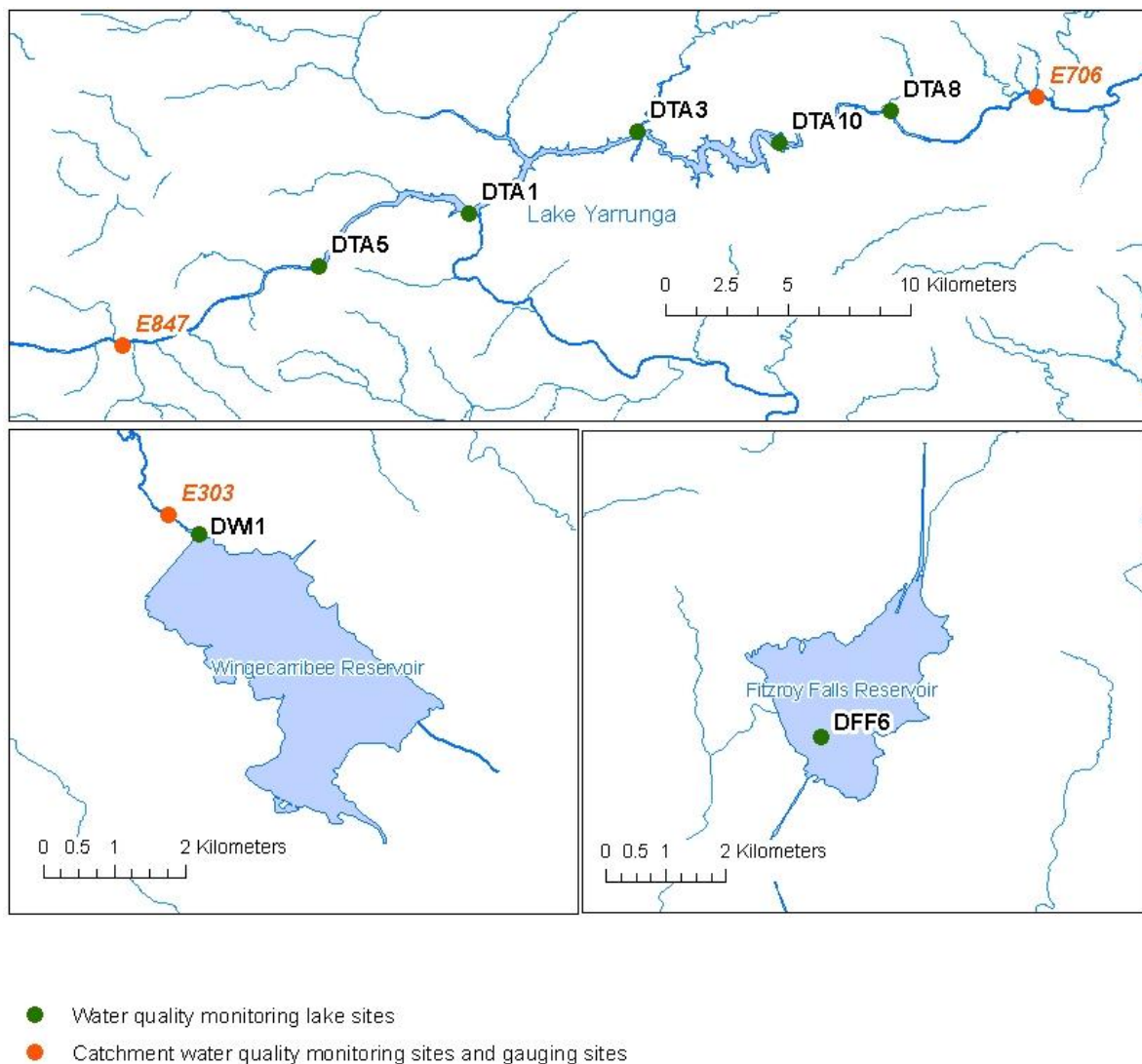


Figure 7.1 Monitoring locations at Tallowa Reservoir Lake Yarrunga (top), Wingecarribee Reservoir (left) and Fitzroy Falls Reservoir (right). Raw water supply and non-supply sites shown

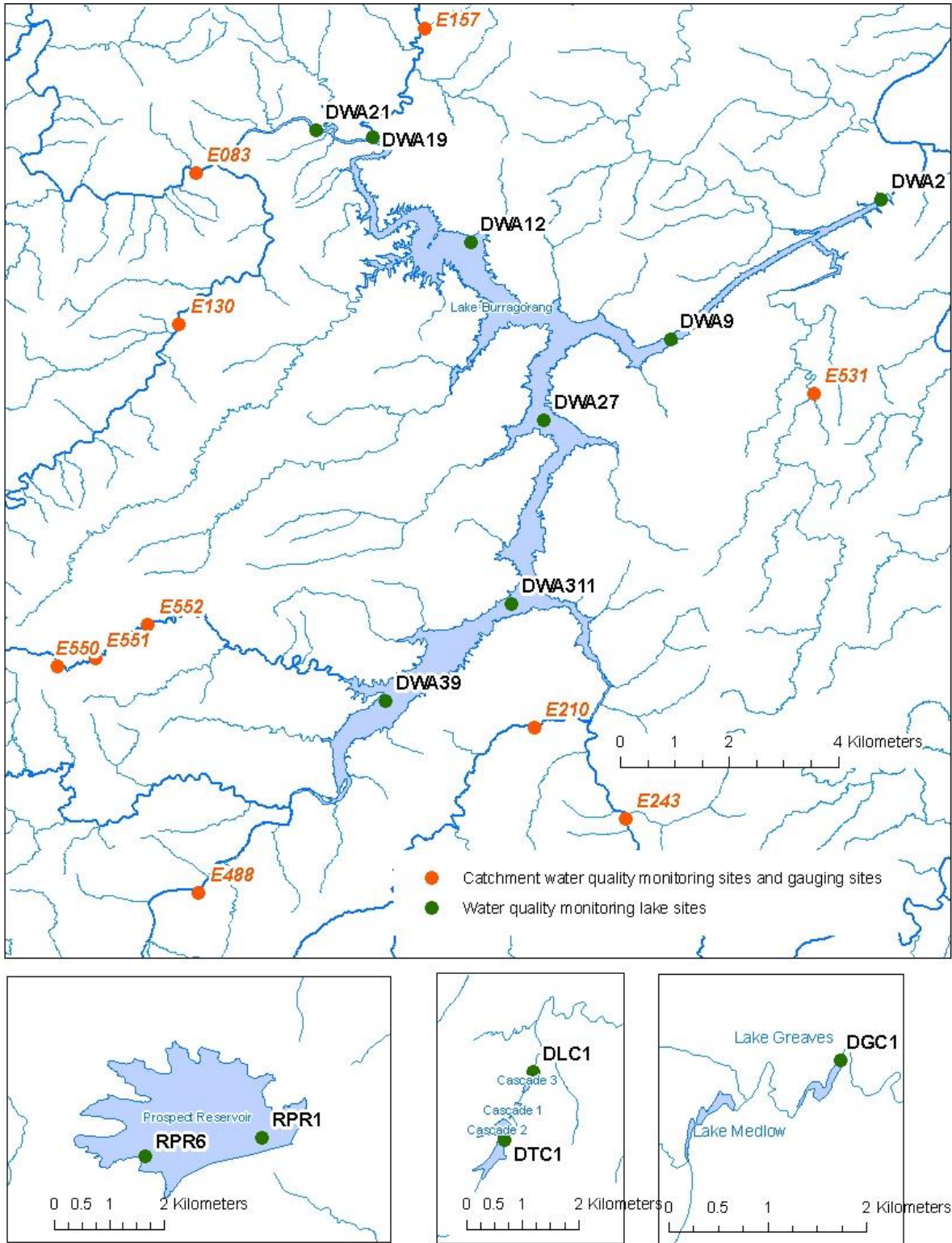


Figure 7.2 Monitoring locations at Warragamba Reservoir (Lake Burragorang) (top), Prospect Reservoir (left) and the Blue Mountains reservoirs (centre and right). Raw water supply and non-supply sites shown

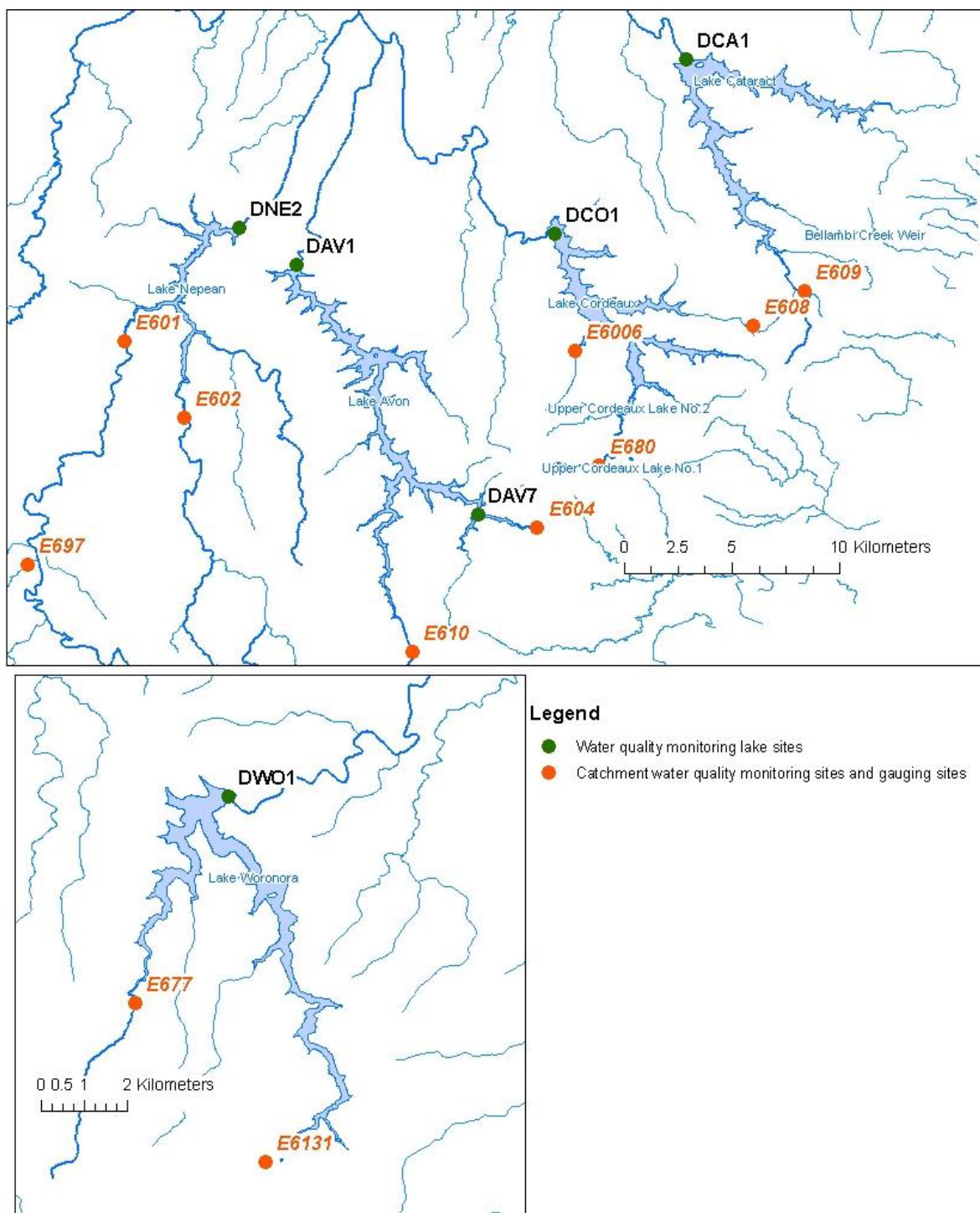


Figure 7.3 Monitoring locations at Nepean, Avon, Cordeaux and Cataract reservoirs (top) and Woronora Reservoir (bottom). Raw water supply and non-supply sites shown

7.2 Cyanobacteria monitoring

The arrangements for ‘routine’ cyanobacteria monitoring in SCA reservoirs are described in both the Water Monitoring Report and the SCA’s Cyanobacteria Response Plan (SCA, 2010b) and are based on:

- time of the year (season)
- existence and proximity of raw water supply offtakes
- concentrations of chlorophyll-a
- concentrations of potentially toxin producing algae.

The schema for the SCA’s cyanobacteria monitoring and for escalation of monitoring to meet the requirements of the response plan are shown in Figures 7.4, 7.5 and 7.6. Figure 7.4 shows the procedure for managing risk through cyanobacterial monitoring for raw water supply offtake monitoring sites. The frequency of monitoring is determined according to season, but depending on the numbers of potentially toxin-producing cyanobacteria detected, monitoring can be increased or escalated to the levels defined in the Cyanobacteria Response Plan (SCA, 2010b) if the risk of toxin-producing cyanobacteria increases. The toxin-producing cyanobacteria thresholds are in line with the Australian Drinking Water Guidelines (ADWG), a well-accepted benchmark for Australian raw water supply (Section 6).

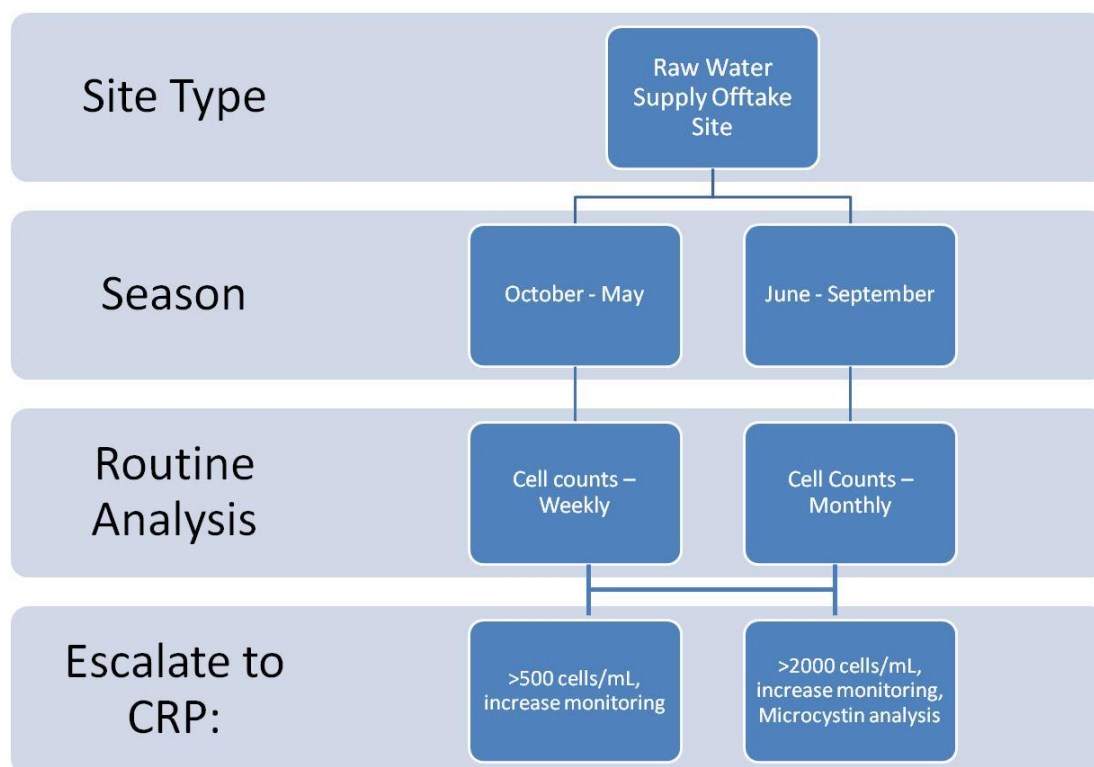


Figure 7.4 Flow chart for routine raw water supply site cyanobacteria monitoring

Figure 7.5 shows the procedure for all other monitoring sites including catchment sites. In this instance, chlorophyll-a rather than cyanobacteria cell counts (because cell counts are not routinely monitored at these sites) is used as the benchmark for determining an 'escalation' of the process, otherwise the process is similar to Figure 7.4.

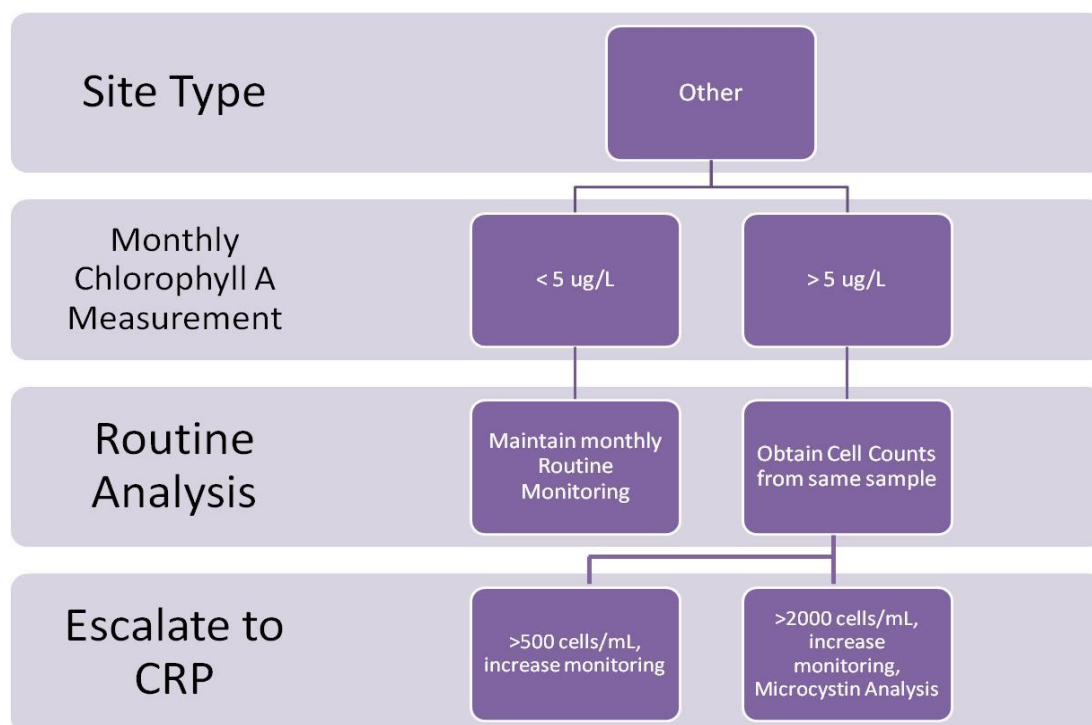


Figure 7.5 Flow chart for routine non-raw water supply site cyanobacteria monitoring

In respect to both of these procedures, elevation of a response is not an automatic process but is implemented as part of a broader evaluation of the situation. This evaluation is undertaken by Water Quality Analysts within the Operations division of the SCA. The decisions are also guided by the specific uses of each storage as indicated in Table 7.1 below.

Depending on the relevant guideline, and the potentially toxin-producing cell counts, the Cyanobacteria Response Plan sets out the monitoring requirements as illustrated in Figure 7.6. The response is designed in such a way to reflect the degree of risk associated with the delivery of good quality water and/or recreational activities. The threshold values are in line with ADWG (NHMRC, 2004) and the Guidelines for Managing Risks in Recreational Waters (NHRMC, 2006):

- Red – High Alert
- Orange – Medium Alert
- Green - Low Alert

These alert levels are described in Section 6 and Appendix C.

Table 7.1 Site specific plans for the CRP according to usage

Site*	Recreational guidelines	Raw water guidelines	Town water guidelines
Tallowa reservoir	Yes	If pumping to Bendeela	No
Bendeela Pondage**	No	Yes	No
Fitzroy Falls Reservoir	If alternative supply provided – storage and releases	No	Yes. If alternative supply provided – picnic area only
Wingecarribee Reservoir	Water releases only	Yes	No
Nepean reservoir	No	Yes	No
Avon reservoir	No	Upper Avon only	Avon picnic area only
Cataract / Cordeaux reservoirs	No	If alternative supply is implemented	Supply to picnic areas and cottages
Woronora reservoir	Releases only	Yes	No
Prospect reservoir	Releases only	If storage is on supply network	No
Warragamba reservoir	Releases only	Yes	No
Blue Mountains reservoirs	Releases only	Yes	No

* Most sites also have Standard Operating Protocol documents for protocol guidance.

** Bendeela Pondage is also guided by the Shoalhaven Water Supply and Power Generation Scheme Operating Protocols during Cyanobacteria Events.

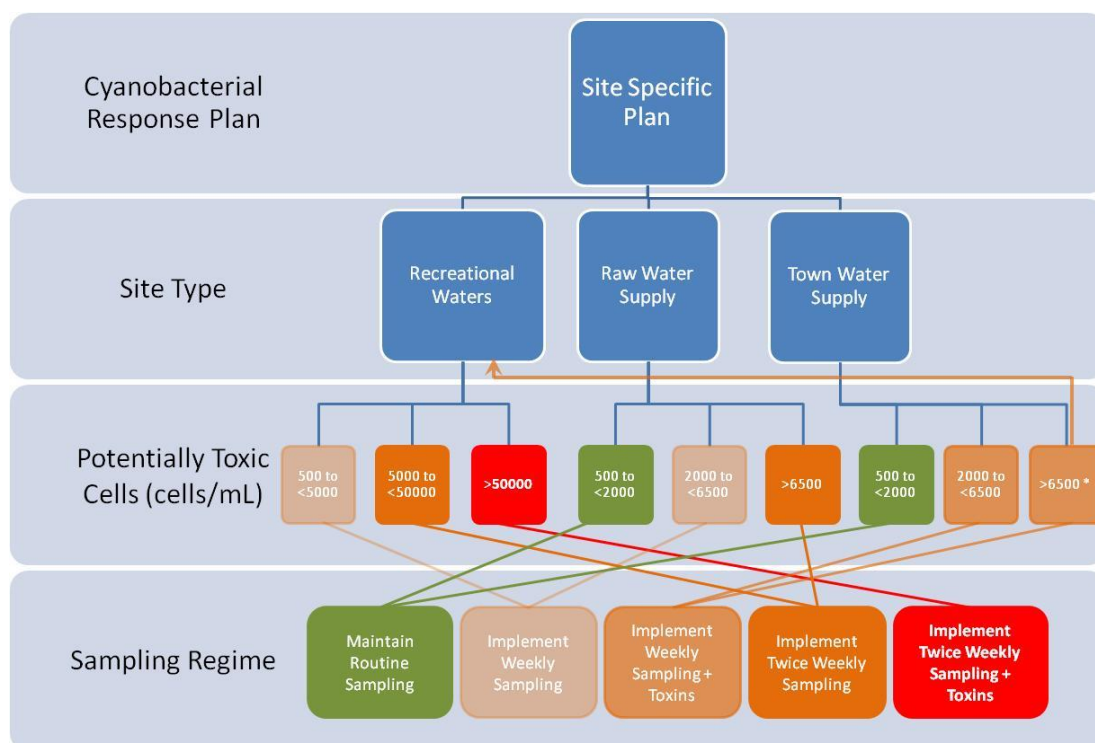


Figure 7.6 Flow chart of monitoring response as noted in the Cyanobacteria Response Plan monitoring

The response plan procedures have generally worked well in previous cyanobacteria incidents but they do have some limitations in that they:

- are captured in a number of inter-related documents which can be confusing
- assume that all potentially toxin-producing algae pose the same degree of risk and are placed at similar thresholds when in reality there are distinct differences in the potential toxicity of different species
- do not address the longer term objectives for risk assessment, investigation of causes and strategic planning that rely upon trend analysis.

It is a simplification to suggest that all cyanobacteria offer a similar toxin risk however this premise is derived from the ADWG and the Guidelines for Recreational Waters (NHRMC, 2008). The SCA Cyanobacteria Response Plan (SCA, 2010b) is based on the total cell numbers of potentially toxin-producing cells such as *Microcystis* and *Anabaena*. In fact, 2,000 cells/ml of *Microcystis* would present a much higher risk than 2,000 cells/ml of *Anabaena*. *Microcystis aeruginosa*, *Anabaena circinalis*, and low risk species, such as *Anabaena flos-aquae* and *Microcystis flos-aquae* are treated equally. Although it is a conservative approach to ensure the safety of customers, a review of these guidelines and thresholds is expected to take place when the new ADWG are finalised by the NHMRC.

The procedures described above are primarily designed to directly meet the SCA's regulatory requirements and respond effectively to developing incidents. The decision processes and analyses are therefore designed around a day to day operational framework. However the SCA also needs to use the data collected for trend analysis and improved understanding of algal bloom behaviour. A rigorous trend or investigative analysis can be significantly compromised by a dataset which varies between monthly, weekly and fortnightly sampling both between sites and between seasons. While the procedures allow an increase in the frequency and suite of measurements as the risk of an algal bloom increases, there is no concurrent increase in sampling for cyanobacteria drivers such as nitrogen and phosphorus. This means that subsequent investigations into the causes of the bloom and improved understanding of the storage dynamics during the incident are limited.

Some of these issues are in part addressed through the SCA's non-routine monitoring program which can be used to collect additional data either during or outside of potential cyanobacteria incidents. More effective use of the non-routine monitoring arrangements is desirable to assist in a range of research and investigative activities and can ultimately lead to a reduction in the extent and cost of routine monitoring. Non-routine investigative activities may review:

- storage behaviour in terms of nutrients and algae following different inflow events
- nutrient and algal responses during destratification/turnover events in shallow storages
- the effectiveness of the HCP in reducing nutrient loadings in different events.

7.2.1 Sampling for cyanobacteria and cyanotoxins

Analytical methods for cyanobacteria and cyanotoxins sampling in Australia are reasonably consistent across water authorities. Burch et al (2005) suggested that certainty of results versus cost is a critical element in designing an algal monitoring program. As algal sampling (and analysis) is labour intensive and expensive, managing the number of samples collected whilst still obtaining the required degree of certainty is critical to cost-effective monitoring in each storage. To provide an appropriate degree of certainty at an acceptable cost the SCA has tailored its cyanobacteria sampling programs to the risks associated with different storages.

The SCA manages this by using differing sampling frequencies, locations and collection types according to its understanding of the storage and the degree of certainty required. If the storage is critical in the water supply network or is at a greater perceived risk of cyanobacteria blooms, then sampling is more frequent with more representative sites such as Wingecarribee Reservoir. As the certainty in understanding or risk lessens, so does the sampling frequency and/or the number of sites.

Various sampling methods are used by the SCA to reduce the cost of sampling. One such method is the use of composite (collected from different depths which are combined and then sub-sampled) as distinct from discrete (obtained at a defined depth) samples. The theory is that as cyanobacteria habitat follows a distribution curve analogous to light penetration in the water column, additional discrete samples are perceived as not providing any extra information than a composite but can significantly increase the cost.

Cyanotoxin sampling is designed to provide spatial and temporal information regarding the risk of toxins to water quality. There are three generally accepted ways of describing toxin levels:

- the concentration of toxin bound in cyanobacteria cells
- the concentration of dissolved toxin in the water column
- the actual toxicity of the toxin.

Each approach defines the sampling methodology, which in turn defines the sample storage and preservation requirements. For example, cell bound toxin measurements require an algal sample from a defined sample volume and the required volume is obtained, filtered and the retentate is preserved for analysis within 48 hours. Dissolved toxin measurements require an aqueous sample, which must be collected, filtered and the filtrate preserved and analysed within 48 hours. Sample storage protocols are aligned with requirements for the analysis. The methods that the SCA uses for cyanobacteria and cyanotoxin measurements are NATA accredited for quality control.

7.2.2 Analysis for cyanobacteria

Methods for estimating abundance of cyanobacteria can be described at a three levels of analytical effort (high, moderate or low) (Burch et al, 2005). The levels of analytical effort are dependent on:

- qualitative or quantitative assessment
- the level of taxonomic identification of specimens
- incorporation of a sample preparation step
- standard of equipment used
- cost versus certainty.

These techniques can be broadly characterised into the methods used for analysis. The SCA requires data on chlorophyll-a concentrations, cell counts and biovolume. The SCA employs laboratories and contractors which use the highest standards of analysis available in Australia and ensures appropriate validation and calibration of all techniques applied (validated by NATA). More details about the cyanobacteria analysis can be found in *Phytoplankton Methods Manual for Australian Freshwaters* (Hötzel and Croome, 1999) and the *National Protocol* (Burch et al, 2005).

The three major areas of uncertainty in algal analysis/speciation are:

- how representative of cyanobacteria is chlorophyll-a
- the accuracy of algal identification (some species look very similar under a microscope to others, for example some *Aphanothece* and *Microcystis* species, and thereby change the risk profile significantly)
- the margins of error and how they are taken into account in risk frameworks.

The error margin is a difficult issue in that as the Cyanobacteria Response Plan is finely leveraged against cell counts, the perceived 40% error in counting leads to a very large area of uncertainty. Effectively 2,000 cells/ml may be as low as 1,400 cells/mL or as high as 3,000 cells/mL, which is a large degree of uncertainty. How this error feeds into risk management of storages is worth considering for future revisions of the cyanobacteria risk protocol.

7.2.3 Analysis for cyanotoxins

A number of techniques are available for measuring cyanotoxins in water, and a number of studies have been undertaken to evaluate and compare these analytical techniques (Nicholson and Burch, 2001). Chromatographic techniques are generally used to quantify most of the toxins. There are other toxin-specific analytical techniques as well. Further, non-quantitative methods are also available to detect the presence of toxins. These techniques include protein phosphatase inhibition assays, enzyme linked immunosorbent assays and mouse bioassays. Nicholson and Burch (2001) discuss.

As with cyanobacteria analysis, the SCA employs high standards of analysis for these parameters. At a research level, both rapid methods (generally qualitative) and quantitative methods are considered. If the method can be validated to a high standard (NATA) and demonstrated to offer advantages over existing methods, then the SCA actively pursues implementation of this method within the analytical program.

7.3 Nutrient monitoring

Cyanobacteria bloom formation, persistence and decline are often defined by available nutrients in the water column. In Australia, this generally involves available nitrogen and phosphorus. The SCA has a routine (and non-routine) capacity for measuring and monitoring phosphorus and nitrogen in the water column. All current analytical methods for these nutrients employ the highest standards of analysis available in Australia (NATA, APHA methods) and are upgraded when improved methods become available.

The sampling resolution for nutrient monitoring is designed to support short term operation decision making but is not suitable for describing cyanobacteria dynamics at all storages. Typically, samples for algal measurements are obtained at or near the surface, while nutrient measurements are captured across the entire water column. In the shallower storages, the disjoint between sampling depths is unlikely to be a problem, but in deeper storages it can make understanding how nutrient loads influence algal growth extremely difficult. Furthermore, the Cyanobacteria Response Plan (SCA, 2010b) does not provide for an increase in nutrient measurements to coincide with the escalation of algal measurements. Without information about the relationship between the nutrients and growth, conclusions are likely to be significantly constrained. In many cases the SCA will instigate non-routine monitoring of nutrients when there is an algal escalation but this depends on ad hoc decisions made during the event.

Nitrogen analysis has remained relatively consistent and robust over time and is therefore suitable, within sampling limitations, for describing trends. However the methodology for phosphorus monitoring has changed a number of times over the last 20 years including the limits of reporting (surrogate for detection), sensitivity, and error bounds. Significantly, the analytical laboratory used has also changed.

Limits of reporting are the lowest values that can reliably be quantified in an analysis. A shift in this value suggests a change in the range of values reported. Depending on results, this creates a significant amount of censored data, which will be discussed shortly. Sensitivity is the potential to differentiate one value or type from the next, which puts uncertainty around actual values. Error bounds are an attempt to quantify the uncertainty (which in turn feeds off sensitivity), which when shifting actually changes the underlying value. Possibly the most difficult analytical element to reconcile are changes in analytical laboratory, which unless cross-validated at the time (across labs) cannot be remediated after the fact.

From an interpretation of long term TP data it is immediately apparent there is a significant amount of left censored data (such as $< X$ or $< Y$) and there is no comparable data or before and after assessment of the impact of these changes in methodology. The SCA currently has no statistically validated method for integrating left censored data with discrete numbers or for making comparisons between these changed methodologies. There are a number of techniques that statistically validate left-censored data into real values but they are generally time consuming and require significant work to validate. It may not be practical to review past method changes and adjust results as the older techniques are difficult to replicate with precision as many are operator dependent. It is worth considering what processes are needed to manage future changes in analysis.

8 Management options

8.1 Overview

Most occurrences of cyanobacteria blooms have considerable complexity in their cause and effect (Figure 8.1). Management measures should be implemented according to the nature and level of concern, and their likely effectiveness. A range of options can be used, such as mitigating the potential effects of the bloom, controlling the algal growth, avoiding the bloom and identifying and managing the causal factors. Even without a bloom, smaller cyanobacteria concentrations may pose a significant health risk should the proliferation occur near the water surface as a virtual monoculture of a toxin-producing cyanobacterial species. In deep lakes or turbid rivers, blooms are confined to the upper layer where there is enough light for growth.

CYANOBACTERIA RISK			
Management Approach	Short-term	Medium-term	Long-term
Setting Management Priorities	Incident Management Plan	Storage Management Plan	Healthy Catchment Strategy
Management Action	Notifications Alerts Algae Removal Selective off-take Bubble Curtains Chemical Treatment Alternative Supply	Destratification Nutrient Removal Seed Control Biomanipulation Dredging	Data Collection Monitoring Modelling Healthy Catchment Development Control Rural Lands Sewage Riparian Stormwater
Research	Early Warning Epidemiology	Limnology Control Measures	Nutrient Budget Control Measures
Community	Education	Education	Education
At SCA	Water Supplies, Catchment Operations, and Corporate Development & Sustainability		

Figure 8.1 Managing cyanobacteria risks

Short, medium and long-term strategies can be applied to minimise the exposure risk to cyanotoxins and cyanobacteria cells. A number of scientific, ecological, economic, ethical and legal issues must be considered when the strategies are assessed. The SCA undertakes a number of activities that collectively influence the presence of cyanobacteria. Some of these activities are generic but can help reduce the risks associated with cyanobacteria. Other activities are targeted to influence the levels of cyanobacteria. The short-term incident responses address the presence of cyanobacteria cells and toxins in the

reservoirs, and are planned and implemented in response to the adopted alert levels. The medium-term plans focus on storage management to manage blooms. The long-term programs attempt to address the causes of blooms both within the reservoirs and their broader catchments.

The most significant activities are:

- contingency planning for health-threatening events
- routine storage management procedures that minimise entry of cyanobacteria and toxins into the distribution system
- upgrading and refinement of water treatment processes as required
- promoting appropriate development and management practices to control the entry of nutrients that support cyanobacteria growth
- water quality monitoring and database management to detect high levels of contamination and allow trend and state analysis
- research targeted to enhance the effectiveness of each of the above activities.

Each of the SCA reservoirs is unique and therefore management options need to be tailored for each storage based on the limnology of the reservoir, hydrology, and nutrient loading of the sub-catchment. The SCA (Vigneswaran and Bales, 2010) prepared a summary with a range of potential options in terms of effectiveness, cost, applicability and implications (**Table 8.1**).

A wide range of potential management options exist for the control of cyanobacteria and the impacts of cyanobacteria in freshwater reservoirs (CRCWQT, 2002; Newcombe et al, 2010; Vigneswaran and Bales, 2010). This section summarises some of these management options relevant to SCA reservoirs.

8.2 Short-term storage management and operational controls

The management of incidents, such as cyanobacteria blooms, is covered by the Corporate Risk Management Framework (CRMF) (SCA, 2010b) which establishes the broad structure for response to incidents. The Raw Water Quality Incident Response Plan (RWQIRP; SCA, 2010b) is part of the CRMF and deals with incidents specific to water quality within the storages and in the supply delivered to customers. The Cyanobacteria Response Plan (SCA, 2010b) is in turn a sub-set of the RWQIRP and deals very specifically with water quality contamination by cyanobacteria.

The SCA's Cyanobacteria Response Plan (called the Blue-Green Algae Contingency Plan) was first prepared in November 2000, with the most recent revision in March 2010. The aim of the plan is to assist in the identification, response and overall management of water quality should a cyanobacteria event occur. This Plan includes operational response plans for each SCA reservoir that may be adversely affected by cyanobacteria.

A range of possible short term, or quick response, management options for addressing cyanobacteria blooms are highlighted in sections 8.2.1 to 8.2.6.

8.2.1 Selective off-take level

Algae cells are buoyant and usually confined to the surface layer, so one of the most effective means of minimising risks posed by their presence is to extract water from below the thermocline. Wherever possible, water should be drawn from the deepest off-take point without disturbing the bottom sediments or manganese balance (Jones and Orr, 2000). Withdrawal depths for SCA reservoirs can be varied, however drawing deeper water may introduce other potential water quality issues if turbidity, metals, and low oxygen levels are present in the deeper water. Such conflicts are particularly common after floods or in the autumn when the reservoir begins to destratify. The SCA faced this challenge during the inflow event in 2007 with highly turbid water in the deeper layer and the cyanobacteria bloom in the surface layer near the dam wall.

The depth of the mixed surface layer is about 5-15 metres in most Australian storages and is often about the same as the euphotic depth. The mixed surface layer depth can go down to a depth of 18 m for Warragamba Reservoir. The SCA has standard procedures to determine the most suitable depth to extract water.

8.2.2 Use of alternate supply

The SCA, as part of its contingency plans, has the option to use alternative supplies during cyanobacteria blooms, allowing contaminated storages to be isolated from supply. However, alternative supplies are not readily available for most of the water treatment plants.

8.2.3 Filtration and other treatment processes

While most algae can be removed by filtration in a water treatment plan when the coagulation process is optimised for cyanobacteria cells, odorous compounds or other organic material that may be released by the death and breakdown of the cells cannot be removed.

The most suitable process is activated carbon filtration which is expensive but often the only available water treatment option. This option is available at Kangaroo Valley and Wingecarribee water filtration plants. There are contingency plans in place to incorporate powdered activated carbon dosing at Warragamba and Orchard Hill water treatment plants. Boiling water can exacerbate the problem of toxins. Chlorination, ozonation and UV irradiation also destroy certain cyanotoxins (Newcombe, 2002).

An extensive analysis of treatment options for cyanotoxin removal is beyond the scope of this document, and can be found elsewhere (Vigneswaran and Bales, 2010; Brookes et al, 2008a and 2008b).

8.2.4 Algal cell precipitation

Cyanobacteria cells can be precipitated from the water column in certain circumstances through the addition of compounds such as alum, lime or clays. The effectiveness of this approach is highly variable and experience using this technique in natural waters is limited

(Jones and Orr, 2000). Reasonably good precipitation is possible when cells are accumulated in dense surface scums, but when cells or colonies (clumps of cells) are dispersed through the surface water layer the treatment will be far less effective.

The logistics of application and cost effectiveness to precipitate cells and nutrients make addition of chemicals prohibitive in large reservoirs. Hence, in-situ precipitation is not suitable for SCA reservoirs.

8.2.5 Bubble curtains

A constant stream of bubbles provided by a submerged diffuser can be used to surround the off-take zone to form a curtain, through which most algae will not travel to reach the off-take. Theoretically, in addition to the blocking mechanism, air bubbles will float the algal cells to the water surface (Jones and Orr, 2000). However, the effectiveness of off-take bubble curtains against cyanobacteria has not been quantitatively assessed, nor is there much practical experience with their use in Australia (Sherman, 2000).

8.2.6 Chemical treatment

Chemical treatment, most commonly the use of an algaecide (usually copper sulphate) can reduce cyanobacteria blooms. SWC adopted this option once in Wingecarribee Reservoir during the summer of 1997-98. Application of algaecides is no longer considered best management because it also poisons non-target organisms such as zooplankton. Chemical treatment may also cause increased toxin concentration in water as the dead cells lyse and release toxins that could have been removed by filtration of intact cells.

Chelated copper algaecides were developed for selective release of copper and to avoid copper precipitation. Despite their relatively widespread use in the USA, the effectiveness of chelated copper algaecides on water chemistry and the long term effect on the aquatic environment are poorly understood (Burch et al, 2002). In consultation with the health authorities, the NSW Department of Environment, Climate Change and Water may allow use of algaecides (registered or permitted by National Registration Authority) as the last resort. A list of alternate algaecides can be found elsewhere (Burch et al, 2002a; CRCWQT, 2002).

8.3 Medium-term storage management approach

Considering the toxicity, economic, environmental and aesthetic risks associated with cyanobacteria, preventing blooms is preferable to treatment to remove the effects of a bloom. There are a number of medium-term options that can be considered for storage (in-reservoir) management to avoid or reduce cyanobacteria cells and toxins. These approaches depend on the regular monitoring of relevant water quality parameters to inform the SCA's decision making and choice of actions. These management options are outlined in Sections 8.3.1 to 8.3.6.

8.3.1 Artificial destratification

Most of the harmful species of cyanobacteria, including all the known toxin-producing species in Australia, tend to proliferate in calm stable waters. Typically they occur in lakes and reservoirs, especially in summer when thermal stratification reduces vertical mixing. Artificial destratification has been used in attempts to remediate lakes and ponds suffering from bottom anoxia (no oxygen) and nutrient loading from the sediments causing cyanobacteria blooms.

The SCA currently employs mixing by compressed air bubbling technique in Prospect, Avon, Nepean and Woronora reservoirs. Pressurised air is percolated through perforations of a long polyethylene pipe. Tallowa Reservoir was also mixed at the dam wall by compressed air bubbling from 2005 to 2009. The reservoirs in the Blue Mountains are destratified by mechanical mixers. Mixing in the SCA reservoirs was done historically to manage metals (iron and manganese) and was not optimised for algal control.

Artificial mixing has frequently failed to prevent cyanobacteria blooms because the mixing principles for optimum performance were neglected (Chorus and Bartram, 1999). There are numerous cases in Australia where destratification has satisfied thermal design criteria but failed to meet chemical and biological criteria. Sherman et al (2000) found that although properly sized destratification systems such as bubble plumes were able to drastically reduce the internal nutrient load, they frequently failed to produce a deeper surface layer. This failure to deepen the surface layer arises when local climatic conditions are not energetic enough (eg mean daily wind speed < 2-3 m/s) to deepen the surface layer even though the stratification has been greatly weakened. Destratification can be expected to reduce average annual algal biomass where internal nutrient loads are significant, but it cannot be expected to cause a shift away from dominance by cyanobacteria.

8.3.2 Control of seed sources

Most species of cyanobacteria have a distinct seasonal pattern in temperate zones, and blooms normally occur in late spring and summer. Some species may survive as resistant spores (akinetes) during winter, whereas others hibernate as a small number of vegetative cells. The akinetes and hibernating cells are essential for the year-to-year persistence of cyanobacteria. A recent study indicated that the vegetative cells and akinetes are found in higher densities in shallow backwaters and lagoons on the flood plains. The backwater may also serve as the nutrient source. Isolation of those backwaters, especially during cyanobacteria risk periods, could reduce the blooms in the main reach of the river (Steffensen et al, 1999).

There is another hypothesis that the cells hibernate at the bottom and resuspend later in certain reservoirs. Cyanobacteria blooms cannot be controlled in SCA reservoirs by controlling the seed sources, as most of the reservoirs do not have specific backwaters and cyanobacteria cells are present throughout the year in almost all SCA reservoirs.

8.3.3 Phosphorus removal

The objective of this approach is to reduce phosphorus levels in the reservoirs and rivers. This procedure is suitable for waters where algal blooms are intensified by excess phosphorus from point sources, runoffs or internal re-suspension of sediments. Alum, sodium aluminate and ferric chloride were used in the past to bind or precipitate dissolved phosphorus. However, addition of aluminium or ferric salts to drinking water sources is not preferred. Smaller reservoirs may be dredged either to remove the bottom sediment or to treat it and replace. There are other temporary medium term methods, such as sediment capping using lime, clay and alum.

A relatively new product called Phoslock has been marketed for phosphorus management. Phoslock incorporates Lanthanum bound to bentonite clays, and claims to bind phosphorus in the water column and sediment pore water. In field application, this clay-based substance is spread over water, allowing it to sink to the bottom. Phoslock must be reapplied periodically to remove phosphorus entering the water body with the inflows. Potential secondary effects of the product on human health due to the potential for elevated concentrations of Lanthanum in raw water supplies, and on ecosystem health, need to be assessed for each potential application. A comprehensive cost-benefit analysis should be undertaken to determine the applicability of this additive in the SCA reservoirs to remove phosphorus (Douglas *et al.*, 1999).

Literature on the longer term effectiveness and implications of the application of Phoslock in Australian lakes is very limited and almost non-existent for drinking water storages. Water Services Association of Australia will undertake a desktop assessment, in consultation with the SCA, about the suitability of the product in Australian water bodies and the implications for drinking water supplies.

8.3.4 Biomanipulation

Biomanipulation refers to altering the food chain in a specific environment so that the predation pressure of fish will be altered. In the reservoir management context, biomanipulation includes the alteration of the food web to favour grazing on algae by zooplankton. Biomanipulation typically involves eliminating fish that feed on zooplankton, but may also include other management actions such as the encouragement of water plants to create refuges from predation that allow the size of the zooplankton population to increase. For biomanipulation to be effective in the control of cyanobacteria, the zooplankton species present must be able to effectively graze on the particular cyanobacteria species causing the problem.

The results of these management interventions in the field have been variable. In some cases initial improvements have not been sustained in the longer term, or the manipulations have actually exacerbated the situation. Biomanipulation is more likely to succeed in closed reservoirs (Yoo *et al.*, 1995; Chorus and Bartram, 1999). The nature of zooplankton population in the SCA reservoirs and their interactions with the cyanobacteria population is not well understood. Hence, effectiveness of biomanipulation as a cyanobacteria control method is uncertain.

8.3.5 Hypolimnetic aeration / oxygenation

Hypolimnetic aeration is used in reservoirs with a stable thermal stratification during summer months. The process results in aeration of the hypolimnion without destratification, thus warming of the lake is avoided. Hypolimnetic aeration may affect the buoyancy of cyanobacteria. Further, this process may indirectly influence phytoplankton population by increasing the aerobic volume, in which the phytoplankton-grazing zooplankton can thrive. However, several studies on hypolimnetic aeration resulted in conflicting outcomes, as some investigators reported reductions in chlorophyll-a while others reported increases, and still others have reported no effects of the process on either the level of phytoplankton production or phytoplankton community structure (Yoo *et al*, 1995).

8.4 Long-term approach

In the long term, actions to try to control the fundamental causes of cyanobacteria blooms are often recommended. The most common focus of these long term strategies is to minimise the input of essential nutrients to the water body. Approaches for the long-term management of cyanobacteria are outlined in Sections 8.4.1 to 8.4.3.

8.4.1 Controlling nutrient inputs

It is the concentration of the key nutrients, nitrogen and phosphorus that, along with light, most influence cyanobacteria numbers in water. Although light intensity cannot be readily controlled and is in fact increased by reducing turbidity of water, nutrient levels can be controlled.

Reducing nutrient concentrations will reduce the algal carrying capacity of a storage without necessarily changing the species composition. The rate of growth of an algal species is dependent upon the available light, and cyanobacteria do not grow well in environments where the surface layer is deeper than three times the euphotic depth. The time scale of nutrient uptake is so much shorter than the time scale of photosynthesis that it is unlikely that nutrient concentrations alone will have a significant effect on growth rate. There is some evidence that the form of inorganic nitrogen (ammonium or nitrate) in the water column may influence competition between cyanobacteria species.

In the SCA's catchments the largest nutrient input originate from agricultural sources, including cropping land and livestock, particularly during large inflows. Although point source urban discharges such as STPs may dominate during low flow periods, the total volume at these times is very low and unlikely to be enough to trigger major cyanobacteria blooms. Overflows of untreated sewage were identified as a potentially significant source of nutrients in the past (eg the 2005 Catchment Audit report), however recent assessment suggests that the contribution of sewer overflows to the total annual nutrient inputs to the Warragamba Reservoir is insignificant (Water Futures, 2008; SCA, 2008d).

Diffuse source management

Nutrients supplied from forested and agricultural areas can lead to cyanobacteria blooms in the receiving waters. Runoff from recreational areas, and leaks and overflows from septic systems and the stormwater network contain high levels of nutrients. Grazing animals also make major contributions to the nutrient increase in some waterways.

The following activities can be undertaken to control the nutrient addition caused by diffuse sources (Yoo *et al*, 1995):

- control of runoff from developing and developed areas
- management (timing, quantity, etc.) of the application of phosphorous based fertilisers in line with soil requirements, climatic conditions and pasture types
- control of overland runoff from feedlots, dairies, piggeries and other intensive animal farming operations by using holding dams, land application and reduced water use
- rehabilitation of riparian strips to provide a buffer strip between land uses and waterways
- reduction of soil loss from cropping lands through erosion control strategies
- control of stock and animal access to waterways (off-river watering, fencing, etc)
- limitation of phosphate based reagents
- careful siting, design and maintenance of on-site systems.

While catchment development controls and interventions can help to stabilise and/or reduce nutrient loads entering storages from catchments during significant rainfall events, the catchments draining to the Warragamba and Tallowa reservoirs are so extensive (9,000 and 7,000 square kilometres respectively) that they are likely to have the capacity to supply enough nutrients during large runoff events to support major algal blooms irrespective of effectiveness of catchment management interventions.

Point source management

Point sources include domestic wastewater (sewage), industrial effluents, stormwater drains and septic systems. In the past, STP discharges were the major contributor of point source nutrients, accounting for at least half of the total phosphorous input into rivers and reservoirs in densely populated areas. Chemical precipitation, in conjunction with biological nutrient removal, can reduce the phosphorous concentrations in domestic wastewater effluent by an order of magnitude. With the upgrade of most the STPs in the SCA catchments (as part of the Accelerated Sewage Program) over the last 10-15 years, the nutrient loads being discharged from these sources have been substantially reduced.

Other methods of point source pollution control include the transfer of sewage discharges off catchment or the land application of wastewater effluent. The Kedumba arm of Warragamba Reservoir was considered to be a high-risk location in terms of cyanobacteria in the 1980s and the 1990s (Hawkins and Hassan, 2003). However, nutrient concentrations and chlorophyll-*a* levels measurably decreased after 1998 when the discharge of effluent from the South Katoomba STP was discontinued and transferred off catchment.

8.4.2 Flow control

Altering flow regimes from those that would occur naturally can alter algal dynamics in some reservoirs. Compared with natural conditions, reduced flows allow for less turbulence in the water column, less dilution of nutrients, reduced turbidity and longer retention times that will allow stratification and conditions favourable to cyanobacterial blooms (Sherman *et al*, 1998). Increased flows, for example through water transfers may reduce the potential for cyanobacteria by increasing nutrient dilution and increasing turbulence in the water column. However, water transfers may also contribute additional nutrients if the transfers are originating from a nutrient rich source, and may also risk cyanobacteria being displaced downstream.

8.4.3 Catchment management

A significant portion of the SCA's activity is targeted to:

- planning and control of future development in the catchments
- rectification or improvement of existing pollution sources or hazard events.

These broader catchment activities are undertaken to address a range of pollution problems including the high nutrient loads which can cause cyanobacteria blooms.

Healthy Catchments Strategy

The SCA has identified the key risks to water quality in each of its drinking water storages through the analysis of historical water quality data and application of its Water Quality Risk Management Framework. At the same time, the CDSS has rated the relative risk from all nutrient sources across the SCA catchment using a weighted hierarchical index based on climate, landscape and land management criteria. This has identified priorities for rectification actions to reduce the potential for nutrient export.

The Healthy Catchments Strategy (HCS) is the SCA's strategy for protection and remediation of water quality and catchment health issues, which will be implemented through the HCP.

The HCS comprises the following seven strategies (SCA, 2009):

- Sewage
- Riparian
- Rural Lands
- SCA land management
- Compliance
- Stormwater
- Catchment information.

The HCP is being delivered through the use of a number of tools including grants and assistance schemes, education programs, regulation and direct management.

Two key initiatives under the HCP have been the On-Site Sewerage Management Program and the Accelerated Sewerage Program. Under the former program, as of May 2010, almost 50% of the estimated 16,000 on-site wastewater management systems (including septic tanks and aerated wastewater treatment systems) have been inspected across the catchments. Around 12% of the systems were found to pose a potential risk to water quality. Councils have worked with property owners to rectify these systems, with most systems repaired and operating safely within six months. The target is for 80% of on-site systems to be inspected by June 2011.

Under the Accelerated Sewerage Program the following projects have been completed:

- Bowral STP upgrade
- Goulburn Sewerage Scheme
- Lithgow STP upgrade - Stage 1
- Bundanoon STP upgrade.

Other key tasks completed as of June 2010 include:

- Braidwood sewerage scheme is 85% complete
- Taralga sewerage scheme – reticulation system is complete and the STP is 50% complete
- Taralga and Braidwood sewerage schemes are to be completed in 2010
- Lithgow Stage 2 (of 2) is 50% complete and will be completed in January 2011
- Wallerawang STP - tenders are being assessed and the project is anticipated to be completed by August 2011
- Robertson sewerage scheme – is in the detailed design phase and will be finished in December 2011
- Kangaroo Valley sewerage scheme is in design and will conclude in August 2012.

Planning and development controls

Local Councils are responsible for planning and development controls within their local areas. The Environmental Planning and Assessment Act 1979 allows councils to impose conditions of consent on any development approval they grant. Councils can include environmental management conditions to ensure the development will not degrade water quality (Water Directorate, 2001).

The NSW State Government has imposed development controls relating to water quality since 1999. The State Environmental Planning Policy (Sydney Drinking Water Catchments) 2010 (the SEPP) is the current legal instrument that sets out development consent requirements in the drinking water catchments. Under the SEPP, proposed developments that require consent must demonstrate Neutral or Beneficial Effects (NorBE) on water quality and should incorporate current recommended practices and performance standards endorsed by the SCA that relate to water quality.

Local councils, in partnership with the SCA, have primary responsibility for implementing the SEPP. Many developments can provide a simple water cycle assessment to council to demonstrate that they will have a neutral or beneficial effect on water quality. However, those developments which pose a greater risk to water quality receive a greater degree of

scrutiny and councils may need to seek the concurrence of the SCA. Following more detailed assessment, the SCA can require conditions of concurrence to ensure a sustainable NorBE outcome. The SCA is working with local councils to apply a NorBE test on all new development in the catchment to ensure that nutrient loads do not increase as a result of landuse changes or intensification.

The SCA and local councils are also focusing on strategic planning in order to provide an improved framework for individual development applications and regional planning. The SCA has developed Strategic Land and Water Capability Assessments (SLWCAs) to help councils ensure future land use in the catchments is consistent with the SEPP. The SLWCAs help councils review their Local Environment Plans (LEPs) to determine land uses that are permissible or prohibited in a particular zone consistent with the physical capability of the land. The SCA has also developed guidelines to assist councils review their LEPs, including details of how to address water quality protection within land use zones to reflect the SLWCA requirements.

9 Communication and consultation

9.1 Relationships with customers and stakeholders

The SCA's Cyanobacteria Response Plan (SCA, 2010b) establishes the response protocols to be undertaken during a bloom event. Table 9.1 outlines the key SCA customers and stakeholders where there is immediate concern when a cyanobacteria bloom occurs.

Table 9.1 Key SCA stakeholders with an interest in cyanobacterial blooms

Name	Relationship	Communication methods	Frequency of reporting	Notes
Sydney Water Corporation	Customer	SLG, JOG, incident protocols	Quarterly	
NSW Health	Regulator	SLG, JOG, incident protocols	Quarterly	
IPART	Regulator	Catchment audit, Operating Licence audit	Triennial Annual	
NSW Office of Water	Regulator		As required	Water Management Licence – advise where cyanobacteria prevents effluent releases
NSW Dept of Environment, Climate Change & Water	Stakeholder			Sediment and nutrient releases, head of super-agency
Recreational users		Signage, media, website		Fishing, boating, picnic areas
Councils	Customer			
Catchment Management Authorities	Stakeholder			
Partner research organisations	Stakeholder			WQRA, eWater, universities etc.

SWC and NSW Health interact with the SCA in a range of forums including the Strategic Liaison Group and the Joint Operations Group. These meetings deal with wide ranging water supply and quality issues including cyanobacteria risks.

Meetings about cyanobacteria issues are also held with other major stakeholders and issues including:

- Wingecarribee Shire Council
- Shoalhaven City Council
- Eraring Energy.

The SCA provides the Minister for Water with a fortnightly or monthly update (depending on the sampling regime) on cyanobacteria levels within its reservoirs, trends in cyanobacteria blooms, and potential for reservoirs to exceed the accepted guidelines.

NSW Health and the Department of Environment, Climate Change and Water are also advised on algal levels in reservoirs on a regular basis by fax and email.

9.1.1 Algal Coordinating Committees

The SCA actively participates in several forums that relate to the management of cyanobacteria, including:

- the State Algal Advisory Group
- regional algal coordinating committees.

State Algal Advisory Group

The NSW Algal Management Strategy is administered by the NSW State Algal Advisory Group (SAAG) and the nine regional algal coordinating committees. The SAAG is chaired by the NSW Office of Water.

The SAAG provides the over-arching policy advice and framework for management of fresh water and marine blooms. Membership of SAAG is made up of the relevant NSW state agencies, NSW local government and the Murray Darling Basin Authority.

While each member is responsible for a specific area of management and technical information, the NSW Office of Water is the lead agency for water management in NSW and coordinates both the SAAG and the Regional Algal Coordinating Committees.

Metropolitan and South Coast Regional Algal Coordinating Committee

There are nine regional algal co-ordinating committees across NSW. The Metropolitan-South Coast Committee takes in the SCA's area of operations and is responsible for the:

- development and implementation of algal contingency strategies
- development and co-ordination of regional algal monitoring systems,
- co-ordination and implementation of algal training.

The SCA has representation on this committee.

Water Industry Directorate

The NSW Local Government Water Industry Directorate (Water Directorate) was established in 1999 to provide independent advice to councils on water and sewerage operations, promote efficient operation of water and sewerage infrastructure, and provide networking opportunities which allow water and sewerage engineers to share knowledge and improve communication within the industry. The Water Directorate released Blue-Green Algae Management Protocols in November 2001 (Water Directorate, 2001). Recently these protocols have been updated with the release of Interim Blue-green Algae Management Protocols (Water Directorate, 2009).

The SCA does not have a direct relationship with the Water Industry Directorate at present.

Catchment management authorities

Thirteen catchment management authorities (CMAs) were established across NSW in 2004 to ensure the protection and sustainable development of land, vegetation and water resources within their catchments. The principal functions of the CMAs are to:

- produce and implement a catchment action plan for their area and identify investment strategies which target high priority areas recommend and manage incentive programs which engage local communities
- provide landholders with access to data needed to prepare property vegetation plans.

CMAs are not directly responsible for the management of algae or cyanobacteria. However, the activities of CMAs impact on nutrient levels in the watercourses.

Three CMAs share their areas of operations with the SCA (DIPNR, 2004):

- Hawkesbury–Nepean CMA - has Warragamba Reservoir and many major rivers managed by the SCA within its boundaries, including the Hawkesbury, Nepean, Wollondilly, Mulwaree, Wingecarribee, Nattai and Coxs rivers.
- Southern River CMA - covers some major rivers of interest to the SCA including the Kangaroo, Shoalhaven and Clyde rivers.
- Sydney Metro CMA - Woronora and Prospect reservoirs are within its boundary.

The SCA has a memorandum of understanding with these CMAs where their boundaries overlap with the SCA's area of operations.

9.1.2 Consultative committees

The SCA established a number of consultative committees to interact with the community and the local government agencies. Issues related to cyanobacteria are also discussed in these forums. These consultative committees include the Local Government Reference Panel.

9.2 Community awareness

The success of catchment management in general and algal management in particular depends on an aware and supportive community which is actively involved in developing, influencing and implementing solutions. It is important that this input is at all levels, from early detection of cyanobacteria blooms in contingency plans to the implementation of cyanobacteria control measures.

The SCA is actively involved in various community programs, such as Streamwatch. Streamwatch is a dynamic environmental action network, educating and empowering communities to work together for healthy catchments. It works with community and school groups to raise awareness of the natural environment by training participants to test the water quality of our rivers and streams.

9.3 Communication procedures during a cyanobacteria event

The communication procedures to be followed during a cyanobacteria event are outlined in the STAR Package Communication Procedure (SCA, 2008f). This procedure identifies the stakeholders and provides guidance on the appropriate communication response in the event of a range of circumstances. It also provides a number of template media releases and guidance to responses to frequently asked questions.

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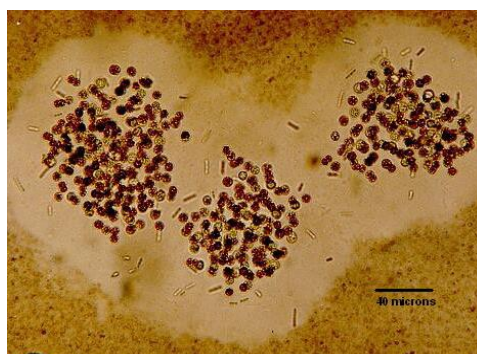
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Appendix A Description of key cyanobacteria species

A.1 Microcystis



Microcystis aeruginosa



Microcystis aeruginosa

A1.1 What is *Microcystis*

Microcystis is a cyanobacterium which is commonly found in fresh surface waters. In nutrient rich waters, *Microcystis* often dominates blooms with extensive and persistent surface scum.

The taxonomy of *Microcystis* is still subject to considerable scientific debate and investigation. The significant variation in size, shape and cell arrangement of the colony is used for identifying the species of *Microcystis*. The commonly found species of *Microcystis* in freshwater are *Microcystis aeruginosa*, *Microcystis wesenbergii*, *Microcystis flos-aquae*, and *Microcystis viridis*.

A1.2 Characteristics of *Microcystis*

The most widely found species in Australian waters is *Microcystis aeruginosa*. Among the *Microcystis* species, the focus is on *Microcystis aeruginosa* due to its well established toxic properties. In freshwater, *Microcystis aeruginosa* can be found as individual cells, and also in colonies of up to many millimetres. These colonies vary in morphology, ranging from more or less spherical to elongated, and often composed of sub-colonies.

These prolate spheroid cells have mean single cell volume of 30-100 μm^3 in Australian waters. Lack of consistency with respect to cell size is common as the Sydney Water Laboratory uses 48 μm^3 per cell, whereas the South Australian Water Corporation Laboratory uses 87 μm^3 per cell. Typical cell diameter is in the range of 4 – 6.5 μm .

Field and laboratory observations have demonstrated that *Microcystis aeruginosa* can produce multiple strains of the potent liver toxin, microcystin. When *Microcystis aeruginosa* cells die, they break open and release microcystin into water. However, *Microcystis aeruginosa* does not produce toxins at all times. Toxicity studies indicate that certain *Microcystis aeruginosa* cells cannot produce toxins, because it is possible that the toxin producing gene can be absent in certain populations. Hence, a common label, potentially toxin-producing species, is used to characterise *Microcystis aeruginosa* (and a number of other cyanobacteria species).

It is generally believed *Microcystis viridis* and *Microcystis flos-aquae* (SW Sydney Water:32 μm^3 SAWC: 22 μm^3) are also potentially toxin producing variants, but *Microcystis wesenbergii* (SW:156 μm^3 SAWC: 113 μm^3) is not a toxin producing variant. The mechanism causing cells to become toxin-producing is not certain. Understanding of the community composition and dynamics of microcystin-producing and non-microcystin-producing *Microcystis* strains in the field is very limited, mainly due to a lack of suitable identification methods.

According to the characterisation by the Algae Laboratory of Sydney Water (SWC), there is another unnamed species of *Microcystis* in Sydney's water supply reservoirs with a mean cell size of 15 μm^3 .

Microcystis aeruginosa does not fix nitrogen from atmosphere. Scientific literature implies that *Microcystis* species do not produce accessory cells, such as akinetes (resting cells that can survive unfavourable environmental conditions and can germinate to produce new growth).

A1.3 Health and taste and odour effects of *Microcystis*

Microcystin is a hepatotoxin, known to cause liver damage and dysfunction in humans and animals. Ingestion or inhalation of water containing toxins may cause vomiting, nausea, headaches, diarrhoea, pneumonia, and fever. There are two potential mechanisms for long-term microcystin damage to the liver, progressive active liver injury and promotion of tumour growth. For vertebrates, a lethal dose of microcystin causes death by liver damage within hours to a few days. No human deaths from ingestion of microcystins have been reported. However, dogs, wildlife and cattle have died following consumption of this toxin.

There are over 80 variants of microcystin which have been characterised to date. Among them, microcystin-LR, microcystin-RR and microcystin-YR are the main concern.

Besides the smell of decaying organic matter, *Microcystis* is not known to produce any specific taste and odour causing chemical compounds.

A1.4 *Microcystis aeruginosa* in the SCA waterways

Microcystis aeruginosa has been found in all SCA reservoirs. The cell populations were reported above medium alert level at least once in last 12 years at Wingecarribee, Fitzroy Falls, Tallowa, Prospect and Warragamba reservoirs. Microcystin toxins were detected in the routine samples in Wingecarribee, Fitzroy Falls, and Tallowa reservoirs, and have been present in excess of the Australian Drinking Water Guidelines in Wingecarribee and Fitzroy Falls reservoirs.

The unnamed species of *Microcystis* (with in an apparent cell size of 15 μm^3) dominated the 2007 bloom near the Warragamba Dam wall. These have been found in large populations in Wingecarribee and Tallowa reservoirs since 2005. Preliminary gene studies indicated that these species did not contain toxin producing genes at a level of concern.

A.2 *Anabaena*



Anabaena circinalis

A2.1 What is *Anabaena*?

Anabaena is one of the common filamentous cyanobacteria found in fresh surface water in all continents. Under favourable conditions, *Anabaena* can proliferate to form visible scum in surface waters. *Anabaena* can produce potent toxins, which are harmful to humans, animals and zooplanktons.

The commonly found *Anabaena* species in Australia are *Anabaena circinalis*, *Anabaena bergii*, *Anabaena crassa* and *Anabaena flos-aquae*.

A2.2 Characteristics of *Anabaena*

Anabaena contains chlorophyll and photosynthesises while in the photic zone. Similar to most of the cyanobacteria, *Anabaena* cells sink during photosynthesis process and float with their gas vesicles during their metabolic process. *Anabaena* is capable of using atmospheric nitrogen through the process of nitrogen fixation. Nitrogen fixation provides a competitive advantage to these organisms when there is limited available nitrogen in water. Nitrogen fixation is confined to poorly-pigmented and thick-walled cells (heterocysts), which are dispersed along the filaments.

According to modern phenotypic and molecular criteria, this well known genus has been reclassified. The generic name *Anabaena* will be maintained for the benthic species without gas vesicles (Komarek et al, 2007). The floating types will be known as *Dolichospermum*. In this document, the traditional name, *Anabaena*, will be used to refer to these organisms.

The descriptions of the shapes of *Anabaena* species are not consistent in the literature. *Anabaena circinalis* is characterised as oblate spheroid (SWC, 168 μm^3) and sphere (SAWC: 250 μm^3) by two laboratories. These cells (typically 7 – 9 μm) are generally found as an open spirally coiled assemblage. *Anabaena crassa* is relatively bigger (SW: 213 μm^3 and SAWC: 330 μm^3), and *Anabaena bergii* (SW: 60 μm^3 and SAWC: 85 μm^3) and *Anabaena flos-aquae* (SAWC: 56 μm^3) are smaller.

Anabaena species are known to form akinetes resting cells, which can survive unfavourable environmental conditions and germinate to produce new growth.

A2.3 Health and taste and odour effects of *Anabaena*

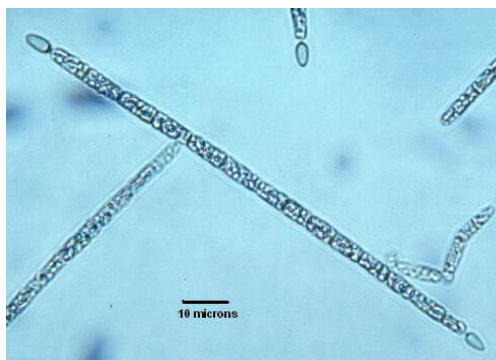
Anabaena species are known to produce microcystin (liver damage), anatoxins and saxitoxins. The primary target organs for anatoxins and saxitoxins (both neurotoxins) are nerve synapses and axons.

In addition to toxins, *Anabaena* species are also known to produce compounds causing unpleasant taste and odour. Two such compounds, MIB (2- methylisoborneol) and geosmin are known for their earthy–musty taste and odour in fresh waters. The major species of concern in the *Anabaena* genus is *Anabaena circinalis* as it is a consistent source of toxic and taste and odour compounds.

A2.4 *Anabaena* in the SCA waterways

Anabaena has been found in SCA reservoirs in all major sub-catchments. The cell populations of *Anabaena* species in general and *Anabaena circinalis* in particular rarely exceeded the taste and odour threshold of 1000 cells/mL, except at Warragamba (during the 2007-08 bloom), Wingecarribee and Tallowa reservoirs. The population has reached the medium alert level at least once in last 12 years at Warragamba (2007/08) and Wingecarribee reservoirs. The SCA does not routinely analyse for the presence of anatoxins and saxitoxins. Occasional investigative analyses for these toxins have not produced any positive results.

A.3 *Cylindrospermopsis*



Cylindrospermopsis raciborskii

A3.1 What is *Cylindrospermopsis*

Cylindrospermopsis raciborskii first came to prominence for its role in the Palm Island Mystery Disease. In November 1979, nearly 150 people, mostly children, became ill with symptoms of severe abdominal pain, vomiting, constipation, kidney malfunction and bloody diarrhoea. An epidemiological study of the incident later confirmed the linkage between the outbreak and the water supply, which had a bloom and was subsequently dosed with copper sulphate.

This potentially toxin producing species' invasive behaviour has resulted in renewed scientific attention. The frequency and quantity of detections of *Cylindrospermopsis raciborskii* has increased significantly in the tropics over last 10 years. They have been found in the subtropical and temperate regions. The current distribution ranges as far as northern Europe, North America, South America (including sub-tropical parts of Argentina), South Africa and New Zealand.

A3.2 Characteristics of *Cylindrospermopsis raciborskii*

Cylindrospermopsis raciborskii photosynthesises in the photic zone. However, because it does not form the characteristic surface blooms this species is somewhat unique cyanobacteria. The peak densities of *Cylindrospermopsis raciborskii* cells occur at two to three metres below the surface, making *Cylindrospermopsis raciborskii* blooms hard to detect. Further, *Cylindrospermopsis raciborskii* does not produce the taste and odour compounds such as geosmin and MIB. This lack of detection increases the risk of ingesting the toxin.

Similar to *Anabaena*, *Cylindrospermopsis raciborskii* cells also vertically migrate during their photosynthesis - metabolic process. Further, it can fix atmospheric nitrogen and form akinetes.

As the name suggests, *Cylindrospermopsis raciborskii* cells are cylindrical in nature with a biovolume of 42 μm^3 (SAWC) to 100 μm^3 (SWC). Typically, the single cell width is 1.5-4 μm ,

and length is 4.5-7 µm. The cells form either straight, slightly curved or spirally coiled assemblages. *Cylindrospermopsis raciborskii* forms restive cells, with mature akinetes of prolate spheroid shape (typical length of 7.5-16.0 µm and width of 3.5-4.5 µm).

A3.3 Health effects of *Cylindrospermopsis raciborskii*

Cylindrospermopsis raciborskii species can produce cylindrospermopsin toxin, and anatoxins and saxitoxins. The primary target organs for anatoxins and saxitoxins are nerves. Cylindrospermopsin attacks liver and kidney, and can cause severe damages. This toxin may possibly be genotoxic and carcinogenic as well.

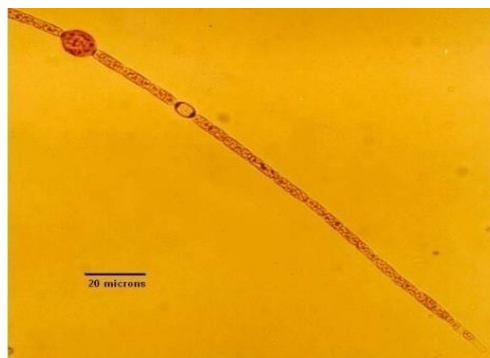
The 2004 Australian Drinking Water Guidelines (ADWG) do not set a guideline value for concentrations of cylindrospermopsin due to the lack of adequate data. However, the ADWG advises that given the known toxicity of cylindrospermopsin, the relevant health authority is informed immediately if blooms of *Cylindrospermopsis raciborskii* are detected in drinking water sources.

A3.4 *Cylindrospermopsis raciborskii* in the SCA waterways

Recent detections of *Cylindrospermopsis raciborskii* in the Hawkesbury River and at the Sydney International Regatta Centre (Penrith Lakes) have resulted in the SCA paying closer attention to these species. It is described as an invasive species, dispersed by boating, waterfowl and wind.

Detections of *Cylindrospermopsis raciborskii* were first reported in Hawkesbury River in April 2004, and in February 2007. A population of over 10,000 cells/mL were found in January to April 2009 and 2010. Occasional presence of undescribed species of *Cylindrospermopsis* was found in Hawkesbury River. A one-off detection of small population of undescribed species of *Cylindrospermopsis* was reported at Wingecarribee River and Macarthur inflow in 2004.

A.4 *Aphanizomenon*



Aphanizomenon ovalisporum

A4.1 What is *Aphanizomenon*

Aphanizomenon flos-aquae (or, invisible flower of the water) was a known food source for some African and Native American tribes. These cells were collected from water, sun-dried and consumed as brittle wafers or cakes. Extracts of *Aphanizomenon flos-aquae* are still available as a food supplement in the organic food markets.

A specific focus is on *Aphanizomenon* genus now, following the detection of toxic properties of certain species. *Aphanizomenon* can form choking blooms in fresh surface waters. Occasionally, *Aphanizomenon* is linked to taste and odour incidents in drinking water sources. Similar to *Cylindrospermopsis*, *Aphanizomenon* was considered to be a tropical organism. It is treated as an invasive species due to the recent detection in the sub-tropical and temperate zones.

A4.2 Characteristics of *Aphanizomenon*

Aphanizomenon cells are generally found as straight or slightly curved assemblages which can be found as single or free floating bundles in fresh waters. They may show considerable differences in morphology between different locations. Due to their relatively similar morphologies, it is not uncommon for *Aphanizomenon* to be confused with either *Anabaena* or *Cylindrospermopsis* assemblages.

Aphanizomenon cells contain air vesicles and vertically migrate during their photosynthesis - metabolic process. They can fix atmospheric nitrogen in nitrogen limited waters and do form restive cells.

There are over dozen common species of *Aphanizomenon*. Among them, the well characterised species are *Aphanizomenon flos-aquae* and *Aphanizomenon ovalisporum*. *Aphanizomenon* cells are cylindrical, with typical length of 3–9.8 μm and breadth of 2–5 μm . The reported typical biovolume of both species is nearly 50 μm^3 .

A4.3 Health and taste and odour effects of *Aphanizomenon ovalisporum*

In Australia, the potential of *Aphanizomenon ovalisporum* to produce cylindrospermopsin toxin is well established. Cylindrospermopsin causes liver and kidney damage, and is a possible carcinogen. In other parts of the world, *Aphanizomenon* has been shown to form saxitoxins (USA), anatoxins (Europe) and cylindrospermopsin (Israel).

Aphanizomenon flos-aquae and *Aphanizomenon ovalisporum* can produce taste and odour compounds.

A4.4 *Aphanizomenon ovalisporum* in the SCA waterways

Aphanizomenon ovalisporum has never been reported as present in the SCA rivers or reservoirs. Uncommon species of *Aphanizomenon* were detected in the Shoalhaven System in low numbers. They were reported from Warragamba and Upper Nepean reservoirs as well, particularly after 2007 June - July inflows.

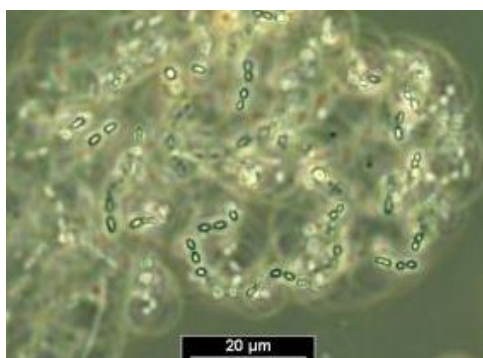
A.5 *Aphanocapsa*, *Aphanothece*, *Cyanodictyon* and *Cyanonephron*



Aphanothece



Aphanocapsa



Cyanonephron



Cyanodictyon

A5.1 What are *Aphanocapsa*, *Aphanothece*, *Cyanonephron* and *Cyanodictyon*

Aphanocapsa, *Aphanothece*, *Cyanodictyon* and *Cyanonephron* are relatively small cyanobacteria species found regularly in SCA waterways. They are considered to be opportunistic organisms as they can grow under conditions which are sub-ideal for cyanobacterial blooms. They generally proliferate just before and immediately after major cyanobacterial blooms. These organisms are not known to produce toxins in freshwater.

A5.2 Characteristics of *Aphanocapsa*, *Aphanothece*, *Cyanonephron* and *Cyanodictyon*

Aphanocapsa species are generally spherical in shape and are irregularly distributed within mucilage. Six different species are generally present in Australian freshwaters. The typical size of *Aphanocapsa incerta* is about $5.69 \mu\text{m}^3$. (SAWC Laboratories use $1.8 \mu\text{m}^3$), and of an unknown species of *Aphanocapsa* is about $0.5 \mu\text{m}^3$.

Aphanothece (invisible box) species occur as many oblong - flattened cells, unevenly distributed within mucilage, and form amorphous colonies. *Aphanocapsa* can be distinguished from *Aphanothece* by the shape of the cells. *Aphanothece* cells are more

elongate and flatter than *Aphanocapsa*. The typical size of *Aphanothece clathrata* is $1 \mu\text{m}^3$. (South Australian Water Laboratories use $2.1 \mu\text{m}^3$), and of an undescribed species of *Aphanothece* is about $0.7 \mu\text{m}^3$.

Cyanodictyon is a generally free-floating organism, generally found in colonies. Individual cells are off-spherical in their appearance, with an approximate diameter of $1 \mu\text{m}$ and a biovolume of $0.5 \mu\text{m}^3$. As they do not have gas vesicles, they cannot self regulate vertically.

Cyanonephron cells are generally prolate spheroid or cylindrical, sometimes composed of sub-colonies with mucilaginous branched stalks radiating from the centre of the colony. There is a general, but not well established, agreement regarding the absence of gas vesicles. The typical size of a cell is $2 - 4 \mu\text{m}$ length and $0.5 - 1 \mu\text{m}$ width.

A5.3 Health and taste and odour effects of *Aphanocapsa*, *Aphanothece*, *Cyanonephron* and *Cyanodictyon*

In Australia, *Aphanocapsa*, *Aphanothece*, *Cyanonephron* and *Cyanodictyon* do not produce taste and odour compounds, and are not known for their potential to create toxins. As a result, there is no particular health concern with respect to these cyanobacteria species.

There is a potential for certain cells to go through the filters at the water treatment plants and into the reticulation system. These cells will be degraded in a well optimised chlorination system.

Until 2004, the cyanobacteria alert level was set along the cell numbers, at 15,000 cells/mL. It is not uncommon to detect small cyanobacteria in such populations in drinking water sources that receive regular catchment runoff. Hence, a combination of *Aphanocapsa*, *Aphanothece*, *Cyanonephron* and *Cyanodictyon* species caused cyanobacteria alerts in the past in Australia.

A5.4 *Aphanocapsa*, *Aphanothece*, *Cyanonephron* and *Cyanodictyon* in SCA waterways

Aphanocapsa and *Aphanothece* species are found in all SCA reservoirs. While the undescribed species of *Aphanocapsa* and *Aphanothece* are present in almost all reservoirs in significant numbers (above 5000 cells/mL), *Aphanocapsa incerta* is reported in large populations mainly in the Shoalhaven reservoirs.

Aphanocapsa and *Aphanothece* species are found in all SCA reservoirs. While the undescribed species of *Aphanocapsa* and *Aphanothece* are present in almost all reservoirs in significant numbers (above 5000 cells/mL), *Aphanocapsa incerta* is reported in large populations mainly in the Shoalhaven reservoirs.

Cyanodictyon and *Cyanonephron* species are also found in SCA reservoirs in all sub-catchments. In terms of significant numbers, *Cyanonephron* was mainly found in Warragamba and Prospect reservoirs, and *Cyanodictyon* was reported mainly in the Shoalhaven reservoirs.

Appendix B Options to manage the development, or treatment of cyanobacteria in reservoirs

Method	Principle	Advantages	Disadvantages	Risks / unknowns	SCA Context
Algicides					
Copper sulphate	<ul style="list-style-type: none"> Heavy metal (cupric ion) toxicity to cells by cell destruction and, inhibition to photosynthesis and cell division. 	<ul style="list-style-type: none"> Very effective, at least temporarily Readily available Relatively economical, compared to other chemicals Simple to apply (in relatively acidic waters) 	<ul style="list-style-type: none"> Toxic to native fish Toxin release Excess organic matter in water and depletion of dissolved oxygen levels due to sudden cell death Not effective under alkaline conditions (acid addition required) Application issues (handling of acid) Toxic sediments Cells may become copper resistant 	<ul style="list-style-type: none"> Dose rates Time of application Effects on non-target aquatic species Persistence and residual effects in water quality (duration to keep the reservoir off-line) Long term ecosystem effects (disturbed balance) 	<ul style="list-style-type: none"> Most of the SCA reservoirs are relatively large, making it impractical to apply the chemical and mix it into the waterbody Difficult to get approval
Chelated copper - amines - citrates	<ul style="list-style-type: none"> Heavy metal (cupric ion) toxicity to cells by cell destruction and, inhibition to photosynthesis and cell division. 	<ul style="list-style-type: none"> Effective, but not more than copper sulphate Readily available Effective in a broader pH range Simple to apply 	<ul style="list-style-type: none"> Toxic to native fish Toxin release Relatively expensive, compared to other chemicals Excess organic matter in water and depletion of dissolved oxygen levels due to sudden cell death Toxic sediments 	<ul style="list-style-type: none"> Dose rates Time of application Effects on non-target aquatic species (may be low) Persistence and residual effects in water quality (duration to keep the reservoir off-line) Long term ecosystem effects (disturbed balance) 	<ul style="list-style-type: none"> Most of the SCA reservoirs are relatively large to apply the chemical and mix Difficult to get approval

Method	Principle	Advantages	Disadvantages	Risks / unknowns	SCA Context
Algicides (contd.)					
Chlorine	Destruction of cells and toxins by oxidation	<ul style="list-style-type: none"> • Very strong oxidant • A familiar substance for water industry • Suitable for smaller water bodies (farm dams, swimming pools, aquariums) 	<ul style="list-style-type: none"> • Toxic to fish • Potential reactions with organic matter and formation of trihalomethanes. • Formation of taste and odour substances • Difficult to apply in a reservoir • Not very effective in the presence of other constituents 	<ul style="list-style-type: none"> • Dose rates • Effects on non-target aquatic species 	Not suitable for SCA waterways
Potassium permanganate	<ul style="list-style-type: none"> • Toxicity to cells • Moderate cell destruction • Oxidation of cyanotoxins 	<ul style="list-style-type: none"> • Effective in smaller waterways (such as farm dams) at high doses • Strong oxidant • Effective in a broader pH range • Can remove toxins 	<ul style="list-style-type: none"> • Not very effective in the presence of other constituents • Not very effective against geosmin or MIB • Environmental impacts • Precipitation of MnO₂ • Pink colour water at high permanganate doses 	<ul style="list-style-type: none"> • Dose rates • Effects on non-target aquatic species • Duration to keep the reservoir off-line • Long term ecosystem effects 	Not suitable for SCA waterways
Hydrogen Peroxide	Degradation of cell membranes and DNA	<ul style="list-style-type: none"> • Effective in smaller water bodies • Can also remove taste and odour compounds 	Not registered for use against cyanobacteria in Australia	<ul style="list-style-type: none"> • Dose rates • Effects of non-target aquatic species 	Not suitable for SCA waterways
Simazine (herbicide)	Toxic to cells by affecting respiration	<ul style="list-style-type: none"> • Effective in water • Suitable for filamentous species 	<ul style="list-style-type: none"> • Herbicide addition is not acceptable in a drinking water reservoir. • Simazine is known to cause ovarian cancer • Known to bind with organic matter 	<ul style="list-style-type: none"> • Dose rates • Effects on non-target organisms • Persistence • Duration to keep the reservoir off-line • Fate of residuals 	Not suitable for SCA waterways
Barley Straw	The decay of the straw releases chemicals that have an inhibitory impact on algal growth	Promoted as a natural and cheap method	<ul style="list-style-type: none"> • Results are variable • Not suitable for larger water bodies • Difficult to apply in a reservoir 	Effectiveness is variable	Only potentially suitable in smallest SCA reservoirs

Method	Principle	Advantages	Disadvantages	Risks / unknowns	SCA Context
Coagulants					
Alum (Alum – lime)	Aggregation and precipitation of cells	<ul style="list-style-type: none"> Well-known coagulant Water professionals are familiar with alum application Suitable for smaller water bodies 	<ul style="list-style-type: none"> High dose rates and low effectiveness in the presence of high levels of cyanobacteria or other organic matter Suitable for alkaline conditions (or lime should be added) Settling of cells (organic matter) with aluminium ions 	<ul style="list-style-type: none"> Dose rates The best way to apply Environmental impacts by alum sediments Longer term impacts Effectiveness in pH<8 Duration to keep the reservoir off-line 	<ul style="list-style-type: none"> Potential application in relatively smaller reservoirs and confined sections. Extensive studies and consultations required Cost would be prohibitive for SCA reservoirs
Ferric salts	Aggregation and precipitation of cells	<ul style="list-style-type: none"> Well-known coagulant Suitable for smaller water bodies 	<ul style="list-style-type: none"> High dose rates and low effectiveness in the presence of high levels of cyanobacteria or other organic matter Number of them are known to have impurities 	<ul style="list-style-type: none"> Dose rates The best way to apply Increasing iron levels in the reservoir Longer term impacts Duration to keep the reservoir off-line 	<ul style="list-style-type: none"> Potential application in relatively smaller reservoirs and confined sections. Extensive studies and consultations required.
Nutrient Control					
Metal salt addition - alum - iron salts - lime	Precipitation of phosphorus	<ul style="list-style-type: none"> Dual action, as coagulant and phosphorus binder Water professionals are familiar with the chemicals 	<ul style="list-style-type: none"> Slow kinetics May not be effective closer to bloom condition as the cells can store adequate phosphorus for further divisions High dose rates and low effectiveness in the presence of high levels of cyanobacteria or other organic matter 	<ul style="list-style-type: none"> Dose rates Environmental impacts Fate of settled phosphorus Duration to keep the reservoir off-line 	<ul style="list-style-type: none"> Potential application in relatively smaller reservoirs and confined sections. Extensive studies and consultations required.

Method	Principle	Advantages	Disadvantages	Risks / unknowns	SCA Context
Nutrient Control (Contd.)					
Activated clay (such as PhosLock™)	Adsorption and precipitation of phosphorus	<ul style="list-style-type: none"> • Tested in Australia, could be very effective as a phosphorus binder • Australian product • Added clay may increase turbidity, and reduce light intensity 	<ul style="list-style-type: none"> • Slow kinetics (nearly two weeks) • May not be effective closer to bloom condition as the cells can store adequate phosphorus for further divisions • Large amount of clay addition in proportion to phosphorus 	<ul style="list-style-type: none"> • Dose rates • Fate of settled phosphorus • Impact of lanthanum on water in a longer term 	<ul style="list-style-type: none"> • May not be appropriate for SCA reservoirs. • Extensive studies and consultations required.
Physical Control					
Isolation	Use booms or floating objects to separate bloom area and water use locations	Simple process, as an impact reduction technique	<ul style="list-style-type: none"> • Not very effective (as cells and toxins can diffuse beneath or through) • Interference with the boat movement (recreation, sampling, etc.) 	False sense of security	Can be used in Lake Yarrunga and other elongated reservoirs where localised blue-green algal proliferations are detected
Variable off-take	Take water from deeper layers where blue-green algal presence is low	Simple and effective technique	<ul style="list-style-type: none"> • Very costly to install a new one in a short time • Moderately beneficial for shallow reservoirs (<10m deep) • May bring water from anoxic zone, which may bring other aesthetic issues 	Hydraulic currents in reservoirs caused by temperature and density distribution	<ul style="list-style-type: none"> • Variable off-takes are available in certain reservoirs. • May not be recommended in a cost benefit point of view where toxigenic cyanobacteria are found at levels of concern

Method	Principle	Advantages	Disadvantages	Risks / Unknowns	SCA Context
Physical Control (Contd.)					
Water mixers and aerators - air bubbles - draft tubes (eg WEARS)	Motion of water and shifting blue-green algal cells to deeper layers, as ideal conditions for blue-green algal blooms include well-lit and calm waters	<ul style="list-style-type: none"> • Known to be effective in certain deep reservoirs • Could be used as a longer-term solution in deeper reservoirs (avoid stratification) 	<ul style="list-style-type: none"> • May not be suitable for shallower reservoirs (<15m deep) • Mixing may be very localised • Induced evaporation • Not suitable as a short term technique • High capital cost • Skill requirements for the operational staff 	<ul style="list-style-type: none"> • Process optimisation • Effectiveness of mixing as a cyanobacteria control technique has not been proven in shallower reservoirs • Ecological impacts of maintaining the reservoir in a turbulent state 	May not be suitable for SCA reservoirs where abundance of cyanobacteria is detected at levels of concern
Physical shading - turbidity - dye	Block out light for photosynthesis	<ul style="list-style-type: none"> • Theoretically suitable • Works well in smaller water bodies (such as farm dams) 	Large addition of external material	<ul style="list-style-type: none"> • Dose rates • Actual efficiency • Health and environmental impacts of dye • Persistence 	Not suitable for SCA reservoirs
Ultrasound	Apply energy to collapse gas vesicles in the algae	<ul style="list-style-type: none"> • Theoretically plausible and proven in the laboratory • Small units are already in the market for small ponds 	Not proven in actual situations	<ul style="list-style-type: none"> • Application methods • Operating conditions • Effects on non-target aquatic species 	Technology still in development and not yet ready for use by SCA
Ultrasound / ozone treatment combination	<ul style="list-style-type: none"> • Apply energy to collapse gas vesicles in the algae • Disrupt algal cells 	<ul style="list-style-type: none"> • Theoretically plausible and proven in the laboratory • Units are already in the market 	Not proven in actual situations	<ul style="list-style-type: none"> • Application methods • Operating conditions • Effects on non-target aquatic species 	Technology still in development and not yet ready for use by SCA

Method	Principle	Advantages	Disadvantages	Risks / Unknowns	SCA Context
Biological control					
Micro-organisms - bacteria - virus - fungi	Selectively infect cyanobacteria by introducing micro-organisms harmful to them	Theoretically plausible	<ul style="list-style-type: none"> • Yet to be proven in the actual situations • Not readily available in large stocks for application • Micro-organisms need time to acclimatise 	<ul style="list-style-type: none"> • Required quantity • Impact of new species on the ecosystem 	Technology still in development and not yet ready for use by SCA
Biomaniipulation - Food chain manipulation - Competitive advantage	Maintain a suitable environment to support the growth of zooplanktons grazing on cyanobacteria	Proven technique in Europe under general conditions	<ul style="list-style-type: none"> • Not a short-term technique (new species need time to acclimatise) • Actual effectiveness during the bloom conditions not known • A Queensland study found enhanced bloom when zooplanktons were introduced 	<ul style="list-style-type: none"> • Required quantity • Impact of new species on the ecosystem 	Potential application in SCA reservoirs after extensive studies and consultations

Appendix C Cyanobacteria guidelines and standards

C.1 Overview

The risks of exposure to cyanobacteria and cyanotoxins for the consumers of Sydney's water supply, the users of water in the SCA reservoirs, and the SCA employees can occur through the following mechanisms:

- Ingestion - the primary risk to consumers from cyanobacteria intoxication is from direct consumption (drinking) and accidental ingestion (during showering and bathing).
- Recreational exposure - primary recreational contact includes all water-related activities where direct contact and immersion in water is the intended action or a probable outcome (such as swimming, and canoeing). Secondary contact includes any activity such as fishing and motor boating, which is carried out on or around a water body where the risk of immersion or contact with water is low. Exposure to aerosols may also cause a risk.
- Occupational exposure - field workers may be exposed to risk by direct contact to cyanotoxins in water and aerosols while carrying out duties.

The primary use for water stored in SCA reservoirs is to supply raw water to SWC and local councils (Shoalhaven City Council and Wingecarribee Shire Council) for treatment and reticulation. Eraring Energy circulates water between the reservoirs in the Shoalhaven System for hydro-electric generation. Each of these customers operates under a bulk water licence or agreement. Other customers (retail customers) purchase water directly from the SCA for domestic and agricultural uses. The SCA supplies water to the residents and users of picnic sites, and to a scout camp (Cataract reservoir) and the National Parks and Wildlife Services (Fitzroy Falls Reservoir). The water is supplied to meet the contractual standards of the agreement. Based on water quality data, it is the responsibility of the users themselves to assess suitability and safety of the water for their own particular requirements.

C.2 Framework and guideline development

The 1996 ADWG (NHMRC, 1996) did not provide any guideline values for cyanobacteria in drinking water; but recommended the need for frequent monitoring in water storages and identification of the species when toxin-producing cyanobacteria counts in drinking water exceed 2000 cells/mL. The first detailed framework for the response to cyanobacteria blooms in the area was developed by the Metropolitan/South Coast Regional Algal Coordinating Committee. This provided two separate guidelines for drinking water and freshwater in terms of cell numbers (RACC, 2000).

The 2004 ADWG (NHMRC, 2004) recommended that total microcystins in drinking water should not exceed 1.3 µg/L expressed as microcystin – LR toxicity equivalent. Due to the lack of data, there is no guideline value for other major toxin-producing cyanobacterial species or toxins. However, given the known toxicity of saxitoxins, the ADWG recommend that the relevant health authority should be advised immediately if a bloom of *Anabaena circinalis* is detected in the drinking water sources (NHMRC, 2004).

The SCA determined (SCA, 2002 and SCA, 2005) that for its waters (raw bulk water, town water supply and recreational water use), based on the framework of World Health Organization (Chorus and Bartram, 1999) the following should apply:

- Additional monitoring would be undertaken and the stakeholders were to be alerted when known toxin-producing cyanobacteria counts exceeded 5000 cells/mL or the cyanobacteria biovolume exceeded 1 mm³/L.
- Water users (mainly SWC, Shoalhaven City Council, Wingecarribee Shire Council and NSW Health) would be notified when these parameters exceeded 15,000 cells/mL or 2 mm³/L, or when the toxicity exceeded 1.3 µg/L expressed as microcystin – LR toxicity equivalent (TE).

The NHMRC and Agriculture and Resource Management Council of Australia and New Zealand (ARMCANZ) have proposed revised maximum guidelines and alert levels (Burch *et al*, 2005) for Australia (Table C.7).

It is the responsibility of the SCA to supply the best quality raw water to the bulk water users who treat the water prior to distribution for domestic use. Much of the water delivered by the SCA to SWC is taken from depths below the surface mixed layer and is likely to contain relatively little cyanobacteria and their associated chemical compounds. Hence, the SCA has a conservative framework with all the potentially toxin producing species.

The SCA recognises it has a responsibility to make information available regarding the cyanobacteria status of their reservoirs so those users can implement best management practices to minimise the risk of cyanotoxin exposure to themselves and their customers.

C.3 Drinking water exposure

The primary risk to consumers from cyanobacteria intoxication are from direct intake of untreated drinking water which is contaminated with cyanotoxins, primary direct contact through showering and bathing, for example, which results in accidental ingestion and cross contamination from sources which have become contaminated by contact with water containing cyanotoxins (such as dishwater and laundry waste).

Health authorities usually consider all household domestic water use as ‘potable use’ because of the difficulties in separating and regulating different types of domestic water use (drinking water, cooking, bathing, washing, garden watering, etc). Unless clear advice to the contrary is obtained from the responsible local health authority, the advisory information provided here should be deemed to apply to all domestic water use. Where dual reticulated supply is available, different levels may be applied to each supply depending on its source and its use but only after consultation with relevant health authorities (Jones and Orr, 2000).

International guidelines formulated by WHO for potable use of water contaminated by cyanotoxins, have so far been derived only for microcystins. The maximum guideline level for drinking water as recommended by WHO is 1 µg (total microcystin-LR equivalents) / L (Chorus and Bartram, 1999). This guideline level is equivalent to approximately 5000 cells mL⁻¹ in raw untreated water and is based on a microcystin-LR cell quota of 200 fg / cell which is amongst the most potent of strains of *Microcystis aeruginosa* found to date.

Most cyanotoxins are chemically stable compounds and are not destroyed by boiling. In the case of some saxitoxins, heating will promote their conversion to the more toxic decarbomyl-GTXs.

The NHMRC Revised Guidelines adapted from Alert Level Framework (Burch *et al*, 2005) for Cyanobacteria in Drinking Water Sources with respect to Public Health are included in C. 7.

C.4 Recreational exposure

C.4.1 Primary recreational contact

Primary recreational contact includes all water-related activities where direct contact and immersion in water is the intended action or a probable outcome of the activity. Primary contact includes, swimming, water and jet skiing, dinghy and catamaran sailing, wind surfing, kayaking and canoeing.

Primary contact recreation activities are not allowed in most of the SCA reservoirs. Controlled activities are allowed at Fitzroy Falls and Lake Yarrunga.

The risk of accidental oral ingestion of cyanotoxins from untreated raw water, and the risk of contact irritation effects may be caused by allergic response to compounds other than the cyanotoxins themselves. The allergens (termed endotoxins) are primarily lipopolysaccharide compounds found within the cyanobacteria cell wall, and are present in all cyanobacteria, whether or not they test positive for toxins.

A study jointly undertaken by the SCA (Burch *et al*, 2002) found that skin irritation was evident only for a small percentage of people when exposed to water containing cyanobacteria. As the response was idiosyncratic and not dose-related, it was not possible to determine the exposure level to prevent skin irritation problems during bathing and recreational activities. WHO has derived a three-tiered guideline system for bathing waters. These could apply more broadly to all forms of primary contact recreation if deemed appropriate by local and state health authorities.

C.4.2 Secondary Recreational Contact

Secondary contact includes any activity not covered under primary activity and which is carried out on or around a water body where the risk of immersion or contact with water is low. This would include activities such as fishing (assuming water is not entered and any fish caught are not eaten), yachting (excluding small capsizable dinghies), and power boating.

Risks from secondary contact are difficult, if not impossible to assess, and no formal cyanobacteria guidelines exist. Generally, secondary contact recreation activities are not allowed in most of the SCA reservoirs.

Based largely on an Australian epidemiological study by Pilotto *et al* (1997), it is recognised that cell concentrations of 20,000 cells (total cyanobacteria) mL⁻¹ may increase the incidence of skin irritations and other symptoms in a small, susceptible percentage of the population.

WHO does not advise that direct contact be restricted when cell concentrations reach this level, rather they suggest that signs be posted advising of a small increase in the risk, of contact irritation effects such as gastrointestinal disorders, skin rashes, eye irritation, and asthma.

Based on the risk of accidental cyanotoxin ingestion, restrictions on bathing are recommended at cyanobacteria cell concentrations at or exceeding 100,000 cells / mL (Chorus and Bartram, 1999).

Irrespective of the cell counts reported from laboratory analyses of collected samples, if cyanobacteria surface scums are observed during routine site inspections, then bathing and other forms of direct contact are not recommended. Cell concentrations in these scums are concentrated at the water surface and can exceed 10 million cells / mL. Ingestion of surface scum material is potentially fatal.

People recreating on lawns that have recently been irrigated with cyanobacteria infested water are also exposed to risk.

Note - WHO have provided for both guidelines levels to be modified to account for smaller cyanobacterial species (refer to Chorus and Bartram, 1999).

C.4.3 Exposure to Aerosols – recreation

Aerosols are fine airborne water droplets, which may contain cyanobacteria cells, or toxins. Sources of aerosols include spray from water-borne boating activities such as power boating, jet skis and skiing, and from town sprinklers and irrigation systems.

C.5 Occupational exposure

Risks discussed in C.4 also apply to the workers exposed to cyanotoxins. Field workers may be exposed by direct contact while carrying out duties related to water quality monitoring. Groundskeepers may be exposed to aerosols generated by impact sprinklers used for spray irrigation. Contractors and consultants also face similar risks.

There are no formal guidelines for exposure to cyanotoxins present in aerosols, although Falconer *et al* (1999) identified aerosols as an important accidental exposure pathway for cyanotoxins through ingestion via the nasal mucosa. Other studies (Fitzgeorge *et al* 1994) have shown that inhaled microcystin can be up to 100 times more toxin-producing than microcystins ingested orally. Additionally, exposure to cyanotoxins in aerosols may produce allergic reactions within the respiratory tract, and this may be sufficient to trigger asthma attack in susceptible individuals.

It is appropriate that guidelines and practices be developed to cover the safety of workers and the public who could be exposed to sources of aerosols that may be contaminated by cyanotoxins and/or cyanobacteria.

C.6 Toxin guidelines

The NHMRC and ARMCANZ reviewed the ADWG (NHMRC 2004) as they relate to cyanotoxins. The guidelines are not mandatory but are designed to form the basic framework (Jones *et al*, 2002) by which communities can decide what is an acceptable quality for drinking water.

Currently, formal recommendations for maximum cyanotoxins concentrations in drinking water in Australia only apply to microcystins. Local authorities in Queensland have adopted provisional guidelines for cylindrospermopsin and in South Australia similar guidelines have been adopted for saxitoxins. These provisional guidelines are not endorsed by the NHMRC as part of the ADWG (NHMRC 2004). At present (NHMRC, 2010), a revision is underway to update the cyanobacteria guidelines in the ADWG.

C.6.1 Microcystin

The Tolerable Daily Intake (TDI) adopted by WHO for human consumption of microcystins is 2.2 μg microcystin-LR toxicity equivalents / kg (body weight) d. WHO allocated 80 % of the TDI to drinking water as being the primary route of exposure but recognised there are other routes of exposure that account for up to 20%. Based on a 60 kg human with an average daily drinking water consumption of 2 L, WHO derived a microcystin concentration 0.96 μg / L that was rounded up to 1 μg / L for convenience.

Whilst retaining the TDI set by WHO, a modified guideline limit of 1.3 μg / L was recommended by NHMRC/ARMCANZ for Australian drinking water. This reflects a larger average adult size of 70 kg, and a higher percentage allocation of the TDI to drinking water (90 %). This value is expected to be maintained in the revised guidelines.

C.6.2 Saxitoxins (Paralytic Shellfish Poisons)

There are no formal guideline concentrations for maximum contamination of drinking water by saxitoxins at present due to the lack of adequate data. Based on the relative molecular toxicities of STX and microcystin-LR and observations of acute exposure effects by Fitzgerald *et al* (1999), the South Australian Health Department have nominally applies a 'provisional health guideline' for total saxitoxins of 3 μg / L. The same value has been recommended for the revised ADWG (NHMRC, 2010).

C.6.3 Cylindrospermopsin

There are no formal guideline concentrations for maximum contamination of drinking water by cylindrospermopsin at present due to the lack of adequate data. State health authority in Queensland informally applies a provisional health guideline for cylindrospermopsin of 1 μg / L (Orr and Schnieder, 2006). The same value has been recommended for the revised ADWG (NHMRC, 2010).

C.7 Drinking Water Advisory Levels

Where a toxin-producing cell count, total cyanobacteria biovolume or cyanotoxin concentration exceeds the threshold level for the issue of an advisory, local health authorities should be informed. Only if the second sample exceeds the threshold, should a formal advisory be issued. The advisory should only be withdrawn following two consecutive readings below the advisory threshold and only after consultation with state and local health authorities.

An Alert Level Framework was developed (Burch *et al* 2005) as a monitoring and management guide with an action sequence for the operators and regulators to respond to a potential bloom in drinking water sources. The proposed Alert Level Framework for drinking water consists of four stages (Table 6.1). As the ADWG (NHMRC, 2004) address toxin levels from a public health view point, the alert level framework focuses on presence of cells, which is characterised by cell numbers and biomass per unit volume of water.

The Detection Level covers the early stages of bloom development when cyanobacteria are detected first at low levels in the water storage. Alert Level 1 represents the level at which the cyanobacteria population is established and localised high numbers may occur. Alert Level 2 characterises the presence of moderate and slightly higher cell numbers of potentially toxin-producing cyanobacteria with a potential for occurrences of toxins above the guideline values. Conditions in Alert Level 3 are indicative of a significant increase in the risk of adverse human health effects from the supply of water.

A standard health advisory wording *pro forma* is held by the SCA and issued directly to customers upon authority from the General Manager, Water Supplies Division. It should be noted that it is not the responsibility of the SCA to advise the general public of an exceedence of the cyanobacteria threshold level unless the risk is to public recreation at one of the SCA's reservoirs. Advisory levels at state and national levels are currently under review and in all cases the SCA should consult with health authorities for advice on the currency and applicability of the cyanobacteria advisory levels proposed in this report.

Sampling protocols need to be adopted to maintain a high quality and reliable sampling program. Burch *et al* (2005) discussed extensively on methods for sample collection, number of required samples, frequency and timing of sampling, transport and storage of sampling and analytical methods in the proposed national protocol for monitoring cyanobacteria in surface waters.

C.7.1 Potable Water

The alert level framework for potable water relates to water supplied to bulk users, retail customers and directly to the public at SCA reservoirs. The recent proposed revision of the ADWG for cyanobacteria and toxins has recommended trigger levels for initial notification to health authorities for a range of known toxin producing species (Newcombe et al 2010). Newcombe et al (2010) imply that a series of alert levels should be derived based on toxin producing capacity of each species.

The notifications and alerts for *Microcystis aeruginosa*, *Anabaena circinalis*, *Nodularia spumigena* and *Cylindropermopsis raciborskii* are presented in Table C.2. However, ADWG does not address the potential for a multi-species toxin bloom.

Microcystis

For a highly toxin-producing strain of *M. aeruginosa* with microcystin cell quota of 0.2 pg microcystin-LR cell⁻¹, 1.3 µg/L is equivalent to a cell count of 6500 cells/mL.

Where untreated water is supplied by the SCA at reservoirs for drinking and the *Microcystis aeruginosa* cell concentration exceeds the advisory level, an alternative water supply should be made available or the raw water treated to remove algal cells and toxins. If either of these is not possible and the water supply cannot be disconnected, signage should be erected advising that the water is not suitable for drinking or cooking; that boiling is not sufficient to remove the toxins, and that an alternative water supply must be used.

In accordance with recommendations in the ADWG, an advisory should be issued if *Microcystis aeruginosa* cell concentrations exceed 6,500 cells/ mL in two successive counts.

Table C.1 Alert Level Framework (Newcombe et al. 2010) for *Microcystis aeruginosa* in drinking water sources with respect to public health

Level	Threshold definition ^a	Recommended actions
Detection Level LOW ALERT	500 – 2 000 cells/mL cyanobacteria (caution at $\geq 1\ 000$ cells/mL) ^b <i>Cyanobacteria detected at low levels</i>	<i>Have another look</i> ➤ Regular monitoring ➤ Weekly sampling and cell counts ➤ Regular visual inspection of water surface for scum adjacent to offtakes
Alert Level 1 MEDIUM ALERT	2 000 – 6 500 cells/mL total cyanobacteria (caution at $\geq 5\ 000$ cells/mL) ^b <i>Microcystis aeruginosa</i> ^c <i>Trigger value for this level can be adjusted for local conditions. Cyanobacteria detected at levels that indicate population is established, and localised high numbers could occur.</i>	<i>Talk to the health regulators</i> ➤ Notify agencies as appropriate ➤ Increase sampling frequency to 2x weekly at offtake and at representative locations in reservoir to establish population growth and spatial variability in source water ➤ Establish the variability (representative-ness) of the offtake sample over time ➤ Decide on requirement for toxicity assessment or toxin monitoring
Alert Level 2 HIGH ALERT	6 500 – 50 000 cells/mL <i>Microcystis aeruginosa</i> ^c -or- the total biovolume of other cyanobacteria ≥ 1 mm ³ /L <i>Established bloom of cyanobacteria (may be potentially toxic); potential for toxin concentration to exceed guideline if treatment is ineffective.</i>	<i>Decide on the significance of the hazard re the guidelines</i> ➤ Advice from health authorities on risk to public health, i.e. health risk assessment considering toxin monitoring data, sample type and variability, effectiveness of treatment ➤ Consider requirement for advice to consumers if supply is unfiltered ➤ Continue monitoring as per Level 1 ➤ Toxin monitoring of water supply (finished water) may be required, dependent upon advice from the relevant health authority
Alert Level 3	$\geq 50,000$ cells/mL <i>Microcystis aeruginosa</i> ^c -or- the total biovolume of other cyanobacteria ≥ 10 mm ³ /L <i>In circumstances no or ineffective water treatment, there may be an elevated risk of adverse human health outcomes if alternative supplies or contingency advanced treatment is not implemented.</i>	<i>Assess potential risk immediately if you have not already done so</i> ➤ Immediate notification of health authorities for advice on health risk ➤ May require advice to consumers if the supply is unfiltered ➤ Toxicity assessment or toxin measurement in source water and drinking water supply ➤ Continue monitoring of cyanobacterial population in water as per Level 1 ➤ In absence of treatment and subject to health risk assessment may require alternative contingency water supply

a. Samples that are taken from the source water, adjacent to the water supply offtake.

b. Sampling and analytical aspects can cause an error of up to $\pm 30 - 50$ % error in counting of cyanobacteria cells. Hence, one should be careful about under-estimating the potential danger.

c. SCA uses total cell numbers of all species of potentially toxin producing species in its risk management.

Table C.2 Alert Level Framework (Newcombe et al. 2010) for major cyanobacteria in drinking water sources with respect to public health

Species or Type	Notification (Alert Level 1)		Alert (Alert Level 2)	
	Cell Numbers (cells/ mL)	Biovolume (mm ³ /L)	Cell Numbers (cells/ mL)	Biovolume (mm ³ /L)
<i>Microcystis aeruginosa</i>	2,000	0.2	6,500	0.6
<i>Anabaena circinalis</i>	6,000	1.5	20,000	5
<i>Cylindrospermopsis raciborskii</i>	4,500	0.18	15,000	2.7
<i>Nodularia spumigena</i>	12,000	2.7	40,000	9.1

Anabaena

For a highly toxic bloom of *Anabaena circinalis* the 3µg / L level currently used in South Australia is equivalent to a cell concentration of approximately 20,000 cells / mL in raw untreated water. An alert level of 6,500 cells/mL is at 30% of the density equivalent, which is suitable to be the Alert Level.

Formal guideline concentrations for saxitoxins have not yet been determined in Australia or internationally due to the lack of adequate data, but are currently under development. In the interim, the SCA should adopt the Advisory level currently used by the South Australian Health Department.

Where untreated water is supplied by the SCA at reservoirs for drinking and the *A. circinalis* cell concentration exceeds the advisory level, an alternative water supply should be made available or the raw water treated to remove algal cells and toxins. If either of these is not possible and the water supply cannot be disconnected, signage should be erected advising that the water is not suitable for drinking or cooking; that boiling is not sufficient to remove the toxins, and that an alternative water supply must be used.

An advisory should be issued if *Anabaena circinalis* cell concentrations exceed 20,000 cells / mL.

It has been well established that *Anabaena* species can cause taste and odour problems in the drinking water. Under appropriate conditions 1000 cells / mL of *Anabaena circinalis* can create adequate taste and odour compounds to cause customer complaints

Cylindrospermopsis

Formal guideline concentrations for cylindrospermopsin have not yet been determined in Australia or internationally due to the lack of adequate data, but are currently under development. In the interim, it is recommended that the SCA adopt the Advisory Level currently used by Queensland Health and considered by the NHMRC.

Unlike microcystins and saxitoxins, extracellular cylindrospermopsin can exceed intracellular concentrations by more than 100-fold (Chiswell *et al* 2000). It is therefore not possible to predict the total dissolved cylindrospermopsin concentration on the basis of cell concentration. Chiswell *et al* (2000) showed that in a field sample containing just 6,000 cells / mL the total toxin concentration in the water exceeded 3 µg / L after the bloom, although the toxin cell quota would have required a cell concentration of more than 6×10^6 cells / mL to exceed that level. A later unconfirmed report (Fabbro, Pers comm.) indicated that in another field sample, dissolved cylindrospermopsin concentrations would have exceeded 3 µg / L at a cell concentration of just 1,500 cells / mL.

Where untreated water is supplied by the SCA at reservoirs for drinking and *Cylindrospermopsis raciborskii* cells are present at concentrations exceeding 1500 cells / mL⁻¹, the water should be tested for cylindrospermopsin as a precaution. A level of 4,500 cells/mL is at 30% of the density equivalent (0.3 µg / L), which is suitable to be the Alert Level. When the *Cylindrospermopsis raciborskii* population exceeds 15,000 cells/mL or the total concentration of cylindrospermopsin (intracellular plus extracellular) exceeds 1 µg / L, an advisory should be issued.

C.7.2 Recreation

WHO has derived a three-tiered guideline system for bathing waters. Based on the WHO recommendation, Jones and Orr (2000) proposed a similar three tier operational advisory systems for storages operated by Southern Rural Water, Victoria. The New South Wales Algal Advisory Group recommends a three-stage Interim Guidelines for recreation waters (Table C.3). These recreational guidelines are similar to the drinking water management with a colour alert scale. Green alert implies low cyanobacteria concentrations but requires monitoring, and amber level being a heightened level of alert, with increased sampling and surveillance. The red alert characterises a state of action where waters are unsuitable for recreation.

Table C.3 Recommended Cyanobacteria Alert Level Framework for Recreational Waters adapted from AAG, 2009

Level	Threshold Definition	Recommended Actions
Surveillance Mode GREEN LEVEL	500 – 5 000 cells/mL of <i>Microcystis aeruginosa</i> or <i>Anabaena circinalis</i> -or- the total biovolume of all cyanobacteria 0.04 – 0.4 mm ³ /L	<i>Have another look</i> ➤ Regular monitoring for cyanobacteria ➤ Regular visual inspection of water surface for scum
Alert Mode AMBER LEVEL	5 000 – 50 000 cells/mL of <i>Microcystis aeruginosa</i> or <i>Anabaena circinalis</i> -or- the total biovolume of all cyanobacteria 0.4 – 4 mm ³ /L <i>Cyanobacteria detected at levels that indicate population is established, and localised high numbers could occur.</i>	<i>Take precautionary actions</i> ➤ Increase sampling frequency at representative locations in reservoir to establish population growth and spatial variability in source water ➤ Investigate into the causes ➤ Undertake a risk assessment
Action Mode RED LEVEL	<u>Level 1</u> ≥ 10 µg/L of total cyanotoxins -or- ≥ 50 000 cells/mL of <i>Microcystis aeruginosa</i> or <i>Anabaena circinalis</i> -or- the toxigenic cyanobacteria biovolume of other cyanobacteria > 4 mm ³ /L <u>Level 2</u> The total biovolume of cyanobacteria ≥ 10 mm ³ /L -or- Consistent presence of visible scum <i>Established bloom of cyanobacteria (may be potentially toxic); potential for toxin concentration to exceed guideline</i>	<i>Decide on the significance of the hazard re the guidelines</i> ➤ Immediate notification of health authorities for advice on health risk ➤ Advice to the users of potential risks ➤ Continue monitoring of cyanobacterial population in water ➤ In absence of treatment and subject to

Appendix D Statistics used in Carlson and Percentage Average Change Values.

D.1 Methods

Methods were chosen to align with previous work:

From: Hassan, S. and Hawkins, P. 2001. *Trends in the Eutrophication Status of SCA Reservoirs and Catchment Waterways*. AWT Report prepared for the Sydney Catchment Authority. Report No. 2001/0165

Carlson Index (Chlorophyll-a, Total Phosphorus)

From: Carlson, R.E. 1977. *A trophic state index for lakes*. Limnology and Oceanography. 22 (2) 361-369.

Carlson Index (Total Nitrogen)

From: Kratzer, C.R. and Brezonik, P.L. 1981. *A Carlson-Type Trophic State Index for Nitrogen in Florida Lakes*. Water Resources Bulletin. 17 (4) 713-715.

Percentage Annual Changes

From: Burns, N. *et. al.*, 2000. *Protocol for Monitoring Trophic Levels of New Zealand Lakes and Reservoirs*. Lakes Consulting Report prepared for the Ministry of the Environment. Report No. 99/2.

D.2 Data preparation

Data used for this investigation consisted of profile data, measurements from discrete points in the water column, from 'key' monitoring locations at each water storage. The definition of 'key' in this instance was based on the following criteria:

- Considered by the SCA as being 'representative' of the assessed lake
- Provided best possible coverage in terms of depth (vertical distance between sampling points) and time (resolution of sampling)
- Site aligned with the previous analyses undertaken by Hassan and Hawkins (2001).

Nutrient Data

For the purposes of this discussion, nutrient data includes TP and TN measurements. The use of nutrient data for this analysis required a number of issues to be addressed including;

- Changes in sampling depth, frequency and methods over time
- Inclusion of bias with the use of 'near sediment' data
- Significant occurrences of left censored data
- Determination of how to aggregate profile data into a single discrete value.

Over the period of investigation, depths, frequency and methods of nutrient samples used for this analysis have changed, potentially reducing the basis for comparison over time.

Changes in sampling depth at most locations were not infrequent, in most instances when a change occurred, it was often a reduction in samples from the bottom of the water column.

There is no accepted method within the SCA for accounting for these changes. A decision was made that while there is potentially a bias with the reduction of samples from deep in the water column, this bias is likely to be insignificant as:

- There is a balance between the likelihood of nutrient provision to the euphotic zone and the frequency of depth sampling. The shallower the storage, the more 'representative' depth samples would have been obtained. Therefore, the storages with the greatest reduction in deep samples have the lowest risk of nutrient provision from this source.
- Most SCA storages have a minor nutrient gradient, if any at all. The loss of samples from such a gradient was not viewed as being significant.

Changes, over time, in sampling frequency and analytical methodology were considered effectively beyond the scope of this work to account for. Sampling frequency changes were not considered a significant issue as the analysis was to define long term trends and small value shifts were expected to be smoothed (with subsequent data treatment) for the purpose of the analysis. Analytical method changes over time, whilst all NATA accredited, seemed to have a more significant influence on phosphorus than nitrogen. Change points in phosphorus values (but not nitrogen) clearly aligned with changes in analytical methods. This was viewed as a limit of detection issue however it was beyond the scope of this analysis to decompose these results and make them directly comparable. For nitrogen, this was not apparent and is not considered a limitation. Therefore, recent point descriptions (Carlson indices) of phosphorus has a degree of validity, however trend analysis are probably limited by the quality of the data used.

The use of 'near sediment' data for nutrient analysis was also considered problematic, as the elevated nutrient values obtained from benthic samples have the potential to significantly bias the results. Datasets were scanned for such and where the depth and the value suggested it was a benthic sample, these were removed from the analysis. Due to the analysis of chlorophyll-a being in the first 12m, this is relevant only for the nutrient analyses for most storages, although this will be discussed later.

Treatment of left censored data was of particular concern. Phosphorus measurements, in particular, are typically below, at or near the analytical detection limits in SCA storages. ADWG (2004) suggests a 50% value replacement of the censored value is applicable and for individual data points where there was no coincidental data, this was implemented. For censored data where duplicates were available, if one value was censored and the other was specific, the censored replacement was taken at 75% of the censored value and then averaged into the 'real' value. The principle behind this was to prevent excessive skewing of any averaged data by reducing the variation from the censored value and the actual value. For example, >5 ug/L and 5 ug/L (by ADWG) would average into 3.75 whereas using the above method, would average into 4.375, closer to the measured value of 5. It should be noted that it was outside of the scope of this analysis to test statistically the validity of this premise although work by Antweiler and Taylor (2008), suggests that this technique probably offers less bias than other methods.

Chlorophyll-a

Algal growth (as indicated by chlorophyll-a) is thought to follow an exponential growth curve which is proportional to light penetration into the water column. To limit the influence of changes in sampling of chlorophyll-a over time, only data from the euphotic zone (considered everything up to and including the top 12m of the water column) was included in this analysis. Where storages were shallower in depth than the 12m delineation of the euphotic zone, chlorophyll-a values were used arbitrarily with a view to avoiding near-sediment samples. To remove algal scum samples, potential outliers were identified and if the value was not supported in profile and/or from before/after sampling, it was removed from the analysis.

D.3 Data Treatment

To calculate both nutrient trophic indices and trends (percentage annual changes), discrete 'daily' (for trend analysis) and monthly (for Carlson calculations) values were required. 'Cleaned' nutrient data was averaged across the profile. Where there were composite samples available, these were averaged against the average from profile samples to provide a specific 'daily' value. These daily values were left 'as is' for trend analysis, but were averaged into a monthly value for Carlson calculations.

Chlorophyll-a data was treated differently, as medians (rather than averages) were taken from in-profile data (as per both the Carlson and Burns Methods). These medians were then averaged against concurrently obtained chlorophyll-a composite samples. This approach, whilst not specifically noted in either method, was considered valid as the purpose of the use of medians in chlorophyll-a data is to manage outliers (perceived in this instance to be generated by algal scum sampling). Removal of algal scum bias in composite samples has probably been achieved by the very nature of obtaining this type of sample. The use of profile medians was considered to have 'cleaned' the discrete data and thereby further cleaning (by the use of medians to aggregate profile and composite data) was not necessary and averaging was considered sufficient.

D.4 Statistical Analysis

Carlson Index

To derive Carlson Index values for this analysis, the Carlson method (as referenced above) was followed. Daily nutrient and chlorophyll-a data was averaged into a monthly value, the requisite Carlson equation was applied and an index value was obtained. Where no samples were obtained for a given month, no interpolation across the month was undertaken. The month was thereby left out of calculations. This was generally not a common issue (possibly one month every 2–3 years depending upon storage and parameter) however it was identifiable and may have biased results when averaging into a one year or two year Carlson value. Due to the infrequency of 'missing months' and the likelihood that the unavailable values were comparable to months both before and after, this bias was considered minor. Carlson values obtained were reported directly.

Trend Analysis (Burns Index)

Trending calculations for this report were obtained using the Burns Method as reference above. This method, for the purpose of providing an indication of long term changes in nutrient and biotic loads, involves three steps;

- De-Eventing of the data (the removal of data that represents intransient phenomena such as inflow events, resuspension events etc.)
- De-Seasonalisation of the data (the removal of the influence of intra-year seasonal variations within the data)
- Determination of the residual trend
- Determination the degree of significance

De-Eventing

The Burns method (referenced above) suggests that the removal of events from an underlying trend is critical for interpreting changes in nutrients or chlorophyll-a over time. There is no set process for achieving this within the method, so the following process was used. Events, for this analysis, were considered to be short term elevation of measured values within the dataset that were not representative of the underlying trend. The process of de-eventing was to remove the influence of inflows, resuspension, analytical error, algal 'scum' sampling and other influences that are not representative of the actual status of the storage. If a short term influence (such as a resuspension event) occurs frequently, it becomes part of the underlying trend for this storage and can be captured in further data treatment (de-seasonalisation, described later). Events were defined numerically using a cumulative frequency distribution, with a number of thresholds tested (up to 10%) to determine at what frequency were the majority of events captured. A value of 5% was chosen as it represented a significant proportion of 'events' and appeared to be consistent across the storages under evaluation. Effectively, the bottom 95% of the cumulative frequency distribution for each data type was used with the top 5% being removed from the evaluation.

De-Seasonalisation

The purpose of de-seasonalisation was to remove the influence of elevated and reduced values from the dataset as a function of the season. An example of this would be resuspension events which are thought to have a greater propensity during destratification, annually a winter phenomena in most SCA storages. Typically, after a resuspension event, water quality generally returns to pre-event levels fairly quickly. There is an argument to say that the influence of a resuspension 'event' would be captured by 'de-eventing', however if it is a small increase or an annual influence, this may or may not be the case.

The methodology for de-seasonalising was as per the Burns method (reference above) with a number of minor changes. The principle is to develop a 4-5 point least squares regression or fit a curve that represented the majority of seasonal variation in a long term dataset over 12 months (effectively 10 years of data across January to December). The resulting equation was then subtracted from the dataset, obtaining a time series of residuals. The residuals were then used for the next step in the method. There are more sophisticated tools that

could be used for this purpose (i.e. box-averaging) but the tools to implement alternative statistical treatments were not available at the time of writing, so it was not tested whether a more complicated statistical tool in this regard would have offered more statistical power.

The changes made to the method were to address an issue with numerical resolution of regression equations. The problem was to numerically describe a year in such a way that 1 January and 31 December are effectively only fractionally different numerically (a problem if you use 1 to 365 (366) to represent these dates). The method chosen to work around this was to use a fraction of 1 to represent 1 to 365 (366) with the start date being 1 July and the end date being 30 June. As chlorophyll-a shows more variability across the spring-summer seasons and is typically low in winter (June – July), it was considered appropriate to apply de-seasonalisation in such a way. The viewpoint being that any error from this approach would be minimised by focussing ‘the error’ into the time period of the dataset (June/July) where it’s likely to have the least influence. There was a concern that using this start/stop date may have biased nutrient calculations but the lack of seasonality to the nutrient data suggests that this approach was valid for nutrients and offered a degree of consistency across all the storages.

With de-seasonalisation completed, the residuals and actual data were plotted again into a nine ‘year’ (July 2000 to June 2009) time series where both the residuals and de-evented data were compared. Effectively, this offered an opportunity to visually determine the validity of the statistical process and whether the residuals appeared representative. This appeared to be the case with all data from all locations.

Residual Trend and Degree of Significance

Once the residuals were obtained, a simple linear regression of the residuals was used to represent the underlying trend of the data. The slope of this regression is a daily value, which in turn was converted to yearly (to provide an annual change value) and an annual percentage was derived by dividing this yearly value by the long term average of the dataset. Effectively this provided the percentage annual change (the PAC value) and this number was reported.

The degree of significance of each linear trend of regression was recorded. In earlier drafts of the report, the significance was recorded with the percentage change. Due to the fact that nearly all trends met a significance of 0.05 and the large number of results that needed reporting, for brevity this information was excluded from this report but is available upon request.

References

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