HydroNumerics

Project to improve management of the potential impacts of climate change on water quality relating to algae

Developing a new framework for future blue-green algae assessment and management

Final Report

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Report prepared for the Victorian Department of Environment, Land, Water and Planning (DELWP)

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>> Executive Summary

The project to *improve management of the potential impacts of climate change on water quality relating to algae* is a body of work focused on understanding the future impacts of climate change on water quality, particularly algae in Victorian waterways. Commissioned by the Department of Environment, Land, Water and Planning (DELWP) through the Pilot Water Sector Climate Change Adaptation Action Plan (WSAAP), the work is underpinned by the recognition that climate change is likely to have significant direct and indirect impacts on water quality, including the impact via changes such as warmer temperatures, drought, bushfires and floods. You can find more information on state-level water sector climate change emissions reduction and adaptation initiatives at www.water.vic.gov.au/climate-change.

> Project Objectives

Through a programme of desk-top analysis and stakeholder engagement, this project responded to the following objectives, which where to better understand:

- the current approaches to managing algal blooms in Victoria across different types of waterways and regions;
- the potential and likely reasons for increased likelihood, severity and prevalence of algal blooms (focused on BGA) in Victoria in response to climate change and non-climate change stressors;
- the sensitivity of different Victorian waterbody categories/types to climate change and non-climate change stressors; and
- how the likelihood, severity and prevalence of algal blooms may change in Victorian waterbodies in the future.

> Project Roadmap

This project required the integration of a range of overlapping, and often deeply technical themes of ongoing research, in addition to considering the real-world practicalities of management and response. The report first examines the traits of BGA, before applying this to a consideration of how these traits lead us to predictions about the likely responses to climate change stressors. Following, a review of the generalised approach to BGA management is provided before the Victorian approach is examined. A final technical chapter details a *framework for future BGA assessment and management,* before key project findings are reviewed, and four key recommendations are defined (further information below). The results of the stakeholder engagement process are provided in an appendix to this report.

This report is organised as follows:

- Chapter 1 - **Project Overview**
- Chapter 2 - **Blue-Green Algae**
- Chapter 3 - **Understanding BGA Response to Stressors**
- Chapter 4 - **Managing Blue Green Algae**
- Chapter 5 - **Managing Blue Green Algae in Victoria**
- Chapter 6 - **Framework for BGA Assessment and Management**
- Chapter 7 - **Summary and Recommendations**
- Chapter 8 - **References**
- Chapter 9 - **Appendices: Framework Application, Rapid Risk Assessment and Stakeholder Engagement Summary**

> Why Blue-Green Algae

Blue-Green Algae (BGA) are photosynthetic bacteria (known as cyanobacteria) that colonise fresh and marine waters globally. They are a natural, and a vital component of balanced aquatic ecosystems, but under favourable environmental conditions, BGA can form dense, potentially toxic, blooms. Across Victoria's network of drinking supply, recreational and coastal waters, as well stock and irrigation resources, BGA blooms can have significant impacts on human, animal and ecosystem health. Blooms may force closures of recreational water bodies, require the supply of alternative drinking and irrigation water supplies, contribute to fish deaths in our rivers, and may cause significant health problems for humans and animals if water with sufficiently high concentrations of BGA are ingested.

The 2016 Murray River Bloom is a case in point: in February 2016 a major BGA outbreak colonised 1,450 km of the Murray River from the Hume Dam all the way to downstream of Wentworth, impacting many river communities for over 12 weeks. Similar, long-lasting blooms are recorded in the Goulburn system in 2019 and 2020, sustained blooms in the Macalister Irrigation District, noting species previously not observed in the region occurred in early 2020.

Blue-Green Algae Bloom in the Murray River 2016. Source: Weekly Times

> The Australian Context

In Chapter 5.1 of this report, we briefly examine the historical development of algae related R&D in Australia. Australia has an extensive history of studying and managing BGA across a range of different waterbodies. Increased awareness and occurrence of BGA and BGA risks lead to scientific efforts that produced numerous globally significant research contributions and Australian expertise from the 1990's onwards. A growing need for evidence-based and effective BGA management culminated in research efforts focused on assessing management options applied in the Australian context. These included, for example, research on phosphorus adsorbents and artificial mixing. Such efforts resulted in many practical guidance papers referred to throughout this report.

Building on the already significant pool of BGA knowledge in Australia are continued efforts in research and development that are focused on multiple aspects of BGA management. Recent examples range from monitoring, functional understanding (Burford et al. 2020), and predictive modelling (Rigosi et al. 2015, Rousso et al. 2020). In most instances the knowledge that is gained throughout Australia is applicable to Victoria (an vice versa) and communication of this information within Victoria and more broadly, Australia, is absolutely critical to successful and timely management of increased BGA related risks in future.

> Understanding BGA & response to climate stressors

A detailed review of BGA physiology and key physiological traits is provided in Chapter 2 of this report. Across their taxonomy, BGA have evolved with a wide range of traits that have enabled their expansion into many of the Earths aquatic ecosystems as either persistent and/or opportunistic occupants, sometimes forming dense blooms when conditions are favourable. These traits provide BGA with advantages over eukaryotic phytoplankton when competing for resources - primarily nutrients, light and carbon.

> ***"Because BGA have evolved through periods of extreme biogeochemical and climatic variations, ranging from solar irradiance, temperature, oxygen levels, nutrient availability, wet and dry periods, volcanism and continental drift, they have developed an extensive ecophysiological***

> ***"playbook" (as described by Paerl 2014) used to respond to habitat changes over time. This structural and functional diversification has enabled BGA to occupy a broad range of contemporary habitats across the globe and means that BGA are well-placed to take advantage of changes to habitats that are inflicted by anthropogenic and climate change stressors." (p. 4)***

Crucial to this project is a recognition of the wide range of physiological traits that BGA possess and how BGA may be managed under future climate scenarios. As discussed in Chapter 2, the extensive 'ecophysiological playbook' that BGA have developed must be considered when developing future management strategies, as BGA has developed a range of strategies to compete for resources – primarily nutrients, light and carbon – which may make them even more proficient under future climate scenarios.

The likely responses of BGA to climate stressors is examined in Chapter 3. Waterbody stressors related to climate change could comfortably be classified as anthropogenic because of their connection to carbon emissions from human activities. In this report, at the waterbody scale we have defined these stressors as climate change stressors, that are distinct from the 'traditional' anthropogenic (non-climate change) stressors, such as catchment degradation, increased nutrient loads, increased abstraction and ecosystem disruptions that have, and will continue to apply stress to water bodies independently of climate change. The impacts of; higher water temperatures, stronger stratification, higher nutrient loads, longer residence times, ecological disturbance, hydro-meteorological events and increased atmospheric CO_2 are examined in section 3.3.

> Managing BGA

Studies have demonstrated that there are potentially complex relationships between bloom intensities and various climate- and non-climate change stressors. Efforts to prevent or control BGA bloom development are therefore not general in nature and will always carry some uncertainty. Furthermore, there is the potential for seemingly *positive* actions to produce *negative* outcomes, particularly if the fundamental nutrient requirements for algal growth remain. Chapter 4 of this report considers the impacts of waterbody processes, finding:

> ***"The role of differing BGA traits and how they combine to formulate a response to environmental change will depend on the physical and biogeochemical processes occurring within a waterbody. There are fundamental differences between the processes that operate in riverine, lake, estuarine and coastal waterbodies and specific details will vary between individual waterbodies."***

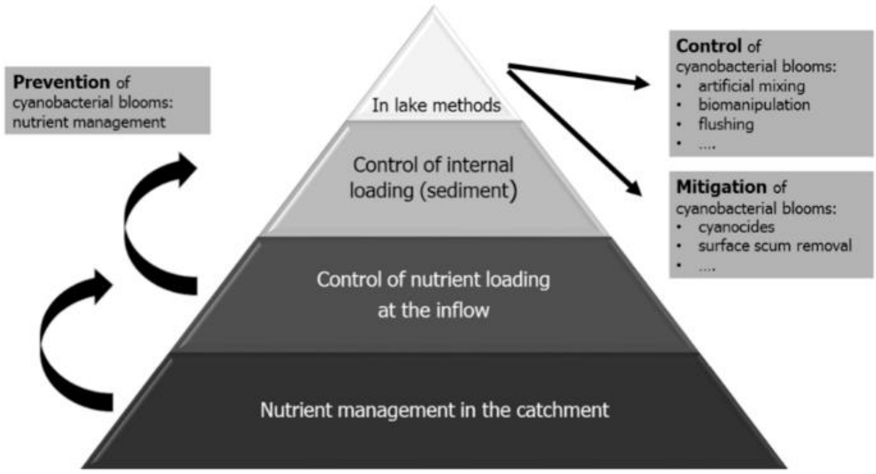
A generalised approach after Ibelings (2016) shows that managing BGA generally falls into three categories, namely prevention (*s. 4.3)*, control (*s.* 4.4) and mitigation (*s.* 4.5). Detailed assessment of the prevention/mitigation strategies and control technologies are included in each section. An important observation is highlighted at the beginning of *s. 4.4* (Control) is that:

> **''Unlike preventative measures of nutrient control, which are likely to be successful irrespective of the type of BGA that is problematic, control strategies need to carefully identify specific BGA traits, and how they function to provide competitive advantages and then exploit potential weakness"**

Prevention: considers management practices that can be implemented to stop the formation of BGA blooms (eg. Nutrient control). Such approaches are likely to be effective in sustaining a mixed algal community that prevents BGA blooms;

Control of BGA considers strategies that can be employed to minimise the potential for occurrence of BGA blooms; and

Mitigation refers to measures that can be taken in response to BGA blooms in an effort to reduce the impacts of the bloom. We define mitigation actions being those that seek to reduce impacts (rather than occurrence) of BGA blooms, whereas control measures, seek to manipulate the waterbody in a manner that suppresses the occurrence of BGA blooms in the first place.



Prevention, control and mitigation measures for cyanobacterial blooms

> The Victorian context

A desktop analysis of available Victorian, regional and local waterway management plans was undertaken to assess the planning, management and response protocols in Victoria, as seen in Chapter 5 . In addition to providing a useful baseline for future BGA management planning, it is a crucial element of the proposed conceptual BGA framework described below. To compliment this review, the following work was undertaken:

- A series of (online) stakeholder workshops were conducted, with representatives from drinking water, health, agriculture and recreation;
- One on one interviews were conducted with water industry stakeholders as well as cross-departmental stakeholders (eg. Agriculture Victoria, DHHS); and
- Interstate water corporations and research organisations were interviewed in an effort to benchmark the Victorian response, and to get information on research and development initiatives in other jurisdictions.

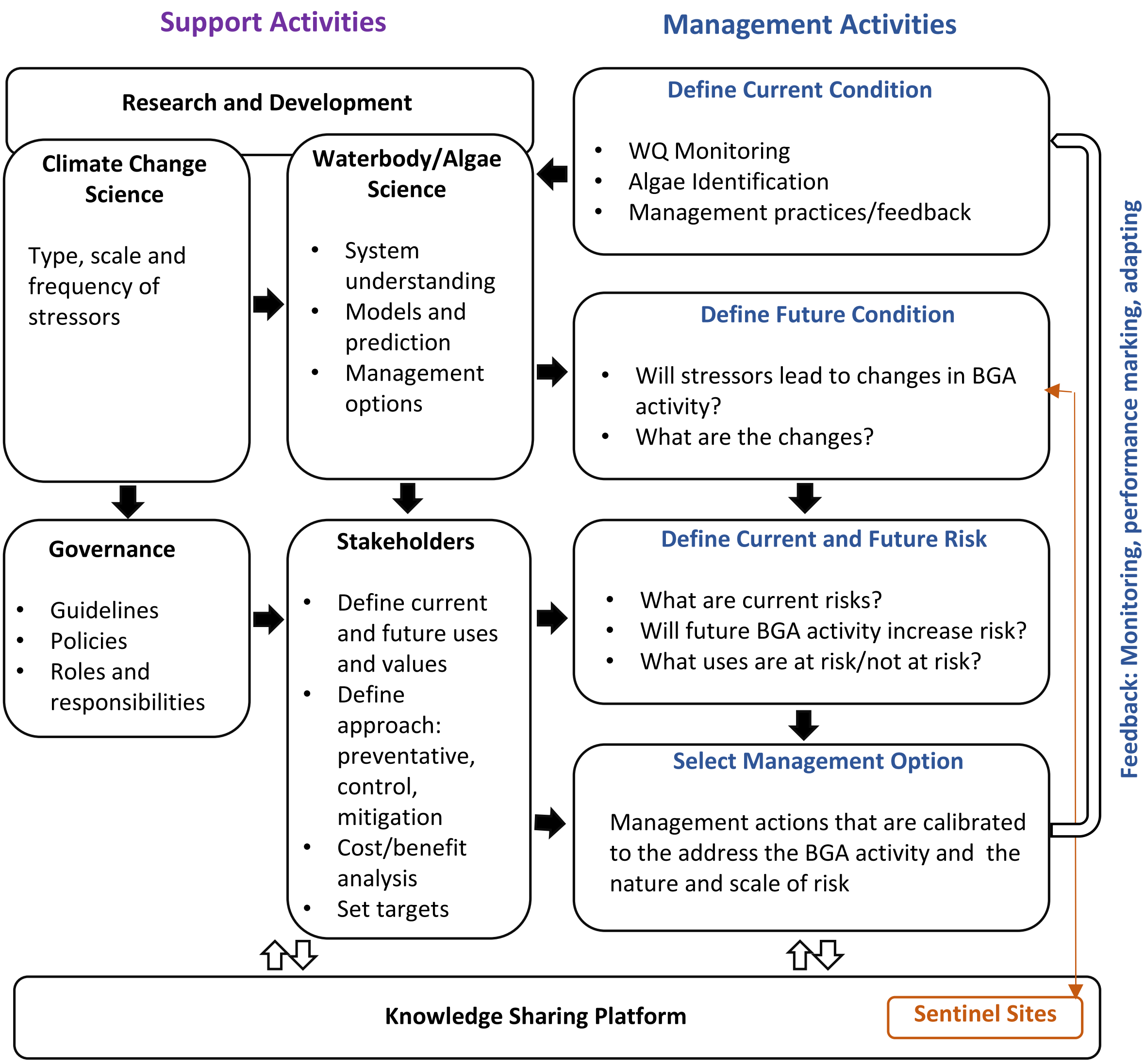
At the state level, the annual ''DELWP BGA Circular'', sets down state-wide management plans and response protocols (DELWP 2019). With few exceptions, the document does not provide specific management plans for any assets, rather, it provides an overarching framework for managing BGA blooms, with particular attention on the roles and responsibilities of various agencies during a bloom. The circular is complemented by local and regional management plans, which broadly follow the same process.

Of particular note to this study is a consideration of the future climate impacts on timing of bloom formations, thresholds and notification pathways, that may need to be reviewed due to more rapid onset of BGA and other algal blooms.

> Linking potential control mechanisms to future management strategies – the framework

In Chapter 6 of the report, we draw together current management practices (Chapter 4), potential options for prevention and control (section 5.4) and the theoretical understanding of BGA traits and response mechanisms developed in Chapters 2 and 3, to propose a conceptual BGA management framework as shown below. The framework is focused on a addressing a key question that is a theme of this report:

- Will climate change stressors lead to problematic BGA activity?



Conceptual BGA management framework

The proposed framework consists of a number of interconnected activities in two main streams (management and support), all of which exist already in the context of Victorian waterways (see Chapter 5). The intent is that this framework is applied across the range of waterbodies in Victoria as a means of contributing to the underlying science and identifying emerging geospatial patterns, trajectories, levels of risk, and science-risk based management options. The framework is necessarily iterative, in the sense that the implementation of management options must be supported by adequate monitoring or pilot testing that provides feedback into the framework.

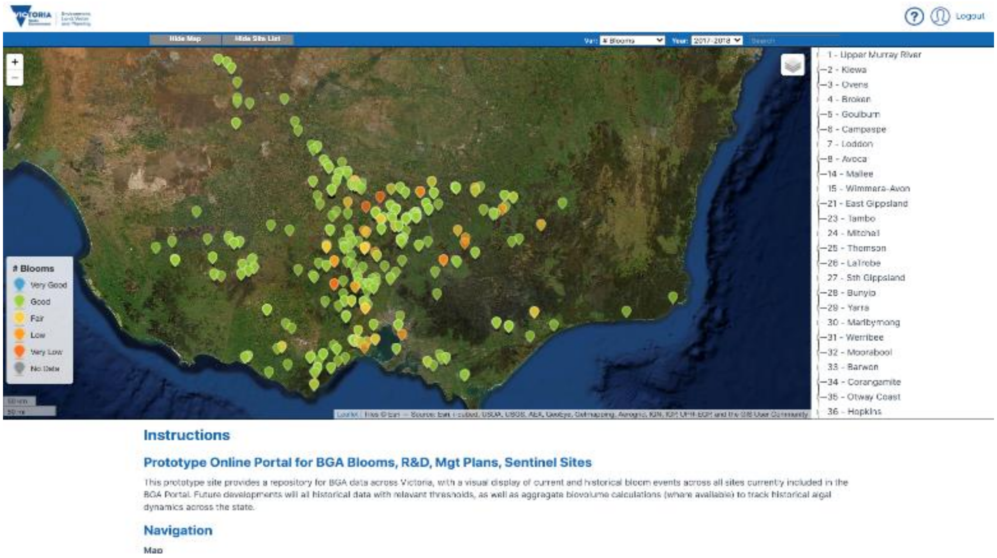
Successful management of BGA therefore requires an integrated knowledge of waterbody processes and BGA functional traits (see section 3.1) that can provide insights into potentially effective management options. Identifying viable and sustainable management options should focus on negating trait-based advantages that the BGA utilise to proliferate and developing strategies to eliminate these advantages. Management practices should therefore not only seek to reduce uncertainty prior to application but also be followed by carefully designed monitoring regimes and robust appraisals of efficacy over adequate time-frames to measure the extent of success or failure and the underlying reasons.

> Recommendations and Actions

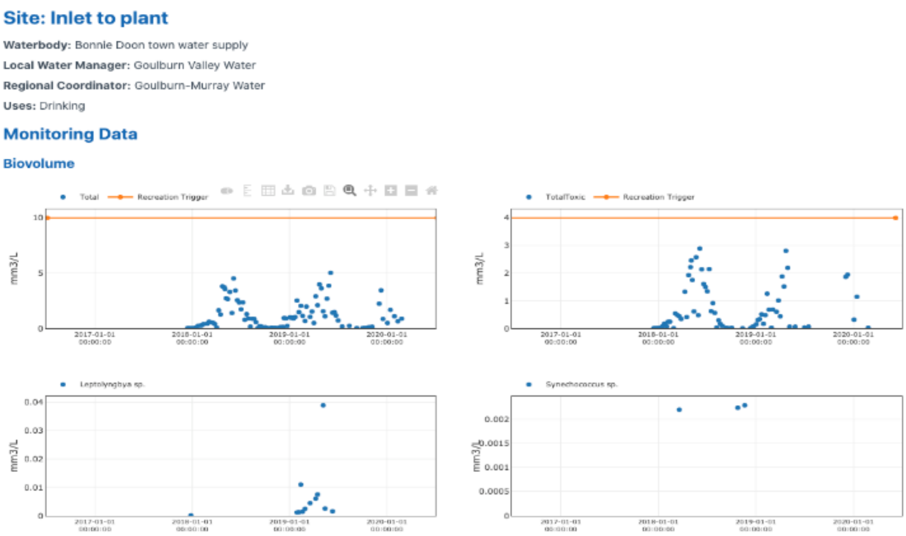
Seen in Chapter 7, three priority actions and three recommendations are provided:

> Action 1: Develop a rapid risk assessment for water bodies across Victoria

Section 7.4 of this report outlines the proposed development for DELWP's *Floodzoom* BGA portal, adding spatio-temporal results from that database so users can see current and historical BGA data and extract and analyse data on the fly as seen in the following two images:



Landing page for prototype BGA site showing number of blooms for all sites



Bonnie Doon town water supply BGA results, recreational trigger (red/orange) and aggregate total and toxic results 2016-2020

Linking the prototype website to the sentinel site concept discussed (section 6.5) is the potential to use the prototype site to run a rapid climate-change risk assessment for Victorian waterbodies based on the framework applied in Figure 4.1, using a simplified risk matrix (for example, future assessment of changes to hydrology, land-use, beneficial use, technological development and anthropogenic pressure). A hypothetical example is provided below, where all sites in *Floodzoom* are ranked according to very large or very small impacts on water quality due to climate change:

- A suite of preliminary risk assessments were conducted on a select number of waterbodies in conjunction with Goulburn-Murray Water and Southern Rural Water. The results of which can be seen in **section 9.1.**

(Hypothetical) "Change in" BGA/Climate Change Risk Assessment

> Action 2: Road-test the proposed framework

- The framework described in Chapter 6 should be applied to a select number of waterbodies before being rolled out across the state. Exactly which waterbodies are prioritised could be linked to the rapid risk assessment described above, and the consideration of the sentinel site network discussed below.
- The proposed framework has been applied to Lake Glenmaggie (Southern Rural Water), and the outcomes from this process are included in **section 9.1**.

> Action 3: Develop a sentinel site network for future research

The challenges of managing BGA that lie ahead are numerous and complex and the resources to do so are not without limitation. Effective, rapid and consistent sharing of knowledge is going to be absolutely crucial to building a collective understanding of the scale of the issues, the highest risk waterbodies and effective management measures.

The proposed use of 'sentinel' sites facilitates a comprehensive understanding of a select number of sites from which learnings can be applied to comparable sites. The sentinel sites offer and means to accelerate our collective learnings about the mechanisms that currently so and may in future lead to BGA bloom proliferation, provide an early warning system of future risks, and a means to test and refine risk mitigation measures. Sentinel sites are a potential means to concentrate and consolidate the funding and efforts required to improve our scientific understanding of future BGA behaviour and develop predictive models that can be applied across the range of Victorian waterways.

- The selection, development and funding of sentinel sites discussed in section 6.5 of this report;
- The risk assessment and prioritisation activities discussed are applied to a select number of sites, to be scaled up once a rapid and simple assessment technique is developed (potentially included in the developed portal); and
- Future development of the online portal to include hot-linked management plans, consolidated R&D initiatives (see Action 1) and interactive data analytics for consistent analysis and reporting.

> Recommendation 1: Consolidate R&D initiatives

- That Regional and Local Waterway managers include a summary of the past years' algal alerts in their management plan as well as historical or planned R & D in their plans (which could also be housed on the revised portal);
- A trans-boundary reporting platform between Victorian and NSW for all algal events, and associated management responses, as well as joint R+D initiatives;
- The existing *Floodzoom* portal is audited to ensure that all event triggers have been recorded in the database. This will ensure that the future adaptation plans have given full consideration to the historical prevalence of blooms;

> Recommendation 2: Future proof governance, especially for threshold trigger levels

- Climate change is likely to change bloom dynamics and may lead to more rapid onset of blooms. This may require alternative public communication and management protocols;
- Guidelines for the implementation of new control and mitigation techniques. The taste and odour issues that arise from managing BGA, as well as toxin production needs to be continually revised in the context of changing BGA assemblages;
- The continual revision of known toxin producers from Australia and internationally, particularly in the context of changing assemblages is recommended;

- Governance models need to take account of trans-boundary sampling, reporting and escalation protocol.

> Recommendation 3: A focus on stock and irrigation supplies to address:

- The impacts on stock and irrigation deliveries are considered to be high risk in the context of shifting assemblages in many of Victoria’s rural supply reservoirs, that have started to see shifts towards species typically thought to only occur in tropical or sub-tropical climates;

- The triggers for production of toxins, and therefore an adaptation plan that included regular review of known / potentially toxic species is recommended; and

- Potential linkages with DHHS and Agriculture Victoria programs investigating rapid toxicity assessments in stock and domestic dams, and the impacts of poor water quality events on various supply chains in the state.

Blue-green algae at Lake Eppalock, Victoria in 2020 (Source: Bendigo Advertiser)

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1 Project Overview

1.1 Objectives

The Victorian Department of Environment, Land, Water and Planning (DELWP) engaged Hydronumerics Pty Ltd to deliver a project to improve management of the potential impacts of climate change on water quality relating to algae, under Action 19 of the Pilot Water Sector Climate Change Adaptation Action Plan (WSAAP).

This project is critical to better understanding of:

- the current approaches to managing algal blooms in Victoria across different types of waterways and regions;
- the potential and likely reasons for increased likelihood, severity and prevalence of algal blooms (focused on BGA) in Victoria in response to climate change and non-climate change stressors;
- the sensitivity of different Victorian waterbody categories/types to climate change and non-climate change stressors; and
- how the likelihood, severity and prevalence of algal blooms may change in Victorian waterbodies in the future.

Hydronumerics has worked in collaboration with DELWP and key stakeholders to compile algal data, information on current approaches to managing algae, and understand the impacts of algal blooms on drinking water and recreational water quality, with a focus on blue-green algae (BGA). Importantly, this work is not intended to replace existing management, or regional coordination plans, but suggests the first steps in identifying actions and pathways that will need to be implemented in future planning cycles to adapt to the various impacts of a changing climate.

You can find more information on state-level water sector climate change emissions reduction and adaptation initiatives at www.water.vic.gov.au/climate-change.

1.2 Tasks and Reporting

Project delivery included four key components, which were:

- Initial data and information collection to understanding how various waterbodies are likely to respond to climate change and non-climate change stressors relating to algal blooms;
- Stakeholder industry workshops to demonstrate the findings and proposed framework and discuss the next steps forward;

- Development and demonstration of a conceptual framework that can be used to support the algae management initiative through Victoria; and
- Development of a prototype of an online portal that can provide a point of reference for stakeholders going forward and foster ongoing stakeholder contribution.

The final chapter of this report reflects on the findings and provides a discussion on the next steps that we recommend to build on this study and provide a direction towards a framework that can assist with management of algae and can be adopted across the various stakeholders.

1.3 Why Blue-Green Algae?

Global studies have shown that observed increases in aquatic primary productivity in the worlds' waterways are due largely to anthropogenic activity, most notability increases in nutrient loads. A recent global survey of long-term historical trends of phytoplankton blooms in large lakes (Ho et al. 2019) shows that since the 1980's, peak summertime phytoplankton bloom intensity has increased in 68% of the lakes studied. Paleolimnological studies looking further into the past have shown that these ecological trajectories have been occurring in lakes over the past century and to date the process of anthropogenic eutrophication has been a more important than a warming climate (Perga et al. 2015). This has also been observed in lakes with only limited eutrophication, where the impacts of climate warming on the biodiversity has so far been exceeded by direct anthropogenic impacts (Jeppesen et al. 2014). Importantly, the authors of this study note that whilst to date climate change has been a lesser factor compared to anthropogenic inputs, climate change has contributed to the responses observed in the sediment cores. This means that impacted lakes remain vulnerable to further change, to the extent that climatic controls may eventually surpass nutrient loading as the major driver of future impacts. Examples of oligotrophic lakes in protected catchments (e.g. Lu et al. 2018) have demonstrated that climate change stressors alone, through increased temperature, changes to inflow patterns, and wind-induced hydrodynamic changes, can be sufficient enough to trigger eutrophication where other anthropogenic stressors have been curtailed.

Studies of global trajectories of increased algal productivity have indicated that the occurrence of blue-green algae (BGA) has increased disproportionally compared to eukaryotic phytoplankton over the last 100 to 150 years, with the shift towards BGA dominance that has accelerated since the mid-20th century (Huisman et al. 2018). This trend is expected to accelerate further in future, which has broad implications for ecosystems, economies and societies that depend on healthy waterbodies that may be impacted on by increased BGA growth. The increasing dominance of BGA is a function of the range of traits that BGA display (Carey et al. 2012), which give them competitive advantages over other waterbody inhabitants and allow them to take advantage of changing environmental conditions, thereby causing a shift in algae assemblages. As a result, the proliferation of BGA and, specifically, the formation of blooms can have detrimental ecosystem impacts, including hypoxia (and fish deaths), disruptions to biogeochemistry cycles and loss of species diversity (Paerl 2014, Hamilton et al. 2014). Furthermore, the full economic and social cost that results from BGA blooms in relation to potable water supply, stock irrigation, recreational use and property value, is often due to or exacerbated by the tendency of some BGA to produce cyanotoxins, and taste and odour compounds, which can trigger water supply emergencies and escalate treatment costs. In a global context, the impact of BGA on aquatic systems is expected to increase in future with ongoing eutrophication and the addition of stressors related to climate change that appear to further promote the dominance of BGA (Visser et al. 2016).

Figure 1.1 The proliferation of BGA and the formation of blooms can have detrimental ecosystem impacts such as fish deaths (a) and socio-economic impacts (b). Source: Geelong Advertiser

Although BGA are the focus of this project, it is important to note that phytoplankton form a very diverse taxonomic group that compete with each other in many ecological settings. When conditions are favourable it may be non-BGA species of algae that proliferate to levels that are harmful or a nuisance. While this may occur in some waterbodies, recent observations suggest that shifts in algae distributions towards dominance by BGA species is a process that is already occurring and one that is aided by continued anthropogenically-induced changes to many of the Earth’s aquatic ecosystems. Maintaining a focus on BGA in this project provides a means to contain the scope; however, because of the diversity of BGA and the waterbodies they occupy in Victoria, the framework approach we develop for BGA management is, by necessity, flexible to the extent that it can equally be applied to assist with the management other problematic algae, if they are identified as the key drivers of risk and impact.

2 Blue-Green Algae

2.1 Overview

Blue-green algae (BGA) are photosynthetic prokaryotic bacteria (known as cyanobacteria) that derive energy from sunlight to convert CO_2 into biomass via photosynthesis undertaken in thylakoids dispersed within their cells (Reynolds, 2006). BGA evolved approximately 2.5 billion years ago and their oxygen production via photosynthesis triggered the oxidation of the Earth's atmosphere (Bekker et al. 2004). Through endosymbiosis, BGA also triggered to the evolution of plastids among photosynthetic eukaryotes (i.e. true algae and plants) (Gould et al. 2008). It is likely that BGA first originated in terrestrial freshwaters (Stal and Cretoui, 2016), but in the time since they have diversified and expanded to colonise a wide range of marine, freshwater and soil habitats. Within these habitats they are natural and important components of balanced ecosystems (Burford et al. 2018), in which their main ecological significance is the oxygen-producing photosynthesis that fuels food chains (Dagan et al. 2012).

The diversity of BGA is extensive with a taxonomy that includes three major morphologically distinct orders, the *Chroococales*, *Oscillatoriales* and *Nostoclales*. Reynolds (2006) provides a brief description of each taxonomic order with some key examples (see Table 2.1). Many species can produce compounds that are toxic (cyanotoxins) to other organisms, ranging from hepatotoxins, nephrotoxins, neurotoxins and dermatoxins (see examples in Table 2.2). The impacts of BGA bloom formation and toxin production make BGA of upmost importance to waterbody management.

Across their taxonomy, BGA have evolved with a wide range of traits that have enabled their expansion into many of the Earths aquatic ecosystems as either persistent and/or opportunistic occupants, sometimes forming dense blooms when conditions are favourable. These traits provide BGA with advantages over eukaryotic phytoplankton when competing for resources - primarily nutrients, light and carbon (Carey et al. 2012, Huisman et al. 2016). Because BGA have evolved through periods of extreme biogeochemical and climatic variations, ranging from solar irradiance, temperature, oxygen levels, nutrient availability, wet and dry periods, volcanism and continental drift they have developed an extensive ecophysiological "*playbook*" (as described by Paerl 2014) used to respond to habitat changes over time. This structural and functional diversification has enabled BGA to occupy a broad range of contemporary habitats across the globe and means that BGA are well-placed to take advantage of changes to habitats that are inflicted by anthropogenic and climate change stressors.

Recognising the functional role of these traits is an important early step in understanding likely BGA behaviour in future and identifying the management strategies that may control their growth. However, BGA range in size across five orders of magnitude (from single cell to colonies) with growth rates that vary widely (Mantzouki et al. 2016) and exhibit combinations of individual traits with phenotypic plasticity that respond to changing environmental conditions (and can be expressed in timescales from seconds to days). As a result, the accurate prediction of their response to future waterbody conditions carries significant uncertainty. This uncertainty needs to be coupled with the differing and perhaps competing traits of co-inhabiting or invasive algae (BGA and non-BGA phytoplankton), which makes the prediction of future BGA assemblages in response to environmental changes a very complex challenge.

Much of the understanding of these traits and how they function has been established through laboratory or small-scale field experiments on a limited range of BGA strains under controlled conditions that mimic a solitary or small number of real-world stressors. At the ecosystem scale the biology is diverse and multiple co-stressors act over a range of spatial and temporal scales and through different pathways, both synergistically or antagonistically. The extent to which BGA traits are expressed, and the realised advantage these traits offer in real-world situations remains the topic of ongoing research (Wells et al. 2020). Despite this complexity a number of well documented BGA traits are summarized below and the way in which they function provides sound explanations of observed BGA community structure and likely future changes.

Table 2.1 Orders of blue-green algae (sourced from Reynolds 2006).

Division: **Cyanobacteria** (blue-green algae)

Unicellular and colonial bacteria, lacking membrane bound plastids. Primary photosynthetic pigment is chlorophyll a, with accessory phycobilins (phycocyanin, phycoerythrin). Assimilation products, glycogen, cyanophycin. Four main sub-groups, of which three have planktic representatives.

Order: CHROOCOCCALES

Unicellular or coenobial Cyanobacteria but never filamentous. Most planktic genera form mucilaginous colonies, and these are mainly in fresh water. Picophytoplanktic forms abundant in the oceans.

Includes: *Aphanocapsa, Aphanothece, Chroococcus, Cyanodictyon, Gomphosphaeria, Merismopedia, Microcystis, Snowella, Synechococcus, Synechocystis, Woronichinia*

Order: OSCILLATORIALES

Uniseriate–filamentous Cyanobacteria whose cells all undergo division in the same plane. Marine and freshwater genera.

Includes: *Arthrospira, Limnothrix, Lyngbya, Planktothrix, Pseudanabaena, Spirulina, Trichodesmium, Tychonema*

Order: NOSTOCALES

Unbranched–filamentous Cyanobacteria whose cells all undergo division in the same plane and certain of which may be facultatively differentiated into heterocysts. In the plankton of fresh waters and dilute seas.

Includes: *Anabaena, Anabaenopsis, Aphanizomenon, Cylindrospermopsis, Gloeotrichia, Nodularia*

Table 2.2 List of common cyanotoxins[1] produced by BGA (Table 1 from Paerl 2014)

Table 1. Most common cyanobacterial toxins known to negatively impact aquatic biota and consumers, including man. Shown are the toxin types, methods currently used for detection/quantification, and CyanoHAB genera known to produce toxins. Table adapted from Paerl and Otten [5].

Toxin	Detection Method(s) *	CyanoHAB Genera
Aeruginosin	HPLC, MS	*Microcystis*, *Planktothrix*
Anatoxin-a /Homoanatoxin-a	ELISA, HPLC, MS	*Anabaena*, *Aphanizomenon*, *Cylindrospermopsis*, *Lyngbya*, *Oscillatoria*, *Phormidium*, *Planktothrix*, *Raphidiopsis*, *Woronichinia*
Anatoxin-a(S)	AEIA, MS	*Anabaena*
Aplysiatoxins	MS	*Lyngbya*, *Oscillatoria*, *Schizothrix*
beta-Methylamino-L-alanine (BMAA)	ELISA, HPLC, MS	*Anabaena*, *Aphanizomenon*, *Calothrix*, *Cylindrospermopsis*, *Lyngbya*, *Microcystis*, *Nostoc*, *Nodularia*, *Planktothrix*, *Phormidium*, *Prochlorococcus*, *Scytonema*, *Synechococcus*, *Trichodesmium*
Cyanopeptolin	HPLC, MS	*Anabaena*, *Microcystis*, *Planktothrix*
Cylindrospermopsin	ELISA, HPLC, MS	*Anabaena*, *Aphanizomenon*, *Cylindrospermopsis*, *Oscillatoria*, *Raphidiopsis*, *Umezakia*
Jamaicamides	MS	*Lyngbya*
Lyngbyatoxin	HPLC, MS	*Lyngbya*
Microcystin	ELISA, HPLC, MS, PPIA	*Anabaena*, *Anabaenopsis*, *Aphanizomenon*, *Aphanocapsa*, *Cylindrospermopsis*, *Gloeotrichia*, *Hapalosiphon*, *Microcystis*, *Nostoc*, *Oscillatoria*, *Phormidium*, *Planktothrix*, *Pseudoanabaena*, *Synechococcus*, *Woronochinia*
Nodularin	ELISA, HPLC, MS, PPIA	*Nodularia*
Saxitoxin	ELISA, HPLC, MS	*Anabaena*, *Aphanizomenon*, *Cylindrospermopsis*, *Lyngbya*, *Oscillatoria*, *Planktothrix*

* AEIA: acetylcholine esterase inhibition assay; ELISA: enzyme-linked immunosorbent assay; HPLC: high performance liquid chromatography; MS: mass spectrometry; PPIA: protein phosphatase inhibition assay.

2.2 Key Physiological Traits of BGA

A wide range of physiological traits can provide BGA with competitive advantages in many waterbody settings. Here we explore some of the key traits the advantages they provide, as a fundamental step in understanding potential managment strategies.

2.2.1 Accessing Nutrients

Ongoing waterbody eutrophication is expected to further promote the dominance of BGA (Visser et al. 2016). Clear links that have been established between nutrient availability and

[1] The authors recognise that there is some doubt in the scientific literature with regard to the toxic effects of BMAA, which should be considered when reviewing this table.

distributions of BGA in aquatic ecosystems with the prevalence of BGA being attributable to the increased nutrient loads (Paerl 2014). In the competition for nutrients BGA demonstrate a number of traits that provide them with a competitive advantage over other algae. Diazotrophic BGA, such as *Aphanizomenon*, *Nodularia* and *Cylindrospermoposis* can fix atmospheric nitrogen during periods when access to alternative sources of nitrogen, such as ammonium and nitrate, is limited. Nitrogen fixation occurs via the nitrogenase enzyme complex in the absence of oxygen (that is produced by concurrent photosynthesis) (see Oliver et al. 2012 for a detailed explanation). This is achieved within specialised heterocyst cells or by the spatial separation of nitrogen fixation and photosynthesis functions within colony forming species (Huisman et al. 2016). This adaptation allows diazotrophic BGA to optimise productivity when other essential nutrients for growth, such as phosphorus and micronutrients, are plentiful. However, nitrogen fixation comes at a high cellular energy cost and is suppressed by diazotrophs when alternative forms of nitrogen are available. Higher temperatures reduce this cost in some diazotrophic cyanobacteria (Brauer et al. 2013) leading to their potential dominance in warm nitrogen-limited waters. In alternative strategies, non-diazotrophic BGA such as *Microcystis*, have evolved with an affinity for uptake of reduced nitrogen (ammonium), as opposed to oxidised nitrogen (nitrate and nitrite), which can trigger their proliferation in eutrophic waterways with higher concentrations of reduced nitrogen (Harke et al. 2016).

Other BGA (also including *Microcystis*) have developed sophisticated means of competing for phosphorus, which allows them to thrive even in low phosphorus waters (Gobler et al. 2016). These traits include high-affinity orthophosphate uptake systems that are activated at low phosphorus concentrations (Harke et al. 2012), the ability to accommodate internal storages of phosphorus (Whitton et al. 1991), and the release of polyphosphatase enzymes that enable them to utilise pools of organic phosphorus. These traits allow *Microcystis* to access sufficient phosphorus over a broad range of concentrations, which has been observed in the laboratory and in the field. Recent surveys in Lake Erie (Harke et al. 2016) have shown that under high orthophosphate concentration (e.g. near river mouths) *Anabaena* and *Planktothrix* dominate, whereas in the pelagic regions with lower orthophosphate concentrations the phosphorus scavenging and storage adaptations of *Microcystis* allow it to dominate algae assemblages. The authors demonstrated that when the waterbody was enriched with phosphorus the total biomass of BGA increased, but the relative abundance of *Microcystis* decreased.

2.2.2 Growth Rate

Although there are numerous and potentially very specific (in terms of species, strain and trait expression) mechanisms BGA can implement to take full advantage of their surroundings, increased growth rate at warmer temperatures (a trait of most algae) may also support BGA proliferation. However, because other algae also benefit from warmer temperatures the competitive advantage is not always clear (Hader and Gao, 2018) and is likely to depend on the initial temperature and the subsequent rise from that initial temperature. Whilst BGA growth rates are matched or outpaced by other phytoplankton at lower temperatures, BGA growth rates tend to increase to optimum range between approximately 27-39 ^{o}C. Although chlorophytes follow a similar trajectory up to 30-32 ^{o}C, their growth rates decline rapidly above these temperatures (see Figure 2.1). Case studies, from nearly every continent, have indicated that maximal growth rates of BGA occur at higher temperatures than for non-harmful eukaryotic algae (Paerl and Huisman, 2009).

Faster growth rates at high temperatures will favour BGA in warm waters as these systems warm further in response to climate change, whilst at the same time inhibiting the growth of competitors unable to grow effectively at higher temperatures (Paerl 2014, Gobler et al. 2020). Warming may not only increase growth rates of BGA but may also promote the geographical expansion of BGA species typically found in warmer climates, into traditionally temperate waterbodies as conditions become more favourable (Paerl and Huisman, 2009). In coastal environments, warming has been linked to increased HAB growth (not only BGA) at mid- and higher latitude regions in a processes whereby the distributions of HABs may be migrating pole-ward with progressive warming, able to proliferate in more favourable water temperatures (Gobler et al., 2017; Griffith et al., 2019).

Figure 5. Temperature-growth relationships among four different taxonomic groups (cyanobacteria, chlorophytes, dinoflagellates and diatoms). The dashed line is for comparison of optimal cyanobacterial growth temperature with temperature-growth relationships in other groups. Data points are 5 °C running bin averages of percent maximum growth rates from 3–4 species within each group. Fitted lines are third order polynomials and are included to emphasize the shape of the growth *vs.* temperature relationship. Data sources and percent maximum growth rates of individual species are provided in [41].

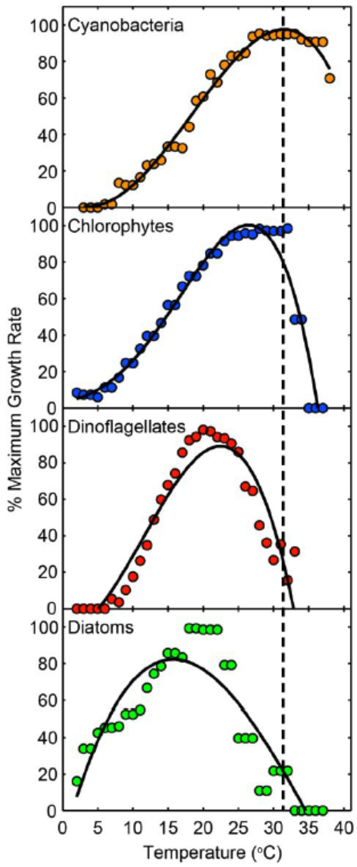

Figure 2.1 Growth rates of different taxonomic algae groups (Figure 5 from Paerl 2014).

2.2.3 *Buoyancy Control*

The ability of some BGA to modify their buoyancy is well documented. These BGA have gas vesicles that act as ballasts, allowing the algae to float towards the surface when turbulent mixing is weak (Mantzouki et al. 2016). When conditions are calm the BGA are close to the surface and gain access to sunlight and carbon dioxide required for photosynthesis, potentially gathering in high concentrations and causing surface scums. This mechanism is highly effective in stagnant and strongly stratified waters where the rates of vertical mixing are insufficient to negate the positive buoyancy of the BGA. These environments include the surface layers of stratified lakes and shallow or turbid waterbodies where competing algae would otherwise rely on physical mixing to gain sufficient exposure to light.

Species of *Microcystis* and *Aphanozomenon* may form large colonies when concentrations are high and waterbodies are sufficiently quiescent so that surface scums can form. Further, localised peak concentration of these scums can occur when winds or currents push the algae into embayment's or shorelines. Whilst the formation of these migrating aggregates can greatly improve their own access to resources, it also shades the water column below and negates the ability of competitors to access sufficient light. High surface concentrations of buoyant BGA can also capture solar radiation near the surface and accelerate heating which, in a feedback between algae and physics, strengthens the stratification and reduces mixing, handing further competitive advantage to the BGA.

Studies have indicated that BGA increases due to the effects of warming may be strongly associated BGA buoyancy regulation in warmer, more strongly stratified waters (Lurling et al. 2012). Increased water temperatures and stability may not only impact peak growth rates but is likely to also extend the periods of the year during which conditions are suitable for BGA growth and bloom formation - both in terms of the temperature and stability of the water column, i.e. stronger stratification and less frequent mixing. Wells et al. (2020) describes these changes potentially playing out as a persistent increase in BGA over the whole year, or increases in summer peaks when heating is greatest (see Figure 2.2 where the end result could involve elements of both.

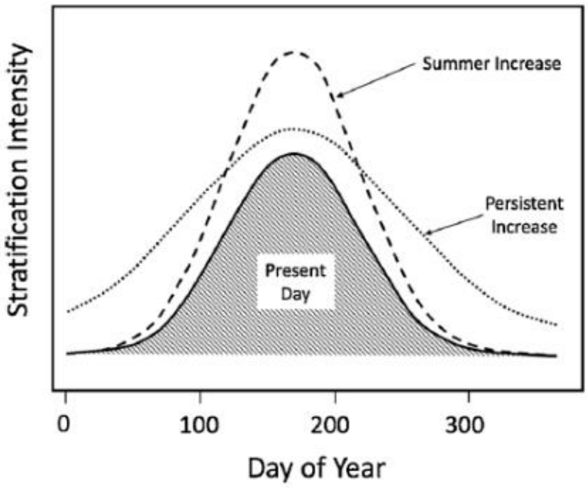

Fig. 1. Generalized possible future stratification scenarios. HABs may be expected to be more prevalent under either future scenario in at least some regions.

Figure 2.2 BGA 'growing season' as a function of stratification (Figure 1 from Wells et al .2020)

2.2.4 Colony Formation

Aside from assisting with buoyancy control by increasing flotation velocity, and the aforementioned shading of competition, the formation of large BGA colonies has other potential advantages. The formation of a colony microcosm or 'cyanoshere' (Alvarenga et al. 2017) within the water column may support a range of addition functions which can benefit the BGA colonies. The cyanosphere may become home to heterotrophic bacteria that respond to cell lysis (particularly late in blooms) by increasing rates of degradation of organic matter and returning nutrients to the nutrient pool immediately available to further growth or succession after a bloom collapse. In a recent study of *Microcystis* bloom, Cook et al. (2020) concluded that coevolution of M. *aeruginosa* and its microbiome creates a synergistic interactome that may help explain the distribution and dominance of M. *aeruginosa* across a broad range of waterbodies.

Studies have also shown that the formation of colonies or filaments offers a level of protection against grazing (Harke et al. 2016). The aggregated BGA may be difficult to ingest by zooplankton and inhibit filter feeding; in addition, for many higher trophic level organisms BGA is also a low-quality food source. However, some grazers, such as *Daphnia*, have evolved to feed on BGA (Huisman et al. 2018).

Despite the advantages of aggregation in stagnant waterbodies, the strategies that lead to dense bloom formation also have potential weaknesses. Some BGA express traits that help them overcome these weaknesses and others have evolved to take advantage of alternative environments (see below), in which floating colonies may not succeed. BGA that form large colonies are potentially at higher risk of infection by microbial pathogens, such as viral cyanophages and parasitic fungi, which can trigger high rates of mortality (Huisman et al. 2016), derail bloom formation and contribute to bloom senescence. As a defence, species such as *Microcystis aeruginosa* have developed primitive immune (antiviral) systems and others like *Planktothrix* species release oligopeptides that act to reduce the virulence of parasitic fungi. Importantly, infection is usually strain-specific and may merely promote a community shift towards resistant BGA species or strains (Huisman et al. 2016).

2.2.5 Light Harvesting

When the physical conditions are more dynamic, such as regular turbulent mixing with weak or fluctuating light climates, the advantages of colony formation may reduced. In these environments BGA such as the filamentous *Planktothrix agardhii* are efficient light harvesters that can adjust their pigment composition in response to changing levels of irradiance (Fietz and Nicklish 2002) and in doing so maintain growth under light-limited conditions. This trait allows *P. agardhii* to occupy turbid and mixed waterbodies or layers, where they may produce the toxin microcystins (Tonk et al. 2005). *P. agardhii* is also tolerant of mild temperatures that can be associated with well mixed waters, or during cooler months. Other species such as *Rhaphidiopsis sp*., which can also produce toxins, have a preference for warm mixed layers and also demonstrate tolerances towards mixing and light limitation.

2.2.6 Carbon Concentrating Mechanisms

High concentrations of BGA in blooms may also need to overcome a CO_2 limitation when photosynthetic consumption outpaces respiration and atmospheric transfer, which raises the pH and shifts available inorganic carbon towards carbonate and bicarbonate forms. To overcome this some BGA have evolved with CO_2 concentrating mechanisms (CCM's) that allow cells to increase CO_2 concentrations in cellular microcompartments (carboxysomes) to levels that can sustain growth rates (Huisman et al. 2016). There are a number of inorganic carbon update systems that support this process, which include CO_2 and bicarbonate uptake mechanisms, and which can be combined in different ways to calibrate carbon fixation rates in response to availability.

Increased atmospheric CO_2 due to climate change (and decrease due to consumption in the water) will increase partial pressures between the atmosphere and the waterbody and therefore increase flux rates into the water column. Studies indicates that BGA may benefit from this increased flux because of the flexibility of the CCMs that accommodate a high degree of phenotypic plasticity, which allows BGA to adjust to maintain carbon fixation rates under changing conditions (Ji et al. 2020). The authors found that the high phenotypic plasticity of CO_2 uptake rate gave *Microcystis* exceptional capacity to respond to increased partial pressure of CO_2 when compared to other species of phytoplankton.

2.2.7 Toxin Production

Grazing pressure on BGA may also be inhibited by the production of toxic secondary metabolites, that can act as a deterrent to predators; however, the exact evolutionary purpose of these toxins (cyanotoxins) is not fully understood (Harke et al. 2016). As with the evolution of co-inhabitants across many ecosystems, some predators, like *Daphnia*, have developed a tolerance to cyanotoxins, however, and more broadly, the production of BGA toxins can have significant impacts on intolerant species or ecosystems, including humans and livestock that interact with impacted waterbodies. In a layer of additional complexity, toxin production is a plastic trait that may respond to a number of variables, such as nitrogen availability and temperature (Burford et al. 2016). Understanding the triggers that promote a switch to toxin production is clearly of high importance to waterbody management and the subject of ongoing research (e.g. Wood et al. 2011).

2.2.8 Dormant Life Stages

A trait that helps some BGA survive unfavourable conditions is their ability to form dormant resting stages, in the form of akinetes or benthic cells (Bartram and Chorus 2002). This strategy is very effective when conditions are unpredictable, as expected under climate change scenarios (Mantzouki et al. 2016). BGA such as *Dolichospermum Cuspidothrix, Aphanizomenon, Cylindrospermopsis, Gloeotrichia*, and *Nodularia* produce akinetes that can survive in sediments of waterbodies during the cooler months of the year (Kaplan-Levy et al. 2010). *Microcystis* has adapted with the similar strategy (Verspagen et al. 2005). whereby vegetative cells have extremely low metabolism and can exist for long periods of time with little or no light exposure Increases in wind, which can lead to higher bottom shear and higher rates of sediment re-suspension, and bioturbation by larger organisms (such as fish) can trigger rapid recruitment from re-suspended BGA cells (Verspagen et al. 2004). In this manner waterbodies with historically high BGA concentrations can endure legacy effects when conditions are favourable and new periods of returned growth are triggered. Benthic cells and akinetes can remain viable within sediments for long periods, with increased water temperatures and light intensity being factors that may trigger germination after resuspension (Kaplan-Levy et al. 2010).

3 Understanding BGA Response to Stressors

The complex morpho-physiological traits BGA exhibit are described in the previous sections, and in this chapter we link these traits with potential responses of BGA to a range of stressors. Figure 3.1 shows the complex and interrelated biogeochemical processes occurring within a waterbody that govern the water quality and algae response. These processes are acted on by external forces; both climate- (eg. lower rainfall and temperature increases), and non-climate stressors (eg. land-use change or pollution). In this chapter, climate-, and non-climate stressors are described in section 3.2, followed by an analysis of the specific impacts of climate stressors on BGA in section 3.3. A generalised summary of projected climate change impacts on water sector in Victoria can be seen in Figure 3.4, after DELWP (2018). A short introductory section 3.1, frames the conceptualisation of future management strategies, by examining the difference between future *change* in BGA activity, as compared to *problematic* changes in BGA activity.

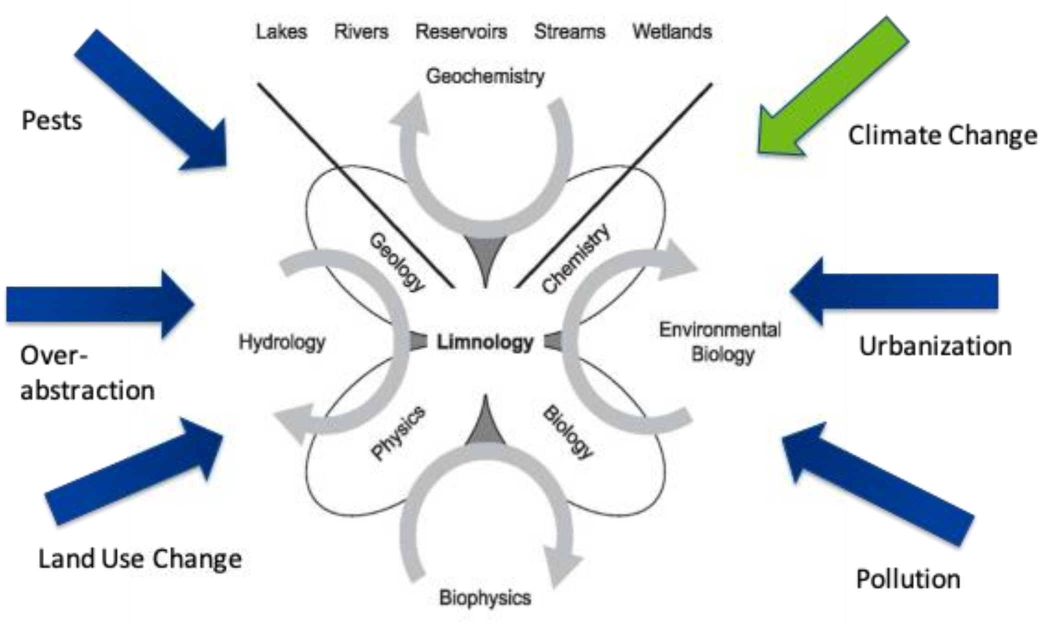

Figure 3.1 Internal processes governing water body processes, combined with (external) climate (green) and non-climate stressors (blue) after Wurtsbaugh et al (2005)

3.1 Overview

When considering the response to stressors in waterbodies within the context of BGA management two overarching questions arise. The first question is:

Will stressors lead to changes BGA activity?

This is a scientific question at brings together current knowledge and future predictions. Current knowledge includes our understanding of existing algal populations, the physical and biogeochemical processes within the waterbody they inhabit and how they respond to external (i.e. catchment) and internal stressors. This knowledge then needs to be utilised to forecast how the waterbody, and its algal population, will respond to those stressors in future (by measure and/or number). This clearly must be supported by a reasonable understanding of how the stressors are likely to change in future, or what new stressors may arise, but must also look more broadly at trends in other waterbodies or systems to allow scientists and managers to incorporate the knowledge of new issues (e.g. changing geospatial distributions of BGA species, toxins and behaviours) that may arise in their waterbodies. The sections below provide a general overview of future stressors and likely responses, but as highlighted above, the exact nature of the response in a given waterbody will be dependent on a host of specific variables and over-generalisation of BGA management strategies may lead to poor outcomes in terms of risk mitigation, time delay and cost. The collection and use of knowledge that is external to historical observations in a waterbody is a challenge for communication between scientists and managers. In addition, future prediction is likely to rely heavily on the ongoing development of increasing better predictive models (see for example Rousso et al. 2020) that incorporate mechanistic process understanding across a range of scales from global climate change down to BGA response (Bhagowati and Ahamad 2019, Ralston and Moore 2020 – see Figure 3.2).

The second, and perhaps more crucial question is:

Will stressors lead to **problematic** BGA activity?

The key distinction between the first and second question is that the second question requires a definition of what is problematic and is no longer purely scientific. This question is tied to the management of beneficial uses and the risks to those uses. BGA are often referred to as either harmful and/or nuisance algae, notwithstanding that BGA are not the only potentially harmful or nuisance algae species. BGA may be harmful in a direct manner, such as through production of toxins, or in an indirect manner because by number or nature they may impact on the efficacy of existing systems, e.g. treatment plants that are designed to mitigate other harmful vectors such as pathogens. The latter could be considered a nuisance rather than harmful, but the spectrum of what is a nuisance may stretch considerably further to include properties such as taste, odour and aesthetics (which, despite being problematic, are not necessarily harmful - see examples in Figure 4.3). The definition and measurement of problematic BGA requires a process that defines the beneficial uses or values of a waterbody and matches these to the forecasts of future BGA activity and future waterbody uses.

These questions can be ‘un-packed’ into numerous footer questions that are discussed in more detail in the sections that follow. The remainder of this chapter is dedicated to question one and looks that the way in which future stressors may impact on BGA activity. Chapter 6 describes a proposed framework that can be implemented to answer question two on a pathway to explore potential management actions.

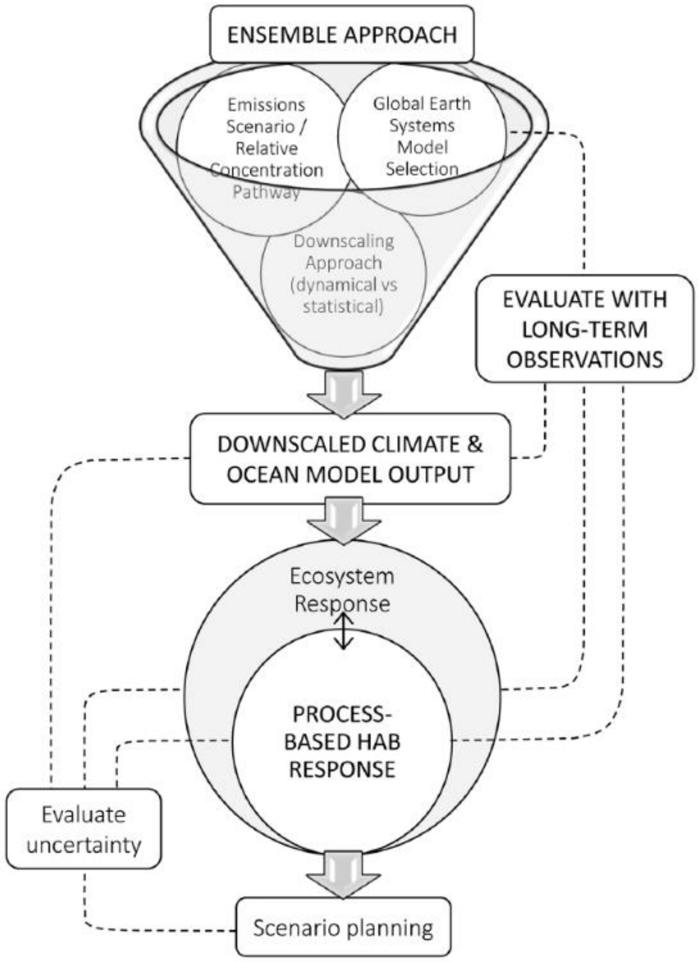

Figure 3.2 Schematic diagram summarizing considerations for improving modeling of HAB response to climate change (Figure 1 from Ralston and Moore, 2020).

3.2 Characterising Climate and Non-Climate Stressors

This section of the report defines climate-, and non-climate stressors for this project. A quick reference guide for the impacts of both stressors on water body processes is seen in Figure 3.3.

Waterbody stressors related to climate change could comfortably be classified as anthropogenic because of their connection to carbon emissions from human activities. In this report, at the waterbody scale we have defined these stressors as climate change stressors, that are distinct from the 'traditional' anthropogenic (non-climate change) stressors, such as catchment degradation, increased nutrient loads, increased abstraction and ecosystem disruptions that have, and will continue to apply stress to water bodies independently of climate change. The interaction between climate change and non-climate change stressors is complex and in most, but not all scenarios, may exacerbate each other in non-linear ways. Therefore, the response of a waterbody needs to be considered through the lens of their combined impact. However, it is also important to keep track of the origins of each stressor because this may provide insights into potential management strategies.

The stressors can be 'mapped' toward different waterbody processes and ultimately BGA responses to generate some level of qualitative understanding of the links between stressors and response (see example in Figure 3.3). These links are made between the stressor and the waterbody and the waterbody and the BGA, based on the BGA traits (as strengths or weaknesses).This mapping exercise immediately illuminates the complexity of the connections between the different co-stressors and responses and that many of the response variables are a function of multiple co-stressors. In this example the climate change stressors listed are those that have been documented in DELWP (2018) – see Figure 3.4.

Reichwaldt and Ghadouani (2011), Paerl (2014 - see Figure 3.5), Wells et al. (2020) and Burford et al. (2019) document similar approaches to mapping the effects of a combination of co-stressors on waterbody function to determine BGA response. In each case the authors stress the importance of understanding the site-specific nature of each waterbody and the trait-specific response of the BGA. The sections that follow explore a number of different stressor scenarios based on waterbody processes and the functional role of BGA that is based on the work of Mantzouki et al. (2016). Whilst it is most efficient to discuss these processes in isolation (as done below) it is clear from their complex interactions that it is a combination of effects that will dictate the overall response.

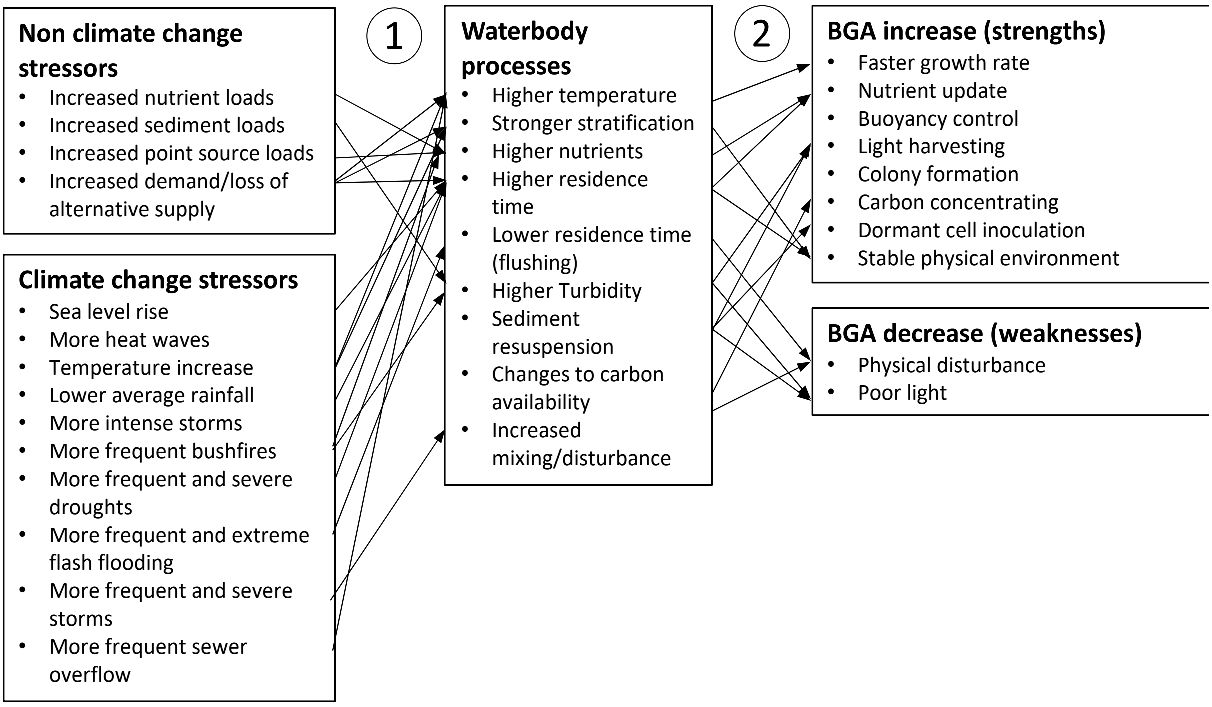

Figure 3.3 Map of pathways between non climate change and climate change stressors, waterbody processes and BGA responses.

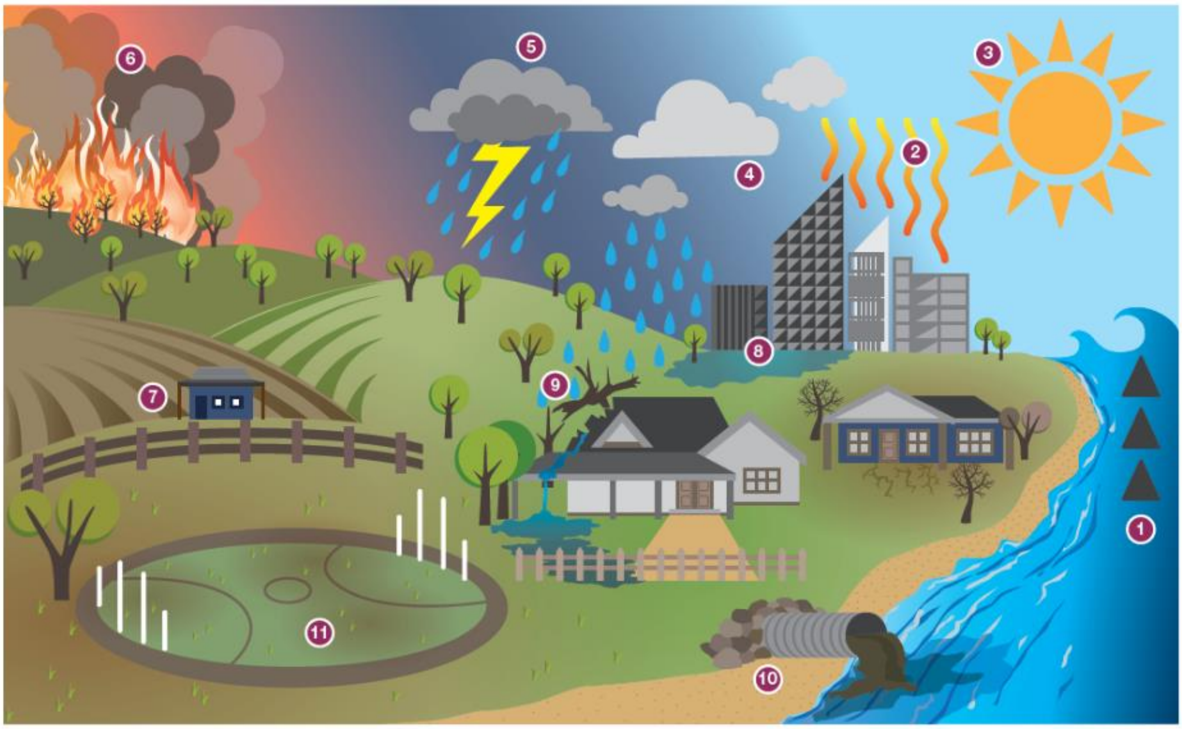

Figure 3.4 Graphic of projected climate change impacts in the water sector of Victoria (DELWP, 2018)

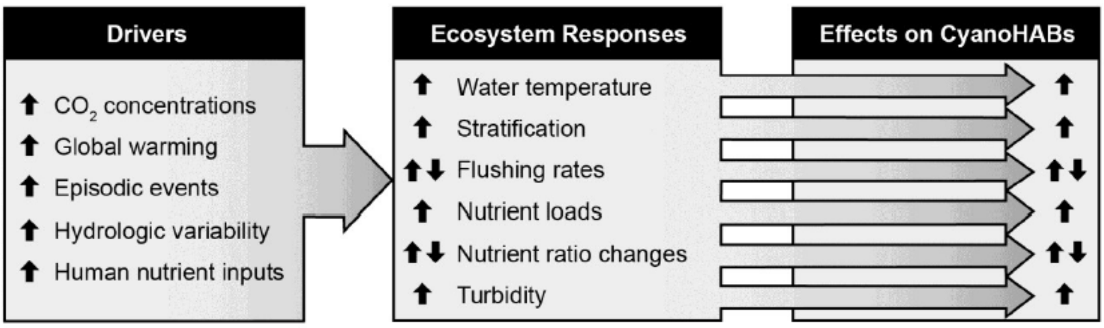

Figure 3.5 Linkages between climate change stressors and BGA response (Figure 6 from Paerl 2014).

3.3 BGA Responses to Climate Stressors

In this final section of Chapter 3, we describe the range of potential responses of BGA to climate stressors. A useful reference point to this body of work are the *Victorian Climate Projections 2019*, which present a set of climate projections for how the regional climate of Victoria could plausibly respond to climate change under different scenarios of anthropogenic greenhouse gas (GHG) emissions.

3.3.1 Plausible climate futures in Victoria: key information and further resources

Of relevance to this study, and building on the pathways described in Figure 3.3, the Victorian Climate Projections 2019 (VCP 2019) (Clarke et al 2019) report found:

- Simulations of future warming under plausible GHG emissions scenarios to 2030 are in the range of 0.5 to 1.3ºC referenced to 1990 conditions;
- Under a high emissions scenario (Representative Concentration Pathway, RCP 8.5), Victoria is expected to warm by 2.8 to 4.3ºC by 2090;
- Under a medium emissions scenario (RCP 4.5), Victoria is expected to warm by 1.3 to 2.2ºC by 2090;
- A projected decrease in annual-averaged rainfall, with higher variability, and Victoria is expected to become drier in all seasons with the exception of Summer;
- Extreme events such as heatwaves, bushfires and extreme rainfall are expected to become more frequent; and
- Higher incidence of ''compound'' events such as prolonged heatwave followed by a very wet period – which could have serious impacts on BGA dynamics in receiving waters.

VCP 2019 also resulted in the production of 10 regional reports. These Regional Reports give a selection of the VCP findings for each of Victoria's Regional Partnership regions and Greater Melbourne; helping readers understand the regional differences in how the climate will change across the state. The VCP technical report, 10 regional reports, datasets, and further guidance, is available on DELWP's website.

Other key sources of information on Victoria's changing climate include:

- Climate Change in Australia website - A repository of national climate change information and tools, including the datasets for VCP19;
- DELWP (2019) Victoria's Climate Science Report 2019 - An overview of the latest findings from scientific research into climate change in Victoria;

- DELWP (due to be published in 2020) Guidelines for Assessing the Impact of Climate Change on Water Availability in Victoria: Provides climate change projections for climate change assessment for water availability, supply and demand in Victoria;

- DELWP (due to be published in 2020) Victorian Water and Climate Initiative (VicWaCI) Synthesis Report - An overview of the scientific findings from the VicWaCI research program from 2017-2020; and

- Bureau of Meteorology (beta version due for release in 2020, full version in 2021) – National Hydrologic Projections.

3.3.2 Higher Water Temperatures

Higher water temperature will result from increased atmospheric temperatures under climate change, a feature expected across all types of waterbodies. Heating of waterbodies may also influence cycles of stratification (discussed below) and there are strong feedbacks between accelerated productivity with increased temperatures and further temperature increase due to heat-trapping by more productive waters in the euphotic zone.

Under climate change predictions, temperatures are likely to undergo a process of gradual increases in average temperatures and increases in summer peak temperature (e.g. heat waves). Because BGA are well adapted to take advantage of increases in temperature by accelerating their growth rates, these changes are likely to lead to an increase in both the seasonal extent of BGA growth (reaching further back into spring and forward into autumn) and in the peak growth rates during the warmer months.

Higher water temperature will also increase the rates of biogeochemical reactions that control the cycles of oxygen and nutrients. Increased rates of nutrient cycling have the potential to extend blooms that may otherwise collapse under nutrient limitation because of increased rates of nutrient replenishment from within the waterbody.

3.3.3 Stronger Stratification

Increased temperatures at the surface of lakes will lead to increases in the duration and strength of stratification. Weakening wind conditions will further increase the strength of the stratification as wind across the water surface induces vertical mixing and distribution of heat captured near the surface. Warm, stable, near-surface waters in either shallow waterbodies or deeper stratified waterbodies are an ideal environment for BGA growth because of the strategies such as buoyancy changes, nutrient scavenging, nitrogen fixing and colony formation that give them significant advantage in these environments.

In environments with sufficient nutrients, such as in the epilimnion of eutrophic lakes, non-diazotrophs such as *Microcystis* can thrive because of their superior buoyancy control. In more nutrient limited mesotrophic and oligotrophic lakes, diazotrophic BGA, such as *Aphanizomenon*, *Nodularia* and *Cylindrospermoposis* may gain advantage through their nitrogen-fixing capability, however their success may be limited by access to other nutrients, most importantly phosphorus. Other *Planktothrix* species combine buoyancy control with efficient light harvesting to colonise the metalimnion of deeper stratified lakes where nutrient availability is typically higher than near the surface. These species may expand the scale and period of their dominance in the event of increased levels of stratification.

Strengthening of summer stratification and the lengthening of the stratified period in lakes can also have profound effects of the biogeochemical cycles in deeper waterbodies, largely because of increased deep-water oxygen depletion. Stratification is a barrier to oxygen transfer to deeper waters which develop redox conditions that promote sediment release of inorganic nitrogen and phosphorus. The eventual load of these nutrients from the sediment will depend on the rate and period of deoxygenation, and events of partial mixing (driven by wind and cold weather), or complete mixing can deliver large nutrient pulses into the shallower euphotic zones, potentially fuelling a rapid escalation in algae production. Moreover, strong nutrient gradients over the depth of the waterbody will heavily favour BGA that can use efficient light harvesting or buoyancy regulation to optimise access to the deeper pools of nutrients.

The blooming of algae in the surface layers of deeper stratified lakes leads to a ‘raining down’ of detritus into the deeper layers as the algae die and their cells sink. While some portion of the nutrients in this detritus will be recycled within the water column a large portion of detrital nutrients will settle into the sediments in the deeper parts of the waterbody. The detritus that does settle will contribute to the oxygen demand of the sediments as in undergoes decomposition, whilst at the same time increasing the sediment nutrient pool; which can be released under reduced conditions as discussed above. Provided the stratification remains intact, and notwithstanding the strategies of some BGA to gain access to deeper nutrient pools, the deep (or hypolimnetic) nutrient pool may remain largely inaccessible to primary producers that inhabit the epilimnion, therefore effectively breaking the nutrient recycling loop, at least over the period of stratification. The frequency and extent to which these hypolimnetic nutrient are entrained into the shallow waters is largely a function of the depth, shape and environmental forcing (seasonal and events). In this way, increasing to the strength of stratification, may in some waterbodies induce severe epilimnion nutrient limitations that constraint algae (including BGA) growth in the absence of species or strains that can overcome these limitations. Equally important is that prolonged stratification (beyond the natural cycles) may support a very large build-up of hypolimnetic nutrients, that, under the correct set of physical circumstances (e.g. a strong storm and/or floods) may be rapidly mixed into the epilimnion leading to very fast and dramatic changes in biogeochemistry and subsequent BGA response.

3.3.4 Higher Nutrient Loads

Although the mechanisms for high nutrient loads to waterbodies may be varied, particularly with the inclusion of climate change stressors, nutrients are essential to algae growth and the positive relationship between nutrient enrichment and increased productivity has been well documented. Under climate change conditions the extent and intermittency of nutrient loads is likely to change as the frequency and severity of wet and dry periods alters. In small shallow waterbodies, the loads may be largely homogenous, whereas in larger waterbodies, or waterbodies with complex shapes the location of the delivery of nutrient loads may lead to significant spatial heterogeneity producing gradients in nutrient availability, and BGA activity.

BGA have some traits that allow them to take full advantage of nutrient-enriched environments (Harke et al. 2016), often forming dense blooms. However, it is important to consider the details within the nutrient load to fully explore the potential response because different BGA have different affinities to nutrient species. *Microcystis*, for example, have evolved with a preference for reduced nitrogen (ammonium), as opposed to oxidised nitrogen (nitrate and nitrite), which can trigger their proliferation in eutrophic waterways with higher concentrations of reduced nitrogen (Harke et al. 2016). BGA, such as *Aphanizomenon*, *Nodularia* and *Cylindrospermoposis* can fix atmospheric nitrogen during periods or in waterbodies where nitrogen is in limited compared to phosphorus (i.e. a low N:P ratio). *Microcystis* have also developed sophisticated means of competing for available phosphorus, that allow them to thrive even in low phosphorus waters (Gobler et al. 2016), including the ability to accommodate internal storages of phosphorus when it is readily available to utilize (and hence maintain growth) when environment sources are scarce (Whitton et al. 1991).

The exact BGA response is therefore difficult to predict when nutrients are increased as it is likely to depend on the enrichment process. Nutrient loads from catchments subject to fertiliser use, via point sources (such as municipal of industrial waste) and via increased run-off from largely natural catchments or bushfire impacted catchments are likely to differ in terms of nutrient speciation and stoichiometric nutrient ratios. Equally, the receiving waters may have very different standing stock of nutrients, ranging from, as a basic example, nitrogen limited coastal waters, to phosphorus limited terrestrial waters and stressor-response analyses needs to be sensitive to these variables. Key non-climate change stressors that adjust nutrient loading may include processes such as fertiliser use, loss or implementation of upstream nutrient-stripping riparian zones or wetlands, increased municipal and industrial effluent (to the catchment or directly into the waterbody) and increased catchment erosion due to de-vegetation. Climate change is likely to add to these nutrient loads via climate related catchment degradation (e.g. via heatwaves and rainfall changes) and subsequent erosive run-off, run-off from bushfire impacted catchments and more extreme run-off events. However, climate-change impacts such as reduced rainfall and run-off and increased frequency of drought, coupled with increased demand means that waterbodies may go through increasingly extreme fluctuations in nutrient availability as they pass through cycles of high and low inflow. In response waterbody productivity may go through more amplified periods of boom, bust and successional change in response to fluctuating nutrient availability, and ultimately depend on the capacity of the waterbody to buffer periods of low external nutrient input, and the adaptive traits of BGA (as individuals or as a collective community) that help them adapt, and adapt quickly, to these extremes. As described above, the internal cycling of nutrients between the sediments and the water column may provide sufficient nutrient enrichment to sustain growth during periods of very low external nutrient inputs and the extent to which this cycle operates may depend on stratification in particular. Sediment stores of nutrient within waterbodies with a history of nutrient enrichment and eutrophication may be vast, leading to a legacy of internally driven nutrient enrichment that may carry on for many years without substantial external input.

The adaptive traits of some BGA, such as efficient nutrient scavenging and nitrogen fixation, may provide them the necessary tools to sustain populations during nutrient poor periods, providing them with a readiness to respond when external nutrient loads increase. The most extreme version of this being the ability of some BGA to produce dormant cells that can germinate when favourable conditions return.

3.3.5 Longer Residence Times

Reduced rainfall and catchment runoff, in addition to reduced mixing in deeper waterbodies can increase the length of stagnation in all or parts of a waterbody. Specific behaviour will depend on the size, shape, operational regime and flow paths within a waterbody, with the potential for complex dendritic waterbodies (such as those with bays, backwaters or arms) to display significant heterogeneity in terms of residence time. Stagnant waters are particularly advantageous to BGA with buoyancy regulating mechanisms, which in the absence of physical disturbance can aggregate in vast colonies to form large surface blooms and potential scums. These formations can dominate the waterbody ecology and perpetuate their advantage over other algae. Increased residence time and bloom formation can promote stronger stratification and higher water temperatures to reinforce this positive feedback.

Longer residence times may result from reduced catchment flows and drought periods due to reduced rainfall but can also be the result of changes in extraction to meet growing demand or transfers to more heavily impacted waterways within connected schemes. Changes to the size and location of structures such as weirs, gates and pumps or changes to bathymetry, such as levees and canals may also lead to increased residence time in modified waterbodies.

In the estuarine and coastal setting structures such jetties, bridges, breakwaters, harbours, constructed embayments and other infrastructure may inhibit the natural cycles of tidal flushing, wind or wave mixing and currents, thus increasing residence times, which can be accompanied by associated and synergistic increases in temperature, stratification, and nutrient concentrations – all of which may combine to increase the likelihood of BGA growth.

3.3.6 Events - Storms, Floods, Drought and Bushfire

Extreme events such as storms and floods that intermittently disturb periods of drought are expected to become increasing severe with climate change. These events have the potential to very rapidly modify the physical and biogeochemical environment of a water body that will temporarily disrupt BGA growth through a variety of mechanisms. At the physical level there is simple flushing of BGA cells out of the waterbody, and increased mixing and dilution that can break up existing blooms or prevent uninterrupted periods of bloom development.

Whilst nutrient availability may increase in response to events, through external loads or mixing that entrains nutrient enriched sediments or bottom waters into the euphotic zone, this may also be accompanied by large increases in sediment loads (and therefore turbidity) due to inflow and or resuspension. With the exception of species that are adapted to efficiently harvest light in turbid environment, such as *Planktothrix agardhii,* the low-light conditions may inhibit BGA growth. Large inflows and deep mixing events may also lead to rapid decreases in temperature that are less favourable to BGA.

Whilst extreme events are likely to promote rapid changes that are detrimental to most ecosystems (including primary producers) in the short term, in the weeks that follow the increased availability of nutrients, re-suspension of dormant cells, lack of competition and diminished predatory population can trigger rapid return of opportunistic species of BGA. This is especially relevant to the waterbodies that experience large events, followed by extended periods of warm dry weather. The frequency of events is therefore very important in terms of BGA bloom formation as frequent disturbances will inhibit bloom development and may be a limiting factor in BGA prevalence, whereas infrequent disturbances may trigger long-term growth periods and shifts in algal communities towards BGA dominance if the BGA benefit disproportionately well from conditions after the disturbance when compared to other algae.

Some studies have shown that increases in the size and magnitude of extreme events alone may be enough to trigger eutrophication in the absence of other co-stressors. This is because catchments may be vulnerable to these extreme events, or repeated extreme events, in terms run-off and erosion (of sediments and nutrients). This in turn may deliver naturally-derived but increasingly large nutrient and sediment loads to waterbodies and trigger eutrophication. The expected increases in fire damage to catchments under climate change conditions could amplify these responses. Depending on the frequency and severity of burns even small flow events in badly damaged catchments may deliver disproportionality large sediment and nutrient loads to receiving waters. Post-fire run-off may also deliver extremely large loads of high oxygen-demand material that greatly increases oxygen demand in the waterbody with the potential modify oxygen dynamics and accelerate internal nutrient releases.

In deep lakes and coastal environments increased storm activity (including cyclones) due to climate change can result in increased upwelling of nutrient resources stored in the deeper layers, leading to nutrient enrichment of the euphotic layer. This process alone may trigger changes to historical BGA distribution in these waterbodies. In contrast, increased freshwater runoff in brackish and saline waterbodies (such as estuarine and coastal environments) may strengthen density stratification and reduce vertical mixing, which can favour BGA capable of vertical migration as they position themselves at physically-chemically favourable depths (Paerl 2014). Droughts and rising sea levels, coupled with increased use of freshwater may lead to increased salinisation of some waterbodies. Although BGA are most common in freshwater ecosystem, different genera are salt-tolerant to varying degrees. Diazotrophs such as *Anabaena*, *Anabaenopsis*, *Aphanizomenon*, *Nodularia*, and some species of *Lyngbya* and *Oscillatoria*, as well as non-nitrogen fixing genera, including *Microcystis*, *Oscillatoria*, *Phormidium* and picoplankton (*Synechococcus*, *Chroococcus*) tolerate higher salinities to the extent that *Microcystis aeruginosa* has been observed thriving in brackish waters (Paerl, 2014).

3.3.7 Increased Atmospheric CO_2

Increased atmospheric CO_2 due to climate change (and decrease due to consumption in the water) will increase partial pressures between the atmosphere and the waterbody and therefore increase flux rates into the water column. Studies indicates that BGA may benefit from this increased flux because of the flexibility of the CCMs that accommodate a high degree of phenotypic plasticity, which allows BGA to adjust to maintain carbon fixation rates under changing conditions (Ji et al. 2020).

3.3.8 Ecological Disturbances

Ecological disturbances to waterbodies that relate to climate change and non-climate change stressors may have more subtle and complex origins but may nonetheless trigger enormous changes in waterbody ecology and BGA response. For example, the introduction or loss of species at all levels of the ecosystem hierarchy may have profound effects, including invasion by pests, introduction of new competitors, loss or gain of predators or introduction of pathogens. In terms of BGA responses these disturbances may trigger the expression of certain traits, such as the production of toxins that will have kick-on effects for the waterbody ecosystem and utilisation of the waterbody.

Some examples in the literature include bioturbation by bottom feeding pests that resuspend dormant cells to trigger BGA blooms; loss of benthic denitrifying bacteria that increases available nitrogen in coastal environment; and the arrival of sub-tropical BGA species in traditionally temperate waterbodies. Although for some disturbances the links between climate change and non-climate change stressors are not clear, logic holds that the accelerating and expanding patterns of environmental change will increase the likelihood of ecological disturbances that may have profound impacts on future BGA distributions. Given the genetic diversity and trait plasticity of BGA, and their distribution over such a diverse range of waterbodies, it also stands to reason that BGA are well placed to adapt to and potentially take advantage of ecological disruptions into the future.

An example of geographic dispersal of BGA into new ecosystems with favourable conditions is *Rhadiopsis*, which has been described as a tropical/subtropical genus. The expanded distribution of *Rhadiopsis* into eutrophic waterbodies at higher latitudes has been observed towards the end of the 20th century (Padisak 1997). Because *Rhadiopsis* is adapted to low light conditions (high turbidity) and prefers water temperatures above 20 °C, is it likely that the combined effects of non-climate change and climate change stressors have contributed to is expanding distribution (Paerl, 2014). This is coupled with the ability to survive adverse conditions using akinetes that are temperature regulated, becoming active again when temperatures rise.

4 Managing Blue Green Algae

This Chapter 4 builds on the consideration given to the potential response of BGA to various climate stressors discussed in Chapter 3. Section 4.1 highlights the complex relationship between governing waterbody processes and water quality (i.e. BGA) responses, building on the discussion earlier concerning Figure 3.1. Following, in section Figure 4.3, an overview of management approaches found in the literature is discussed (viz. prevention, control and mitigation). The final three sections provide detailed information on these three 'approaches'. A generalised overview of in-lake water quality treatment options after Hydronumerics (2015) can be found in *Table 9.6,* and can be read in conjunction with this chapter.

4.1 A Consideration of Waterbody Processes

The role of differing BGA traits and how they combine to formulate a response to environmental change will depend on the physical and biogeochemical processes occurring within a waterbody. There are fundamental differences between the processes that operate in riverine, lake, estuarine and coastal waterbodies and specific details will vary between individual waterbodies. Although parallels can be drawn between waterbodies of similar size, depth, trophic status, mixing, stratification, flushing rate and landscape settings, broad generalisation must be considered with caution. For a given set of stressors, some waterbodies will demonstrate far higher vulnerability (in terms of BGA related risk), whilst others will remain comparatively resilient. For example, the manner and extent to which a large deep reservoir is disturbed by increased flow or storm activity will be very different to the response of a shallow wetland or lake, which could potentially be permanently altered. Some systems, such as shallow eutrophic, polymictic lakes are considered particularly vulnerable to BGA proliferation due to climate change (Hamilton et al. 2016).

Studies have demonstrated that there is a lack of clear and consistent relationships between bloom intensity and temperature increase, precipitation, fertilizer-use or other hypothesised anthropogenic-related drivers (Ho et al. 2019). Efforts to prevent or control BGA bloom development are therefore not general in nature and will always carry some uncertainty. Furthermore, there is the potential for seemingly *positive* actions to produce *negative* outcomes, particularly if the fundamental nutrient requirements for algal growth remain. For example, the managed reduction of phosphorus loads in Lake Bourget, France, (Jacquet et al. 2005) reduced phytoplankton biomass and increased transparency in the surface layers. However, the highly specialised *Planktothrix rubescens,* which occupies the mid-depth, was able to dominate the algae population as the restorative processes took the lake from eutrophic to mesotrophic. It was not until some years later when the lake returned to its natural oligotrophic state that *P. rubescens* was absent from the algal community. Understanding the traits that make BGA successful in particular waterbodies provides valuable information that can be used to manage their growth. By avoiding or disrupting conditions where BGA benefit from their functional traits, managers can implement better means of bloom control.

4.2 Generalised Approaches to Managing BGA

Recent literature (Ibelings et al. 2016, Mantzouki et al. 2016 and Stroom and Kardinaal 2016) discusses BGA management by first addressing activities within three core approaches as seen in Figure 4.1:

- **Prevention**: considers management practices that can be implemented to stop the formation of BGA blooms. Mantzouki et al. (2016) adds that the goal of prevention is restoration towards a more balanced ecosystem, such as lakes with macrophyte communities that complete for nutrients, stabilise sediment and provide shelter for BGA predators. Such approaches are likely to be effective in sustaining a mixed algal community that prevents BGA blooms. The specifics of preventative the end-goals will depend on the type of waterbody the measures are applied too.

- **Control** of BGA considers strategies that can be employed to minimise the potential for occurrence of BGA blooms; and

- **Mitigation** refers to measures that can be taken in response to BGA blooms in an effort to reduce the impacts of the bloom. Some authors note that there is a 'grey area' between actions of control and mitigation (Stroom and Kardinaal 2016); in this discussion we define mitigation actions being those that seek to reduce impacts (rather than occurrence) of BGA blooms, whereas control measures, seek to manipulate the waterbody in a manner that suppresses the occurrence of BGA blooms in the first place.

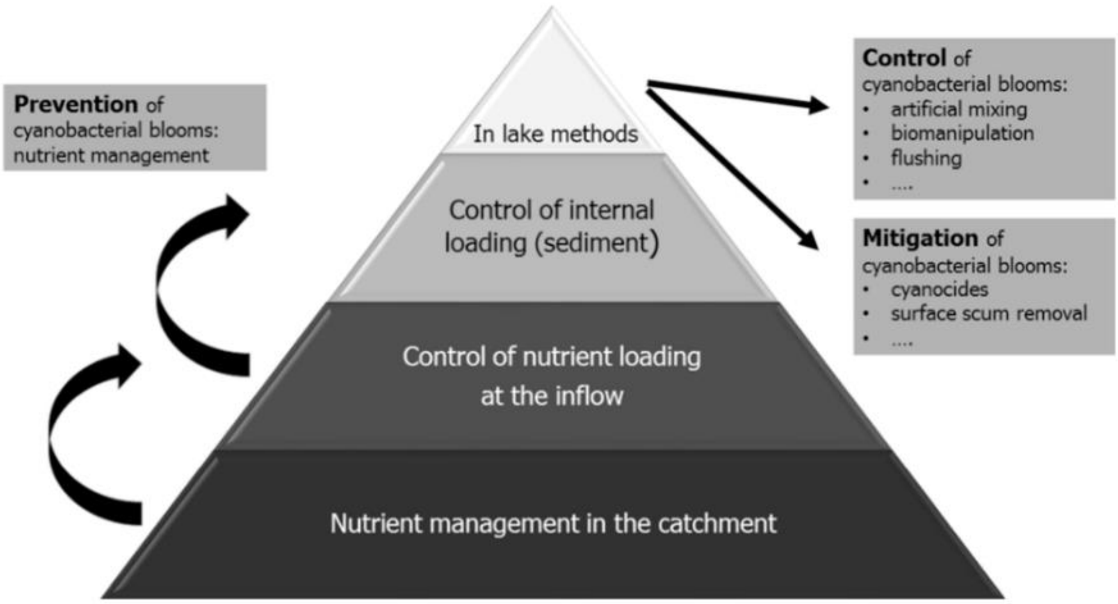

Figure 4.1 Prevention, control and mitigation measures for cyanobacterial blooms (Figure 1, Ibelings 2016).

‘Roadmaps’ for management have been developed in the literature (Examples are included below - Ibelings 2016, Figure 4.2 and Paerl et al. 2016, Figure 4.3) to help identify potentially effective management actions. Hydronumerics (2015) applied a similar framework to assessing in-lake remediation options to lakes Burley Griffin and Tuggeranong (ACT), for which a consolidated list of options is shown in Table *9.6*.

In the example of Ibelings (2016) the traits of the BGA have been grouped following Mantzouki et al. (2016), which are as listed below.

- Non-nitrogen fixing filamentous BGA that tolerate low light conditions (S_1/S_2) and inhabit turbid mixed layers of deep or shallow lakes;

- Filamentous, nitrogen fixing BGA that tolerate low nitrogen and light conditions, have optimal growth rates at elevated temperatures and resting stages (S_N) that inhabit warm mixed layers;

- Filamentous, nitrogen fixing, buoyancy regulating BGA with resting stages that tolerate low nitrogen and carbon conditions (H_1/H_2) and inhabit small to large mesotrophic lakes;

- Colony forming, buoyancy regulating BGA that tolerate carbon deficiency and stratification (L_o/L_M). These inhabit mesotrophic to eutrophic lakes, in particular the epilimnion in summer;

- Non-nitrogen fixing filamentous BGA that regulate their buoyancy and tolerate low light conditions and segregation between access to light and nutrients (R). These BGA inhabit the metalimnion of mesotrophic stratified lakes.

The decision-making process that leads to one or more of potential management pathways will also be influenced by strong non-technical forces such cost, policy, operational capability and pressure from stakeholders or public to act quickly. The benefits of preventative measures may take considerable time to be realised because of the legacy effects associated with a history of waterbody eutrophication. This can lead to significant restoration hysteresis over years or possibly decades so that other combined measures are required to manage BGA in the short to intermediate term. Lurling and Mucci (2020) (Figure 4.4) provide a graphical depiction of restoration hysteresis for shallow lakes that occurs between two stable states - the preferred ‘clear water’ state that is dominated by macrophytes, and the impacted turbid water state dominated by algae. The pathways between degradation (red line and arrow) and restoration (blue line and arrow) illustrate the hysteresis and the additional ‘effort’ that is required to shift from the deteriorated state to the preferred clear water state.

In addition, managers may need to consider concurrent ‘multiple barrier’ approaches that can be implemented to adequately safeguard waterbody functions and provide sufficient redundancy to appropriately address elevated levels of risk. Depending on the end-use, efforts to improve bloom conditions within waterbodies may need to be coupled with effective downstream treatment. For example, the requirement to build water supply treatment plant facilities that account for BGA-impacted raw waters prior to distribution. These technologies are a separate subject matter that are not explored herein. The sections below describe some of the management strategies available to address BGA bloom formation within waterbodies, in efforts to reduce potential risks and/or treatment costs.

Strategies should strive to be adaptable to climatic variability so that they can change with time and remain effective means of long-term control of BGA (Paerl, 2014) and in some waterbodies the duration of positive outcomes from control and mitigation measures may be strongly influenced by subsequent nutrient input reduction – i.e. prevention (Lurling and Mucci 2020). When the underlying cause is linked to external nutrient loads, control measures may need to be maintained or repeated indefinably. The cost of repeating or maintaining these practices needs to be part of the decision-making process and, importantly, the cost of doing nothing should be also be weighed up the process (Paerl, 2014).

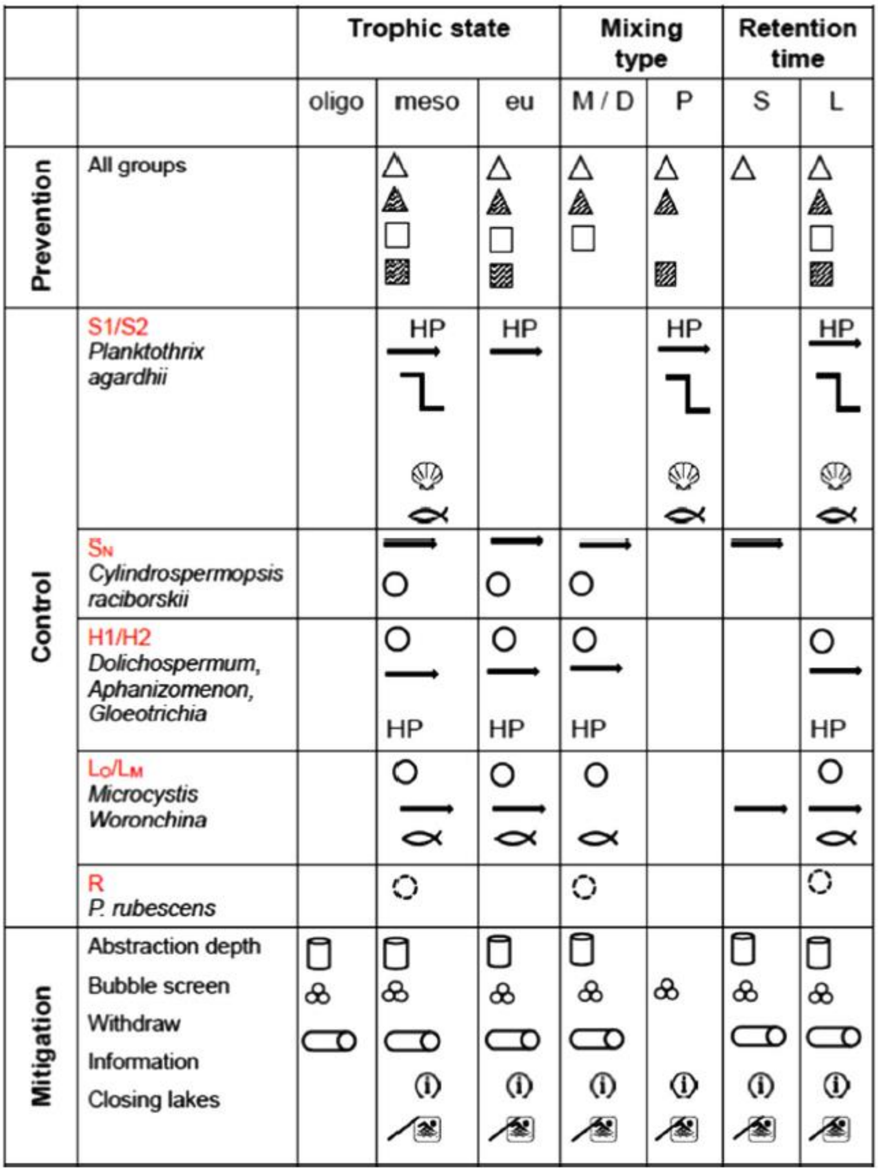

Fig. 2 Schematic overview of methods for the prevention, control and mitigation of cyanobacterial blooms as presented in the Special Issue of Aquatic Ecology. The table brings together key functional traits of cyanobacteria (following the system designed by Reynolds et al. (2000) adapted for use in this Special Issue on management of cyanobacteria by Mantzouki et al. (2016)] with key lake properties like tropic state, mixing type and residence time with the several management options (see explanation of the *symbols* underneath the table). Symbols used in the figure: M, Monomictic; D, Dimictic; P, Polymictic; S, Short; L, Long; △, P and N-control in catchment; ▲, P and N internal control—chemically; □, P and N internal control—hypolimnetic aeration; ▨, P and N internal control—dredging; HP, Hydrogen peroxide; ⟶, Flushing; ⅂, Water level management; 🐚, Biomanipulation with mussels; ∝, Biomanipulation with fish; ○, Artificial mixing; ◌, Weakening of stratification; ▯, Abstraction depth; ஃ, Bubble screen; ⊂⊃, Withdraw (scums) from surface; ⓘ, Information for bathers; ▧, Closing of bathing sites

Figure 4.2 Schematic of potential prevention, control and mitigation measures (Figure 2 from Ibelings 2016).

CyanoHAB genus	N₂ fixation		HAB characteristics						Toxins produced													Mitigation options (numbered in order of priority)								
	Yes	No	Surface scums	Throughout water column	In metalimnetic layers	Odors and taste	Hypoxia generating	Food web disrupting	Aeruginosin	Anatoxin-a	Anatoxin-a(S)	Aplysiatoxins	Beta-methylamino-L-alanine	Cyanopeptolin	Cylindrospermopsin	Homoanatoxin-a	Jamaicamides	Lyngbyatoxin	Microcystin	Nodularin	Saxitoxin	Nutrient input reductions	Encourage macrophyte growth	Lake depth and photic zone	Manipulate turbidity	Upstream wetland dev.	Enhanced flushing (*)	Enhanced mixing (*)	Sediment capping (*#)	Dredging ($)
Anabaenopsis	X		X			X	X												X			1	2	3	4	5	6	7	8	9
Aphanizomenon	X		X			X	X	X		X					X				X		X	1	2	3	4	5	6	7	8	9
Cylindrospermopsis	X			X		X		X		X			X		X	X			X		X	1	2			3	4		5	6
Dolichospermum	X		X			X	X	X		X	X		X	X	X	X			X		X	1	2	3	4	5	6	7	8	9
Gloeotrichia	X			X		X																1				2	3			
Lyngbya	S	M	X			X	X			X		X					X	X			X	1	3			4	2		5	6
Microcystis		X	X			X	X	X		X	X		X	X	X				X	X		1	2	4	5	3	6	7	8	9
Nodularia	X		X			X	X	X					X							X		1				2	3	4	5	6
Nostoc	X			X		X		X					X						X			1				2			3	
Phormidium		X		X		X		X		X			X			X			X			1				2	3		4	5
Planktothrix		X		X	X	X	X	X	X	X			X			X		X		X		1			2	3	5	4	6	7
Raphidiopsis		X	X	X		X		X						X	X							1				2	4	3	5	6
Synechococcus		M		X		X							X						X			1				2	3			

Figure 4.3 Traits, toxin production and management options for major BGA genera (Table 2, Paerl et al. 2016.)

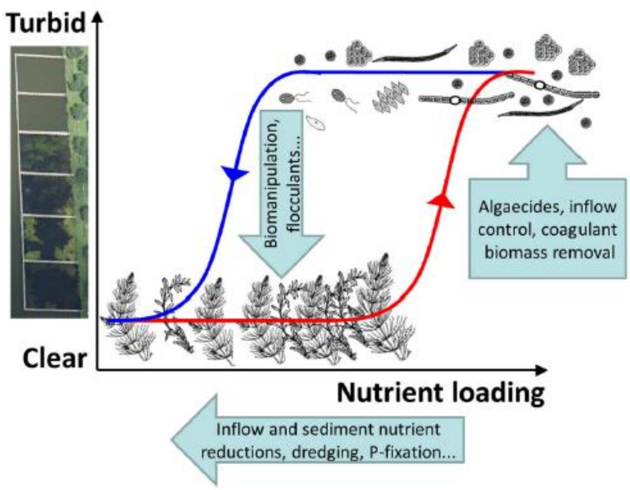

Fig. 2 Typical hysteresis of nutrient loading and water transparency in shallow lakes. Successful restoration requires interventions along both axes

Figure 4.4 Recovery hysteresis (Figure 2, Lurling and Mucci, 2020).

The following three sections include detailed information on the three management approaches: prevention, control and mitigation. Noting the discussion earlier that there is a lack of clear and consistent relationships between bloom intensity and temperature increase, precipitation, fertilizer-use or other hypothesised anthropogenic-related drivers (Ho et al. 2019), the following sections can be considered applicable even in the absence of future climate change. The discussion compliments the Framework for BGA Management developed as part of this project seen in Chapter 6.

4.3 Prevention

Mantzouki et al. (2016) argues that nutrient control must always be the basis of waterways restoration that is aimed at preventing BGA blooms, and both the scale and targeted nature of nutrient reduction needs to be considered. The traits of some BGA suggest that targeting phosphorus reduction is a sound strategy, which is based on the fact that diazotrophic BGA can overcome nitrogen limitation. However, the response to selective reductions needs to be carefully considered in terms of waterbody characteristics and the problematic BGA species (Lewis and Wurtsbaugh 2008). As illustrated by Gobler et al. 2016 (Figure 4.5) the diazotrophic trait becomes advantageous when phosphorus concentrations are high and nitrogen concentrations are low, yet in other nutrient ranges alternative assemblages are likely to arise. Recent studies in eutrophic waterbodies with BGA issues typically show highest algal growth in response to combined additions of nitrogen and phosphorus, not just phosphorus, and in some waterbodies nitrogen additions alone trigger the highest growth (Paerl 2014, Hamilton et al. 2016). It is expected that nutrient reduction targets that consider both nitrogen and phosphorus are required for long-term management of BGA blooms and this combined approach is likely to be effective in reducing all groups of BGA, regardless of their traits (Ibelings et al. 2016).

Nutrient reduction strategies need to consider both point source inputs and non-point source inputs, noting that control of point source pollution may be more easily obtained via diversions and treatments. Although non-point source pollution arising from land management may be a much larger challenge the scientific community calls for greater attention to be placed on non-point sources of nutrients, which includes maintaining agronomically optimal levels of nitrogen and phosphorus in agricultural soils (and avoiding excess) and enhancing the attenuation of these pollutants along transport pathways (Hamilton et al. 2016)

The level of detail in setting nutrient reduction targets should extend to the speciation of the nutrients between organic, inorganic, oxidised and reduced forms because of the demonstrated differences in the ability of BGA to utilise different forms of nutrients (e.g. Harke et al. 2016). Aside from nutrient reduction, the reduction of catchment sediment loads or sediment resuspension may also be effective in reducing waterbody turbidity, therefore decreasing the prevalence of BGA's specialised in harvesting light in turbid waters, such as *P. agardhii*. (Mantzouki et al. 2016) and promoting macrophyte growth.

Nutrient reductions should also take a whole-of-system approach, whereby the catchment, groundwater, waterbody, and downstream environments as considered as part of the management strategy (Ibelings et al. 2016). This breadth of thinking is important to ensure that downstream environments, at best, benefit from upstream measures, or, at worst, don't incur new or increased impacts that result from upstream management activities. This is perhaps particularly important when considering approaches that selectively remove phosphorus concentrations to reduce BGA in phosphorus-limited terrestrial waterbodies, but in doing so neglect the role of nitrogen in downstream coastal receiving waters, where nitrogen limitation may control BGA growth. In this example, reducing upstream growth (and hence nitrogen utilisation) may result in higher nitrogen concentrations in the coastal and estuarine waters, that are sensitive to nitrogen inputs (Conley et al. 2009).

Despite implementing management strategies that target external point source and non-point source nutrient inputs in the tributaries and catchments, waterbodies with a history of high external nutrient loads are likely to undergo significant hysteresis because of the legacy effects associated with the internal loading of trapped (i.e. in the sediments) nutrients. This internal nutrient pool may potentially sustain high productivity for many years, even in the absence of high external loads (Ibelings et al. 2016), and non-realised climate impacts. The process-specific details and rates of the internal nutrient cycling will depend on the physical and biogeochemical characteristics of the waterbody, yet the conceptual cycling pathways remain the same, as illustrated by Paerl (2014) and shown in Figure 4.6. Where the external nutrient reduction strategies aim to reduce the inputs into the cycle (shown to the left of the figure) internal control mechanism aim to interrupt the nutrient recycling by reducing or preventing nutrient release from the sediments and promoting long term burial. A key difference between the two cycles is that aside from advective loss, denitrification contributes to loss of nitrogen, whereas phosphorus accumulates within the sediments. Because the nitrogen cycle is significantly more complex and linked to atmospheric sources, it is both harder to quantify (as a first management step) or exert control over, when compared to phosphorus. Disruption of the nutrient cycles generally targets ways of preventing phosphorus release from the sediments, effectively trapping the phosphorus in the benthos where it becomes unavailable to BGA. The means by which this is achieved includes the use of chemical treatments that cap the sediments or precipitate and bind nutrients to the sediments (e.g. application of Phoslock® - see Copetti et al. 2016 for a review) or by maintaining a sufficiently oxygenated sediment-water interface that prevents release of nutrients under reduced conditions.

Alternatively, removal of nutrient-rich sediments (e.g. by dredging) can be undertaken in smaller waterbodies. However, the effectiveness of this process is not well documented with the potential for unexpected or short-lived results (Lurling and Mucci, 2020). In addition, this practice is both expensive and destructive to other ecosystem functions and may therefore have limited scope.

Maintaining oxygenated bottom sediments can be achieved in a number of ways that are all underpinned by tipping the oxygen balance in favour of replenishment over consumption. In sufficiently deep terrestrial waterbodies thermal stratification due to diurnal or seasonal heating creates a barrier to vertical mixing that inhibits adequate exchange of atmospheric oxygen to deeper waters. In coastal waterbodies the oxygen exchange may also be limited by density differences that relate to salt concentration gradients where fresh and brackish waters meet, such as in a tidal river estuary. The lack of oxygen transfer to depth combined with the oxygen demand of the sediment and water column means that the deeper reaches may become oxygen deficient, leading to redox conditions that promote the release of nitrogen (as ammonium) and orthophosphate. Orihel et al (2015) describes a ‘nutrient-pump’ that links cyanobacterial blooms to phosphorus release from the hypolimnetic sediments that in turn lowers stoichiometric N:P ratios in the euphotic zone.

Breaking down the strength of the stratification using mechanical mixing devices or air-bubble destratification systems can increase the rate at which oxygen is transferred from the atmosphere to depth via mixing or injecting air or oxygen directly into the deeper waters (as bubbles or oxygenated water) can also maintain higher oxygen concentrations at the sediment-water interface. Higher oxygen concentrations will restrict sediment nutrient release, which can potentially reduce the likelihood and/or intensity of BGA blooms. In addition, and described below, artificial mixers induce turbulent mixing that interrupts the positive buoyancy traits utilised by some BGA.

For some waterbodies complementary external and internal nutrient control strategies may be particularly important if the impacts of climate change cannot be sufficiently mitigated within the catchment or in the case that the time required to realise the benefits of catchment management is excessive. Because of legacy effects, achieving successful external nutrient reductions does not necessarily guarantee diminished eutrophication and BGA issues (Lurling and Mucci 2020). However, internal nutrient control strategies have practical limitations that will depend on the size, depth and shape of the waterbody to be managed and the technologies that are available. These variables need to be carefully considered when selecting additional actions, and should include a combined understanding of the function of the waterbody (physical and biogeochemical) and the traits of the BGA that are being managed. This is needed to avoid ineffective measures or unintended consequences linked to a poor understanding of the limnological processes at play, or poor application of available technologies. For example, increasing mixing of shallow waterbodies may increase physical disturbances that promote the release of phosphorus from sediments, which could ultimately increase BGA growth rather than prevent it (Lurling et al. 2016, Visser et al., 2016b).

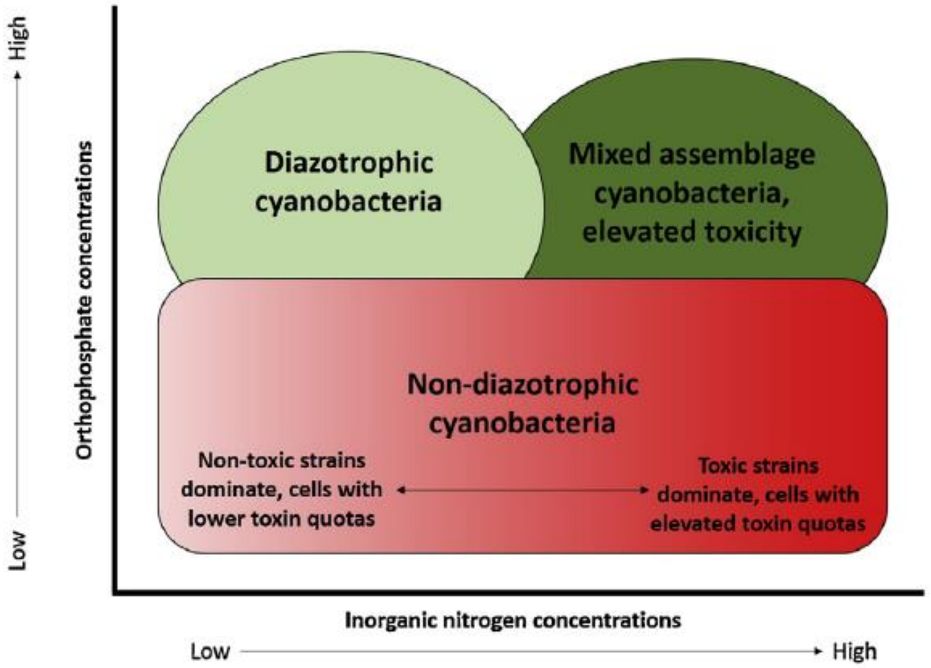

Fig. 5. Conceptual diagram of shifts in cyanobacterial populations that can be facilitated by high and low levels of N and P. While ecosystem-specific exceptions to this general depiction are likely, this paper emphasizes mechanisms that control instances wherein changes in N_i and P_i concentrations facilitate shifts among cyanobacterial populations.

Figure 4.5 Conceptual figure of BGA shifts in response to nutrient availability (Figure 5 from Gobler et al. 2016)

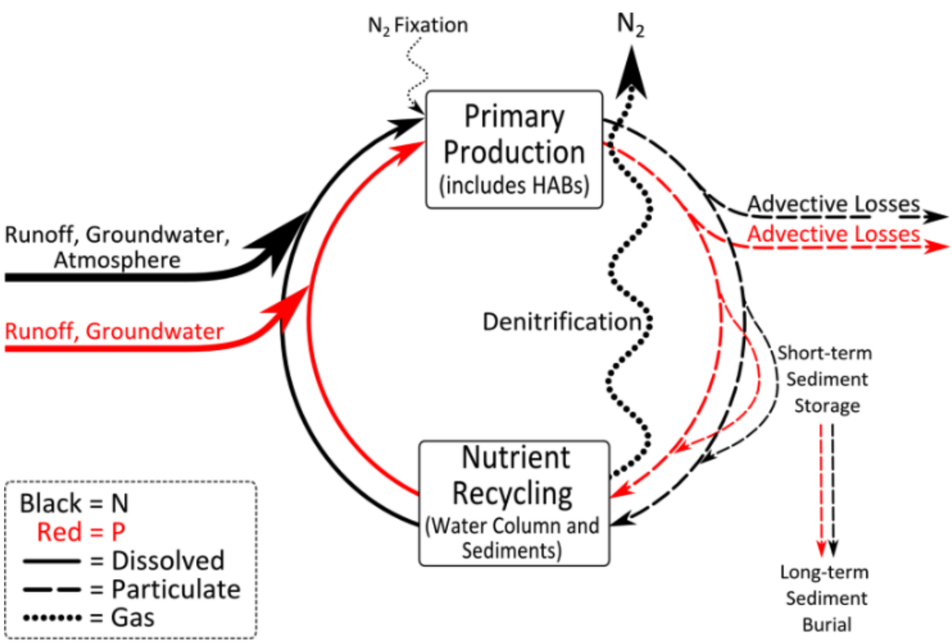

Figure 4.6 Conceptual diagram of waterbody nutrient cycles (Figure 4 from Paerl 2014)

4.4 Control

At the second tier of BGA management are a number of strategies that can be employed in efforts to control the growth of BGA and minimise the development of blooms that are not limited by nutrient control (i.e. preventative approaches). Unlike preventative measures of nutrient control, which are likely to be successful irrespective of the type of BGA that is problematic, control strategies need to carefully identify specific BGA traits, and how they function to provide competitive advantages and then exploit potential weakness (Mantzuoki et al. 2016).

In this section, we discuss:

- Reducing residence times;
- Artificial mixing;
- Bubblers and aerators;
- Biological control measures; and
- The importance of taking a whole-of-system approach to BGA management.

Reducing waterbody residence time by increasingly the frequency of flushing (particularly in shallow water bodies) has been demonstrated as a means to accelerate the recovery of BGA-impacted waterbodies (Reynolds 2006, Jeppesen et al. 1991) because it expels nutrients (see Figure 4.6) and favours faster growing green algae that can respond better to the dynamic physical environment. Reducing residence time to periods shorter than the growth rates of the BGA is a measure that can be effective against almost all BGA (Ibelings et al. 2016). This is evidenced in rivers that suffer from BGA issues when waters become stagnant (i.e. high retention time), (Bowling and Baker, 1996). Experiments on *Microcystis* have shown that blooms can be suppressed when sufficient flushing brings residence times down to about 20 days (Verspagen et al. 2006). However, depending on the physical characteristics of the waterbody and the BGA present, increasing flushing rates may not produce adequate BGA reduction, particularly if the flushing is localised (e.g. along a certain flow-path or restricted to the surface in deeper lakes), leaving environments within the waterbody that remain suitable for BGA growth.

Artificial mixing that adjusts natural mixing and light climates has also been shown to be effective in the control of BGA that use buoyancy regulation to gain competitive advantage. Research has shown for relatively deep waterbodies (minimally 15–20 m) destratification can induce a shift away from BGA dominance towards green algae and diatoms (Reynolds et al. 1983, see review by Visser et al., 2016b). Visser et al., 2016b list a number of preconditions for successful mixing, which include: mixing rate should be sufficiently high; the mixing should be deep enough cause BGA light limitation; and the number and distribution of mixers needs to be sufficient to mix a large portion of the waterbody. As with the case for mixer design to control internal nutrient release, the characteristics of the waterbody play a significant role in the practical limitations and likely efficacy of artificial mixing approaches designed to induce light limitation.

Studies of *Microcystis aeruginosa* (Visser et al. 1996) have demonstrated that the action of bubble plume mixers promoted a shift to a mixed community of non-buoyant algae. The shift was triggered not only by changes to the light regime but also by the reduced sedimentation rates of non-buoyant algae due to the mixing, which negates the advantage of buoyancy mechanisms employed by *M. aeruginosa.* The resultant fluctuating light climate (as the cells are mixed up and down) better suits eukaryotic primary producers. Diazotrophic BGA can also potentially be supressed by reducing light availability, which decreases the supply of energy required to partake in nitrogen fixation. Moreover, artificial mixing may also reduce the availability other nutrients – phosphorus and micronutrients (e.g. Fe) required for nitrogen fixation. For some species that inhabit the metalimnion of deeper waterbodies, such as *Planktonthrix rubescens*, weakening of stratification, without complete mixing may be a sufficient control measure to disrupt their growth (Ibelings et al. 2016).

Biological control methods attempt to change the waterbody ecosystem towards less favourable conditions for BGA (Lurling and Mucci 2020). Biological control includes such efforts as the introduction of filter feeders or other predators that directly consume BGA, removal of bottom feeding fish that disturb sediments and increase turbidity or fish that feed on planktivorous zooplankton, the addition of fish that prey on other planktivorous fish, or macrophyte planting. Whilst these biomanipulation practices have shown promise in some waterbodies, sustained success is not likely in systems with internal nutrient loads that remain elevated (Søndergaard et al., 2007). Moreover, subsequent decline or rebound in manipulated populations will see a rapid return to pre-controlled state. Biological manipulation may be promoted by physical controls, such as maintaining water levels to provide a stable environment that sustains the development of littoral habitats and macrophyte beds to promote higher ecosystem biodiversity and competition for resources (primarily nutrients). The application of so-called ‘effective micro-organisms’ (EM) to compete with BGA has thus far not been demonstrated as effective (Lurling et al. 2010).

Other technologies, such as high-energy ultrasound devices, show promise in the laboratory, but cannot be practicably scaled up to a waterbody setting (Luring and Mucci 2020) and others may have numerous dependencies that limit their applicability. Luring and Mucci (2020), provide a critical appraisal of numerous control (and mitigation) approaches, which clearly demonstrates that for many of the options assessed, adequate efficacy has not been demonstrated (Table 4.1). The authors stress that the pursuit of management actions to reduce future BGA risk needs to be guided by adequate science and understanding of the BGA and the waterbody to avoid the implementation of actions that do not solve or reduce the issues that need to be addressed. This mantra needs to be at the core of management frameworks to avoid ill-directed expenditure and costly delays implementing effective measures. This notion is powerfully presented in their massage (verbatim, see below) regarding the recent history of management of eutrophic Dutch lakes and serves as blunt warning to all waterbody managers that are tasked with BGA control and mitigation.

"More than 25 years ago it was already emphasized that "each lake has to be studied before restoration measures can be applied" (Van Liere & Gulati, 1992), yet these words still need to be repeated. Water authorities, municipalities and lake managers should spend more energy in such proper diagnoses than in wasting taxpayers' money by blindly believing the magic claims made by 'quick-fix' advocates." (Lurling and Mucci, 2020).

Table 4.1 Overview of efficacy of BGA management options (Table 1 from Lurling and Mucci 2020).

Hydrobiologia

Table 1 Overview of different measures and efficacy to counteract cyanobacterial nuisance directly via targeting the cyanobacteria or indirectly via reduction of nutrient availability

Mitigation measures	Target	Efficacy	Duration	Treated lake area
Physical methods				
Air-bubble screen	Inflow cyanobacteria	Low	Only when in operation	Local, harbour entry[a]
Surface aerators/mixers	Scums, odour	Low in shallow waters	Only when in operation	Local[a]
Fountains	Scums, odour	Low	Only when in operation	Local
Oil screen	Inflow cyanobacteria	Low	Long term	Relative small scale[a]
Dam of a part of the lake	Inflow cyanobacteria	High, costly, affects lake integrity	Permanent	Shallow lakes
Low-energy ultrasound	Cyanobacteria/algae	No effect	Only when in operation	n.a.
High-energy ultrasound	Cyanobacteria/algae	High effect, kills everything, costly	Only when in operation	n.a.
Excavation or dredging	Nutrients	Moderate/high effect, costly	1 to > 10 years[3]	0.002[b] to ~ 94 km^2[c]
Hypolimnetic withdrawal	Nutrients	High, cheap, downstream effects	1–30 operation years[d]	0.02–14.9 km^2[d]
Superficial skimming	Scums	Low/moderate	Depends on inflow	Small, near shore[a]
Macrophyte harvest	Nutrients	Low/moderate	1–4 × per season	100 ha[e]
Chemical methods				
Copper-based algaecides	Cyanobacteria	High, legal permission issues	Short, needs repetitions	Ponds— ~ 81 km^2[f]
Hydrogen peroxide	Cyanobacteria	No—high, repeated dosing needed	0–8 weeks	Ponds— ~ 1 km^2
Herbicides	Cyanobacteria	High, potential side effects	Max. 1 season	Ponds, small lakes
Coagulation	Cyanobacteria	High, repeated dosing needed	Max. 1 season	Small, deep lakes
Phosphate binder	Nutrients (phosphate)	High, repeated dosing needed	< 1 year to > 10 years	Ponds–dozens km^2[b]
Biological methods				
Macrophytes	Water clarity/nutrients	High, when able to grow	Long term	Littoral zone
Bottom resuspending fish	Sediment, turbidity	High, when strongly reduced	~ 7–10 years	Up to 26.5 km^2[g]
Piscivorous fish	Zooplankton-eating fish	No effect	In theory long term	10 ha spawning site[h]
Filter-feeding fish	Cyanobacteria/algae	No effect/very low effect	Short, nutrient release	Each lake
Dreissenids	Cyanobacteria/algae	Variable results	Medium/long term	Hard substrates
Effective micro-organisms	Cyanobacteria/nutrients	No effect	No effect	Ponds

[a]Burger et al. (2007)
[b]Lürling et al. (2020)
[c]Zhong et al. (2018)

4.5 Mitigation

Mitigation of BGA blooms comprises of ways to minimise the impact of blooms that have or will occur. Whilst mitigation could be considered a last resort, the constraints of cost, timing and uncertainty mean that mitigation strategies are an important part of BGA management. In this final section, we examine mitigation via:

- Algicides and chemical dosing;
- In-lake mitigation measures, such as using alternative offtakes; and

- Physical removal of algae or algae barriers.

Mitigation can be done via algicide dosing, however, the type of chemicals used needs to carefully consider the broader ecological impacts of algicide dosing. Use of copper sulphate ($CuSO_4$) for example, has potentially serious ramification or waterbody ecology and water use, as the copper is broadly ecotoxic and can accumulate in the sediments (Stroom and Kardinaal, 2016)[2]. Application of hydrogen peroxide as an alternative is highly effective for BGA and has no long-term ecological implications (Stroom and Kardinaal, 2016). Despite the highly effective and immediate results that algaecide dosing can provide the rapid lysis of large concentrations of BGA and the release of cell contents into the waterbody may have other impacts, such as treatment impacts, particularly if the lysis releases cyanotoxins. From a practical perspective the effective application of algaecide may be largely limited to small waterbodies, where adequate coverage and dosing can be applied.

Less aggressive chemical treatments of blooms include the formation of flocs of algae cells, whereby promoting sedimentation of algae. This may include the introduction of chemicals that promote coagulation, such as alum or modified clays (Stroom and Kardinaal, 2016). The latter approach is attractive when seeking to avoid complications that may arise from introduction of new chemical additives. Chitosan coagulants have been proposed as biodegradable alternatives to metal-based coagulants (Li and Pan 2013). This mitigation measure is distinct from preventative chemical dosing that aims to bind and precipitate nutrients (in particular P) to prevent algal bloom formation in the first place.

Avoiding the extraction of bloom-impacted waters can be another approach that is taken and will depend on the shape, size and operational flexibility of the waterbody. For deeper waterbodies from which water is extracted for a variety of uses, selective withdrawal from deeper layers that are not impacted on by BGA is one option. This requires the flexibility to selectively withdraw waters from different layers. Alternatively, nutrient rich water layers that promote BGA growth can be released to prevent bloom formation. However, deeper waters in stratified eutrophic waterbodies may be subject to other issues such as cold temperature, high metals concentrations and low oxygen concentrations that need to be considered, particularly in the context of environmental releases.

When surface scums are apparent, there is the potential to physically remove of those scums (via vacuuming, skimming or release) to mitigate their impact. The concept of compartmentalisation of waterbodies (Stroom and Kardinaal, 2016) can be considered in attempts to concentrate efforts that restore or preserve parts of larger waterbodies. Bubble curtains, booms, or circulation devices can be installed to physically keep BGA away from sensitive areas, such as extraction points and bathing waters. This approach, particularly in larger water bodies, may increase the options available for mitigating the impacts of BGA within sensitive compartments.

[2] Trials of an alternative copper sulphate dosing regime are currently underway and are reported in section 5.4 of this report.

Importantly, mitigation may resort to communication and educational exchanges between managers and stakeholders or public to inform of issues, such as beach closures, as they arise, as a means to remove the risk associated with certain activities (such as swimming and water sports).

5 Managing Blue Green Algae in Victoria

This section outlines the body of work focused on understanding the current approaches to the regulation and management of BGA in Victoria. Of particular note is the threshold 'notification' levels for drinking and recreational waterways shown in Figure *5.1* (DELWP, 2019).

A desktop analysis of available Victorian, regional and local waterway management plans was undertaken. In addition to providing a useful baseline for future BGA management planning, it is a crucial element of the proposed conceptual BGA framework described in Figure 6.1, below. To compliment this review, the following work was undertaken:

- A series of (online) stakeholder workshops were conducted, with representatives from drinking water, health, agriculture and recreation (Section 9.1 includes an overview of the stakeholder engagement activities, as well as survey results from attendees);
- One on one interviews were conducted with water industry stakeholders as well as cross-departmental stakeholders (eg. Agriculture Victoria, DHHS); and
- Interstate water corporations and research organisations were interviewed in an effort to benchmark the Victorian response, and to get information on research and development initiatives in other jurisdictions.

This section of the report is organised as follows:

Chapter 5.1 – A short introduction to the Australian setting

Chapter 5.2 – Introduction and policy framework;

Chapter 5.3 – Review of current Victorian BGA Management strategies;

Chapter 5.4 – A summary of the stakeholder engagement process; and

5.1 Research and management in the Australian context

Australia has an extensive history of studying and managing BGA across a range of different waterbodies. Increased awareness and occurrence of BGA and BGA risks lead to scientific efforts that produced numerous globally significant research contributions and Australian expertise from the 1990's onwards. These contributions included improved understanding of the mechanisms that lead to BGA dominance in a range of typical BGA-impacted environments found across Australia, such as stratified weir pools (Sherman et al. 1998), anthropogenically impacted tidal estuaries (Orr et al. 2004), stratified supply reservoirs (Bormans et al, 1999) and lowland rivers (Webster et al. 2000).

A growing need for evidence-based and effective BGA management culminated in research efforts focused on assessing management options applied in the Australian context. These included, for example, research on phosphorus adsorbents (e.g. Robb et al. 2003), artificial mixing (Antenucci et al. 2005, Burford et al. 2006, Brookes et al. 2008a), and culminated in industry-focused practical guidance papers, such as Brookes et al. (2008b) and Newcombe et al. (2010) which provide reference points between science and management.

Building on the already significant pool of BGA knowledge in Australia are continued efforts in research and development that are focused on multiple aspects of BGA management. Recent examples range from monitoring (John et al. 2019), functional understanding (Burford et al. 2020), and predictive modelling (Rigosi et al. 2015, Rousso et al. 2020). In most instances the knowledge that is gained throughout Australia is applicable to Victoria (an vice versa) and communication of this information within Victoria and more broadly, Australia, is absolutely critical to successful and timely management of increased BGA related risks in future.

In the sections and chapters that follow we describe in detail the existing frameworks in Victoria and explore how future BGA management challenges in Victoria can the addressed. However, whilst Victoria is our focus, we stress the crucial importance of striving for shared knowledge, good communication and collective goal-setting with other states, particularly our neighbouring states of NSW and SA with which Victoria shares the geographical setting and benefits of waterways that are of critical environmental, cultural and economic importance to not only to these states but the nation as a whole.

5.2 Introduction and policy framework

Many different water bodies are found across Victoria, in fresh and marine environments, from pristine alpine lakes, complex bays and tidal zones, rivers, wetlands and private storages. The waterways are shared between a large number of stakeholders, for many beneficial uses including drinking water, for recreation and for agriculture. A large number of these resources support multiple, and often conflicting priorities, providing a delicate balance for drinking, recreation and agricultural demands. A spatial characterisation of waterways in Victoria can be found in *s.* 3, Schedule 1 of the State Environment Protection Policy (Waters), (Victoria 2018).

Managing water quality across this portfolio, for the many beneficial end-uses comprises various forms of legislative and policy instruments, as well as site-specific, local and regional management and response plans. Various technical and industry reports also comprise the body of knowledge attending to water quality management in Victoria. For the management and response protocol for algae, the most notable of these documents is the ‘’DELWP BGA Circular’’, the annual publication setting down the state-wide management plans and response protocols (DELWP 2019). With few exceptions, the document does not provide specific management plans for any assets, rather, it provides an overarching framework for managing BGA blooms, with particular attention on the roles and responsibilities of various agencies during a bloom (See for example Figure 1 and Chapter 6: Incident management roles).

The rights and responsibilities of organisations managing water, particularly for drinking and recreational purposes are set down in *The Water Act 1989.* A *Statement of Obligations* details catchment authorities’ obligations with regard to blue green algae management. These provisions are complimented by the provisions of Section 4I(2) of the *Water Industry Act 1994,* which provides the Minister the opportunity to issue a Statement of Obligations to a Regulated Entity (i.e. water corporation or authority), specifying obligation of the entity in performing its functions and exercising its powers. The current Statement of Obligations requires entities to:

- Manage risk to protect public safety, quality and security of supply (c. 1-6.1);
- Must develop an emergency management plan for incidents and emergencies covering all hazards and measures, including risk to water quality (c. 5-2.1(f));
- Must report BGA blooms impacting on water supply or delivery (c. 5-4.1); and
- If the corporation is a nominated Regional Coordinator, the corporation must ''develop and maintain on an annual basis a contingency plan for regional blue green algal blooms'', and ''undertake its duties as a Regional Coordinator in accordance with that contingency plan and the Blue Green Algae Circular" (c. 5-4.2 (a,b)).

It is instructive here, particularly in the context of future climate adaptation and management, to consider the current notification guidelines for BGA events in Victoria, the relevant thresholds and notification pathways (i.e. to consider if future climate impacts necessitate alternative indicators or lower thresholds). Figure *5.1*, below, shows the trigger levels for drinking water, recreational water bodies and for seafood.

The toxin forming *Microcystis aeruginosa* is used as the indicator for both drinking water and recreational water bodies (albeit at different thresholds). In addition the combined biovolume of any 'potential' toxin-forming species any 'potential' toxin forming species can also trigger an event, similarly at different thresholds for drinking and recreational waters. Section 5.3 examines when and how the collection of these samples is determined.

Of note to this pilot study:

- There are no reference triggers for water designated, or used for stock purposes (i.e. animals drinking water from farm dams);

Triggers	Recipient
Any water body - BGA at or in excess of a biovolume of 0.2mm^3/L. Notification will be made via the *Algal Blooms Module*.	DELWP, Regional Coordinator
Water supplied for drinking[5] with any one or more of the following: • Total *microcystins* detected at ≥1.3 ug/L (*microcystin*-LR toxicity equivalents); • *Microcystis aeruginosa* is present at ≥ 6,500 cells/mL; • Total combined bio-volume of known toxic *cyanobacterial* species ≥ 0.6 mm^3/L; • Total combined bio-volume of all *cyanobacterial* species ≥ 10 mm^3/L; or • BGA is present in drinking water at levels that may cause widespread public complaint, e.g. through taste and/or odour. • BGA is present in concentrations that the water agency believes may pose a risk to public health	DELWP, Regional Coordinator, DHHS (Water Unit)
Recreational water bodies when any one or more of the following occurs: • ≥10 µg/L total microcystins; • *Microcystis aeruginosa* is present at ≥ 50,000 cells/mL; • Total combined biovolume of known toxic *cyanobacterial* species is ≥ 4 mm^3/L; • Total combined biovolume of all *cyanobacterial* species is ≥ 10 mm^3/L; or • *Cyanobacterial* scums are consistently present[6].	DELWP, Regional Coordinator, DHHS (Water Unit)
Seafood when confirmation that a toxin producing species has reached a biovolume of ≥ 0.4 mm^3/L at two or more sites within one week. Note: see *Protocol for managing the risk to seafood safety from harmful algal blooms in the Gippsland Lakes 2017-2020* for detailed health guideline values for cyanobacterial toxins in seafood (fish, prawns and mussels/molluscs).	DELWP, Regional Coordinator, DHHS (Water Unit), DJPR, PrimeSafe, Environment Protection Authority (EPA)

Figure 5.1 Trigger Levels for drinking water, recreation and seafood (DELWP 2019)

5.3 Victorian Management Framework

The provisions of the *Emergency Management Act 1986* and the resultant Emergency Management Manual Victoria (EMMV) link the **statutory obligations** of Responsible Entities and the **strategic** (long-term planning) and **operational** (event response) responsibilities in relation to managing algae. Part 7 of the EMMV *Emergency Management Agency Roles* defines DELWP as the Control Agency for BGA emergencies (p. 7-3), in addition to a small number of sites assigned to Parks Victoria where it is designated as either the waterway manager or under the direction of the relevant catchment management authority (p. 7-83)(State of Victoria 2020). The Department of Health and Human Services (DHHS) is required to receive notification of BGA events that reach relevant trigger levels in drinking water supplies under *s.* 22 of the *Safe Drinking Water Act 2003*.

A feature found in all BGA management plans reviewed for this project was the characterisation of the components of the plan in accordance with the EMMV described above and the relevant statutory requirements discussed in section 0 into three components shown below and seen in graphical form in Figure 5.2.

1. Prevention and Preparedness

2. Response

3. Recovery

As Figure 5.2 highlights, the framework generic, and can therefore be used for any waterway in Victoria. Most importantly, it accommodates the various agencies and orgainsations that may be involved in the management of a water body, i.e. catchment management authorities, local waterway managers and stakeholder organisations.

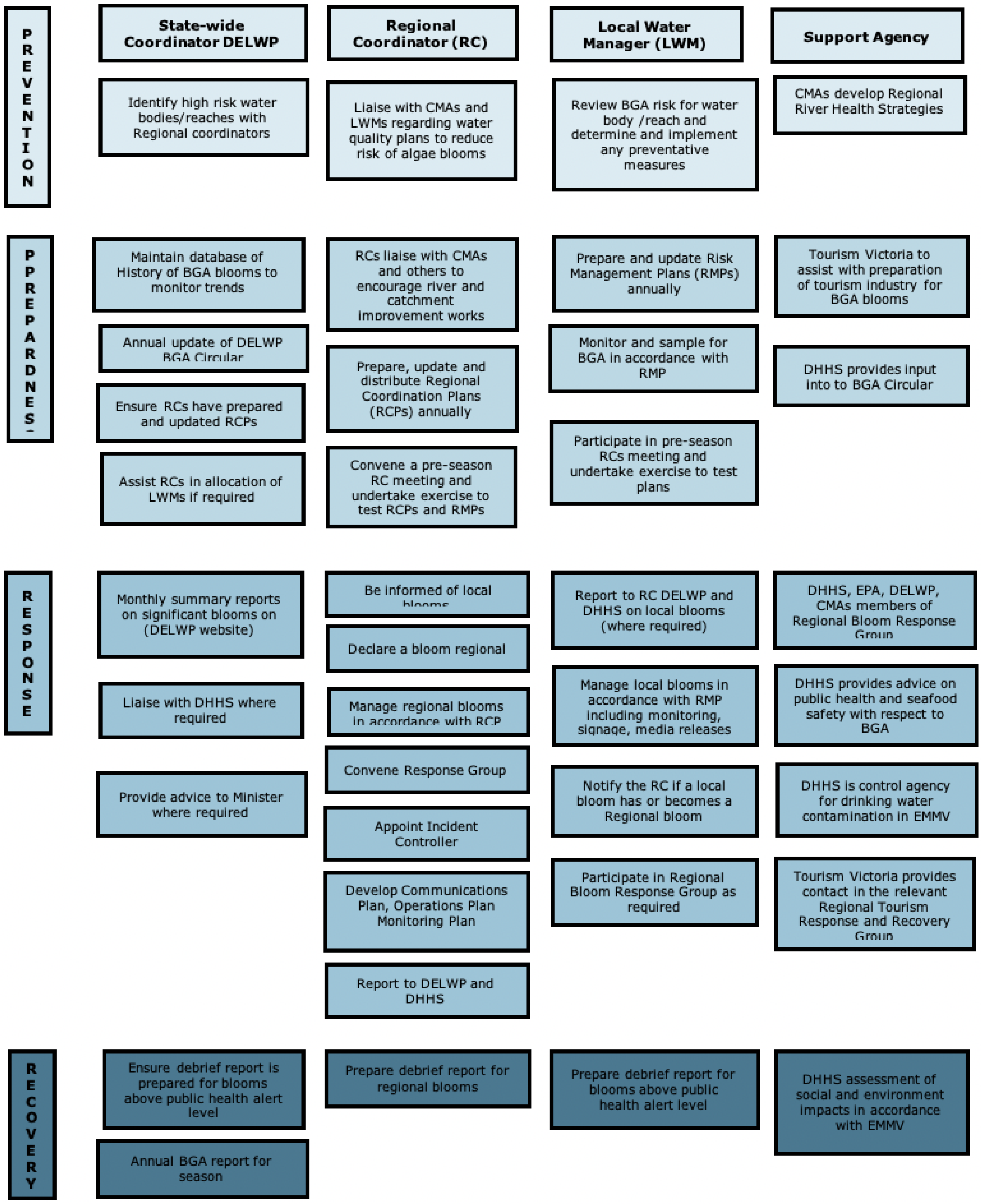

Figure 5.2 Roles and responsibilities in the management of BGA (Source: Melbourne Water)

The following two sections provide more information on the first two components of the plan (prevention and response). The final component 'Recovery' is not included in this report as it was considered that it was unlikely to be impacted by future climate pathways.

5.3.1 Prevention and Preparedness

The information contained in the *Prevention* section of Figure 5.2 provides critical information for managing BGA events under future climate change, noting the roles and responsibilities of various agencies. It is useful to highlight the Regional Coordinators responsibilities to 'liaise with Local Waterway Managers (LWM) and Catchment Management Authorities (CMA) regarding water quality plans to reduce risk of algal blooms', and the implementation of 'preventative measures' by LWM's after a risk assessment of their waterbodies.

At the Regional Coordinators' level, this is achieved by a pre-season regional coordinators' meeting to cover:

- The Annual DEWLP BGA Circular;
- An overview of high-risk water bodies and potential risk reduction strategies;
- Local Water Manager Risk Management and Incident Response Plans;
- Regional Coordination Plan;
- Season preparation (i.e. training, resources); and
- An exercise to test Regional Coordination Plan[3]

Of the reports reviewed for this project, there is generally little information included in any of the management concerning '**potential risk reduction strategies**'. With one significant exception, which, for each of that organisations' reservoirs included potential algal risk, possible control measures (ranging from aeration, chemical dosing, alternative supply mechanisms), as well as an assessment of the likely efficacy of the proposed treatment methods.

This may be due to a range of factors including:

- Limited 'end-of-pipe' control options for local and regional managers;
- The difficulty in capturing parallel water quality initiatives with different time-scales (i.e. land-management initiatives may take several years), be managed by different sections of an organisation and indeed may not identify BGA dynamics as an outcome of the project;

[3] See for example management plans of eg. Western Water, Melbourne Water.

- In-situ control measures may only be incidentally improving BGA regimes, however they are originally installed for different reasons (i.e. aerators in reservoirs may be used to control iron and manganese concentrations, incidentally helping to mitigate BGA events); and

- Systems where water retailers are not responsible for the management of the waterway (either for direct abstraction or transfer systems), whereby local waterway managers have little control of source water management.

The National Health and Medical Research Council (NHMRC, 2008) provides simplified 'susceptibility category' for grading recreational water bodies that are at risk of BGA blooms, work which was based on a global literature study and analysis of a large number of Australian reservoirs. As seen in Figure 5.3, the framework uses historical BGA blooms information, water temperature, phosphorus concentration and prevalence of thermal stratification to establish a susceptibility category for a domain of interest. There is some criticism that this is an overly-simplified risk assessment and may be biased towards bloom-forming, nuisance species found in South-Eastern Australia, but nevertheless, it is a useful point of reference in the development of this pilot adaption plan, and how flexible frameworks and risk assessments might be developed for individual reservoirs.

Environmental factors (singly or in combination)				
History of cyanobacterial blooms	Water temperature (°C)	Nutrients: total phosphorus (µg/L)	Thermal stratification	Susceptibility category
No	< 15	< 10	Never present	Very low (good)
Yes	15–20	< 10	Infrequent	Low
Yes	20–25	10–25	Occasional	Moderate
Yes	> 25	25–100	Frequent and persistent	High
Yes	> 25	> 100	Frequent and persistent/strong	Very high (poor)

Figure 5.3 Simplified recreational risk analysis (NHMRC, 2008)

5.3.2 Response

This 'second' component of the current management approach defines the responsibilities and actions during at BGA event. From Table 2 (DELWP 2019 – Incident Trigger Levels) we can see that when a waterbody used for any beneficial end-use, yields a sample result that exceeds a relevant alert level (eg. Figure 5.1) the response and de-escalation plan will be activated according to the spatial extent of the bloom recorded. A useful ready-reckoner for thresholds and notification pathways for drinking water and recreational water is shown below.

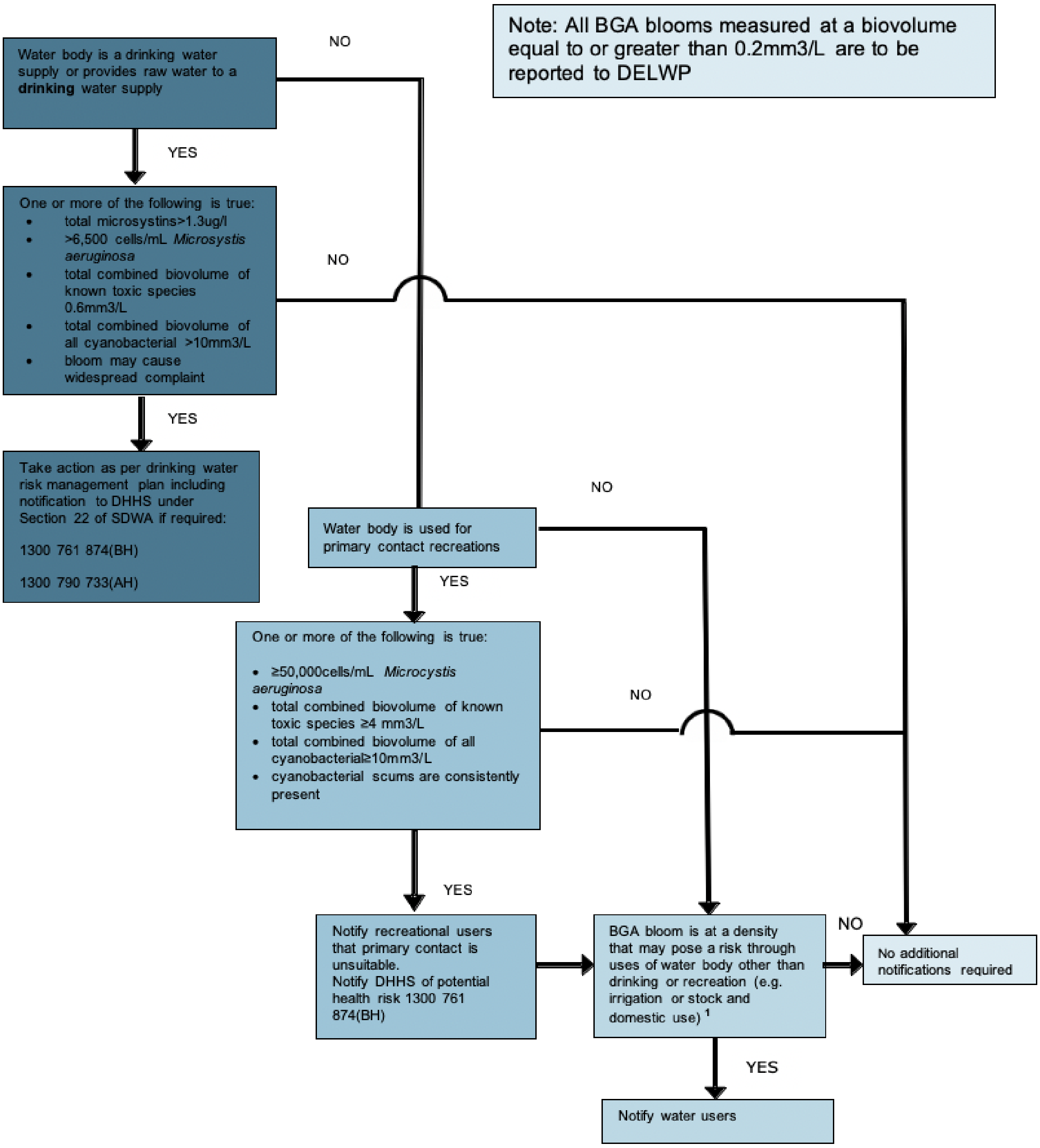

Figure 5.4 BGA Notification and Response Pathway (Source: DELWP)

Of particular interest to this project is:

- Waterbodies are generally sampled monthly in cooler months and fortnightly in summer (generally from October), and in the case of Gippsland Lakes, weekly samples are conducted from late December. Given the information discussed in section 3.3.2, routine monitoring programs may need to be modified to accommodate BGA seasons that start earlier and/or are prolonged into the cooler Autumn/Winter months;

- Waterbodies that support primary recreation activities (i.e. where there is full immersion likely to result from an activity; swimming, skiing) present higher public health risks than those for secondary, non-contact recreational activities. Parks Victoria conducts weekly sampling for high-risk locations, for example Lysterfield Lake, during summer months, but management response is limited to excluding visitors (via warning signs), which is largely self-regulated.

- There is little information contained in the Response Plan for water used for stock purposes and this was highlighted as a key cross-departmental link throughout the stakeholder process;

- Agriculture Victoria publishes brief management circulars on its website (see for example: http://agriculture.vic.gov.au/agriculture/farm-management/blue-green-algae-issues/managing-blue-green-algae-in-farm-water-supplies, highlighting the significant effects that BGA can have on livestock health. The following information was highlighted in GWMWater's 2019 BGA Management Plan for livestock drinking water guidelines:

  - *If visual scums are present, then a High alert should be declared. This would be applicable for both farm dams and publicly managed water bodies*
  - *Where blooms are dominated by Microcystis aeruginosa, 11,500 cells/mL should be used.*
  - *Where blooms dominated by Dolichospermum circinale are present, guideline of 25,000 cells/mL should be used.*
  - *Blooms other than M. aeruginosa and D. circinale will constitute a High alert when a total BGA algal biovolume is in excess of 6 mm^3/L.*

The following passage from the Melbourne Water Regional Coordination Plan (*s. 6.3.3)* highlights the key linkages and gaps for stock, domestic and irrigation response mechanisms:

Currently there is insufficient data to set risk-based trigger levels for BGA in water bodies used for other purposes, such as stock and domestic supplies or irrigation water. The LWM should undertake a risk assessment for blue-green algal blooms in these water bodies to determine whether the water is potentially hazardous. If it is considered that a risk may be posed due to the presence of BGA, then all relevant users of the water should be notified.
For domestic water uses (such as showering and bathing, cooking or other kitchen purposes and domestic garden watering), the use of the drinking water trigger levels for BGA are recommended. While this is likely to be conservative, it can be used in the absence of a more detailed risk assessment for the specific scenario in question. Less conservative approaches can be adopted if a detailed risk assessment is completed

In terms of current or historical research initiatives:

- The plans, particularly the annual Response Plan do not contain any information research and development that was conducted by any of the stakeholders during the previous year; and

- There is no centralised location for information related to treatment and remediation technologies available to stakeholders. An interview with Water Research Australia (WaterRA) revealed that WaterRA is commencing a project to standardise the methods to assess the efficacy of BGA remediation technologies, and this may be a useful incorporation in future adaptation plans.

5.4 Options for Prevention and Control

There are various options for preventing and managing blooms available to waterway managers, especially for drinking water reservoirs, and highly valued public assets. Detailed theoretical background was earlier provided in Chapter 4. Options can be broadly categorised into physical controls (nutrient and sediment management, artificial destratification and source water selection), and chemical or biological controls (algaecides, sediment caps, biomanipulation). In addition to water quality outcomes associated with any preventative or control options, proponents must consider; community expectations and values, life-cycle costs (i.e. capital and operational expenditure, renewal and decommissioning), as well as the full suite of ecological impacts (both positive and negative, i.e. chemical dosing may have ecological impacts well beyond the application dates).

Example measures can be broadly grouped into the five following categories, which are shown below. Further information on each option is provided in *s. 9.3* and general information, in the context of the proposed framework is included in Chapter 2. Readers should note that site-specific hydrometeorological conditions, site morphology, biological assemblage, as well as those over-arching considerations listed above must be addressed in the design and implementation of any prevention or control measure.

- Land management and vegetation control;
- Mixers and aerators;
- Sediment treatment;
- Engineering options; and
- Water column treatment

The detailed notes published in *Management Strategies for Cyanobacteria* (WQRA, 2010) provides a useful companion document to the information *s.2.2 – Physiological Traits,* particularly from an operational perspective. Of interest is the information relating to the use of algaecides, noting that an early treatment is preferable to minimise the release of intracellular toxins and odour metabolites, as well as secondary impacts on coagulation and filtration performance at treatment plants (p.55). Further caution, and legislative requirements for local waterway managers considering the application of algaecides to drinking water sources is seen in Appendix G of the Algal Bloom Response Plan (DEWLP, 2019).

5.4.1 Case Studies and Current Initiatives

As highlighted in *s. 5.3.2*, a current, centralised database of research and development initiatives relating to BGA prevention and control does not exist for Victoria. This would be a useful addition to future updates of the BGA portal. Only a limited number of case studies were provided by Victorian stakeholder for this project. A summary of current research initiatives and historical case studies is provided below. Relevant papers are highlighted for each study and details are included in the reference section. Of particular interest are the three initiatives focused on remote (satellite) sensing for BGA blooms in Victoria (DELWP), NSW (WaterNSW) and nationally through CSIRO and the SmartSat CRC.

Table 5.1 Relevant case studies and research initiatives

Case Study/Research	Key Agency	Key Findings	Reference / Note
Application of a novel algaecide (EarthTec®) to a small drinking water reservoir	South Gippsland Water	Commenced dosing in March 2020 Successfully reduced taste and odour compounds in reservoir and PAC (Powdered Activated Carbon) dosing rate at WTP	Not published Unclear from research notes what the results where in terms of algae concentrations and toxicity (if any)
Satellite remote sensing for recreation and drinking water resources	DELWP	Use of medium resolution satellite imagery and bespoke algorithm to estimate BGA levels Trial commenced in early 2020, results unavailable to date Potential to rapidly identify waterbodies with BGA blooms and manage accordingly	Potential to improve management in remote locations due to logistics of sampling. Additional research is being conducted at PhD level at UNSW, but is yet to be published.
Remote sensing to measure spatial and temporal distribution of BGA growth in surface waters	WaterNSW	Sentinel 2 with 10m resolution measuring NDCI (normalised difference chlorophyll-a index) with custom script to detect turbidity and surface algal density	
Space technology to boost national water quality management	AquaWatch Australia (CSIRO, SmartSat CRC)	A 12-month scoping study to investigate potential for satellite imagery coupled to ground based sensors to deliver real-time updates on water quality including BGA	Due for completion late 2021
Water Quality Improvements from pontoon coverage in a recycled water storage lagoon	Yarra Valley Water	Installation of a floating pontoon solar system in the Wallan Treatment Plant. Part of the project is a proposed area of research to determine and quantify the water quality improvements based on the pontoon coverage, which may help prevent future algal blooms	In Progress.
Development of a Toxic Cyanobacteria Management Plan for Southern Rural Water	Southern Rural Water	Risks of cyanotoxins to human health, both direct and indirect with regard to *Microcystis aeruginosa* and *Anabaena circinalis (Dilochospermum circinale).* Report also included research into risks for: - Drinking and domestic water - Recreation - Livestock watering - Pasture, fruit and vegetable irrigation And interestingly, indirect consequence of raw water exposure: OH&S considerations for farm and industry workers, as well as risk categorisation for type of irrigation practice on food contamination. Developed a physical prediction method for reservoir risk assessment based on standard morphological features and water quality (P, Chl-a, cell count) Developed alternative framework for livestock exposure and microcystins. With a guidelines value of 10,000 cells/ml for M. aeruginosa (similar to level seen in WaterNSW advisory, above.	Jones and Orr (2000)
2019 Bloom Debrief	Southern Rural Water	During the 2019/20 Summer season, SRW observed *Microcystis aeruginosa*	Pers. Comms, SRW.

Case Study/Research	Key Agency	Key Findings	Reference / Note
		and *Dilochospermum circinale* in its reservoirs located west of Melbourne, which displayed general boom and bust activity. However, in Lake Glenmaggie, to the east of Melbourne, *Chrysosporum ovalisporum* was recorded and had elevated cell counts for ~6 months	
Operational Challenges of a three-month long bloom	Goulburn Valley Water	Paper discussing the operational effects of the 2016 BGA Red Alert for potentially toxic algal species. - Differences in declaring a regional bloom (between Victoria and NSW) added confusion to notification and management pathways - PAC was used to dose at plants, but small, regional sites don't justify permanent PAC dosing so a mobile unit was designed and built by GVW - Aluminium Sulphate used as pre-treatment in raw water resources can be effective in controlling *Chrysosporum ovalisporum* - Blooms of *Chrysosporum ovalisporum* are likely to result in the release of nitrogen and ammonia after collapse which could promote taste and odour issues (MIB and geosmin)	Newham (2016)
Managing supply issues during regional bloom	Grampians Wimmera Malley Water	Review of the 2016 bloom that extended some 2,360 km across Victoria and NSW and over 1,700 km of the Murray River alone (Dominant species, *Chrysosporum ovalisporum*). - Highlighted complicating factors that included uncertainty in health risks for stock and domestic users - Issues with customers not having enough buffer supply (72 hours) caused additional problems - System resilience, in the form of ''Reverse pumping'' options (whereby GWMWater could pump out to customers from inland storages provided much needed supply - Regulatory guidelines did not include biovolumes for toxic BGA species for regulated water, stock and domestic uses - GWMWater developed a risk framework for supply type and algal species for various levels of alert.	McDonald, Ferguson and Whorlow (2017)
Assessment of the Impacts of Climate on Reservoir Water Quality	The Water Research Foundation / WaterRA	The researches looked at three reservoirs in temperature, humid and Mediterranean climate zones to assess future impacts of climate change. Integrated modelling showed that elevated temperatures will result in increased strength and duration of stratification. Reducing contaminant runoff and controlling stratification and oxygen	van der Linden et al (2018)

Case Study/Research	Key Agency	Key Findings	Reference / Note
		concentrations in reservoirs are viable management opportunities. Duration of the thermal stratification period will expand a month either side of current period, with attending anoxia in the deep layers and in reservoir sediments. This is likely to promote upward mobilisation of nutrients from the bottom layers to the surface during turnover.	
Assessing the economic impact of harmful and nuisance algal blooms to the Australian water industry	UNSW/WaterRA	Literature review and economic assessment to understand management, monitoring and response costs for drinking water and recreation to manage hazardous and nuisance algal blooms across Australia.	Project commenced 2020.
Developing Guidance for Assessment and Evaluation of Harmful Algal Blooms, and Implementation of Control Strategies in Source Water	WaterRA	A project conducting a literature review of assessment, monitoring and assessment procedures in Australia and internationally, and review of source water control strategies (interventions) is currently being undertaken by WaterRA and industry partners.	Unpublished – In progress.

6 Framework for BGA Assessment and Management

In this final chapter, we propose a framework for managing the climate change impacts on BGA in Victorian waterbodies. It draws together the key threads of each of the earlier sections of the report, culminating in a generalised framework shown in Figure 6.1. This chapter is constructed as follows:

- The ***conceptual design*** is discussed in section 6.1;
- Framework ***management*** activities are discussed in section 6.2;
- Framework ***support*** activities are discussed in section 6.3;
- *Knowledge* ***sharing*** initiatives are discussed in section 6.4; and
- A proposal for the development of '***sentinel sites***' – those for focused research, development and demonstration is given in section 6.5.

6.1 Conceptual Design

Below we describe a proposed conceptual framework that pivots around answering the second question highlighted in section 3.1: *Will stressors lead to problematic BGA activity?*

In answering this question, the framework also seeks to provide guidance towards management options that are calibrated to account for the nature and scale of the BGA problems and the nature and scale of risk they create. A graphical representation of the framework is given in Figure 6.1. The proposed framework consists of a number of interconnected activities in two main streams, all of which exist already in the context of Victorian waterways (see Chapter 5). These activities are described further in the sections that follow.

The intent is that this framework is applied across the range of waterbodies in Victoria as a means of contributing to the underlying science and identifying emerging geospatial patterns, trajectories, levels of risk, and science-risk based management options. The framework is necessarily iterative, in the sense that the implementation of management options must be supported by adequate monitoring or pilot testing that provides feedback into the framework. At a state level the critical measures of the success of the framework should lie in the consistency of the approach and the efficient dissemination of information across all activities, in which the former facilitates the latter.

The proposed framework has also been designed with elements of flexibility, adaptability and scalability in mind. Flexible in the sense that it can be applied to different waterbodies and can apply to any problematic algal variables (whether BGA related or non-BGA). These variables may include toxin production, ecosystem disruption, odour, taste, aesthetics etc, because any number of these issues can be introduced into the risk assessment via policy and stakeholder engagement that considers beneficial uses and the treats to these uses. It is adaptable in that the activities are concurrent (including feedback) with new information playing a role in each step of the process. Scalability comes again from the risk assessment approach, which may be considered at a waterbody-by-waterbody level or in the context of system-wide network of interconnected waterbodies for which an array of additional operational variables (such as alternative supply) can be considered as means to mitigate overall risk.

Importantly, whilst the framework follows a logical flow of information and activities, the ‘launching point’ for a given manager may differ, depending on resource, cost and time constraints. As an extreme example a manger under pressure to take immediate action may need to work backwards to rapidly verify an appropriate action, and in doing so may rely heavily on learnings from other waterbodies, and less so on an intricate understanding of the specifics at play in their waterbody.

Successful management of BGA therefore requires an integrated knowledge of waterbody processes and BGA functional traits that can provide insights into potentially effective management options. Identifying viable and sustainable management options should focus on negating trait-based advantages that the BGA utilise to proliferate and developing strategies to eliminate these advantages. Management practices should therefore not only seek to reduce uncertainty prior to application but should also be followed up by engaging in carefully designed monitoring regimes and robust appraisals of efficacy over adequate time-frames to measure the extent of success or failure and the underlying reasons. Importantly, management approaches should be fastened to, and guided by, ongoing efforts to improve the monitoring, scientific understanding and modelling of BGA which supports successful and adaptive management actions.

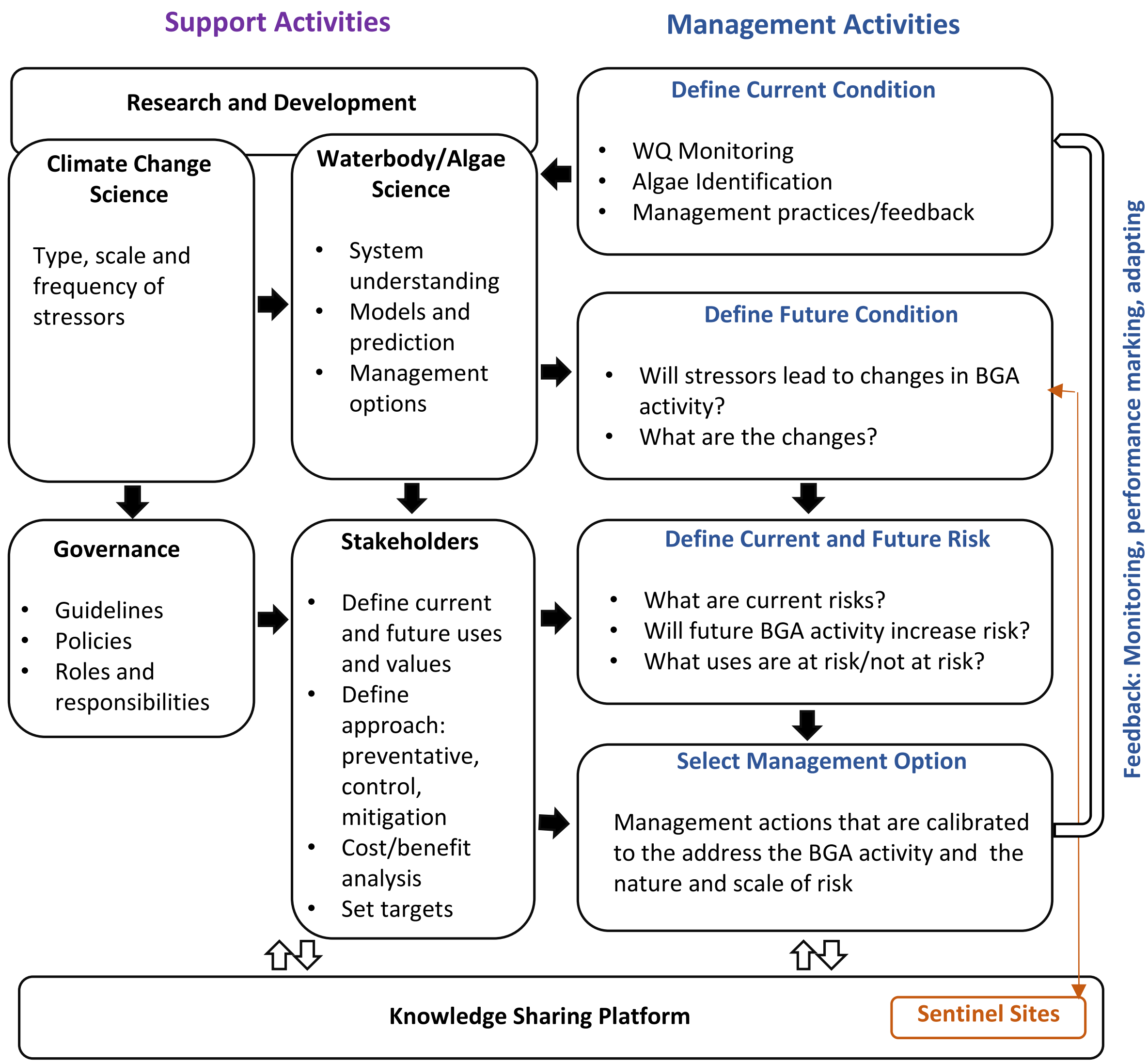

Figure 6.1 Conceptual BGA management framework

6.2 Management Activities

The management activities consist of five parts, which are described below:

6.2.1 Defining Current Condition

Defining the current condition of the waterbody, which is supported by efforts in science (see below) and includes general water quality, existing stressors, algae identification and function and the success (or not) or current management practices.

6.2.2 Defining Future Condition

Defining future conditions of the waterbody using the scientific understanding of the waterbody, BGA occupants and future stressors to forecast the potential future conditions, answering the first question of: *Will stressors lead to changes in BGA activity?*

6.2.3 Defining Current and Future Risk

Defining current and future risk by addressing the second question of: *Will stressors lead to problematic BGA activity?* The process of risk analysis integrates policy, stakeholder and management with the prediction of future conditions to answer a range of questions and assign a measure of future risk based on the intended beneficial uses. Some examples of specific questions are given below, but the full suite of questions that need to the raised will depend on inputs from policies and stakeholders specific to a waterbody. For multi-purpose waterbodies such as those used for supply and recreation the risk assessment may need to be multi-faceted to address risk across the different beneficial uses, policies and stakeholder groups.

- What are the beneficial uses and values that need to be upheld in future?
- What is the current risk? – i.e. What are the existing BGA problems and do current management practices protect the beneficial uses?
- Will future BGA activity jeopardise beneficial uses and to what extent?
- What is the future risk? - i.e. Will current management options and practices cope with future problems (Flow variability, temperatures, non-climate stressors)?
- Is this risk systemic and encompasses a series of interconnected waterbodies within a system?

A diverse range of stakeholders needs to be considered, and included in the risk assessment to ensure that the full range of cultural, environmental and social values are included in the risk assessment.

6.2.4 Select Management Option

The management activity within the proposed framework melds the assessment of risk to the type and level of management action available and seeks to determine what constitutes a calibrated and effective response to the risk. Through a mechanistic understanding and models of waterbody and algae behaviour, which is developed as part of efforts in waterbody and algae science, suitability effective solutions can be identified. Chapter 4, above provides an overview of the way in which management options can be targeted to reduce the dominance of BGA. However, a critical step is to consider to what extent the level and nature of the identified risk(s) warrants management actions and the type of actions that match the risk and accommodate stakeholder concerns.

Management decisions pivot around a number of variables ranging from proactive responses (prevention and control) to reactive responses (mitigation) that must consider policy, cost and societal constraints. The implications and cost of doing nothing should be part of this assessment.

6.2.5 Feedback

It is important that the learnings from management practises are fed back into the framework using monitoring systems that are sensitive to the management actions that are taken and targets that are set. Equally, these monitoring efforts should be geared to provide very clear metrics that quantify the levels of success of management options. This clarity is absolutely critical to continually and successfully adapt management approaches based on near-real time feedback and is valuable information for other managers considering similar management actions for their waterbodies.

The length of time over which feedback is necessary and the type of feedback required to track and quantify efficacy will differ depending on the type and extent of management practices that are implemented. For example, preventative catchment nutrient reduction may take many years to achieve success and monitoring regimes need to consider cost viability and efficiency of long-term efforts to track success. Alternatively, assessing the efficacy of engineering control management practices such as bubble mixers may be better served by short term intense monitoring efforts to define the direct effect and then tapering into longer-term and less intense monitoring efforts that track efficacy over time. The optimal way in which the follow-up monitoring is done needs to consider the type of management action, the potential type and length of monitoring required and the available infrastructure and funds.

6.3 Support Activities

6.3.1 Research and Development

Effective, proactive and cost-effective management strategies will only become apparent through concurrent efforts in research and development. The global experience with BGA management demonstrates that a process-based site-specific understanding of the waterbody and algal science is key to identifying and exploiting the few weaknesses of BGA in order to implement effective management solutions. Feeding into waterbody and algal science are broader efforts in global climate and downscaled ecosystem science required to provide predictions of responses to future stressors. The scope of this effort goes well beyond the water industry but the connection to water management (in both directions) needs to be continually explored.

Efforts in waterbody and algal science itself span a large number of disciplines from biology, ecology, limnology and modelling. These efforts seek to improve:

- Monitoring, identification, classification of BGA and their functional characteristics and identification and measurement of cyanotoxin production;
- Monitoring of current and changing waterbody characteristics such as temperature, water quality and biology;

- Mechanistic understanding of the relationship between waterbody processes and algal responses (including cyanotoxin production) and the building of models fit for extrapolating to future prediction;

- Prediction of future climate-change conditions by coupling a mechanistic understanding and modelling to quantify response to stressors; and

- Identifying existing and potentially new avenues for management based on sound mechanistic understanding.

6.3.2 Governance

As seen in Chapter 5 of this report, a range of policies, legislative instruments and guidance notes impact on the management of BGA in Victoria, and waterways it shares with other jurisdictions. Of particular note is the notification protocols already developed by DELWP and DHHS, which serve as a fundamental component of the current management protocol and the proposed adaptation framework. Key aspects of this activity are:

- Clear connections to risk assessment described in s.6.2.3 - Defining Current and Future Risk, such that future guideline values can be developed, for example, for emerging toxins and new species risks;

- Climate impacts on bloom development may require alternative communication protocol due to rapid onset of blooms and known toxicity via emergent technology;

- Guidelines for the implementation of novel control and mitigation techniques, particularly the use of algaecides needs to be continually updated. The resultant taste and odour issues, as well as toxin production needs to be continually revised in the context of changed BGA assembly and new and emergent species[4];

- As highlighted in the McDonald, Ferguson and Whorlow (2017), governance models need to take account of trans-boundary sampling, reporting and escalation protocol, as historical differences in threshold level triggers for some species may have delayed bloom response.

6.3.3 Stakeholder Engagement

Victoria has a large, engaged and active group of stakeholders across the water industry, including volunteer water quality monitoring groups, Traditional Owners, waterway and land stewardship groups as well as the government and non-government bodies that have statutory responsibilities for managing and protecting water in Victoria. As such, the nature and extent of stakeholder engagement needs to be designed to manage the expectations of all interest groups. A key feature of the proposed framework is that the non-linear approach provides

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[4] The results for example of John et al (2019), which showed the presence of the anotoxin-a toxin in samples from Victorian waterways, which were previously thought to be absent from Australian surface waters.

opportunity for stakeholder engagement at all steps of the planning process, not just to provide information to once a project or plan is finalised for marketing. Noted in the Framework is key inputs into the current and future risk planning phase, which implies that all stakeholders can undertake assets proposals with individual risk assessment for inclusion in future adaptation plans.

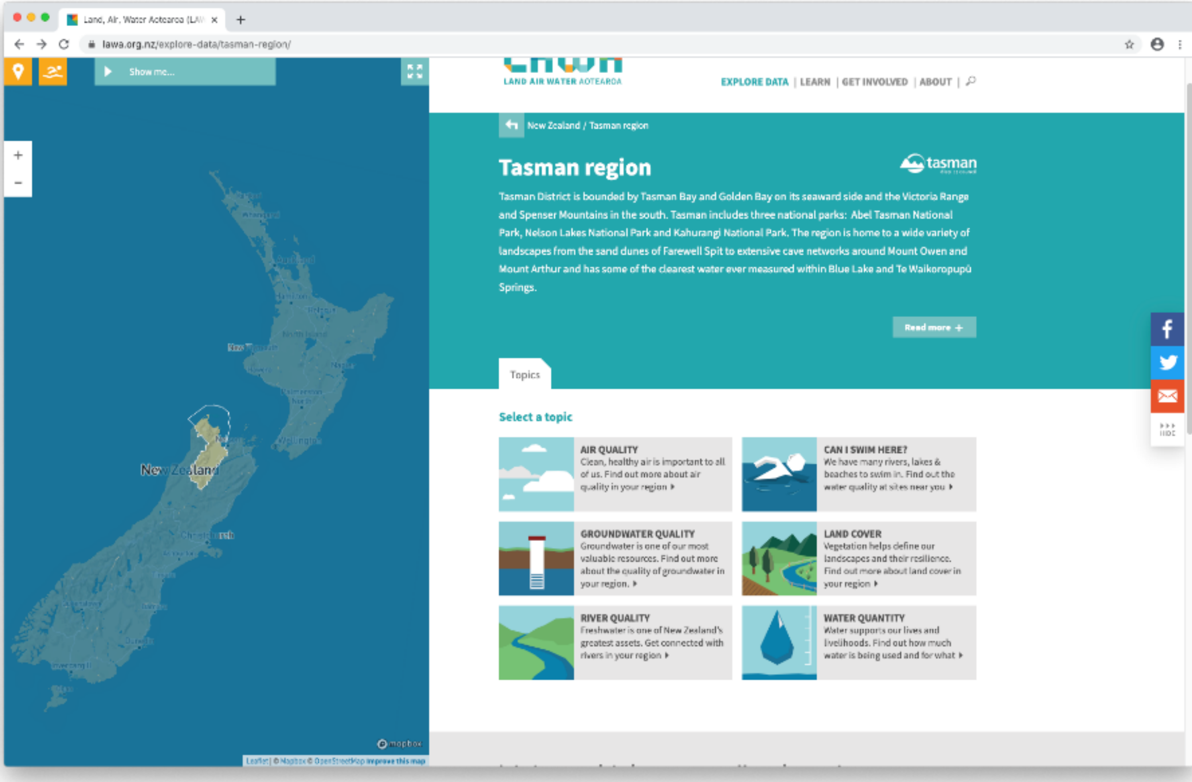
6.4 Knowledge Sharing

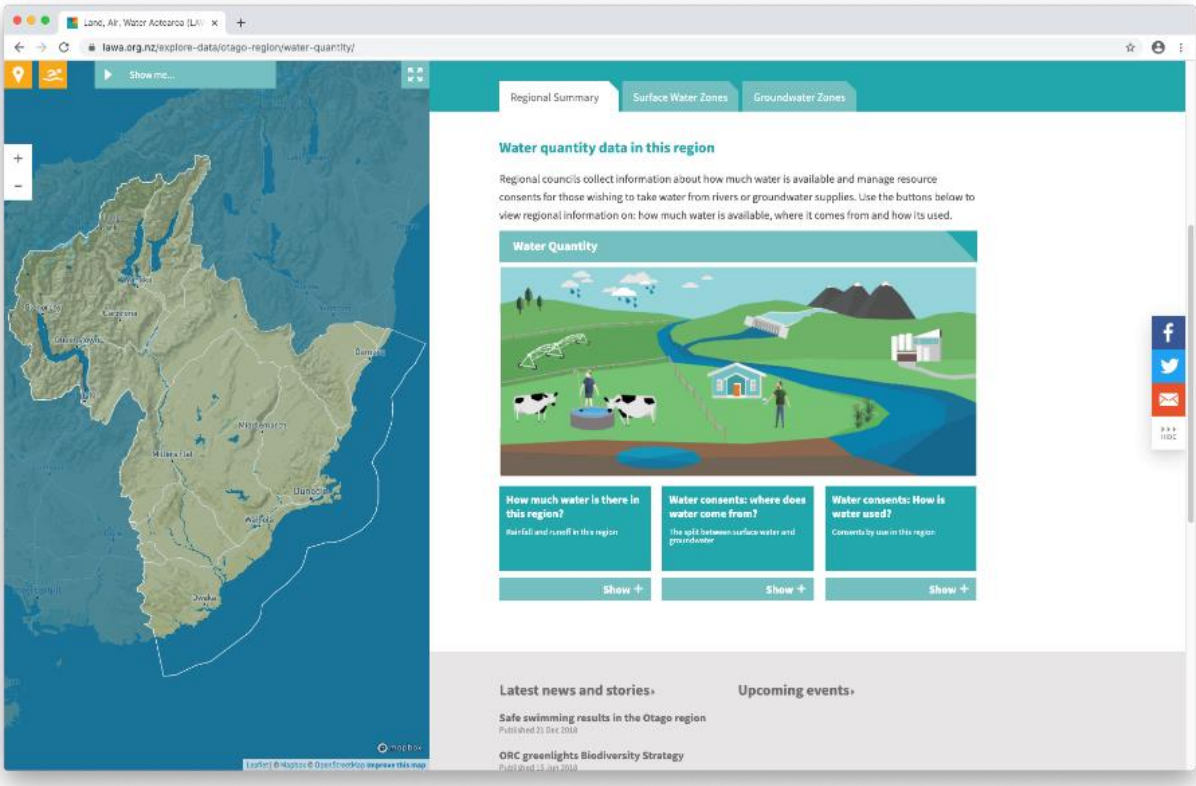
6.4.1 Sharing Platform

A critical component to the success of the proposed framework is knowledge sharing that can be supported by numerous online tools. This component aims to build on current BGA data sharing that disseminates geographically placed content across layers of information that includes:

- Background water quality and algal data;
- Extent and nature (i.e. species specific) of BGA productivity and problems (such as toxins) and how they relate to beneficial uses;
- Understanding of current drivers of BGA issues;
- Current risks and management practices and strategies;
- Key future stressors, likely responses and future risks; and
- Initiatives, such as R+D that are being undertaken to address uncertainty.

A selection of online data collation and presentation examples are provided below. In addition, the prototype online portal that was developed for this project, which includes all data currently included on DELWP's BGA Portal is shown in section 7.4.


lawa.org.nz/explore-data/tasman-region/
LAND AIR WATER AOTEAROA
EXPLORE DATA | LEARN | GET INVOLVED | ABOUT
New Zealand / Tasman region
Tasman region
Tasman District is bounded by Tasman Bay and Golden Bay on its seaward side and the Victoria Range and Spenser Mountains in the south. Tasman includes three national parks: Abel Tasman National Park, Nelson Lakes National Park and Kahurangi National Park. The region is home to a wide variety of landscapes from the sand dunes of Farewell Spit to extensive cave networks around Mount Owen and Mount Arthur and has some of the clearest water ever measured within Blue Lake and Te Waikoropupū Springs.
Read more +
Topics
Select a topic
AIR QUALITY
Clean, healthy air is important to all of us. Find out more about air quality in your region
CAN I SWIM HERE?
We have many rivers, lakes & beaches to swim in. Find out the water quality at sites near you
GROUNDWATER QUALITY
Groundwater is one of our most valuable resources. Find out more about the quality of groundwater in your region.
LAND COVER
Vegetation helps define our landscapes and their resilience. Find out more about land cover in your region
RIVER QUALITY
Freshwater is one of New Zealand's greatest assets. Get connected with rivers in your region
WATER QUANTITY
Water supports our lives and livelihoods. Find out how much water is being used and for what
New Zealand


lawa.org.nz/explore-data/otago-region/water-quantity/
Regional Summary
Surface Water Zones
Groundwater Zones
Water quantity data in this region
Regional councils collect information about how much water is available and manage resource consents for those wishing to take water from rivers or groundwater supplies. Use the buttons below to view regional information on: how much water is available, where it comes from and how its used.
Water Quantity
How much water is there in this region?
Water consents: where does water come from?
Water consents: How is water used?
Show +
Show +
Show +
Latest news and stories
Upcoming events
Safe swimming results in the Otago region
ORC greenlights Biodiversity Strategy

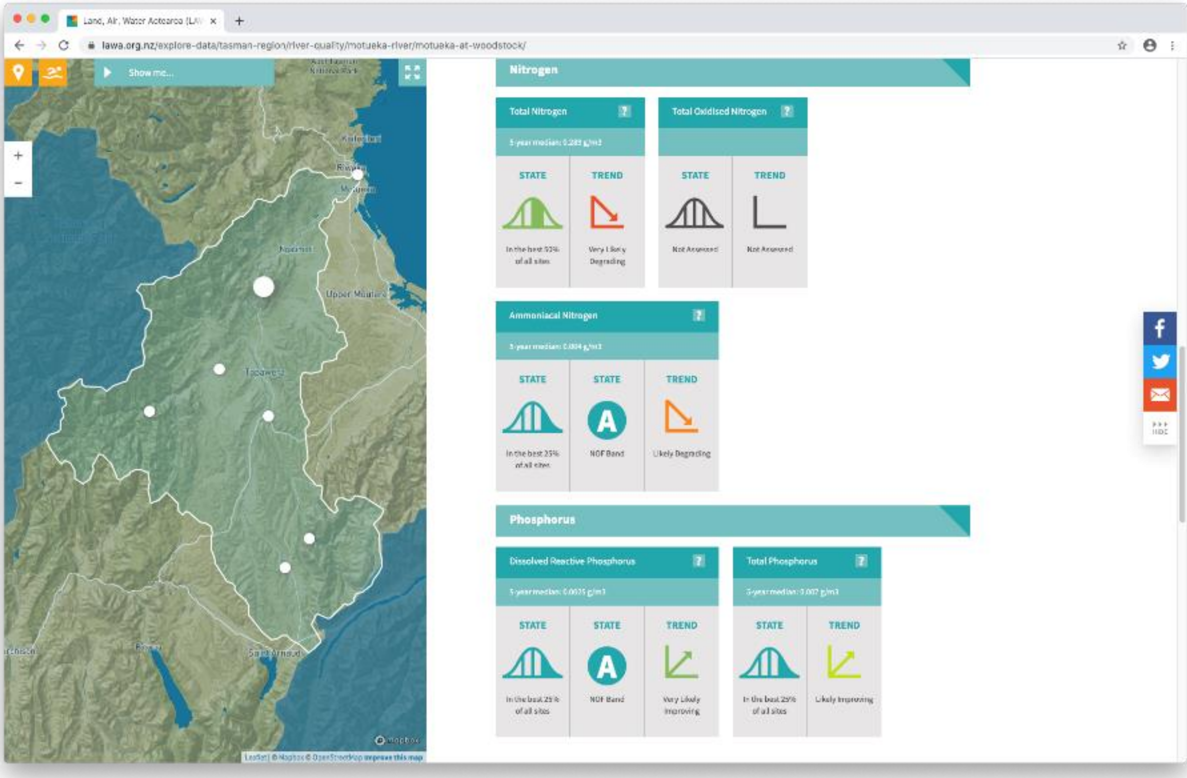


Figure 6.2 (a) Regional overview of Land and Water Aotearoa (LAWA, NZ) multi-variable online portal, (b), inforgraphics for stakeholder engagement and (c), detailed water quality information including trend analysis (Source: LAWA)

Figure 6.3 Aggregate Water Quality Index results for Yarra Catchment (Source: Hydronumerics)

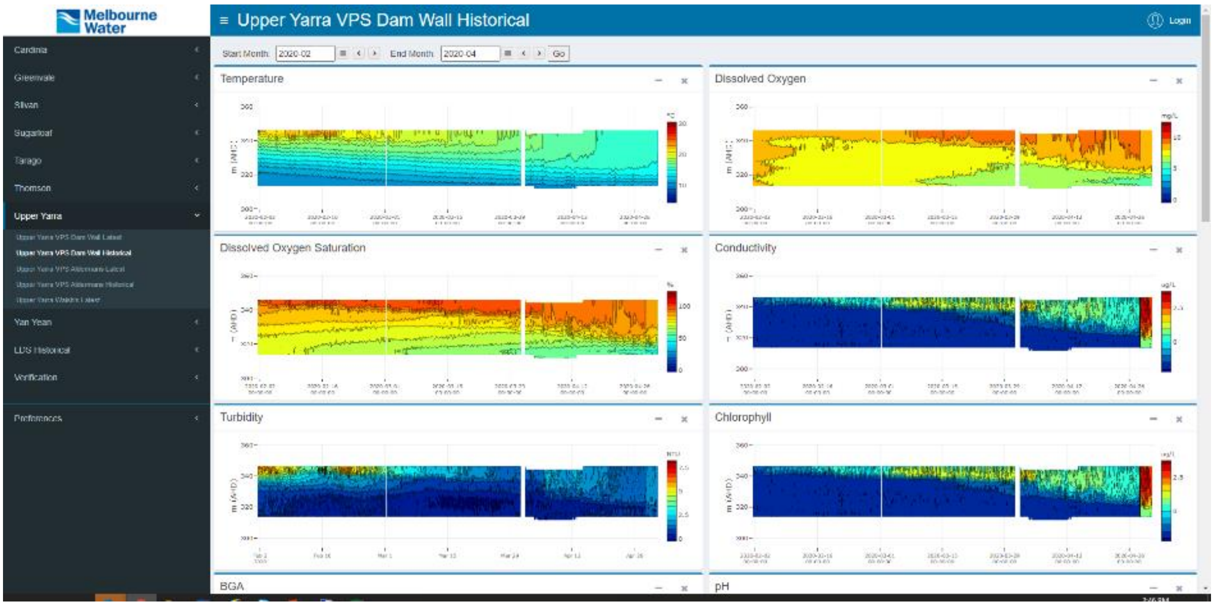


Figure 6.4 Detailed water quality information from an in-house water quality profiler (Source: Melbourne Water)

6.4.2 Communication

The framework would be well served by regular bulletins and workshops that nurture an information sharing culture amongst Victorian waterbody managers and with other Australian counterparts.

6.5 Sentinel Sites

The challenges of managing BGA that lie ahead are numerous and complex and the resources to do so are not without limitation. Effective, rapid and consistent sharing of knowledge is going to be absolutely crucial to building a collective understanding of the scale of the issues, the highest risk waterbodies and effective management measures.

The proposed use of 'sentinel' sites facilitates a comprehensive understanding of a select number of sites from which learnings can be applied to comparable sites. The sentinel sites offer and means to accelerate our collective learnings about the mechanisms that currently so and may in future lead to BGA bloom proliferation, provide an early warning system of future risks, and a means to test and refine risk mitigation measures. Sentinel sites are a potential means to concentrate and consolidate the funding and efforts required to improve our scientific understanding of future BGA behaviour and develop predictive models that can be applied across the range of Victorian waterways.

Although all Victorian waterbodies make important contributions to the overall collective framework, forecasting the trajectory and risk in lesser understood waterbodies may need to rely heavily on the application of knowledge from other better-understood sentinel sites, at least until the resources required to study a growing number of waterbodies becomes available. In this way sentinel sites provide a platform upon which informed management decisions can be rapidly made to manage at-risk or high-risk waterbodies for which detailed science is lacking, but timely action is required to stem alarming trends.

BGA research has demonstrated that their behaviour is highly site-specific and will in future be dependent on three key factors:

- the nature and scale of the stressors;
- the characteristics of the waterbody; and
- the specifics of the BGA that occupy or may occupy the waterbody.

Within each of these are a multitude of variables that may lead to very site-specific behaviours so that seeking effective management strategies that translate from one site to the next is likely to be difficult. In addition, the operational flexibility needs to be considered, as, for example, some waterbodies will facilitate flow manipulation, whereas others will not. Therefore, an important early step in setting up the concept of sentinel sites is to understand the limitations of transferring knowledge from one site to the next.

Another consideration is how sentinel sites should reflect the spectrum of risk so as to closely track the shift of waterbodies towards higher risk and pay close attention to those likely to move from historically low risk to future elevated risk. As discussed above, the measurement of risk will depend on the current and future beneficial uses that are defined for a waterbody.

Lastly there is an uneven distribution of resources between the managers of waterbodies, both monetary and in personnel, particularly for research and development. It is therefore an intention of the framework to identify opportunities to build collective knowledge and rapid means of sharing this knowledge. Sentinel sites provide a potential mechanism to pool resources and develop better tools (such as monitoring, fundamental science, models and treatment technologies) that have collective benefits. They may also provide a forum that facilitates closer relationships between scientists of different disciplines, managers and policy makers.

The selection of appropriate sentinel sites needs careful consideration and could use a 'first-pass' of the framework that can provide a starting point for comparisons between waterbodies and better-informed decisions about suitability and benefits of individual sites. Alternatively, sites deemed at the most risk from the impacts of climate change could also be considered.

This would need to be followed by a testing phase of short-listed candidates to explore the merits and applicability of a sentinel sites system. As an initial thought exercise, the selection of sentinel sites may come from a suite of different waterbodies that represent, for example:

- Large rivers prone to intermittent drought such as the Murray River;

- Small compromised wetlands and lakes in highly modified asset-rich environments such as urban lakes like Albert Lake;
- Impacted urban and peri-urban rivers such as the lower Yarra River;
- Impacted, complex and multi-use estuarine systems such as Gippsland Lakes;
- Impacted coastal environments such as Port Phillip Bay;
- Complex multiple-use rural waterbodies such as Lake Nagambie;
- Large multi-use reservoirs or lakes, such as Lake Eildon; and
- Critical, large and typically low trophic status water supply reservoirs such as Upper Yarra Reservoir.

7 Summary and Recommendations

The objective of this Action 19 of the Pilot Water Sector Climate Change Adaptation Plan was to characterise the current approaches to managing algal blooms across Victoria, to understand the potential for future changes in severity and prevalence of algal blooms in Victoria in response to climate and non-climate stressors, and, to assess the sensitivity of waterbodies to climate change with respect to algae with a focus on BGA.

This summary and recommendation chapter is organised as follows:

- Section 7.1 reviews the combined themes of BGA traits, response to climate-stressors and likely future impacts of climate change on BGA;
- Section 7.2 moves to the general approaches for BGA management, as well as management in the Victorian context;
- Section 7.3 summaries the proposed future management framework and the sentinel site concept;
- Section 7.4 introduces the prototype online portal for historical BGA triggered events, a conceptual risk assessment tool and discussion on the selection of sentinel sites; and
- Section 7.5 summaries key recommendations from this programme of work.

7.1 Traits, Stressors and Future Impacts

Global studies have shown that observed increases in aquatic primary productivity in the worlds' waterways is due largely to anthropogenic activity, most notability increases in nutrient loads. Within these global trajectories of increased algal productivity, studies have indicated that the occurrence of BGA has increased disproportionally compared to other phytoplankton over the last 100-150 years and that the shift to BGA prevalence has accelerated since the mid-20th century. This trend that is expected to increase, and has numerous ramifications for ecosystem, economic and societal functions of waterbodies into the future.

Global studies to date do not clearly identify consistent relationships between bloom intensity and temperature increase, precipitation, fertilizer-use or other hypothesised anthropogenic-related drivers. This provides a note of caution in the development of standardised response and adaptation plans due to the wide range in hydrometeorological conditions waterbodies experience, morphology, catchment setting, water quality and microboiological regimes. The way in which each waterbody, and its ecosystem (including BGA) respond to external stressors will depend on the type and magnitude of the stressor(s) and on the physical and biogeochemical processes that occur within the waterbody.

When considering the response of stressors in waterbodies within the context of BGA, Chapter 3 of this report posed two key questions:

- Will stressors lead to *changes* in BGA activity? And
- Will stressors lead to *problematic* BGA activity?

The key distinction between the first and second question is that the second question requires a definition of what is problematic and is no longer purely scientific. The definition and measurement of problematic BGA requires a process that defines the beneficial uses or values of a waterbody and matches these to forecasts of future BGA activity and future waterbody uses (as seen in the proposed Framework). In the context of future climate change, the response of water bodies in Victoria to various stressors; including higher water temperatures, stratification, nutrient loads, the impact of the hydrological regime on residence times, floods and storms and ecological disruptions are discussed in sections 3.3.1 to 3.3.6, and should be read in conjunction with the discussion in Chapter 2 regarding the dynamics of various algal species observed in Victoria.

7.2 BGA Management: General Approaches and the Victorian Context

Chapter 4 of this report provides an introduction to the management of BGA, synthesised into three key components; prevention, control, and mitigation. Building on the earlier discussions concerning the relationships between specific BGA traits, waterbody processes and the effects of external stressors (See for example Figure 3.1), Chapter 4 again highlights the demonstrated lack of clear and consistent relationships between bloom intensities and climate-, and non-climate stressors. The work of Lurling and Mucci (2020), quoted in section 4.4Figure 4.4, provides an useful end-note to the discussion on quick-fix control measures for BGA:

"More than 25 years ago it was already emphasized that ''each lake has to be studied before restoration measures can be applied'' (after Van Liere & Gulati, 1992), yet these words still need to be repeated. Water authorities, municipalities and lake managers should spend more energy in such proper diagnoses than in wasting taxpayers' money by blindly believing the magic claims made by 'quick-fix' advocates."

In Chapter 5 of this report, Victorian BGA management frameworks were reviewed, attending to the primary research objective of this program. The literature review and extensive engagement with Victorian and inter-state agencies showed that the management of BGA events is largely standardised across the state, with specific guidance provided by DELWP and DHHS on trigger levels, notification and emergency management protocols for drinking water, marine and recreational water bodies. However, there is comparatively little information available on trigger levels for stock and irrigation end-uses, notably because of the wide range of end uses and limited information on toxicity of various algal species on various flora and fauna.

Across the various group and individual stakeholder engagement interviews that were undertaken during this project, two common threads emerged shown below. Further information is included in section 9.1:

- The need for a centralised research and development archive across the state, potentially sitting as an additional resource within the BGA portal, or in future developments of the proposed online portal;
- Alert trigger levels for stock and irrigation purposes would be of great use to managers that supply farming districts. Following from Jones and Orr (2000), this is not just for plant and animal health, but also for the safety of farm and industry workers that may be exposed to toxicants present in water.

7.3 A Framework for BGA Assessment and Management

A *Framework for BGA Assessment and Management* is provided in Chapter 6 of this report, which focuses on addressing question two, above – will stressors lead to problematic activity. In answering this question, the framework also seeks to provide guidance towards management options that are calibrated to account for the nature and scale of the BGA problems and the nature and scale of risk they create. The proposed framework has also been designed with elements of flexibility, adaptability and scalability in mind. Flexible in the sense that it can be applied to different waterbodies and can apply to any problematic algal variables (whether BGA related or non-BGA). These variables may include toxin production, ecosystem disruption, odour, taste, aesthetics etc, because any number of these issues are introduced into the risk assessment via policy and stakeholder engagement that considers beneficial uses and the treats to these uses. The framework can be applied to future 'sentinel' sites to develop site-specific, or generalised information about classes of waterbody response for future climate change adaptation. The linkages between the ''management'' activities (proposed actions) and ''support'' activities (those that inform management) are described in Figure 6.1. A preliminary application of the framework to Lake Glenmaggie is described in *section* 9.1.

In the final section of Chapter 6, the concept and benefits of ''Sentinel'' sites was introduced, via the following introductory consideration:

"The challenges of managing BGA that lie ahead are numerous and complex and the resources to do so are not without limitation. The effective sharing of knowledge is absolutely crucial to building a collective understanding of the scale of the issues, the highest risk waterbodies and effective management measures."

The potential use of 'sentinel' sites facilitates a comprehensive understanding of a select number of sites from which learnings can be applied to comparable sites. Although less-understood waterbodies remain important contributions to the overall collective framework, forecasting the trajectory and risk in these waterbodies may need to rely heavily on the application of knowledge from other better-understood sites. The concept of sentinel sites that support the development of the framework are a potential means to concentrate and consolidate the funding and efforts required to improve our scientific understanding of future BGA behaviour and develop predictive models that can be applied across the range of Victorian waterways.

7.4 Proposed online portal

A prototype online portal has been developed for this project, using all available data currently in *Floodzoom*'s BGA Portal from 2015 - 2020. The objective of developing the prototype site was to improve the spatio-temporal reporting and visualisation of data blooms compared to the existing *Floodzoom* site, which currently only presents 'open' or 'active' blooms. In addition, historical records are housed separately to 'active' records, making both site-specific historical analysis, and annualised state-wide assessments difficult.

A new (password protected) site has been developed by Hydronumerics (www.delwp.hydronumerics.com.au) which provides an annualised spatial assessment of blooms per site (Figure 6.1), and users can navigate to a desired site to access all historical data via the drop down menu on the right hand side (organised by reporting basin) or by clicking on a site of interest. Figure 6.2 shows the results for *Bonnie Doon town water supply*, showing *total, total toxic* and individual species results from 2016 – 2020. Data within the figures can be easily exported for data analysis or reporting by hovering over the pop up menu on each figure.

Key recommendations for the overall project are listed in the following section, however, subject to final stakeholder feedback, we suggest that the portal is further developed to include:

- A centralised R&D portal to house all relevant research from Victoria and other relevant studies. This would ensure Victorian authorities can quickly reference work that has been completed, as well as obtaining information on sentinel sites;
- Each site would have hot-links to relevant management plans and strategies;
- Relevant (current) known toxin guidelines would be housed on the site (referred to above);
- In addition to presenting data by reporting basin, users could search for all recreation/drinking/stock and domestic site for reporting purposes; and
- Multi-year and multi-site data analysis could be performed in the site.

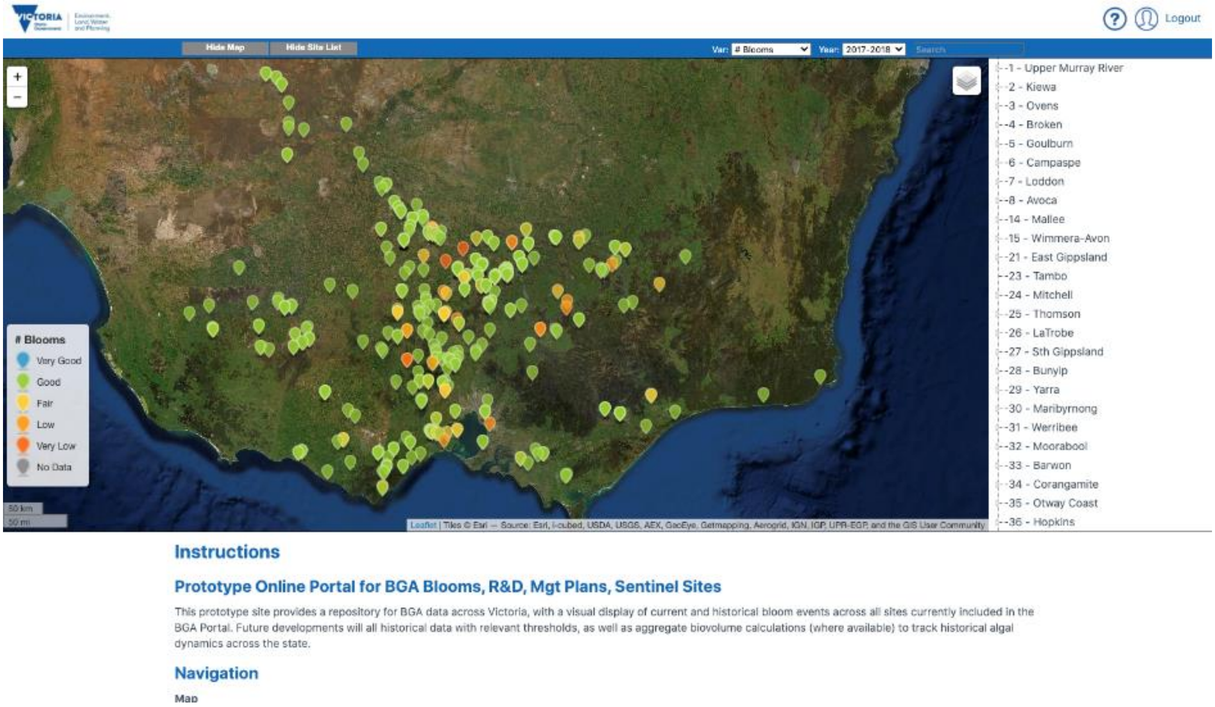


Figure 7.1 Landing page for prototype BGA site showing number of blooms for all sites

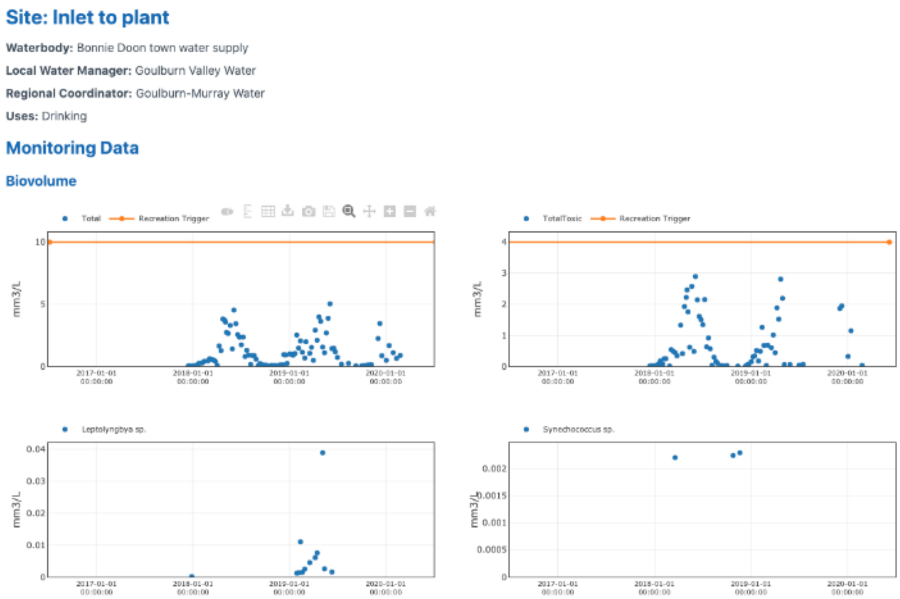


Figure 7.2 Bonnie Doon town water supply BGA results, recreational trigger (red) and aggregate Total and Toxic results 2016-2020

7.4.1 Future risk assessment and selection of sentinel sites

Linking the prototype website to the sentinel site concept discussed above (section 6.5) is the potential to use the prototype site to run a rapid climate-change risk assessment for Victorian waterbodies (or potentially a sub-set following this initial WSAAP) based on the framework applied in Figure 4.1, using a simplified risk matrix (for example, future assessment of changes to hydrology, land-use, beneficial use, technological development and anthropogenic pressure).

As a hypothetical (data are randomised numbers) exercise, a ''current'', ''future'' and 'total change'' climate risk assessment was performed on all sites in flood zoom, the results of which can be seen in Figure 6.3 and Figure 6.4 (''Future'' is not shown). This is an interesting conceptualisation of how waterbodies across Victoria could be prioritised for climate adaptation efforts (Figure 6.3, current), as well as looking to future impacts (Figure 6.4, total change). The change in risk ranges from *very positive* (considerable improvement compared to current condition) to *very negative* (significant decline), the results of which provide another avenue for both prioritisation of adaptation and mitigation works, and selection of sentinel sites.

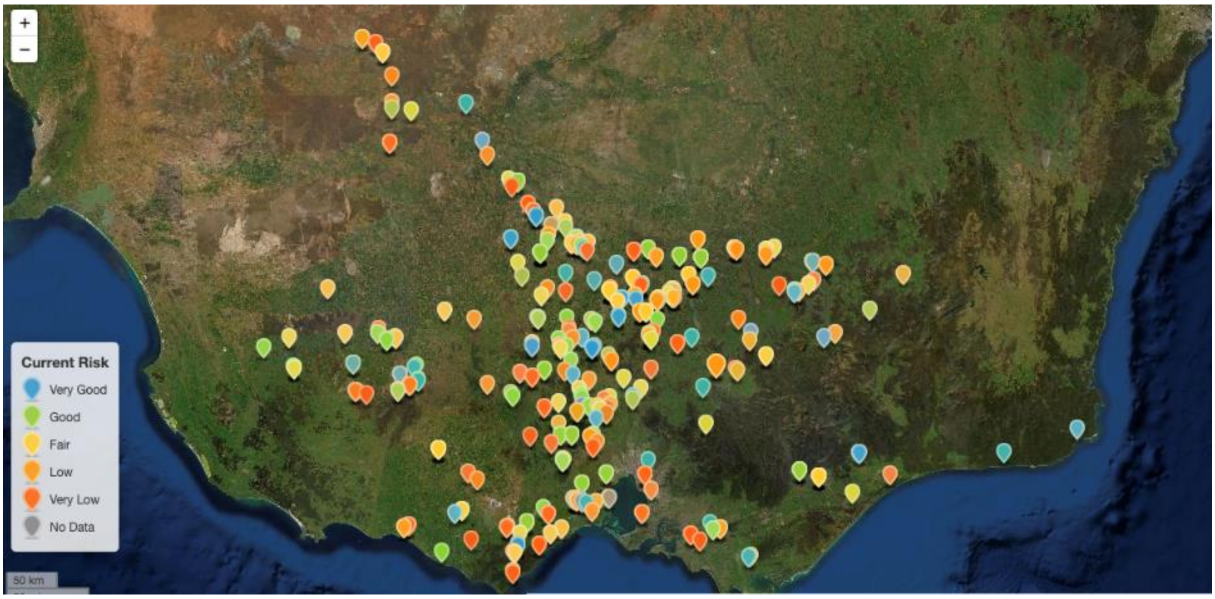


Figure 7.3 (Hypothetical) ''Current'' BGA/Climate Change Risk Assessment

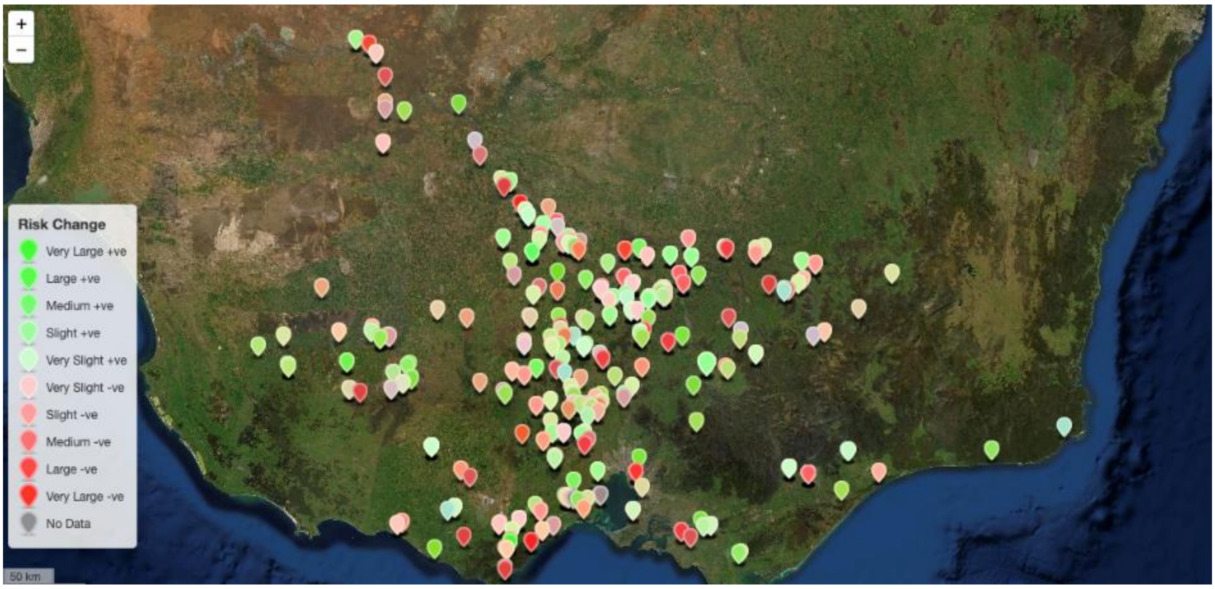


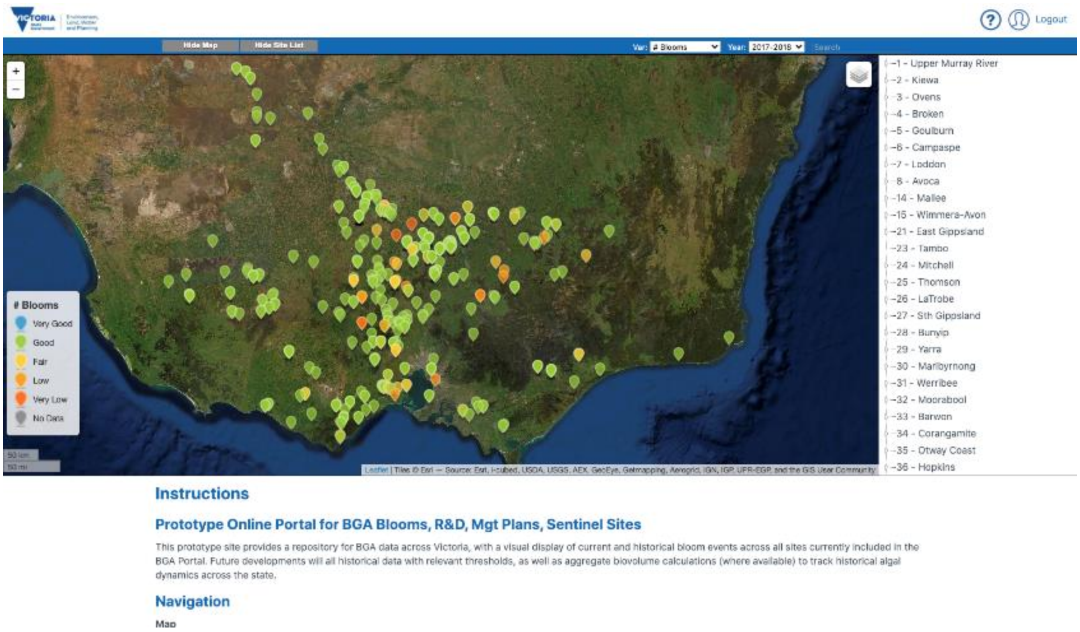
Figure 7.4 (Hypothetical) "Change in" BGA/Climate Change Risk Assessment

7.5 Recommendations

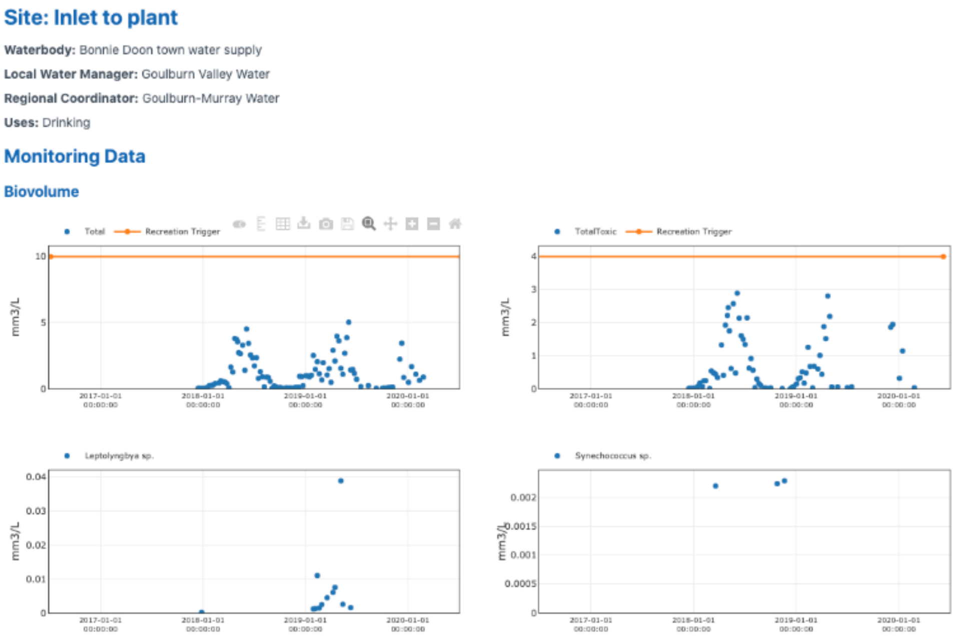
Three priority actions and three recommendations are provided:

ACTION 1: Develop a rapid risk assessment for water bodies across Victoria

Section 7.4 of this report outlines the proposed development for DELWP's *Floodzoom* BGA portal, adding spatio-temporal results from the existing database so that users can see current and historical BGA data, as well as extract and analyse data on the fly as seen in the following two images:



Landing page for prototype BGA site showing number of blooms for all sites



Bonnie Doon town water supply BGA results, recreational trigger (red) and aggregate Total and Toxic results 2016-2020

Linking the prototype website to the sentinel site concept discussed (section 6.5) is the potential to use the prototype site to run a rapid climate-change risk assessment for Victorian waterbodies based on the framework applied in Figure 4.1, using a simplified risk matrix (for example, future assessment of changes to hydrology, land-use, beneficial use, technological development and anthropogenic pressure). A hypothetical example is provided below, where all sites in *Floodzoom* are ranked according to very large or very small impacts on water quality due to climate change:

(Hypothetical) "Change in" BGA/Climate Change Risk Assessment

ACTION 2: Road-test the proposed framework

- The framework described in Chapter 6 should be applied to a select number of waterbodies before being rolled out across the state. Exactly which waterbodies are prioritised could be linked to the rapid risk assessment described above, and the consideration of the sentinel site network discussed below.

ACTION 3: Develop a sentinel site network for future research

The challenges of managing BGA that lie ahead are numerous and complex and the resources to do so are not without limitation. Effective, rapid and consistent sharing of knowledge is going to be absolutely crucial to building a collective understanding of the scale of the issues, the highest risk waterbodies and effective management measures.

The proposed use of 'sentinel' sites facilitates a comprehensive understanding of a select number of sites from which learnings can be applied to comparable sites. The sentinel sites offer and means to accelerate our collective learnings about the mechanisms that currently so and may in future lead to BGA bloom proliferation, provide an early warning system of future risks, and a means to test and refine risk mitigation measures. Sentinel sites are a potential means to concentrate and consolidate the funding and efforts required to improve our scientific understanding of future BGA behaviour and develop predictive models that can be applied across the range of Victorian waterways.

- The selection, development and funding of sentinel sites discussed in section 6.5 of this report;
- The risk assessment and prioritisation activities discussed are applied to a select number of sites, to be scaled up once a rapid and simple assessment technique is developed (potentially included in the developed portal); and
- Future development of the online portal to include hot-linked management plans, consolidated R&D initiatives (see Action 1) and interactive data analytics for consistent analysis and reporting.

RECOMMENDATION 1: Consolidate R&D initiatives

- That Regional and Local Waterway managers include a summary of the past years' algal alerts in their management plan as well as historical or planned R & D in their plans (which could also be housed on the revised portal);
- A trans-boundary reporting platform between Victorian and NSW for all algal events, and associated management responses, as well as joint R+D initiatives;
- The existing *Floodzoom* portal is audited to ensure that all event triggers have been recorded in the database. This will ensure that the future adaptation plans have given full consideration to the historical prevalence of blooms.

RECOMMENDATION 2: Future proof governance, especially for threshold trigger levels

- Climate change is likely to change bloom dynamics and may lead to more rapid onset of blooms. This may require alternative public communication and management protocols;
- Guidelines for the implementation of new control and mitigation techniques. The taste and odour issues that arise from managing BGA, as well as toxin production needs to be continually revised in the context of changing BGA assemblages;
- The continual revision of known toxin producers from Australia and internationally, particularly in the context of changing assemblages is recommended;
- Governance models need to take account of trans-boundary sampling, reporting and escalation protocol.

RECOMMENDATION 3: A focus on stock and irrigation supplies to address:

- The impacts on stock and irrigation deliveries are considered to be high risk in the context of shifting assemblages in many of Victoria's rural supply reservoirs, that have started to see shifts towards species typically thought to only occur in tropical or sub-tropical climates;

- The triggers for production of toxins, and therefore an adaptation plan that included regular review of known / potentially toxic species is recommended; and

- Potential linkages with DHHS and Agriculture Victoria programs investigating rapid toxicity assessments in stock and domestic dams, and the impacts of poor water quality events on various supply chains in the state.

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9 Appendix

9.1 Worked Examples: Rapid Risk Assessment and Framework Application

9.1.1 Rapid Risk Assessment

On 24 November 2020, two final stakeholder workshops were conducted. A preliminary workshop discussed the project outcomes, lessons learnt and reviewed the key recommendations and actions. The second workshop of the day presented the results of the preliminary suite of rapid risk assessments. The objective of this initial, rapid, risk assessment was to develop an understanding of the current appreciation of climate and non-climate stressors on water quality. In addition, the process allowed the project partners to consider appropriate risk categories, and various methods to calculate 'risk'.

Please note that these rapid risk assessments are conceived as *complimentary* pieces of work to standard risk assessments that waterway managers complete for their assets and are not designed to replace these tools.

To start this process, a follow-up survey was sent to workshop invitees prior to the November workshops, which asked the questions listed below. Unfortunately, no responses were submitted prior to the workshop taking place.

- What is the waterbody used for (drinking, recreation, irrigation, mixed use)?
- Incidence of historical algal blooms?
- Has the organisation conducted any climate-specific risk assessments?
- Has the organisation conducted any assessments of likely future inflows?
- Are there any planned management interventions (prevention, control and mitigation) that may mitigate the impacts of climate change?
- Known land-use change in the catchments?
- Is the site used for major events or as site for primary production? and

- Does the site have any significant cultural or social values, is it subject to any international treaties (i.e. RAMSAR) that could be affected by poor water quality caused by climate stressors?

Following, a simplified suite of risk categories was applied to lakes managed by Goulburn-Murray Water and Southern Rural Water using the following five categories:

I. **History of BGA blooms** – as an indicator of likely future blooms;

II. **Likely changes in future inflows** – as seen above, reduced inflows are likely to exacerbate problematic algal blooms in many cases;

III. **Economics** – future changes in algal activity associated with climate change negatively impacting on major events or primary production;

IV. **Management –** does the waterway manager have plans, or current capacity to modify the operation of the waterbody to mitigate the future algal blooms; and

V. **Cultural | Social | Health** – As above, does the site have any significant cultural or social values that could be affected by poor water quality caused by climate stressors? This also includes sites that are subject to international treaties (RAMSAR, UNESCO).

A single-digit risk ranking (1-5) was developed for each category according to the descriptors shown in Table 9-2. The authors note that this risk ranking combines elements of 'frequency' and 'consequence' that are normally combined to infer risk rankings for particular assets. As discussed in the final stakeholder meetings, we noted that this is a proposed rapid risk assessments, developed to compliment over-arching waterbody risk assessments. See for example Tables 1, 2 and 3 and 4 in the *Sample BGA Risk Management Plan (2014)* for further information.[5]

The risk rankings are largely self-explanatory and the nominated risk rankings (shown below) were developed in conjunction with G-MW and SRW. To quantify the potential reduction in future inflows, the *Guidelines for Assessing the Impact of Climate Change on Water Supplies in Victoria (2016)* were used.[6] Table 3 of that publication provides the predicted change in average annual runoff relative to 2040 from low (10^{th}-ile), medium (50^{th}-ile) and high (90^{th}-ile) results obtained from running 42 global climate models (page 13).

To derive a risk 'ranking' for reduced future inflows, the predicted reduction in average runoff per basin under the 50^{th}-ile results were ranked for all basins. Those basins with highest reductions received a higher risk ranking (i.e. predicted to have greater reduction in average annual inflow).

[5] https://www.water.vic.gov.au/__data/assets/word_doc/0033/65598/Sample-BGA-Risk-Managment-Plan-2014.docx
[6] https://www.water.vic.gov.au/__data/assets/pdf_file/0014/52331/Guidelines-for-Assessing-the-Impact-of-Climate-Change-on-Water-Availability-in-Victoria.pdf - due for update in 2020.

Under this preliminary rapid risk assessment, results for each category were simply added together to get the overall risk for each site according to the following Table 9.1. We note that future developments of the risk assessment could apply a weighting to various categories, or could expand the risk characterisation and calculation. This could include for example, non-annual phenomena such as summer storms or reduced autumn inflows.

Table 9.1 Overall risk ranking (aggregate scoring method)

Score	Ranking
0-10	very low
II - 14	low
15-17	moderate
18-19	high
20-25	very high

Table 9.2 Rapid risk rankings – category, ranking, description.

Category	Ranking	Description
History of BGA Blooms	1	Infrequent
	2	Large bloom 1:5
	3	Large bloom 1:2
	4	Annual
	5	Annual + prolonged
Future inflows	1	20%-ile of median reduction
	2	40%-ile of median reduction
	3	60%-ile of median reduction
	4	80%-ile of median reduction
	5	90%-ile of median reduction
Economics	1	No disruption / economic impacts
	2	Minor, localised impact
	3	Moderate impacts (closure of event)
	4	High, localised impacts (boating in one area)
	5	Sustained closure, productivity impacts
Management	1	Short + long term adaptability
	2	Long-term change possible, some options in short term
	3	Moderate capacity for operational change
	4	Low change capacity, change constraints
	5	No avenue for change/mitigation
Cultural/Social/Health	1	No impact or existing management plan
	2	Managed local impact
	3	Localised impact, can be managed partially

	4	Moderate impact on cultural/social/health
	5	Severe impact on cultural/health services

9.1.2 Rapid Risk Assessment – Results

Table 9-3 provides the results of the preliminary risk assessment for seven sites managed by SRW (Glenmaggie, Pykes and Melton), and G-MW (Hume, Eppalock, Waranga and Kow/Ghow). The risk rankings are based on coarse qualitative assessments and should not be considered/published as approved by the organisations who participated in this assessment.

Many of the waterbodies received high scores under the cultural, social and health assessments. For example, as Lake Glenmaggie discharges water downstream to the Gippsland Lakes, a RAMSAR listed wetland, future (climate-driven) increases in BGA activity are likely to have significant negative impacts.

The results for the Kow (Ghow) Swamp system illustrate an important part of the application of the rapid risk assessment. Despite scoring relatively well (13/25 = *low* risk of future impacts of BGA associated with climate change), the Kow Swamp System has significant cultural significance, and therefore could potentially warrant an elevation to 'very high risk' as is the norm in many other risk assessment practices (i.e. if one very high trigger is passed, the site gets an automatic very high).

The results of this phase of the risk assessment allow us to move beyond the entirely hypothetical future risk rankings shown in Figure 7-4 above, to a more realistic (albeit on a somewhat smaller scale) spatial assessment of BGA risks under climate change. The results of this assessment are shown in Figure 9-1 below. Once this is further developed, the prioritisation of at-risks sites is recommended. Figure 9-2 shows the individual result for Waranga Basin (outlet). The results have been uploaded to the online portal, so that the CC risk assessment, historical BGA data and management plans are in one place.

Table 9.3 Rapid risk assessment – results (Category Key: A – BGA, B – Inflows, C – Economics, D – Management, E – Cultural, Social, Health). (Use key: DS – Domestic and Stock, D – Drinking, I – Irrigation and R- Recreation).

Waterbody Name	Basin	Use	A	B	C	D	E	Score	Rank
Lake Glenmaggie	Thomson	DS, D, I, R	4	3	2	4	5	18	High
Pykes Creek Reservoir	Werribee	D, R	3	2	4	4	5	18	High
Melton Reservoir	Werribee	DS, I, R	4	2	4	4	5	19	High
Lake Hume	Upper Murray River	DS, D, I, R	4	3	4	4	3	18	High
Lake Eppalock	Campaspe	DS, D, I, R	4	4	4	4	4	20	Very High
Waranga Basin	Goulburn	DS, D, I, R	2	2	2	4	2	12	Low
Kow (Ghow) Swamp System	Loddon	DS, I, R	2	2	1	3	5	13	Low*

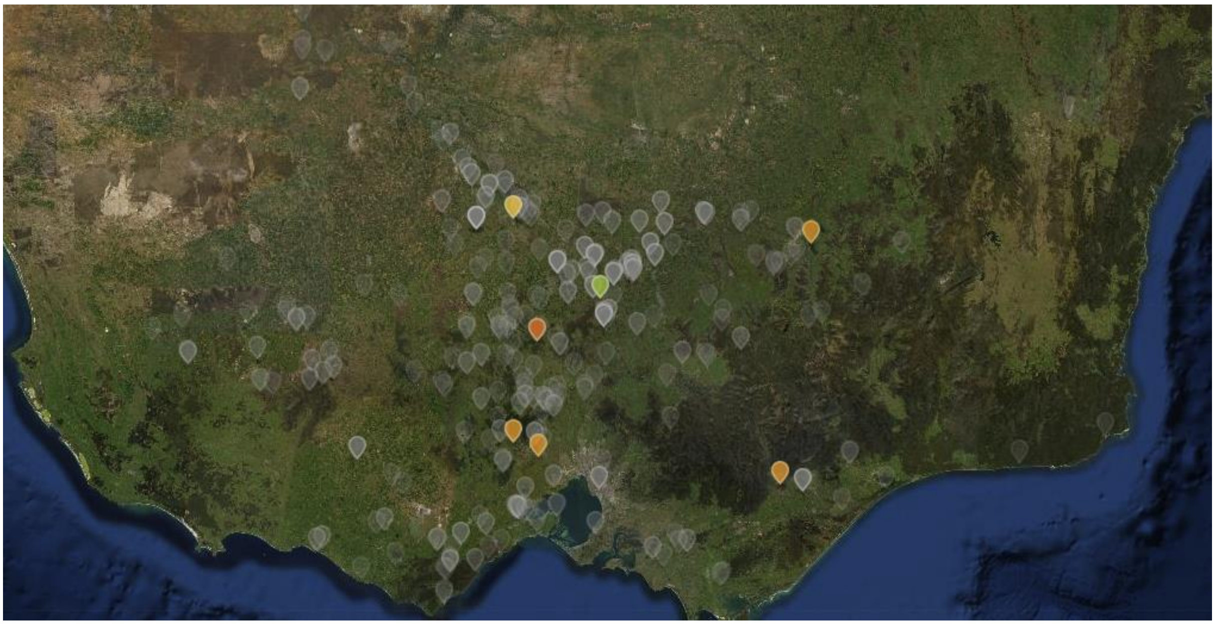


Figure 9.1 Visual results of the preliminary rapid risk assessment for seven sites

Figure 9.2 Rapid risk assessment results uploaded to the prototype online website, including risk assessment results and historical BGA data

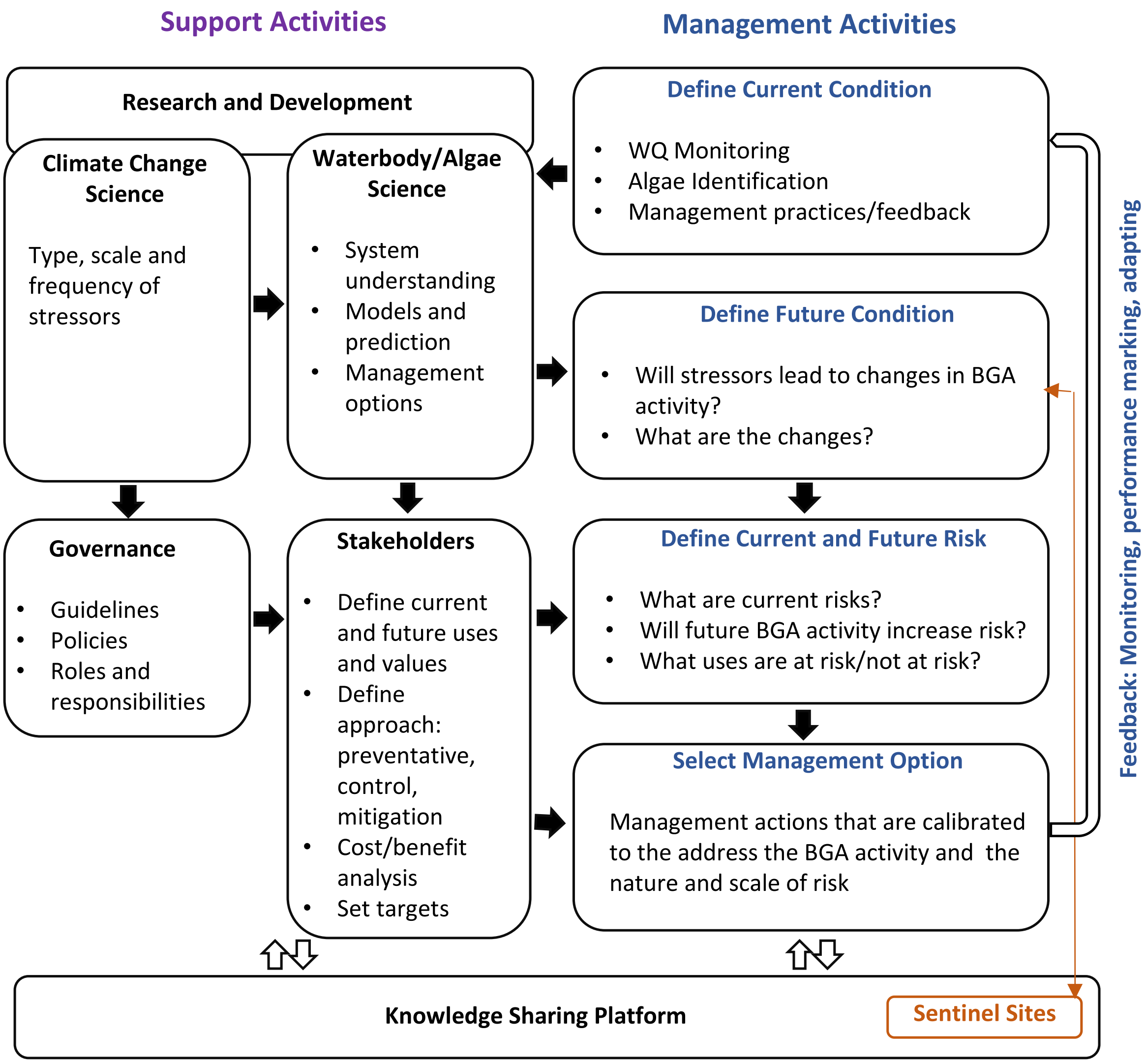
9.1.3 *Framework Application at Glenmaggie: Methodology and background*

We applied the BGA management framework described in Chapter 6 of this report to Lake Glenmaggie, an on-stream storage on the Macalister River in Central Gippsland, managed by Southern Rural Water. We address each section of the framework and provide key recommendations and actions in the table in the following section.

As noted below, the framework application is necessarily iterative. Given the current understanding of the water quality, limnological processes and likely future climate impacts (set-down to be assessed by SRW by the end of 2021), a series of recommendations have been made that can inform SRW's internal vulnerability assessments. These recommendations are broadly around the preliminary phases of the framework which look at system processes and key risks. Later sections, such as the definition of preferred management options are likely to be more fully examined following the detailed vulnerability assessments in 2020/21.

As described in section 3.1 of this report, when considering the response to stressors in waterbodies within the context of BGA management, two overarching questions arise, listed below. The framework is designed to address the **second** question listed below. The key distinction between the first and second question is that the second question requires a definition of what is problematic and is no longer purely scientific. This question is tied to the management of beneficial uses and the risks to those uses. BGA are often referred to as either harmful and/or nuisance algae, notwithstanding that BGA is not the only potentially harmful or nuisance algae species.

I. Will stressors lead to changes in BGA activity? and
II. Will stressors lead to problematic BGA activity?



Conceptual BGA management framework

The framework is necessarily *iterative*, in the sense that the implementation of management options must be supported by adequate monitoring or pilot testing that provides feedback back into the framework.

Successful management of BGA therefore requires an integrated knowledge of waterbody processes and BGA functional traits (see section 3.1) that can provide insights into potentially effective management options. Identifying viable and sustainable management options should focus on negating trait-based advantages that the BGA utilise to proliferate and developing strategies to eliminate these advantages. Management practices should therefore not only seek to reduce uncertainty prior to application but also be followed by carefully designed monitoring regimes and robust appraisals of efficacy over adequate timeframes to measure the extent of success or failure and the underlying reasons.

9.1.4 Framework Application at Glenmaggie: Rapid application results

Lake Glenmaggie is an on-stream storage on the Macalister River in central Gippsland. Raised by the forming of the Glenmaggie dam wall in 1919, and managed by Southern Rural Water, the lake provides water for domestic & stock, drinking, recreation and Irrigation purposes. Water released from Lake Glenmaggie can make its way downstream to the Gippsland Lakes, which is included as a protected site in the RAMSAR convention for wetlands. At full supply level (FSL, 77.1 mAHD), the dam wall impounds 177, 628 ML and has a surface area of 1,760 ha.

Prior to 2020, the lake has experienced infrequent Level 1 (a) blooms and is considered a 'moderate' risk according the SRW BGA Incident Management Plan 2019-2020. Elevated levels of both total biovolume and known toxic cyanobacterial species have been observed throughout 2020.

Table 9.4 Framework Application – Lake Glenmaggie

Activity	Activity Step	Information/Discussion	Recommendations
Supporting	**Climate Change Science** Type, scale and frequency of stressors	• Extreme rainfall events are expected to be become more intense on average through the century, but remain variable in space and time • Increased variability in flow associated with changed rainfall pattern (could include increase/decrease or shifts in pattern). • By 2030s, increases in daily maximum temperature of 0.9 – 1.8 deg. C relative to 1990 are expected • Longer heatwaves are expected, and bushfire seasons are projected to commence earlier and become longer. • Conditions that constitute a drought are likely to become more frequent Source: SRW	Examine changes to future inflows – utilising the recently updated 2020 update on the Guidelines for Assessing the Impact of Climate Change on water Availability in Victoria (DELWP)
	Waterbody/ Algae Science System Understanding Models and prediction Management options	There is currently little information available on the limnological behaviour of Lake Glenmaggie, or the general water quality characteristics of the inflows. Routine water quality samples are useful sources of information and are used to characterise algal species across the lake. The 2020 sampling programs have highlighted consistently elevated levels of total biovolume and known cyanobacterial species in the lake at all three sampling sites.	• Objective 4.2 of the SRW Adaptation Plan concerns research into monitoring and management of water quality issues with remote sensing and or on-water sensors. • Continue investigation into on-water water quality probes • Full characterisation of limnology and inflow water quality characteristics is recommended

Activity	Activity Step	Information/Discussion	Recommendations
	Governance Guidelines, policies, roles and responsibilities	SRW set down a (draft) Climate Change Adaptation Plan in October 2020. The comprehensive plan defines roles and responsibilities, a broad-scale vulnerability assessment adaptation pathway, and a programme of works that are generally drafted for delivery in 2021/22.	Downscaling of vulnerability assessment and study of climate risk for Lake Glenmaggie (i.e. Objective 4.1).
	Stakeholders Future uses and values Control mechanisms Economics Targets	Planned actions for March – October 2021 • Prioritisation of climate variabilities for all areas of SRW • Broad-scale assessment of climate change induced risks to SRW infrastructure • Mapping exercise to understand interferences of climate impacts, stakeholders and relationships amongst these	• Combine known algal species and climate impacts to estimate future BGA scenarios and impacts on stakeholders (i.e. irrigators) • Mapping should ensure downstream stakeholders, particularly those in Gippsland Lakes are included in mapping exercises.
Management	**Define Current Condition** WQ Monitoring Algae identification Management practices/feedbac k	• There is currently limited information on water quality throughout Lake Glenmaggie • SRW has investigated deploying remote sensors onto the lake to obtain information relating to water column temperature, dissolved oxygen, light and electrical conductivity, however this has not been commissioned yet • Species are identified event-based sampling in the lake and can be used for future risk characterisation • Notices are erected to warn recreational users of algal blooms • In low-storage systems such as the distribution network for the Macalister Irrigation District, there are few options for managing/treating/wasting the water due to infrastructure constraints.	• The proposed vulnerability assessments for Lake Glenmaggie should include a detailed characterisation of the lakes bulk limnological processes, and how these are interacting with the inflows to support sustained algal growth • Modelling of likely climate scenarios and baseline algal dynamics will inform future management practices and the adaptation pathways highlighted in the SRW Adaptation plan • Routine monitoring of the water column structure (thermal and oxygen profiles) will improve the understanding of the behaviour of Lake Glenmaggie, and likely future responses/ management requirements.
	Define Future Conditions Will stressors lead to changes in BGA activity What are the changes	BGA specific risks highlighted by SRW: • Lower average rainfall • Higher average temperatures and runoff from the catchment • Bushfire affected inflows resulting in increased instances of BGA blooms (and other water quality impacts) • This may affect ability to provide water for drinking and irrigation as well as recreation as Lake Glenmaggie hosts triathlons and boating events	

Activity	Activity Step	Information/Discussion	Recommendations
		• Inability to supply vegetable growers from affected waters	
	Define Current and Future Risk Current Risks Will BGA activity increase risk What uses are at risk/not at risk	• Lake Glenmaggie is currently classified as a 'moderate' risk under SRW's BGA management plan and is visually inspected monthly in cooler months and fortnightly over summer. Water samples are taken when visual inspections suggest a bloom • The rapid risk assessment shown above suggests that lake is at high risk of climate change impacts, mostly due to risks to downstream UNESCO sites and history of problematic algal blooms (post January 2020) • All uses are expected to be affected by increases in BGA (Stock and Domestic, Drinking, Irrigation and Recreation • The Macalister Irrigation District is at significant risk due to limited storage in the distribution network meaning vegetable growers may be offline. • Increased risk of BGA blooms in Gippsland lakes could cause reputation issues • Increased risk to recreational waterbodies creating public health and reputation issues.	• SRW is committed to undertaking vulnerability assessments as highlighted above, the results of which will inform future risks of BGA to the uses defined in this table • Characterisation of algal species and process drivers will inform future risks to these beneficial uses.
	Select Management Option	• SRW has investigated the potential to use ultrasonic methods to destroy BGA in Lake Glenmaggie, as currently being trialled by various partners in the Intelligent Water Network (Victoria).	• As discussed above, this framework is iterative. • Given the current understanding about waterbody processes, inflow water quality characterisation and future inflow assessment, all set-down for review by SRW by October 2021, SRW could potentially examine available in-lake and catchment management options at this stage as per the information contained in section 9.3 of this report.

9.2 Stakeholder Engagement

Traditional methods of stakeholder engagement were impacted by government mandated work-from-home protocols during this project. However, the project team was able to run a series of general and focused stakeholder workshops throughout the project, in addition to forming a Project Control Board[7], which looked more specifically at the conceptual framework model and it's relationship to current BGA science. Engagement with non-Victorian entities was also undertaken in an effort to gain further insights to BGA management across the country, and to identify any novel research / response initiatives that could enhance Victoria's adaptation strategies.

9.2.1 *Preliminary stakeholder meeting*

A preliminary meeting (14 May 2020) was conducted to introduce the project team to inter-departmental contacts, to discuss the preliminary adaptation framework (an earlier iteration of Figure 6.1 not shown in this document) and identify additional sources of data or information that may be useful for this project. Key messages from that meeting included:

- Key requirement moving forward to understanding impact of climate change and BGA toxicity on stock drinking from private farm dams – what safety mechanisms can be implemented?
- The framework should look for practical solutions to managing BGA, and that mitigation as well as adaptation should be considered as part of the plan
- The impacts of bushfires (associated with a changing climate) need to be considered in the context of further impacts on water quality
- The timing and cost associated with quantifying toxicity of algal blooms is prohibitive in many cases

Follow up interviews were conducted with regional coordinators, Parks Victoria, EPA Victoria and DELWP counterparts following this initial meeting.

9.2.2 *Focused stakeholder meetings and survey responses*

- A second series of stakeholder workshops was conducted on 16 June 2020 comprising the following four sessions (participants could select which sessions to attend), with over 40 participants joining for the introductory session. Each focus session included an 'industry perspective overview' to set the scene and provide further context for cross-departmental knowledge sharing for this adaptation plan.

I. A project overview, including work to date and refinements to the conceptual framework;

II. A focused discussion on drinking water and human health;

III. A focused session on recreation and environment; and

[7] The PCB is comprised of representatives from MW, G-MW, WaterNSW and DELWP. A final PCB meeting is currently scheduled for 17 July 2020

IV. A primary industry focus session.

The key messages/suggestions from preliminary sessions were:

- Future adaptation plans require better integration of policy decisions;
- Policy is available to all departments via e.g. One Health;
- Can existing data on BGA blooms be overlaid onto other sources, eg. BoM data, land-use planning tools;
- The requirement to ensure consistent approaches to assessing risks across all AAP's
- In addition to considering BGA blooms under climate change, there is a requirement to consider other water quality impacts of BGA (which may or may not be exacerbated by climate change), particularly taste and odour forming compounds that are readily associated with BGA bloom events;
- Land management initiatives can be complicated due to the management / legal arrangements for riparian zones and catchment / land ownership.

The key messages/suggestions from the drinking water session were:

- Blooms are causing prolonged impact on drinking water resources (> 150 days in the 2016 Murray River Bloom) and affecting multiple towns;
- Amount of chemical and operational expenses that are required to combat these extended blooms is increasing, and this will have significant impact on expenditure under future climate scenarios;
- Inability to treat some metabolites (particularly the those cause taste and odour issues, Geosmin and MIB) requires a multiple barrier approach;
- BGA blooms response cannot just be examined in isolation, and careful consideration needs to be given to mineral concentration, toxicity and concentrations of metabolites discussed above. At high concentrations, availability of chemicals and maximum dosing rates may not be sufficient to provide sufficient treatment;
- There is little information on the nutrient dynamics available for the range of species that are being observed in Victoria's waterways, and more work needs to be conducted to characterise novel species and understand their behaviour in a range of Victorian waterways;

- Managing water quality in reservoirs is extremely complex, and in addition to climate change, acute events such as bushfires and high flow events can dramatically change the water quality in a reservoir ; and

- Better understanding of algal dynamics, including the new and invasive species will prevent over capitalisation and the avoidance of building 'regret-capital' in the adaptation plan.

The key messages/suggestions from recreation and environment session were:

- Multipurpose reservoir management is tremendously complex (see earlier discussion on threshold levels) and will become more important with climate change, population growth and drive to open up more assets for recreation;

- A key initiative would be to shift the mindset away from using our rivers as drains, and to treat them as drinking water/pristine water sources;

- The public health risk in open waterways is significant, particularly with multiple sources of entry to many locations and the unknown presence of toxins in many waterways due to lack of testing;

- Following, this is particularly important in multi-use domains such as Gippsland Lakes, Hobsons Bay, Port Phillip Bay, where large, toxic blooms could have impacts on human and animal health, aquatic flora and aquaculture activities;

- How do we manage public expectations where there is (or isn't) visual indicators of a BGA blooms (i.e. there could be an absence of scum, but still toxic BGA present and vice-versa) (noting that it BGA is still a bacteria, so even in the absence of toxins, there can be negative health impacts);

- There is some evidence to suggest that phenotypes that produce toxins will be more prevalent under climate change;

- Toxins are not a 'notifiable' disease required by DHHS, and therefore full extent of toxic bloom presence around Victoria is not known; and

- There are key links to environmental water allocations in understanding water quality (i.e. impact of black-water events and increased residence times in wetlands), which highlight the ongoing importance of managing Victoria's environmental water allocation.

The key messages/suggestions from primary industry/agriculture session were:

- Agriculture doesn't operate in isolation, and therefore impacts of climate change on water quality relating to algae have key impacts food production and livestock health;

- Key threats to agriculture are land management, invasive species and BGA;
- Agriculture, forestry and fisheries rely on availability of water of a suitable quality, and therefore future deterioration of water quality due to BGA will have flow on effects for these industries;
- Private storages are a key risk for agriculture due to lack of monitoring, long residence times and prohibitively expensive monitoring costs;
- Noting again that impacts of toxins are not a notifiable disease and therefore there are no registers of the full extent of impacts across the state;
- There are no specific thresholds for trigger levels for stock in Victoria;
- An increase in the control mechanisms contained in the EPA legislation will see improved agriculture management (e.g. Effluent management, reuse of nutrients) which could partially offset any negative impacts of future climate change on BGA events.

9.2.3 Survey Results

An online survey was created to develop and understanding of stakeholders conceptualisation of current and future issues surrounding BGA management, information on any research and development initiatives and if respondents had any case studies they could share that would improve knowledge across the industry. The results of the survey are shown in the *s. 8.*1 of the appendices, and summarised below:

Thirteen respondents completed the survey;

- Very limited information on current/historical research initiatives. This is limited to a single destruction method (ultrasound) and three reports of chemical dosing with varying success. There is no comprehensive database of historical research and development initiatives across the state. The work discussed in s. 5.3.2 currently being undertaken by WaterRA would be a useful starting point for future knowledge sharing across the industry; and
- The future risk of toxin producing species, understanding their dynamics, the nature and extent of the toxicity and known impact pathways are key areas of interest for the respondents, and will likely form key adaptation pathways under the AAP.

Table 9.5 SurveyMonkey stakeholder survey results, n = 13.

Q1: What are the biggest issues you see for future BGA management in your organisation?	**Q2: What are the biggest areas of uncertainty for BGA management?**	**Q3: Have you undertaken, or plan to undertake any research, including field trials for BGA control? Please include any capital works undertaken for BGA control (e.g. WTP upgrades), and any land management initiatives**	**Q4: Do you have any BGA event management or research case studies that you would be happy to include in the pilot project report?**	**Q5: Any other questions / topics you would like to see included in the Action 19 programme?**	**Q6: Would you like the project team to contact you to further discuss anything?**	**Q7: Post Workshop Questions / Comments: Do you have any comments or suggestions after the workshops on Tuesday 16 ? Please indicate which session/s you attended**
The risk of increased frequency and severity of algal blooms, as well as the changing nature of those blooms (**toxicity**, species etc.). Applicable to all water uses (drinking, recreation and agriculture). Risk to agricultural users and the role our organisation plays in advising customers on BGA management.	**Toxicity**. Triggers for onset of blooms. Use of BGA-affected water for agricultural purposes; huge variety in use, sensitivities, infrastructure. Changing toxicity over lifetime of a bloom further complicates things.	Have investigated use of ultrasound wave tech to prevent blooms. Very expensive and effectiveness uncertain, especially in larger water bodies. Generally speaking land management or catchment improvement works in liaison with CMA's etc to improve water quality in general, including BGA. In Gippsland, Land & Water Management Plan for Lake Wellington catchment is a good example.	Yes. Incident management in Macalister Irrigation District.	Agriculture is a huge gap and presents a significant ongoing risk, not just for water supply management but on-farm. There needs to be some thinking as to how to best prepare farmers in all contexts for BGA management, including tools for monitoring BGA at the point of offtake and with their specific end-use in mind. In general, there doesn't seem to be any coordinated work on the shifts in BGA trends across the state/beyond our borders. We upload a lot of data to DELWP's portal. We analyze our own, but in terms of climate change trends in species distribution etc. could be useful in terms of preparing appropriate plans etc.	Yes (CJO emailed 27 June)	

Q1: What are the biggest issues you see for future BGA management in your organisation?	Q2: What are the biggest areas of uncertainty for BGA management?	Q3: Have you undertaken, or plan to undertake any research, including field trials for BGA control? Please include any capital works undertaken for BGA control (e.g. WTP upgrades), and any land management initiatives	Q4: Do you have any BGA event management or research case studies that you would be happy to include in the pilot project report?	Q5: Any other questions / topics you would like to see included in the Action 19 programme?	Q6: Would you like the project team to contact you to further discuss anything?	Q7: Post Workshop Questions / Comments: Do you have any comments or suggestions after the workshops on Tuesday 16 ? Please indicate which session/s you attended
Drinking water treatment plant capacity. A lot of inherited facilities are older sedimentation/clarifier style Plants that are not really designed to handle Algae (really only clays/silts, general turbidity). Classical treatment of algae laden water is based around addition of activated carbon to deal with potential toxins. The blooms we are seeing have biovolumes greater than 20mm3/L so the physical demands on the removal processes outweigh the possible issues of toxicity.	**Toxicity**. Having lists of known toxigenic species is only really helpful in targeting the type of toxicity tests undertaken. To respond to various levels of biovolume based on toxicity is pointless. The toxicity limits for stock and humans are relatively similar (see Australian and New Zealand Guidelines for Fresh and Marine Water Quality Volume 3: Primary Industries — Rationale and Background Information) so in the first instance the blooms should be categorised using qPCR or other emerging tech and then appropriate warnings given to ALL users not just recreational	Diatomix dosing trials being run at three locations Consideration of EartTec copper dosing at Raw water storages or directly in plant		Future of Drinking Water Treatment Operator training needs to be invested in. RTO's providing the service are limited and in the decline in Victoria which may leave the Victorian Water Industry in trouble. Formal courses (Full apprentice style training) could be considered in addition to one off training modules.		I attended all sessions The conversation regarding possibly not issuing recreational alerts purely because the authority may receive backlash of "you ruined my holiday" needs to be addressed. This should be addressed by removing authorities as Regional Coordinators, with conflicts of interest (That are both a Local & Regional water managers), and replacing them with a higher level of government (Say a CMA) as the Regional Coordinator. Bulk water suppliers have too much vested interest in hiding results from the public rather than issuing the warnings required & do not consider that warning domestic & stock (agriculture) users is part of their roll. Consideration should also be given to changing the "alert" system and rewording it to "Advisory", "Warning", "Health Alert" instead of alerts level 1, 2 & 3. This would need further work to inform the public and help tourism & agriculture to adapt to the changing BGA issues. For stock usage refer to the previous agriculture

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						guidelines https://urldefense.proofpoint.com/v2/url?u=https-3A__www.waterquality.gov.au_sites_default_files_documents_anzecc-2Darmcanz-2D2000-2Dguidelines-2Dvol3.pdf&d=DwMFAg&c=JnBkUqWXzx2bz-3a05d47Q&r=MhDEpolY_leRa6gvGOj20EHUJWvw1uEvLDdGAX42hxT0eapqjHTWULAvFYRuII6X&m=R13wYkb3R8cXR5cUZNKo29U_SjHhzW00gCzL9ec8UOY&s=J67MWMgBBK5CwppZmFlzdols9zViRxsxAfWchdnAeXM&e=

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Transitioning the water quality monitoring program to include remote sensing and high frequency in situ data logging.	The impact of climate change and how both temp and CO2 will serve to promote increased growth and extended algal seasons. The rate at which community needs to adapt and change management and use of aquatic ecosystems.	I am completing a review of effects oriented interventions and one key recommendation is for the organization to support mesocosm and controlled experiments due to the confounding variables.	Yep happy to provide research paper on the effect of CO2 on key species and currently we are using Satellite imagery with customized script to detect and measure spatial and temporal extent of blooms.		Yes	Thanks for the invitation and it was great to see the progress.
Water Supply restrictions, complaints on taste and odour, cost	Prediction of timing of algal blooms					
Irrigation is the greatest user of water. If there is BGA in the supply system crop/pastures still need to be irrigated and stock watered. There are no alternative supplies to meet the required volumes.	Irrigating crops/pastures with BGA water and the impacts of this. Does it contain **toxins** or not?					
Timely information whether the bloom is **toxic** and/or the concentration of taste and odour compounds	Have trailed copper based controls in the past for small reservoirs; have also trailed ultrasonic technology; WTPs which have BGA risk have Powdered Activated Carbon installations;					This may or may not be of value?, however in a changing climate, the value of recycled water will rise. There is a lot of recycled water being used in Victoria at Class C for Agricultural purposes, primarily for cropping, and I expect that this will continue. Class C water (recycled from municipal sewage) often has significant bio-volumes of BGA which needs to be managed. It is difficult to manage (the BGA), and we need to assure that processes exist to protect

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						stock and end users of any BGA threat. This may also bring into the equation the need for additional treatment, which may leave the product (Class C recycled water) non-viable.
increased frequency of blooms (lower inflows, increased temp) and therefore increased management implications. Increased emphasis on recreational opportunities and storage management implications/costs- meeting competing expectations will take more time/negotiation Storage manager can only manage in storage whereas is the catchment that contributes the sediment/nutrient loads unpredictable nature of the BGA blooms (different species) and uncertainty around the potential impacts of BGA toxins to public health.	large ongoing blooms become the norm- people expect greater level of management response- what would that look like when we are not sure of the toxin producing species mechanisms and associated stressors inducing the toxin production. Complexity of management of blooms, with unknowns relating to the potential public health risks associated with this poorly characterised species of BGA. Treatment options can continue to feasibly address potential water quality risks associated with BGA					
Cross department action that leads to meaningful results	Who's role is it to reduce the risk?					

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Maintaining water quality, reporting, monitoring and testing, managing local and recreational stakeholders and having a DELWP BGA Website that is reporting water quality status on all water bodies in Victoria.	on going funding for dedicated Regional BGA specialists to enable timely monitoring, testing, reporting and regular communications, engagement and media management covering BGA blooms across multiple stakeholder networks and user groups.		Have local District Response Plan developed to enable staff and key stakeholders to better understand response activities when a BGA blooms impacts recreation water bodies in the Otway District			
More frequent, longer duration blooms consuming greater resources to manage. Exposure to litigation.	Poor understanding on bloom dynamics, species and toxins and effects of **toxins** on livestock.	Undertaken a feasibility study on treatment options off the Murray River. We have used control and coagulant to try and control BGA in some storages with mixed success.			Yes	
Always having the most up to date information and complete data sets	Trigger levels for stock, irrigation and impact on agriculture					
Consequences of BGA are diverse, different events may be primarily recreation impacts, biodiversity impacts, agricultural impacts, human health The major BGA event along the Murray River a few years ago was very protracted, complex for stakeholders. Initial impacts of BGA can be hard to detect from normal event noise	Consistent messaging across interstate borders with stakeholder complexity Primary industry does not have true viable alternative water source	Not sufficiently informed to discuss capital works initiatives Some improvement in environmental flows i.e. Goulburn River	The review of the Murray River event of a few years ago is worth review	How would Agriculture respond to a Murray River event if actual widespread **toxicity** occurred		

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cost of controlling BGA and the water quality issues from dosing copper sulphate.	When dosing a reservoir, there is destruction of the reservoir ecosystem leading to poorer water quality issues.	trial of a copper sulphate product that claims to be less destructive in the drinking water reservoir ecosystem and controls the release of MIB & geosmin	Yes - supplied	any research on helping to control BGA once in a reservoir. I understand limiting nutrients etc but want to understand more about what may be happening in the reservoir ecosystem and how to enhance that aquatic ecosystem to help control BGA.	Yes	

9.3 Prevention and Control Measures

Table 9.6 Generalised preventions and control measures after Hydronumerics (2015)

Option ID	Classification	Title	Pros	Cons
1	Vegetation	Constructed wetland/macrophyte remediation (Emergent/submerged)	High capacity to treat sediment and nutrient loads Provide visual amenity and options for passive recreation Habitat zones Flexible design and community engagement Accepted, mature technology Increase shading + flexible planting (emergent/submerged)	Compete with in-lake primary/secondary recreation options Relatively inflexible operation/location once installed
2		Floating wetlands	Restoration to macrophyte dominant state Flexible solution to move wetland during recreation events (i.e. triathlon/rowing) Shading to reduce BGA growth if surface area large enough Flexible solution to integrate with other solutions (pontoons, baffles) Unlikely grazed by carp	Harvesting may be required Large area required for floating wetland may impact on recreation opportunity May require high minimum cover (30 – 40 % of lake) Can become nesting sites for pest species of birds Potential safety issues with swimming/unauthorised access May impact on wind-forced mixing in lakes

Option ID	Classification	Title	Pros	Cons
3	Mixers/Aerators	Submerged Bubblers	High impact on stratification Reduced impact on secondary recreation (i.e. rowing) Large horizontal impact (piping) Flexible operation (on/off)	Negative Visual impact (generator) on land
4		Mixers/SolarBee	Increase oxygen in hypolimnion Unobtrusive to secondary recreation if placed in correct location	Limited observed benefit in operational domains
5		Surface aerators	Easy to move, lightweight and low energy consumption	No impact on Hypolimnion Generally only limited to 1-2 m depth
6		Fountains	Increased visual amenity	Permanent fixture – hard to move Moderate impact on recreation
7		Curtains	Reduce sediment load to offtake and into lake Benefits light regime	Limited benefit if positioned downstream of silt traps and weirs
8		Inflow baffles/weirs	Possible to reduce short-circuiting in lake Confer benefits to suspended solids regime downstream of installation	Unless flexible mesh – very hard to move
9	Sediment Treatment	Dredging/silt removal	Remove contaminated sediments and nutrients Positive impact on rowing due to some areas already heavily silted impacting on rowers	Strict EPA regulation relating to dumping of dredged material May require draw down for extended periods of time
10		Sediment Barriers	Active Calcite and zeolite material can reduce release of Phosphorus and Nitrogen from sediment during anoxic conditions preventing the remobilisation of these nutrients	Limited evidence on efficacy Observed P release after 10-12 days of anoxia in hypolimnion under test conditions Visual amenity and exclusion during application Limited understanding in the Australian context
11	Engineering	Siphon Outlets	Ability to selectively withdraw poor quality bottom waters	Limited control over timing – increased man power requirements
12		Variable depth off takes (as differentiated from surface water abstraction)	Ability to selectively withdraw poor quality bottom waters Greater control compared to #11 with fixed engineering solutions	More expensive than #11 Requires more intervention and possible draw down of lake/coffer dam
13		Dam Wall Augmentation/hydrological modification	Augmentations to the dam wall that reduce detention time (HRT) can be effective options for controlling in-lake BGA	High cost and may have negative impacts on secondary users (i.e. rowers) and primary recreation (swimmers)
14		Alternative off takes - irrigation	Reduce effective detention time	Need to ensure sustainable supply – especially for customers during droughts etc.
15		Augmented water cycle (in-lake reticulation/recycling)	Mostly effective on improving overall quality in d/s discharge	Limited impact on overall nutrient load in-lake due to recycling of nutrients
16		Synthetic Covers	Reduce light to inhibit BGA growth	Poor flexibility Limited opportunity to change under variable hydrological regimes Major impact on visual amenity and recreational opportunity in area affected by cover

Option ID	Classification	Title	Pros	Cons
17	Water Column Treatment	Augmentation of in-lake salinity	Increase salinity can decrease overall diversity of blue-green algal species, transition to diatoms	Reduce ability to use water for irrigation Negative impacts on downstream receiving water Poor control Requires extensive ongoing maintenance
18		P-cycle augmentation	Removes readily available P sources from water column to inhibit potential BGA growth	Limited information on permanent binding of reactive P in sediments Impact on visual amenity during application and possible exclusion periods
19		Algaecide Application	When used with hydrodynamic and water quality model can be targeted at problem species Effective for short term control of problematic BGA blooms	Does not impact on factors contributing to BGA blooms Costly, short-term intervention Negative impact on aquatic fauna Mandatory exclusion from lake during and after application (up to 2 weeks) Can be unsightly and create short-term odour issues