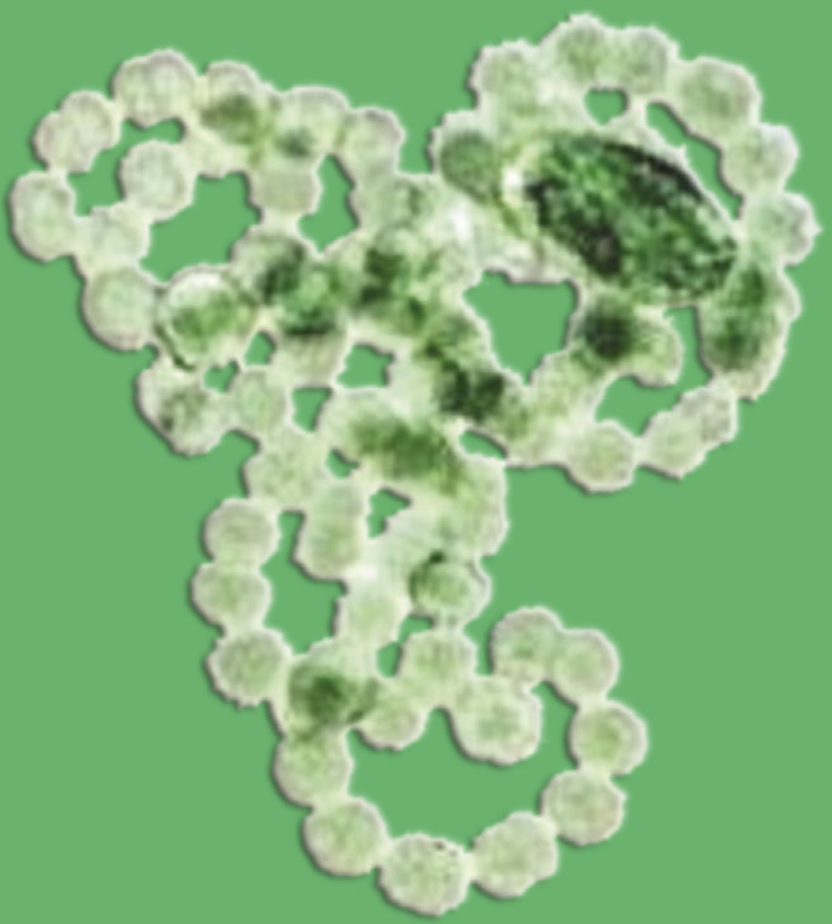
Generic Incident Management Framework

for Toxic Blue-Green Algal Blooms, for Application by Potable Water Suppliers

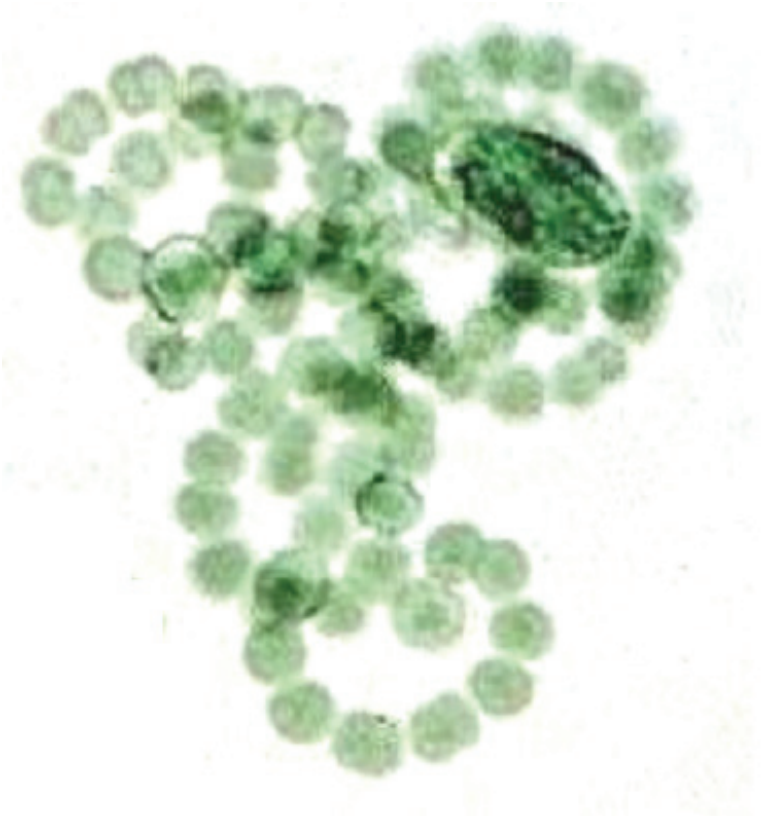
Hein du Preez & Leoni van Baalen



TT 263/06

Water Research Commission

Generic Incident Management Framework for toxic blue-green algal blooms, for application by potable water suppliers



Hein du Preez and Leoni van Baalen

Report to the
Water Research Commission
by
Rand Water

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EXECUTIVE SUMMARY

BACKGROUND AND MOTIVATION

In South Africa, as in many countries throughout the world, the proliferation of algae and cyanobacteria (blue-green algae) in surface waters such as reservoirs and rivers plays a significant role in the production of drinking water from such sources,. The proliferation of algae and cyanobacteria in the source water variously causes problems such as ineffective coagulation, flocculation and sedimentation, penetration of sand filters, clogging of sand filters, increase of organic loading of the water and the release of taste and odour compounds as well as toxic compounds.

The taste and odour problems in drinking water have either directly or indirectly been linked to cyanobacterial production of compounds such as geosmin (trans-1,10-dimethyl-trans-9-decalol), MIB (2-methylisoborneol), IBMP (2-isobutylmetoxypyrazine), IPMP (2-isoproylmetoxypyrazine and β- cyclocital. Geosmin and MIB in water drinking cause the water to have an earthy-muddy-musty taste and odour. Although not toxic to consumers, this justifiably generates suspicion with regard to the quality and health effects of the drinking water, leading to customer complaints and consumers seeking alternative sources of drinking water.

The ability of many cyanobacterial species to produce a range of extremely potent toxins (cyanotoxins) is of particular interest to Drinking Water Utilities as the drinking of water may be an important route of exposure to cyanotoxins. This exposure route has resulted in the development of drinking water guidelines and investigations into the effective removal of cyanobacteria and cyanotoxins during the drinking water treatment process. In practice, however, drinking water treatment managers have found it difficult to implement the recommendations arising from these investigations in a coordinated manner. Furthermore, in many countries like South Africa, have guidelines for cyanotoxins in drinking water (only for microcystins; DWAF, 1996) but are not specified in the drinking water specifications (e.g. the SABS 241 Specifications for drinking water in South Africa) or national drinking water standards (e.g. SANS 241:2005 South African National Standard for Drinking water) . The consequence is that, in general, most Drinking Water Utilities in South Africa have not made any provision for skilled staff to monitor for cyanobacteria or their toxins. Some Drinking Water Utilities monitor only for geosmin and 2MIB due to the unpleasant taste and odours they cause in drinking water in order to avoid complaints from consumers. Furthermore, most drinking water treatment plants in South Africa are not equipped or designed effectively to treat source water containing toxic cyanobacteria. It was therefore necessary to develop a guidance management framework for drinking water suppliers in South Africa - describing how to deal proactively with cyanobacteria and their associated toxins in source water by using a step-by-step Alert Levels Framework so as to ensure safe drinking water to the consumer. The proposed ALF is designed to be both cost effective and making use of existing organisational capacity.

AIMS OF THE PROJECT

The aims of the project were to:

- Summarise the available literature on management frameworks for cyanobacteria (blue-green algae) with special emphasis on drinking water.
- Develop a Generic Incident Management Framework effectively to manage the supply of drinking water when toxic cyanobacteria blooms are present in the source water. The

Incident Management Framework should provide operations managers and operators with easily understandable information that would enable them to make informed decisions regarding the basic requirements for monitoring and dealing with cyanobacteria in source water. This will minimise the risk of exposure by consumers of drinking water to cyanotoxins.

MAJOR RESEARCH FINDINGS

Cyanobacteria and their associated cyanotoxins (See also Chapter2)

Cyanobacteria are a natural part of the phytoplankton population of many surface freshwater bodies. Their occurrence may vary drastically (temporally and spatially), with seasonal changes from only a few in the water column to excessive numbers occurring as 'blooms' at the surface of a water body. Their distribution in the water column may vary from being at the surface of the water column, a few metres below the water surface (meso-limnetic layers)_or at the bottom of the water body (benthic cyanobacterial mats). In South Africa cyanobacteria blooms comprise mainly the *Microcystis*, *Anabaena*, *Oscillatoria* and *Cylindrospermopsis* genera. The occurrence of cyanobacteria is highly seasonal but is widespread and frequent.

Many cyanobacteria genera (Table E.1) synthesise cyanotoxins as secondary metabolites within the cells (Table E.1). The cyanotoxins usually remain contained within the cells, but are released during cell lysis (breakdown of algal cells) and cell death. This is important for both the monitoring and prevention of cyanotoxins in drinking water.

TABLE E.1: A summary of cyanotoxins, the cyanobacteria that produce them, and some of the recorded mammalian clinical symptoms of cyanotoxin

TOXIN	CYANOBACTERIAL GENERA	CLINICAL SYMPTOMS
Cyclic peptides		
Microcystins	*Microcystis, Anabaena, Oscillatoria, Planktothrix, Nostoc*	Blistering around mouth, gastro-enteritis, fever, pains in muscles and joints, nausea, vomiting, diarrhoea, swollen liver, death by liver failure
Nodularin	*Nodularia*	Gastro-enteritis, fever, pains in muscles and joints, nausea, vomiting, diarrhoea, swollen liver, death by liver failure
Alkaloids		
Cylindrospermopsin	*Cylindrospermopsis, Aphanizomenon, Anabaena, Raphidiopsis, Umezakia,*	Abdominal pains, vomiting, swollen liver, liver failure, pathological damage to the kidneys, spleen, thymus and heart
Anatoxin-a	*Anabaena, Planktothrix, Oscillatoria, Aphanizomenon*	Muscle weakness, respirator distress, exaggerated abdominal breathing, hyperactivity, hypersalivation, numbness around the lips, paralysis
Anatoxin-a(S)	*Anabaena, Aphanizomenon*	Muscle weakness, respirator distress, exaggerated abdominal breathing, hyperactivity, hypersalivation, numbness about the lips, paralysis
Saxitoxins	*Anabaena, Aphanizomenon, Lyngbya, Cylindrospermopsis*	Numbness around the lips, complete paralysis, death from respiratory failure

Lipopolysaccharides		
Lipopolysaccharides	All	Allergic reactions, inflammatory, irritation, gastro-enteritis

Monitoring strategies should for example, focus on both the total cyanotoxin concentrations and the cell-bound cyanotoxins. Cyanotoxins (e.g. microcystins) that are water-soluble are difficult and expensive to remove during the drinking water purification process. It is therefore imperative to remove living and intact cyanobacteria during the treatment process.

The recorded cyanotoxin effects on mammalian health range from being neurotoxic (e.g. anatoxins and saxitoxins) or hepatotoxic (e.g. microcystins and nodularin) to inflammatory or irritants (e.g. lipopolysaccharide endotoxins) as well as having a combination of effects (e.g. cylindrospermopsin). However, only a few suspected human poisonings are on record, probably due to the fact that people avoid the drinking of offensive-smelling water and more importantly, that the common symptoms of cyanotoxin poisoning (vomiting, diarrhoea, stomach pains and headaches) are also the symptoms of gastrointestinal illness due to bacterial, viral and protozoan infection, and are thus not linked to cyanotoxin poisoning.

Due to the increasing evidence for the potential of human health effects after consuming drinking water that contains cyanotoxins, in 1999 the World Health Organisation (WHO) issued a provisional guideline for microcystin–LR (microcystin–LR: 1 μg/L), which is the most common variant of microcystins (WHO, 2004). To date, guideline levels or concentration standards for microcystins have been incorporated in the national drinking water guidelines in Australia, New Zealand, Brazil, Canada and the European Union. As stated, although South Africa does have guidelines but no specifications or standards for cyanotoxins in drinking water, Drinking Water Utilities like Rand Water do have internal operational specifications for cyanotoxins. However, the guidelines do not address the issue of short-term exposures, as they aim to protect humans over a lifetime of consumption and are thus conservative. To address short-term exposure to cyanotoxins, Fritzgerald *et al.* (1999) recommended that the exposure could be increased 10-fold. Subsequently, it was proposed that Drinking Water Utilities in Southern Australia should use a guideline value of 10 μg/L for microcystins and nodularin as their alert levels. However, it was argued by Falconer (2005) that this value was too high and that a more conservative approach should be followed as people may be exposed to cyanotoxins several times a year. Based on the above approaches and recommendations, as well as practical experience, it is recommended that the cyanotoxin guidelines (specifically for microcystins, nodularin and cylindrospermopsin) be incorporated in the Alert Levels Framework for drinking water as follows:

- **Guideline value of 1 μg/L** (microcystins, nodularin or cylindrospermopsin).
  This is for lifetime exposure.

- **Alert level 1 concentration of > 0.3 μg/L and < 0.8 μg/L** (microcystins, cylindrospermopsin or nodularin).

- **Alert level 2 concentration of ≥ 0.8 μg/L and < 2.5 μg/L** (microcystins, cylindrospermopsin or nodularin)
  This is a short-term exposure to concentrations above the guideline value. During this period the Drinking Water Utility must take steps to reduce the cyanotoxins according to the guideline value.

- **Alert level 3 concentration of ≥ 2.5 μg/L and < 5 μg/L** (microcystins, cylindrospermopsin or nodularin) for a period of not more than 8 days.

During this period the Drinking Water Utility must take steps to reduce the cyanotoxins according to the guideline value. If the cyanotoxin concentration is ≥ 2.5 µg/L and < 5 µg/L for more than 8 days or if the cyanotoxin concentration is > 5 µg/L for 2 days then notify the Health Authorities and general public as well as supply alternative drinking water.

Water treatment options for cyanobacteria rich water (see Chapter 3)

The organic compounds (offensive taste and odour compounds, cyanotoxins that can affect the health of people) that are produced by the cyanobacteria must be removed during the treatment process to ensure that the drinking water is aesthetically acceptable and does not pose a health risk to consumers. The Drinking Water Utility can reduce the risk of exposing consumers to cyanotoxins by optimising the extraction of source water, optimising their conventional treatment process and by implementing advanced treatment processes (Figure E. 1). If plant operators have some understanding of cyanobacteria cell and toxin characteristics this will further aid in the selection of appropriate actions.

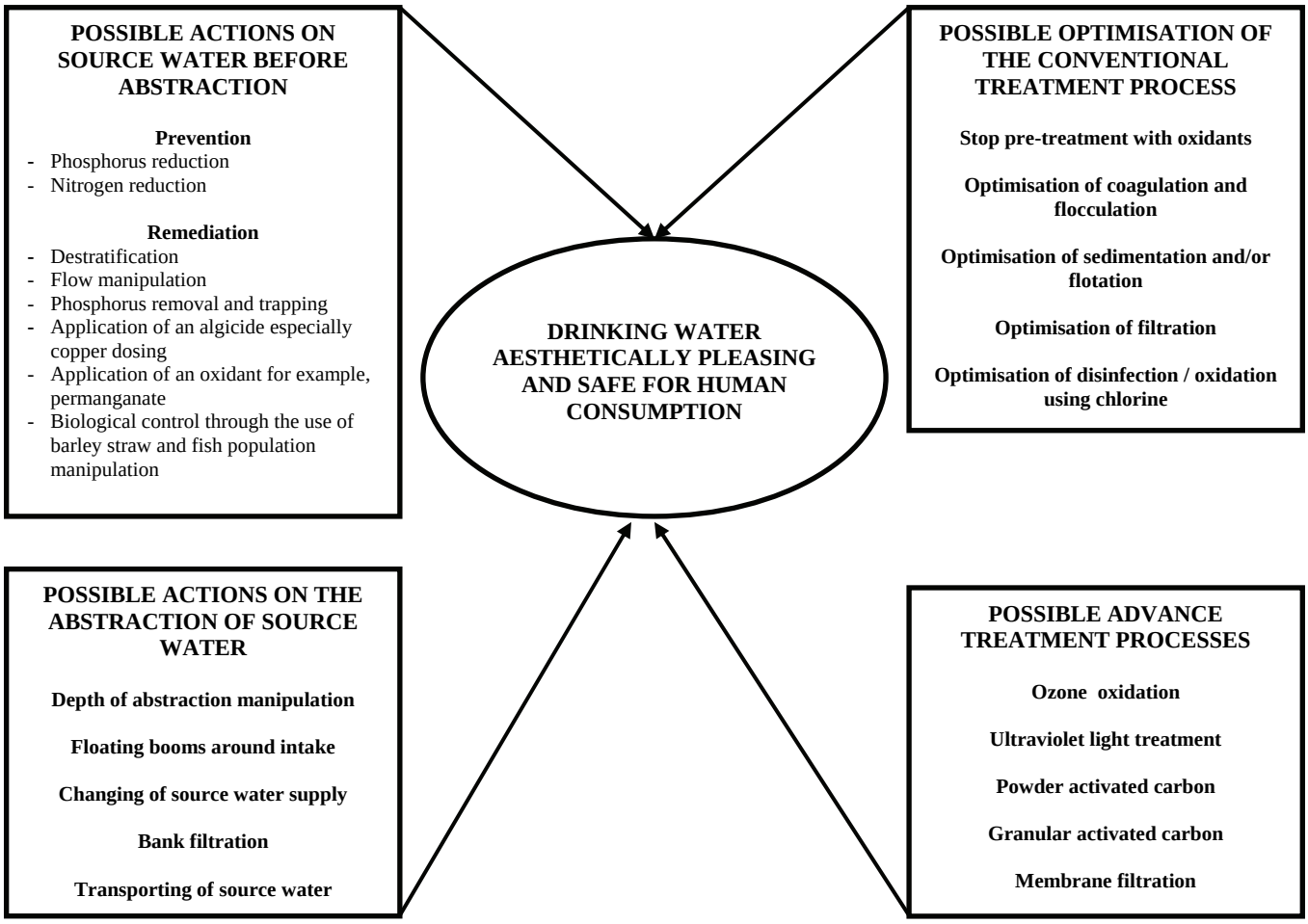

FIGURE E.1: Actions that can be taken to reduce the risk of cyanobacteria effects on drinking water production.

Cyanobacterial Incident Management Framework (see Chapter 4)

A Cyanobacterial Incident Management Framework (CIMF) is a monitoring and management action sequence that Drinking Water Utilities can use proactively to monitor the presence of cyanobacteria

in the source water. It assesses the Utility's ability to deal with cyanobacteria, to develop action plans that can be implemented during the treatment of source water contaminated with cyanobacteria and to provide a graduated response to the onset and progress of a cyanobacteria bloom in source water.

Burch (1993) developed one of the first comprehensive management frameworks for cyanobacteria-rich water resources in Australia. The Burch model is based on cyanobacterial cell numbers in the source water, which are set as triggers linked to a routine monitoring programme and three alert levels. The Burch model is additionally useful to Drinking Water Utilities as it also describes some operational actions (e.g. altering off-take depth, the deployment of booms, the use of powder activated carbon (PAC), etc.) that could be undertaken, the analyses (e.g. cyanobacteria identification, cyanotoxin analysis) and the consultation process that should be undertaken (e.g. with the Health Authorities). The Burch model thus formed a generic framework, which could be or has been adapted by many Drinking Water Utilities to include in their specific management and site-specific operational capabilities. Good examples of this are the CIMF developed by the Word Health Organisation, that developed by Van Baalen & Du Preez (2001) for internal use by Rand Water in South Africa and that developed by Burch *et al.* as part of the national protocol for the monitoring of cyanobacteria and their toxins in surface fresh waters for human use in Australia.

The Van Baalen model is based on the principles of the Burch and WHO models, but adds additional criteria to make it more practical for day-to-day application by drinking water treatment managers. This CIMF model consists of various levels of action, namely: Routine Monitoring ↔ Vigilance Level ↔ Alert Level 1 ↔ Alert Level 2 ↔ Alert Level 3. Between each action alert there are primary (phytoplankton identification and enumeration), secondary (cyanotoxin concentration) and tertiary (mouse bioassay test result) triggers, which allow for "movement" (step-up or step-down) between the action alerts. As in the Burch and WHO models, each alert level describes the monitoring and actions that should be considered and undertaken by drinking water treatment managers and Drinking Water Utilities at large.

In this report two CIMF models are described namely (1) a CIMF using cyanobacteria identification and enumeration as primary trigger and (2) a CIMF using chlorophyll-*a* as primary trigger (Figures E.2 & E.3). These frameworks are based on the same principle, but differ in minor actions taken, especially at the lower alert levels. The need for the CIMF based on chlorophyll-*a* is that the drinking water suppliers in South Africa differ significantly in their capacity (i.e. amount of funding, type of infrastructure, skills and know-how, capacity available to perform operational tasks) to monitor and deal with cyanobacteria and cyanotoxins. It must however be stressed that the CIMF based on chlorophyll-*a* is not as specific as the phytoplankton CIMF and acts more as a screening tool for the source water and should be diligently used in conjunction with the results of the outsourced samples. Furthermore, in using the chlorophyll-*a* CIMF, there will be an increased risk of not detecting the cyanobacteria and their toxins at lower levels, compared to the cyanobacteria identification and enumeration CIMF (Risk: chlorophyll-*a* CIMF > cyanobacteria identification and enumeration CIMF).

It is envisaged that the developed CIMFs would be the platform on which to evaluate the capacity to manage a cyanobacteria incident. Based on the requirements stipulated in the CIMFs and their assessment, the Drinking Water Utility would then develop and implement their customised CIMF. This process would not only ensure that the Drinking Water Utility has structures in place to deal with a cyanobacteria incident but will also assist in improving the knowledge and understanding of cyanobacteria and cyanotoxins by the various role-players within the organisation.

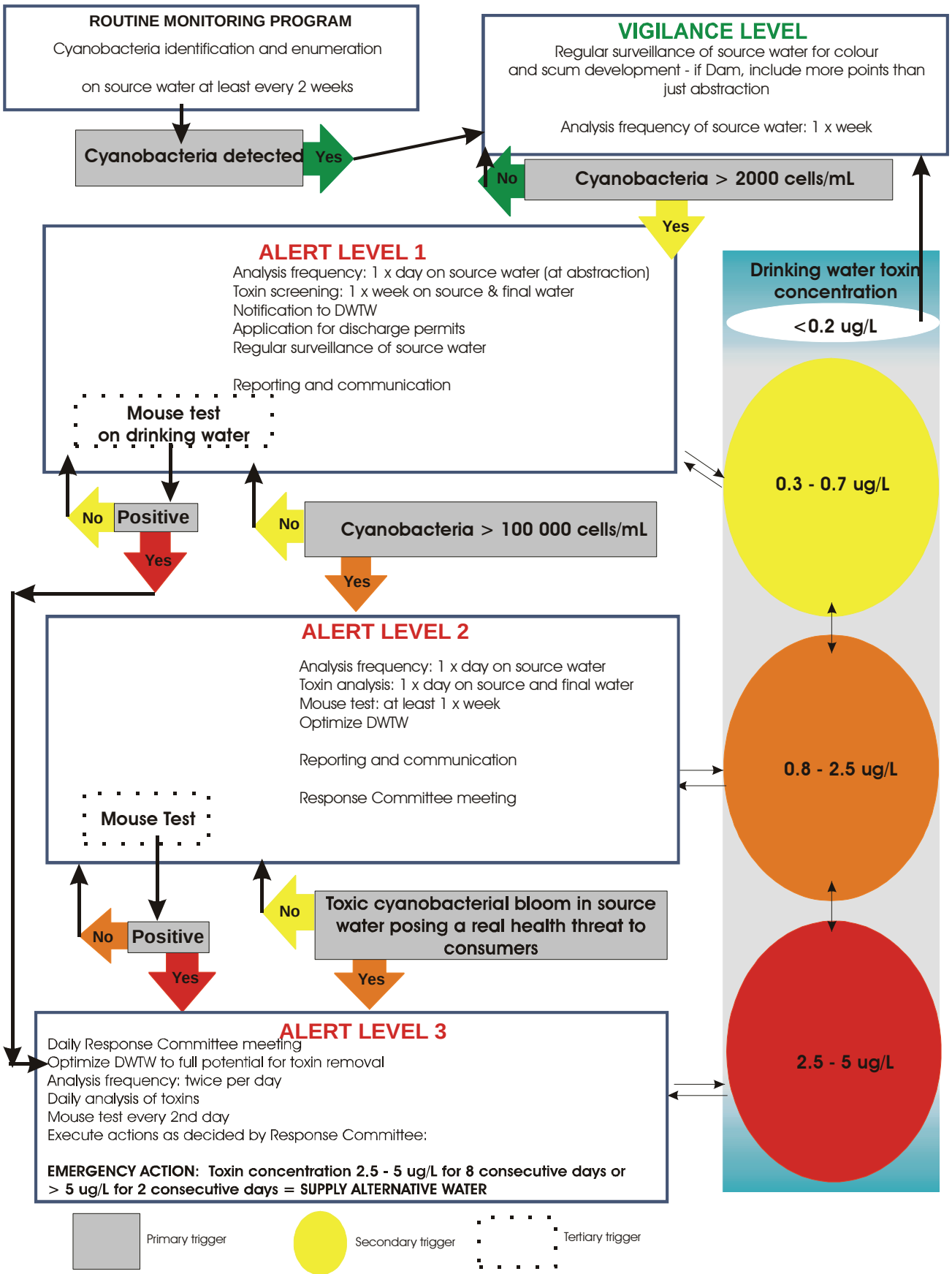

FIGURE E.2: Cyanobacterial Incident Management Framework using cyanobacteria concentration as a primary trigger.

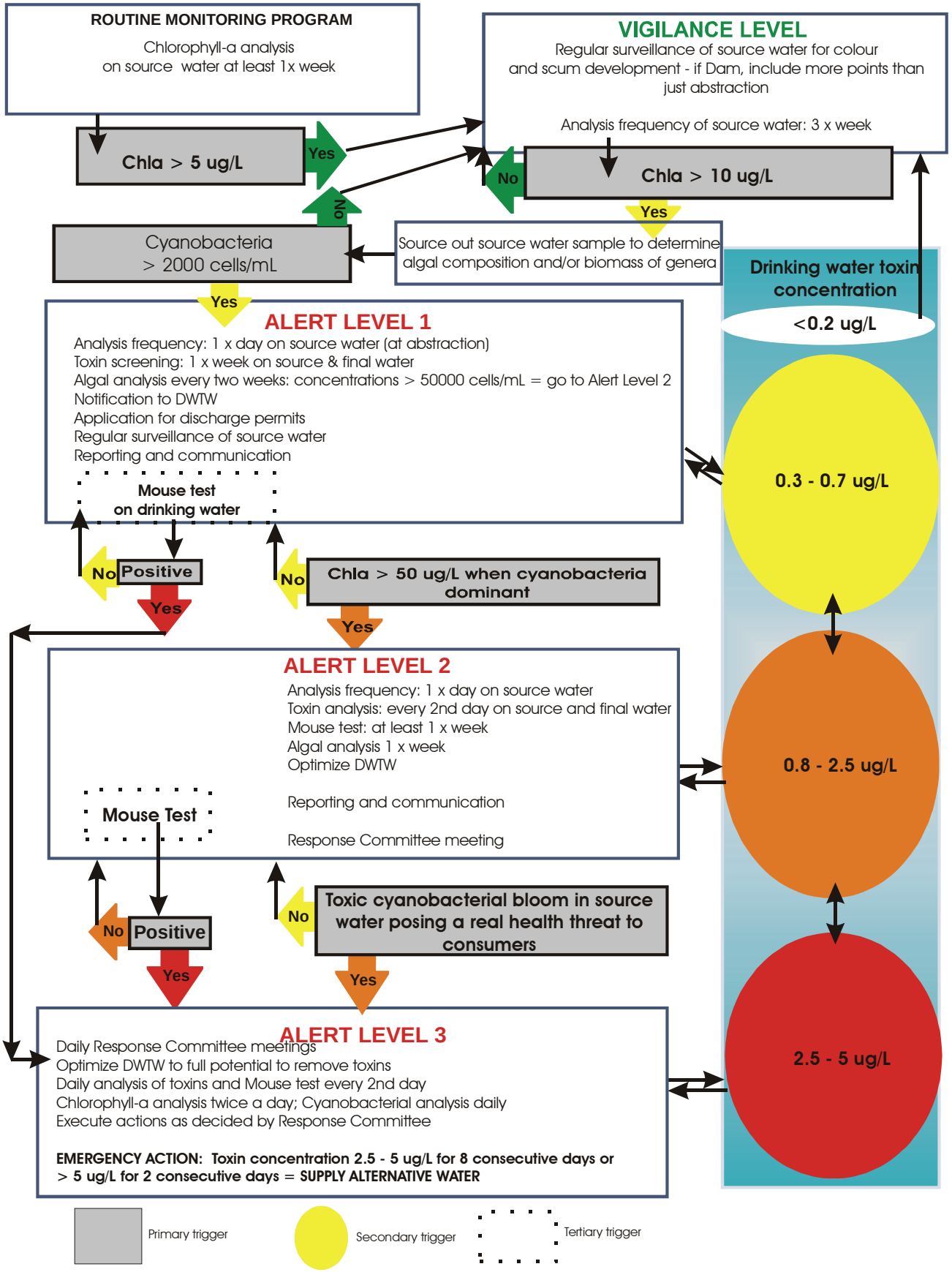

FIGURE E.3: Cyanobacterial Incident Management Framework using chlorophyll-*a* concentration as a primary trigger.

Extent to which contract objectives were reached

The contract objectives were reached as follows:

- A summary of the available literature on management frameworks for cyanobacteria (blue-green algae) with special emphasis on drinking water is provided in Chapter 4. **OBJECTIVE 1**
- Possible treatment options for the removal of cyanobacterial cells and toxins from source and drinking water are provided in **Chapter 3.** This was not an objective, but was included as requested by role-players during the capacity-building intervention.
- Generic CIMFs were developed to manage drinking water supply effectively when toxic cyanobacterial blooms are present in the source water. These CIMFs provide operations managers and operators with easily understandable information that would enable them to make informed decisions regarding the basic requirements for monitoring and dealing with cyanobacteria in source water. The CIMFs are discussed in Chapter 4. **OBJECTIVE 2**
- The development of three CIMFs, to accommodate Drinking Water Utilities with different capacities, contributes to the knowledge base currently available in South Africa. Whereas knowledge on how to manage cyanobacteria and their associated toxins effectively during drinking water purification was confined in only a few Drinking Water Utilities it is now also available to all the Drinking Water Utilities.
- Knowledge transfer and capacity building was also achieved and is detailed below.

All the objectives of the project were achieved.

Capacity building and information transfer

Capacity building and information transfer concerning the Cyanobacterial Incident Management Frameworks (CIMF) were performed on various occasions and are as follows:

- A workshop in Upington, (15-16 July 2003) organized by DWAF. A presentation was given on the principle of using an Incident Management Framework for blue-green algal toxins by potable water suppliers. A work session was also included where information was given regarding appropriate internationally recognized practices to deal with blue-green algal toxins in the drinking water industry. Information was given to assist water treatment works in the Northern Cape to handle toxic blue-green algal blooms.
- A workshop or Lower Orange River Remediation Forum (LORFF) meeting was held in November 2003, where a presentation was given on Incident Management Frameworks and the possible treatment options for drinking water suppliers. A discussion session was also held on what factors would be appropriate primary triggers for use by small treatment works that do not perform routine analysis.
- Capacity-building for L Sebola and A. Chapman (Rand Water) took place by means of tasks to review the literature received and the summarisation of the necessary information into a comprehensive literature review. Capacity-building was also achieved by training I Dushrath and A Swanepoel (Rand Water) in the use of the Incident Management Frameworks.
- Training workshop on CIMF: A training workshop on the Incident Management Frameworks (which included training on Chapters 2, 3 and 4) was completed on 17 August 2004. A total of 19 delegates attended a training session held at Rand Water Analytical Services. This included representatives from Cape Metropolitan Council, Midvaal Water, Magalies Water, Johannesburg Water, Water Treatment Northern Cape, Rand Water, Amatola Water, Lepelele Water, Sedibeng Water, Metsi Chem, Iikhara Hais Municipality, Mhlathuze Water, Umgeni Water and DWAF Resource Quality Services. The workshop was considered successful by positive feedback obtained from the delegates.

Recommendations

The recommendations arising from this project are as follows:

- Technical courses should be developed in the field of identification and enumeration of cyanobacteria and of phytoplankton in general. The target group should be laboratory personnel associated with Drinking Water Utilities.
- A short training module should be developed on the monitoring, impacts and treatment of cyanobacteria and cyanotoxins as well as the development and implementation of CIMFs that can be incorporated in the formal training of drinking water plant operators or which could also be presented as short courses.
- Centres of excellence should be established at certain Drinking Water Utilities throughout South Africa that have the capacity 1) to identify and enumerate cyanobacteria, as well as phytoplankton in general, 2) to analyse cyanotoxins and 3) which have the technical knowledge to implement and manage CIMFs. This proposal is also contained in the WRC Strategic Plan for Algal Management in South Africa.

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Chairman:	Ms A Moolman	- Water Research Commission
Secretary:	Ms C Bosman	- Rand Water
Members:	Ms C van Ginkel	- DWAF - RQS
	Ms K Hodgson	- Umgeni Water
	Mr J Parsons	- Rand Water
	Dr W Harding	- DH Environmental Consulting
	Ms M Kruger	- Midvaal Water Company
	Mr P Grobler	- Lepelele Water

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Thinus Nel	- Magalies Water
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GLOSSARY

Abstraction point / area	Location in a dam, river or reservoir from whence water is pumped or gravitated to a drinking water purification plant.
Biomass / concentration	Physical quantity of algae in a water sample.
Bloom	Abundant growth of an algal species visually colouring the water.
Chlorophyll	The green pigment in algal cells which enables them to photosynthesise.
Colour	The colour of the water, as observed with the human eye.
Cyanobacterial Incident Management Framework (CIMF)	Monitoring and management action sequence which enables pro-active management of cyanobacteria and their toxins in source water used by a drinking water utility.
Cyanobacteria	Group of alga-like organisms containing (green) chlorophyll and also blue pigments which give the cells a blue-green colour. Because of this colour this group of organisms are commonly called 'blue-green algae'.
Cyanotoxins	Toxins that are produced by cyanobacteria during their growth phase, which act as liver- and nervous system toxins in humans and animals.
Drinking water company / utility	An organization that purifies and supplies drinking water to clients.
Drinking water / Final water	Purified water that is suitable for consumption by humans, which does not pose any known health risks, and which complies with the drinking water quality standard (SABS 241)
Drinking water treatment works / purification plant	Establishment where drinking water is produced from river-, dam- or reservoir water, through various processes such as coagulation, flocculation, sedimentation, filtration and disinfection.
Enumeration	The physical counting of algal cells in a sample with the aid of a microscope.
Genus	A group of one or more species.
Phytoplankton	Free-floating or suspended algae living in water.
Prokaryotic	The cells of the organisms (bacteria and cyanobacteria) lack membrane bound nuclei and the DNA is in the form of naked filaments surrounded directly by cytoplasm.
Scum	Abundant surface accumulation of algal cells.
Source water / Raw water	Natural, unprocessed water contained in a river or a dam or underground
Visual colour	The colour of the water as observed with the human eye.

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CHAPTER 1
INTRODUCTION

1.1 BACKGROUND

Globally the management of surface waters has become a priority in many countries. Daily there is increasing evidence, in both developed and developing countries, that past and present anthropogenic activities are negatively affecting both the quantity and quality of surface water (Hellawell, 1986; Ellis, 1989; Mason, 1991; Dallas & Day, 1993; Johnson, 1996; Du Preez, 2001). The deterioration of surface water quality due the pollution from point source discharges (e.g. waste water treatment works and industrial effluent) and diffuse surface runoff (e.g. modern agriculture, industrialization and urbanization) has thus been recognized as a major global water resource concern.

One of the primary effects of pollution is nutrient enrichment in receiving waters (Vollenweider, 1968; US EPA, 1999; EEA, 1998; Walmsley, 2000). This enrichment is commonly referred to as eutrophication, which leads to an array of symptomatic changes, amongst which increased production of algae, cyanobacteria and aquatic macrophytes, the deterioration of water quality and other symptomatic changes are found to be undesirable and to interfere with water usage (Dunst *et al.*, 1974; OECD, 1982; Chorus & Bartram, 1999; Walmsley, 2000; Falconer, 2005). It must be stressed that the wider implications of eutrophication are now also linked to the sustainable use of natural resources, nutrient flux in ecosystems and multi-dimensional impacts on the environment as a whole (EPA, 1999: Canadian Department of Environment, 2000; Walmsley, 2000). Eutrophication is currently viewed as the single greatest single threat to surface water quality globally (Harding, personal communication 2006).

The importance of the negative impacts of eutrophication is further highlighted by the fact that, since the 1960s, most of the world's developed countries have regarded eutrophication as a priority water quality issue (OECD, 1982; Morse *et al.*, 1993; Rast & Thornton, 1996; EEA, 1998). In South Africa, with its highly enriched surface waters, eutrophication initially received considerable attention, especially in the 1970s and 1980s (Toerien, 1974, 1975; 1977; Toerien *et al.*, 1975; Walmsley & Butty, 1980; National Institute for Water Research, 1985). Unfortunately, eutrophication management in South Africa subsequently become somewhat incapacitated as the result of an inability to transform policy into practice (Quibell *et al.*, 1997) and, as in other developing countries, eutrophication now receives secondary status (Harding & Paxton, 2001). However, the importance and current extent of eutrophication in South Africa has recently been highlighted in reports by Van Ginkel *et al*. (2001), Van Ginkel (2004), and also by the development of an implementation manual for a National Eutrophication Monitoring Program by DWAF (2002) and the National Eutrophication Assessment Protocol, NEAP, (WRC, 2005). In South Africa, eutrophied surface water plays a significant role in the production of drinking water, as many eutrophic water bodies are also sources of raw potable water. The proliferation of algae and cyanobacteria in eutrophic source waters causes problems such as ineffective coagulation, flocculation and sedimentation, clogging of sand filters, occurrence in final water due to penetration of sand filters, increase of organic loading of water and the release of taste and odour compounds as well as of toxic compounds (AWWA, 1990; Dickens *et al*., 1996; Rae *et al*., 1999; Falconer, 2005; MWH, 2005).

The taste and odour problems in drinking water have either directly or indirectly been linked to cyanobacteria which can produce compounds such as geosmin (trans-1,10-dimethyl-trans-9-decalol), MIB (2-methylisoborneol), IBMP (2-isobutylmetoxypyrazine), IPMP (2-isoproylmetoxypyrazine and β- cyclocital (Kenefick *et al*., 1992; Rae *et al*., 1999). The regular occurrence of geosmin and MIB in drinking water during the warmer months of late spring, summer and autumn in South Africa

is of concern to Water Utilities as these compounds cause the drinking water to have an earthy-muddy-musty taste and odour. Although not toxic to the consumers this tends to generate suspicion with regard to the quality and health effects of the drinking water, leading to customer complaints and consumers seeking alternative sources of drinking water.

Many genera of cyanobacteria (e.g. *Microcystis, Anabaena, Planktothrix, Oscillatoria, Cylindrospermopsis and Nodularia*) synthesise toxins as secondary metabolites within their cells. These cyanotoxins are a diverse group of chemical compounds, which can broadly be grouped into cyclic peptides, alkaloids and lipopolysaccharides (Chorus & Bartram, 1999; Chorus, 2001; Falconer, 2005; WHO, 2004). The many reported mammalian health effects of these cyanotoxins range from their being neurotoxic (e.g. anatoxins and saxitoxins) or hepatotoxic (e.g. microcystins and nodularin) to inflammatory or irritants (e.g. lipopolysaccharide endotoxins) as well as having a several combined effects (e.g. cylindrospermopsin). However, only a few suspected human poisonings are recorded, probably due to the fact that people avoid drinking offensive-smelling water and, more importantly, the common symptoms of cyanotoxin poisoning (vomiting, diarrhoea, stomach pains and headaches) are also the symptoms of gastrointestinal illness caused by to bacteria, viral and protozoan infection, and are thus not linked to cyanotoxin poisoning (Falconer, 2005). Nevertheless, suspected human poisoning due to cyanotoxins in drinking water has been recorded (Falconer, 2005) in Brazil (Caruaru dialysis incident), the United States of America (Sewickley gastrointestinal disease incident), Zimbabwe (Harare gastro-enteritis incident) and Australia (Armidale liver damage incident; Palm Island poisoning incident). The potential for human health implications from consuming drinking water that contains cyanotoxins prompted the World Health Organisation to establish a provisional guideline for microcystin–LR (microcystin–LR 1 μg/L), which is the most common variant of microcystins (WHO, 2004).

To date, guideline levels or concentration standards for microcystins have been incorporated in the national drinking water supply regulations in Australia, New Zealand, Brazil, Canada and the European Union (Falconer, 2005). In South Africa, Water Utilities have to produce water of acceptable quality as stipulated by the South African National Standards: Drinking Water (SANS, 2005). This standard focuses on: (1) physical and organoleptic requirements, (2) macro-chemical determinant requirements, (3) micro-chemical determinant requirements, (4) organic chemical determinant requirements and (5) microbiological requirements. However, the standard does not require any monitoring of cyanotoxins in drinking water. The consequence of this is that most Water Utilities in South Africa do not have skilled staff to monitor for cyanobacteria or their toxins. Some Water Utilities only monitor geosmin and 2MIB, due to the unpleasant taste and odours they cause in drinking water, so as to avoid complaints from consumers. Furthermore, most drinking water treatment plants in South Africa are not equipped or designed effectively to treat source water containing toxic cyanobacteria or cyanotoxins. It was therefore necessary to develop a guidance management framework or guidance document for drinking water suppliers in South Africa describing how to deal pro-actively with cyanobacteria and their associated toxins in source water by using a step-by-step alert levels framework to ensure safe drinking water to the consumer, both cost effectively and by using existing capacity.

1.2 AIMS

The aims of the project were to:

- Summarise the available literature on management frameworks for cyanobacteria (blue-green algae) with special emphasis on drinking water.
- Develop a Generic Incident Management Framework effectively to manage the supply of drinking water when toxic cyanobacterial blooms are present in the source water. The Incident Management Framework should provide operations managers and operators with easily understandable information that would enable them to make informed decisions

regarding the basic requirements for monitoring and dealing with cyanobacteria in source water. This will minimise the risk of exposing the consumers of the drinking water to cyanotoxins.

CHAPTER 2
CYANOBACTERIA AND THEIR ASSOCIATED TOXINS

2.1 INTRODUCTION

Cyanobacteria, also known as blue-green algae, blue-green bacteria or cyanophytes, are part of a primitive group of organisms whose existence, as derived from stromatolite fossil records, encompasses a period of some 3.5 billion years (Brock, 1973; Schopf, 1996). Cyanobacteria are gram-negative (prokaryotic) bacteria, which possess chlorophyll and perform oxygenic photosynthesis. Many of these micro-organisms have a characteristic bluish-green 'cyan' colour because of phycocyanin pigment contained in the cells - hence the name blue-green algae. Some species may appear red due to the presence of the carotenoid and phycoerythrin pigments (Carr & Whitton, 1982;Whitton & Potts, 2000; Falconer, 2005).

Cyanobacterial species display a remarkable diversity in cell morphology or form (aerotypes). The unicellular cyanobacteria have spherical, ovoid or cylindrical cells that can occur single-celled or may aggregate into irregular colonies (Figure 2.1). A slimy matrix secreted during the growth of the colony holds it together. More ordered colonies could also be produced (Figure 2.1). A filamentous morphology is typical of many cyanobacteria where the filamentous arrangement is called a trichome, which can be straight or coiled (Figure 2.1).

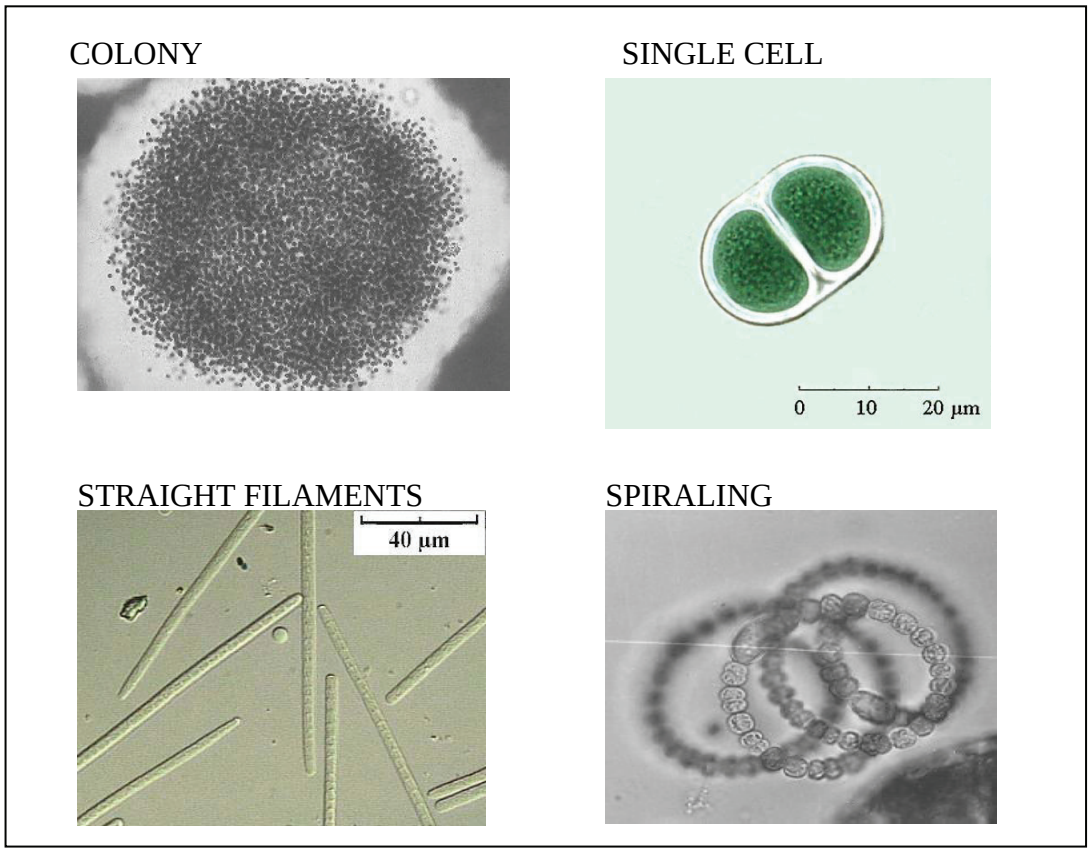

FIGURE 2.1: Different morphological cell forms of some cyanobacteria (photographs from Algepak, 1999; York *et al.* 2002).

The life cycle of cyanobacteria requires water, carbon dioxide, inorganic substances (such as phosphorus and nitrogen) and light. Although energy metabolism is primarily through photosynthesis, where sunlight and carbon dioxide are used to produce energy-rich molecules and

oxygen, some species can survive in complete darkness, while yet others have heterotrophic abilities (Carr & Whitton, 1982;Whitton & Potts, 2000;Chorus & Bartram, 1999). Some cyanobacterial species also have specialised cells called heterocysts, which enable that particular species to fix atmospheric nitrogen. It is thus not surprising that cyanobacteria can live nearly anywhere on earth, from freshwater to salt and brackish water, from rainforests to the desert, in the air, in soil and other terrestrial habitats.

In the sections that follow there will be a brief introduction to cyanobacteria in surface water, the cyanotoxins they produce, and to the occurrence of cyanobacteria in South Africa. This will provide operations managers and operators with basic information regarding cyanobacteria. For those who already have an in-depth understanding of cyanobacteria, or who wish to familiarise themselves with cyanobacterial occurrences in South Africa, the following publications are recommended:

- The Biology of Cyanobacteria (Carr and Whitton, eds. 1982). Blackwell Scientific Publications.
- Algal Toxins in Seafood and Drinking Water (IR Falconer, ed. 1993) Academic Press.
- *Toxic cyanobacteria in water: A guide to their public health consequences, monitoring and management* (Chorus & Bartram, 1999)
- *The ecology of cyanobacteria: Their diversity in time and space* (Whitton & Potts, 2000)
- *Cyanotoxins: Occurrence, causes, consequences* (Chorus, 2001)
- *Cyanobacteria in South Africa: A review* (Harding & Paxton, 2001)
- *Assessment of the trophic status project* (Van Ginkel *et al*., 2001)
- *A national survey of the incidence of cyanobacteria blooms and toxin production in major impoundments* (Van Ginkel, 2004)
- *Cyanobacteria monitoring 1990-2000: Evaluation of SA data* (Downing & Van Ginkel, 2004)
- *Current approaches to cyanotoxin risk assessment, risk management and regulations in different countries* (Chorus, ed. 2005) Federal Environmental Agency, EU. WaBoLu-Hefte Publication. Berlin, Germany.
- *Cyanobacteria toxins of drinking water supplies: Cylindrospermopsins and Microcystins* (Falconer, 2005)
- CYANONET: A Global Network for Cyanobacterial Bloom Management and Toxin Risk Management. Initial Situation Assessment and Recommendations. UNESCO Technical Documents in Hydrology 76 (Codd *et al*., 2005).

2.2 CYANOBACTERIAL OCCURRENCE IN FRESHWATER

Cyanobacteria are a natural part of the phytoplankton assemblages of many surface freshwater bodies. Their occurrence may vary radically, with seasonal changes from only a few per unit volume in the water column to excessive numbers occurring as ‘blooms’ at the surface of a water body. Their distribution in the water column may vary from being at the surface of the water column, a few metres below the water surface (mesolimnetic), or at the bottom of the water body (benthic). The changes that occur in a phytoplankton community, and ultimately the formation of cyanobacterial blooms, are the result of complex and dynamic relationships between physical, chemical and biological factors (NHMRC, 1994; Chorus & Bartram, 1999; Harding & Paxton, 2001; Falconer, 2005). These factors include light intensity, water temperature, pH, carbon dioxide, nutrient availability (nitrogen, phosphorus, iron, and molybdenum), physical characteristics of the water body (shape and depth), water column stability, and also aquatic ecosystem structure and function.

Cyanobacteria have a wide range of temperature tolerance, but rapid growth rates are usually achieved when the water temperatures exceed 20°C. In South Africa water temperatures are

favourable for cyanobacterial growth for a large part of the year, with peak concentrations usually occurring in summer and early autumn. A distinct temperature gradient can develop between the warm upper water layer (light-rich; oxygen-rich; nutrient-poor) and the cooler bottom layers (light-poor; oxygen-poor; nutrient-rich) resulting in a physically-stable (stratified) water body. Over time these conditions will become more conducive to cyanobacterial growth as they will have a competitive advantage over other phytoplankton.

Various cyanobacteria have the capacity to grow at various depths; this ability varies with species and is strongly influenced by nutrient and light availability (either the turbidity or the clarity of the water). Many cyanobacteria genera (e.g. *Planktothrix* and *Cylindrospermopsis*) are also adapted to grow in light-limiting environments. This enables the cyanobacteria to utilise nutrient rich environments at various depths (bands of *Planktothrix* can occur at a depth of 12m; layers of *Cylindrospermopsis* filament at a depth of 7m). Some cyanobacteria, such as the filamentous *Anabaena* sp., prefer higher light intensities, and *Planktothrix* will form dense bands just below the water surface. Many cyanobacterial species (e.g. *Microcystis* sp. which are commonly found in surface waters in South Africa) possess gas vacuoles, which enable them to slowly move up and down in the water column, thereby positioning themselves where the light and nutrient availability will potentially enhance their growth. The cyanobacterial species which contain these gas vacuoles are usually responsible for the forming of floating scum, when excessive growth occurs under hot calm weather conditions.

Cyanobacteria are effective users of phosphorus and out-compete green algae, especially in phosphorus-limiting environments, as they (1) have a greater affinity for phosphorus, (2) can store phosphorus (polyphosphate) and (3) have the ability to position themselves at optimal phosphorus concentration in the water column. Cyanobacteria (e.g. *Microcystis* sp.) can store nitrogen in proteins (cyanophycin and phycocyanin), which can be utilised during nitrogen-limiting conditions. Other cyanobacteria (e.g. *Cylindrospermopsis, Anabaena*) can utilise atmospheric nitrogen and can thus proliferate and out-compete green algae in nitrogen-poor surface water where sufficient light is available.

Many lakes and impoundments have warm shallow sheltered areas such as embayments that provide ideal conditions for cyanobacterial growth and thus increase the probability of cyanobacterial blooms. Source water abstraction points situated in these areas thus have a higher risk of abstracting water with high cyanobacterial concentrations. Furthermore, if the abstraction points are situated downwind relative to prevailing winds during summer and early autumn months, cyanobacterial scum (e.g. *Microcystis* sp.) will be blown towards the abstraction points further increasing the risk of abstracting source water with very high cyanobacterial concentrations.

2.3 CYANOBACTERIAL TOXINS

The most alarming characteristic of the cyanobacteria is the ability of many species (Table 2.1) to produce a range of extremely potent low-molecular-weight cyanotoxins. The cyanotoxins are a diverse group of natural toxins, which can broadly be grouped into cyclic peptides, alkaloids and lipopolysaccharides (Chorus & Bartram, 1999; Sivonen & Jones, 1999; Chorus, 2001; WHO, 2004, Cox *et al*., 2005; Falconer, 2005; Harding 2005). Mechanisms of cyanobacterial toxicity effect are diverse and the mammalian health effects range from their being neurotoxic (e.g. anatoxins, saxitoxinsand Beta-methylamino L- Alanine) or hepatotoxic (e.g. microcystins and nodularin) to inflammatory or irritants (e.g. lipopolysaccharide endotoxins) as well as having a several combined effects (e.g. cylindrospermopsin).

The cyanotoxins are synthesised within the cyanobacterial cells and usually remain intracellular. However, cyanotoxins are released in substantial amounts during cell death and lysis (breakdown of

cells) (Sivonen & Jones, 1999; Falconer, 2005). This is important for both the monitoring and prevention of cyanotoxins in drinking water. Monitoring strategies should for example, focus on both the total cyanotoxin concentrations (i.e. those within the cyanobacterial cells and released into the water column during cell death and cell lyses) and those that are cell-bound (within the cyanobacterial cells). Cyanotoxins (e.g. microcystins) that are water-soluble are difficult and expensive to remove during the drinking water purification process. It is therefore imperative to remove living and intact cyanobacteria at the beginning of the treatment process.

Cyanotoxins are generally produced in a seemingly random, unpredictable fashion and therefore complicate the management of cyanotoxin exposure to both animals and humans. A typical comment would state–that a given cyanobacterial bloom was not producing toxins during a set of analyses performed; but then with the next set of analyses the toxins were detected. It is for this reason that all cyanobacterial blooms should be considered toxic, unless proven otherwise by laboratory analyses

TABLE 2.1: Summary of the cyanotoxins and the cyanobacterial that produce them as well as some of the recorded mammalian clinical symptoms of cyanotoxin exposure (adapted from NHMRC, 2004; Chorus & Bartram, 1999; Sivonen & Jones, 1999; Chorus, 2001; Falconer, 2005)

TOXIN	CYANOBACTERIA GENERA	CLINICAL SYMPTOMS
Cyclic peptides		
Microcystins	*Microcystis, Anabaena, Oscillatoria, Planktothrix, Nostoc*	Gastro-enteritis, fever, pains in muscles and joints, nausea, vomiting, blistering around mouth, diarrhoea, swollen liver, death by liver failure
Nodularin	*Nodularia*	Gastro-enteritis, fever, pains in muscles and joints, nausea, vomiting, diarrhoea, swollen liver, death by liver failure
Alkaloids		
Cylindrospermopsin	*Cylindrospermopsis, Aphanizomenon, Anabaena, Raphidiopsis, Umezakia,*	Abdominal pains, vomiting, swollen liver, liver failure, pathological damage to the kidneys, spleen, thymus and heart
Anatoxin-a	*Anabaena, Planktothrix, Oscillatoria, Aphanizomenon*	Muscle weakness, respirator distress, exaggerated abdominal breathing, hyperactivity, hypersalivation, numbness around the lips, paralysis
Anatoxin-a(S)	*Anabaena, Aphanizomenon*	Muscle weakness, respirator distress, exaggerated abdominal breathing, hyperactivity, hypersalivation, numbness about the lips, paralysis
Saxitoxins	*Anabaena, Aphanizomenon, Lyngbya, Cylindrospermopsis*	Numbness around the lips, complete paralysis, death from respiratory failure
Lipopolysaccharides		
Lipopolysaccharides	All	Allergic reactions, inflammatory, irritation, gastro-enteritis

In view of the potential health risks of people drinking water that is contaminated by cyanotoxins, it is important to highlight the few suspected human poisonings due to cyanotoxins in drinking water that have been recorded (Chorus & Bartram, 1999; Falconer, 2005):

- Paulo Afonso gastro-enteritis incident in the region of Bahia State in Brazil: The people in the surrounding villages, who were supplied with conventional treated water from the newly

built Itaparita Dam experienced severe gastro-enteritis (2000 cases were reported, of whom 88 people died). The investigation revealed that the source water from the Itaparita Dam contained very high concentrations (approximately 10^6 per millilitre) of *Anabaena* and *Microcystis* and people became sick after drinking boiled water from the dam.

- Caruaru dialysis incident in Brazil: In 1996 an outbreak of severe hepatitis occurred at a Brazilian haemodialysis centre in Caruaru, Brazil. One hundred patients developed acute liver failure, of who 52 people died after receiving routine haemodialysis treatment. The clinical symptoms included visual disturbances, nausea, vomiting, muscle weakness and painful hepatomegaly. Microcystins were found in the source water, the water in the water delivery tanker, and in the dialysis unit's holding tank as well as in the iron and carbon filters from the dialysis centre's in-house treatment system. Microcystins were also detected in the blood sera and liver tissue of both live and deceased patients.
- Sewickley gastro-enteritis incident in the United States of America: Approximately 62% of the people receiving piped water from the distribution network become ill, experiencing abdominal pains and diarrhoea. Due to a hole in the groundwater intake structure more than 40% of the source water supply came from the Ohio River. Cyanobacteria were found in the open finished-water reservoirs and it was concluded that the contamination of the distribution network was through these reservoirs.
- Harare seasonal gastro-enteritis incidents in Zimbabwe: Seasonal gastro-enteritis in children is possibly due to the lysis of the cells of the annual *Microcystis* blooms that occur in the source water reservoir. The naturally-liberated cyanotoxin could probably not effectively be removed during the basic drinking-water purification process.
- Armidale liver damage incident in Australia: The water in the Malpas Dam, which supplies water for the drinking water treatment plant which purifies water for the town of Armidale was regularly treated for cyanobacteria with copper sulphate (1 µg/L in the upper 1m of the water column) after complaints about taste and odour. *Microcystis* scum formation around the abstraction point put additional stress on the drinking water treatment process, resulting in cyanobacterial cells passing through the treatment process and leading to re-growth in the open post-treatment drinking water tanks. Highly exaggerated/elevated enzyme activity in the sera of some town residents strongly suggests considerable liver damage. The presence of *Microcystis* and subsequent cyanotoxins released during the lysis of the cells may be responsible for the observed liver damage.
- Palm Island poisoning incident, Queensland, Australia: In 1979, there was a major outbreak of hepato-enteritis amongst the children of the Aboriginal community after drinking water from the treatment works that received its source water from the Solomon Dam. Clinical symptoms included anorexia, vomiting, headache, painful liver enlargement, initial constipation followed by bloody diarrhoea and dehydration. It was concluded that the poisoning was due to the release of cyanotoxins during the lysis of the cyanobacterial cells after treating the surface water of the reservoir with copper sulphate. Subsequent evaluations confirmed that the poisoning was due to the presence of the cyanobacterium *Cylindrospermopsis raciborskii* in the dam.

2.4 CYANOTOXIN DRINKING WATER GUIDELINES

One of the primary objectives of a drinking water supplier is to provide water that is safe for human consumption. Safe drinking water is defined by WHO (2004) as 'drinking water that does not present any significant risk to health over a lifetime of consumption, including different sensitivities that may occur between life stages. It is thus not surprising that due to the increasing evidence of the potential of human health effects after consuming drinking water that contains cyanotoxins, WHO issued a provisional guideline for microcystin–LR (microcystin–LR: 1 µg/L), which is the most toxic variant of microcystins (WHO, 2004).

The provisional guideline for microcystin–LR was derived using the following equation:

Guideline value (µg/L) = (TDI x Bw x PI)/DI

where:

TDI = An estimation of the amount of a substance in the drinking water expressed on a body mass basis (µg/kg), that can be ingested over a lifetime without significant health risks. The TDI (µg/kg/day) is calculated as (NOAEL or LOAEL) / Uncertainty factors. The NOAEL is the highest dose or concentration of a substance that causes no detectable adverse health effect. The LOAEL is the lowest observed dose or concentration of a substance at which there is a detectable adverse health effect. The source of uncertainty is from interspecies variation, intraspecies variation, adequacy of studies or databases and the nature and severity of the effect. The uncertainty values (factor of 10) thus ranges from 10 to 10000.

Bw = The average body weight of an adult (60 kg) or child (10 kg) or infant (5 kg).

PI = The portion of intake due to drinking water. This value is usually 10%. However, cyanotoxins intake is mainly via drinking water and is thus taken as 80 to 90%.

DI = The average drinking water consumption per day of an adult (2L) or child (1L) or infant (0.5L).

Therefore:

Guideline value (microcystin–LR as µg/L) = [(40/1000) x 60 x 0.8)]/2
= 0.96 µg/L
= 1 µg/L microcystin-LR

where:

TDI = NOAEL is 40 µg/kg/day and the uncertainty factor is 1000.

Bw = The average body weight of an adult is 60 kg.

PI = The portion of intake due to drinking water is 80%.

DI = The average drinking water consumption per day of an adult is 2L.

It is important to stress that the provisional guideline is only for microcystin–LR and thus excludes the toxicity as a result of other microcystins (more than 60 variants) that may be present (Chorus & Bartram, 1999; Falconer, 2005). It is therefore advisable for drinking water suppliers not to base their guidelines on microcystin–LR alone. To overcome this problem, it has become common practice to use the 1.0 µg/L microcystin-LR guideline value as a surrogate for all microcystin variants (total microcystins) to reduce the exposure risk to microcystins. Therefore the frequently used guideline is 1.0 µg/L microcystin equivalents (equivalent toxicity to microcystin-LR). The microcystin equivalents are calculated from the available microcystins variant toxicity data, assuming equivalent toxicity to microcystin–LR for those with no toxicity data available. Furthermore, the guideline value 1.0 µg/L total microcystins is also used based on the ELISA bioassay. This approach is frequently used by those water treatment facilities that do not have the capacity to monitor the full spectrum of microcystin variants, or by those that incorporate it as part of their Cyanobacterial Incident Management Framework.

Falconer (2005) followed a similar approach to that of the WHO (2004) in developing a drinking water guideline for Cylindrospermopsin:

Guideline value (cylindrospermopsin as µg/L)	=	[(30/1000) x 60 x 0.9)]/2
	=	0.81 µg/L
	=	1 µg/L

where:

TD = NOAEL is 30 µg/kg/day and the uncertainty factors is 1000 (10 for intraspecies variation, 10 for interspecies variation, 10 for data adequacy).
Bw = The average body weight of an adult is 60 kg.
PI = The portion of intake due to drinking water is 90%.
DI = The average drinking water consumption per day of an adult is 2L.

It must be stressed that the guideline concentrations for both these toxins are not directly applicable to short term exposures as they aim to protect humans over a lifetime of consumption and are thus conservative (Falconer, 2005). This is very important for drinking water suppliers, as they may experience higher concentrations for short periods. Fitzgerald *et al*. (1999) recommended that the safety factor of 10 could be omitted from the TDI calculation as the data are mainly based on subchronic exposure duration. The guideline for short-term exposure can thus be increased 10-fold. Subsequently, it was proposed that Water Utilities in Southern Australia use a guideline value of 10 µg/L for microcystins as well as for nodularin as their alert levels (Fitzgerald *et al*., 1999). Falconer (2005) argued that this value was too high and that a more conservative approach must be followed as people may be exposed to cyanotoxins several times a year. It is thus recommended that a concentration of 5 µg/L be used for both the alert level and the drinking water guideline for alerting the health authorities regarding cyanotoxins.

Based on the above approaches and recommendations as well as on practical experience, the following is recommended for the incorporation of cyanotoxin guidelines (specifically for microcystins, nodularin and cylindrospermopsin) in an Alert Levels Framework for drinking water:

- **Guideline value of 1 µg/L** (microcystins or nodularin or cylindrospermopsin).
  This is for lifetime exposure.
- **Alert level 1 concentration of > 0.3 µg/L and < 0.8 µg/L** (microcystins or cylindrospermopsin or nodularin).
- **Alert level 2 concentration of ≥ 0.8 µg/L and < 2.5 µg/L** (microcystins or cylindrospermopsin or nodularin).
  This is a short-term exposure to concentrations above the guideline value. During this period the Water Utility must take steps to reduce the cyanotoxins according to the guideline value.
- **Alert level 3 concentration of ≥ 2.5 µg/L and < 5 µg/L** (microcystins or cylindrospermopsin or nodularin) for a period of not more than 8 days.
  During this period the Water Utility must take steps to reduce the cyanotoxins according to the guideline value.
  If the cyanotoxin concentration is **≥ 2.5 µg/L and < 5 µg/L for more than 8 days, or if the cyanotoxins concentration is > 5 µg/L for 4 days** notify the Health Authorities and general public as well as supply an alternative drinking water source.

2.5 CYANOBACTERIA IN SOUTH AFRICA

The first suspected 'toxic algal' (cyanobacterial) occurrence in South African freshwaters, , was recorded in a pan in the Wakkerstroom area as far back as 1927, when the first few cases of cyanobacterial poisoning were diagnosed by the Onderstepoort Veterinary Institute. Throughout the

twentieth century many incidents of stock animal and wildlife deaths have been documented. However, no known human health effects or deaths have been directly linked to cyanotoxin poisoning in South Africa. This may be due to the fact that people avoid drinking offensive-smelling water and a case wrongly attributed the health-related symptoms to bacterial, viral and protozoa infections (Falconer, 2005). The review by Harding & Paxton (2001) gives an historical perspective of cyanobacteria in South Africa.

An analysis of recent data indicates that cyanobacterial blooms in South Africa are mainly associated with *Microcystis* (Figure 2.2), *Anabaena* (Figure 2.3), *Oscillatoria* (Figure 2.4) and *Cylindrospermopsis* blooms (Van Ginkel *et al*., 2001; Downing & Van Ginkel, 2004; Van Ginkel, 2004). Other cyanobacterial genera include *Nostoc and Nodularia*. The occurrence of cyanobacteria is highly seasonal, but is also widespread and frequent (Downing & Van Ginkel, 2004). The monitoring of cyanobacterial toxicity throughout the country is, however, limited due to there being insufficient analytical capacity. Nevertheless, confirmed cyanobacterial toxicity (mainly microcystins) has been recorded from freshwater bodies throughout South Africa (Figure 2.5). It is important to stress that many, if not most, of the freshwater bodies where cyanobacteria were recorded in South Africa are also source waters for drinking water purification plants. There is thus a real possibility that most of the drinking water treatment plants could be confronted with the challenge of treating source water that contains high concentrations of cyanobacteria.

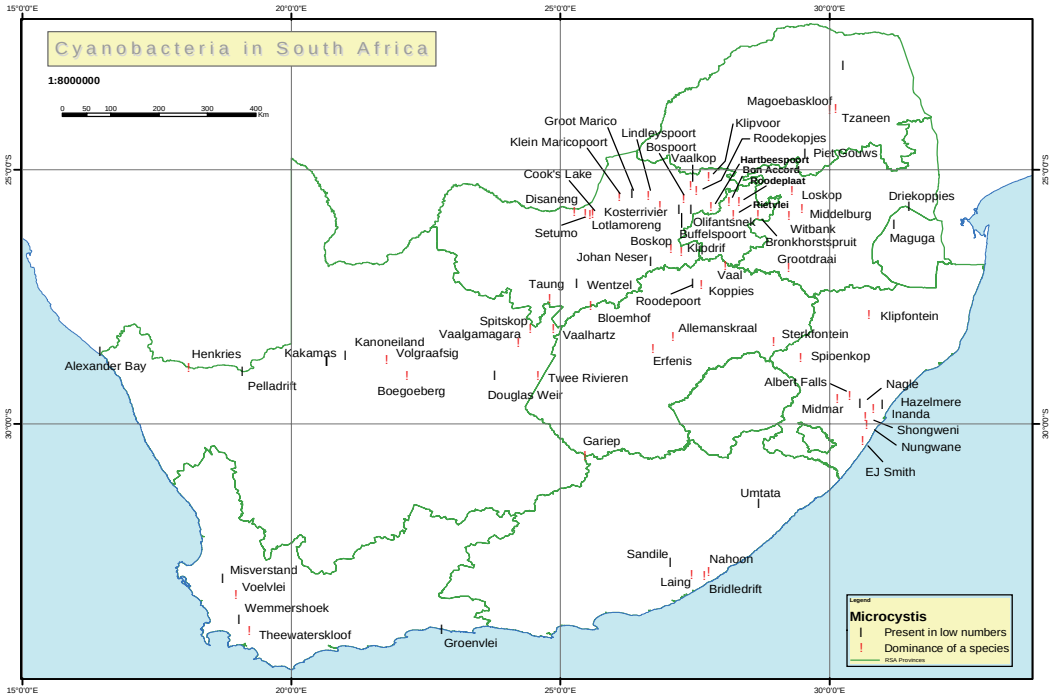

FIGURE 2.2: Recorded distribution of *Microcystis* in South Africa (Van Ginkel, 2004).

FIGURE 2.3: Recorded distribution of *Anabaena* in South Africa (Van Ginkel, 2004).

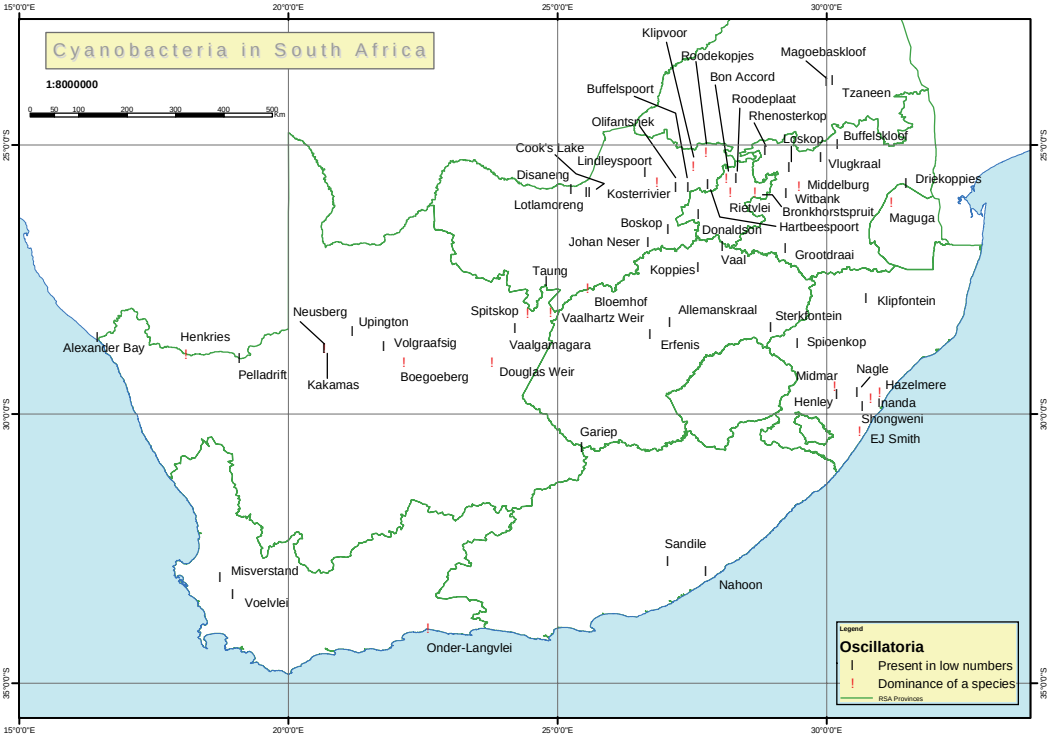

FIGURE 2.4: Recorded distribution of *Oscillatoria* in South Africa (Van Ginkel, 2004).

FIGURE 2.5: Known distribution of cyanotoxins (microcystins) in South Africa (Van Ginkel, 2004).

2.6 CONCLUSION

Cyanobacterial bloom formation in freshwater systems (rivers, reservoirs, lakes) is a worldwide phenomenon. In South Africa the occurrence of cyanobacteria is highly seasonal but is widespread and frequent. The cyanobacterial genera that are mainly responsible for bloom formation are *Microcystis, Anabaena, Oscillatoria* and *Cylindrospermopsis*. Many, if not most, of the freshwaters where cyanobacteria have been recorded in South Africa are also source waters for drinking water purification plants. The occurrence of cyanobacteria in freshwater is of special importance to the drinking water suppliers as several genera of cyanobacteria can produce offensive taste and odour compounds, as well as cyanotoxins that can affect human health. As cyanobacteria and their associated cyanotoxins can penetrate the drinking water supply network it is important to develop and implement cyanotoxin drinking water guidelines, as well as management plans for water treatment plants so as to ensure that the risk of human exposure to cyanotoxins is minimised.

CHAPTER 3
WATER TREATMENT OPTIONS FOR CYANOBACTERIA-RICH WATER

3.1 INTRODUCTION

The main objective of Drinking Water Utilities is to supply to consumers drinking water that is aesthetically acceptable, does not pose a health risk and is affordable. Cyanobacteria are commonly found in freshwater systems (rivers, reservoirs, lakes) that are the source waters for the production of drinking water and can thus have a direct impact on this objective. This impact is linked to the ability of cyanobacteria to produce offensive taste and odour compounds (Kenefick *et al*., 1992; Rae *et al*., 1999) as well as cyanotoxins that can affect human health (Falconer, 2005). The Drinking Water Utilities are thus compelled to act so as to ensure that the risk of producing offensive-tasting and -smelling drinking water, or drinking water that contains cyanotoxins, is reduced. The actions taken by the Drinking Water Utility will, however, have financial implications which increase the end cost of producing drinking water. It is therefore important that the operation managers at a Drinking Water Utility have a sound knowledge of what actions can be taken if confronted with cyanobacteria in the source water.

The ability of a Drinking Water Utility to undertake these actions will depend on a range of factors including the legal framework in which it operates, the current infrastructure, the availability of advanced treatment products such as carbon, as well as financial constraints. Nevertheless, it is essential that the Drinking Water Utility assesses their capability and capacity to deal with a potentially toxic cyanobacterial bloom. Furthermore, some understanding of cyanobacteria and cyanotoxin characteristics will further aid in the selection of appropriate actions.

3.2 CHARACTERISTICS OF CYANOBACTERIA AND THEIR INFLUENCE ON DRINKING WATER PURIFICATION

Generally, the significance of algae as well as cyanobacteria to drinking water treatment is identified through the type of species/genera that are dominant in the source water. Literature (e.g. Palmer, 1980) is available to guide water treatment operators on the significance of a variety of algal genera and cyanobacteria during drinking water treatment. The morphological characteristics (size, shape, mucilage layers) of cyanobacteria, their ability to move about, to exhibit a surface charge and their ability to produce taste- and odour-compounds and cyanotoxins can variously influence the treatment process.

Cyanobacteria are morphologically diverse. They may be unicellular or filamentous (Figure 3.1) and may occur singly or form colonies consisting of many cells. The size of the individual cells can vary from 1 μm to 40 μm, while the filaments can be as long as 100 μm. Some of the filamentous genera may during cell division form branches that protrude from the cells (Whitton & Potts, 2000). Based on the findings of Steynberg & Du Preez (2000) that large algal species are more effectively removed than smaller round-celled species, it can be predicted that the impact of cyanobacteria would be very similar. In many cases, cyanobacterial species have thin or thick layers of mucilage and/or firm sheaths that surround their cells and support the colony structure. If these species are not removed by the coagulation/flocculation and sedimentation processes, they can effectively clog filter beds (MHW, 2005).

At the pH values observed during the drinking water treatment process cyanobacteria generally have a negative surface charge. Coagulation must therefore be optimal to neutralise these forces, to ensure optimal floc formation and effective sedimentation (MHW, 2005).

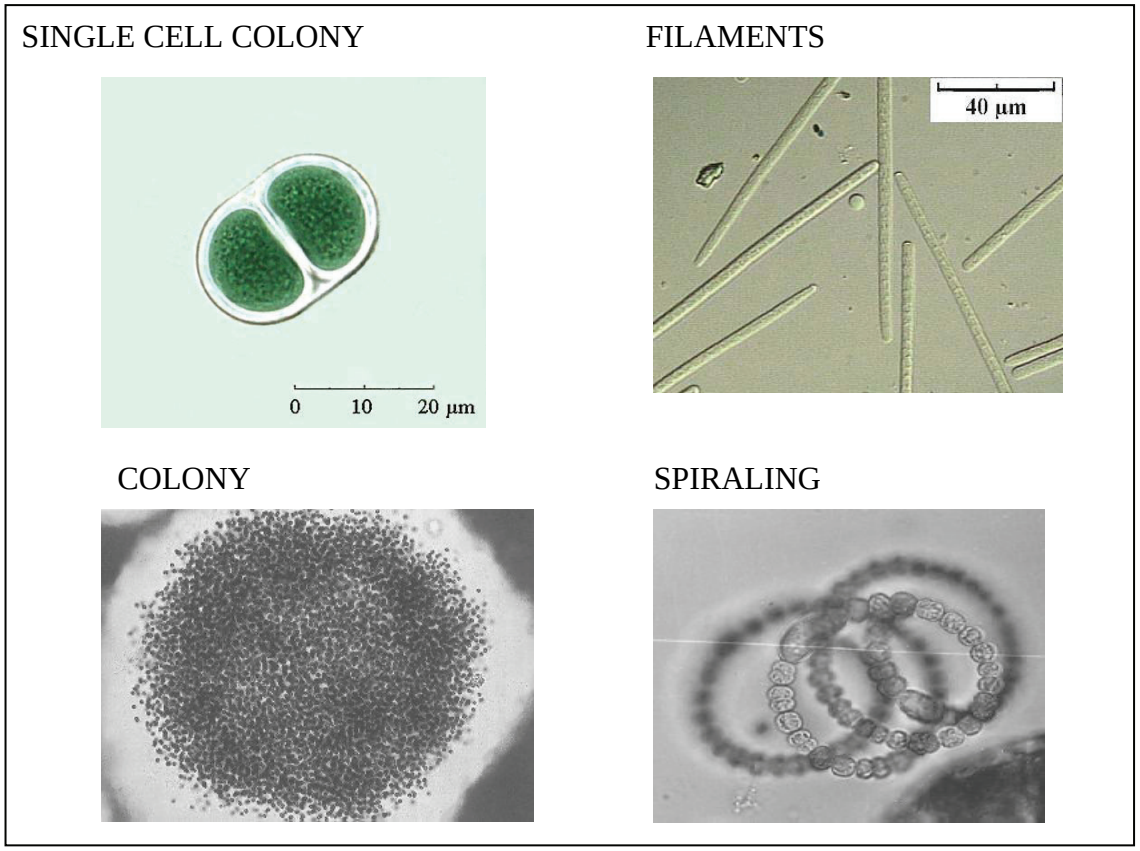

FIGURE 3.1: Examples of the different morphological cell forms of some cyanobacteria that may affect the drinking water treatment process (photos from Algepak, 1999; York *et al.* 2002).

Furthermore, the thick layers of mucilage and/or firm sheaths of some cyanobacteria will affect the treatment process, as it will be difficult to neutralize these cells to form flocs. Some species of cyanobacteria also have gas vacuoles to aid in buoyancy and vertical positioning in the water column. When the source water is laden with high concentrations of gas-vacuolated cyanobacteria, it reduces the process' ability to form sturdy flocs, which would result in effective sedimentation. Instead, the cells tend to destabilize the flocs and render sedimentation less successful. A similar effect can be observed in an 'open-air' sedimentation tank where any live cyanobacteria present in the water photosynthesise, thereby producing oxygen. The oxygen can form air bubbles which float to the surface, thereby destabilizing the flocs formed and rendering the sedimentation process less effective. If a formed floc containing toxin-containing cells is retained for too long the build up of cells in the flocculation chamber can lead to a net increase in toxin at the chamber outlet.

The ability of many cyanobacterial species to produce low-molecular-weight toxins is of concern to drinking water treatment works in South Africa and the rest of the world. At least a third of more than 50 genera of freshwater cyanobacteria exhibit toxic properties and 50 – 70% of cyanobacteria blooms are toxic (Chow *et al.*, 1997). However, the production of the cyanotoxins is not constant throughout the life cycle of the cells while some cyanobacterial cells do not produce toxins at all. The cyanotoxins are not visible in water and do not impart a taste or odour thereto. They can therefore go unnoticed if the routine monitoring of cyanobacteria and their toxins does not form part of the general operations water quality monitoring programme. If this were not undertaken, the only

hint of the possible presence of cyanotoxins would be the occurrence of a cyanobacterial bloom in the abstraction water, or consumers complaining of health effects.

The position/location of cyanotoxins in the water is very important during drinking water purification, as this will affect decisions made on how to adapt the process to remove the cyanotoxins. For example, dissolved (extracellular) cyanotoxins are not successfully removed during conventional treatment processes. During the active growth phase (generally during the warmer spring and summer months) it can be expected that the toxins will be primarily located within the cyanobacterial cells (intracellular). With the onset of winter (or when algaecides are added to the water) the cyanobacterial cells start to die and release the cyanotoxins so that by the end of the growing season (usually autumn and early winter), most toxins should be extracellular or dissolved in the surrounding water (Figure 3.2).

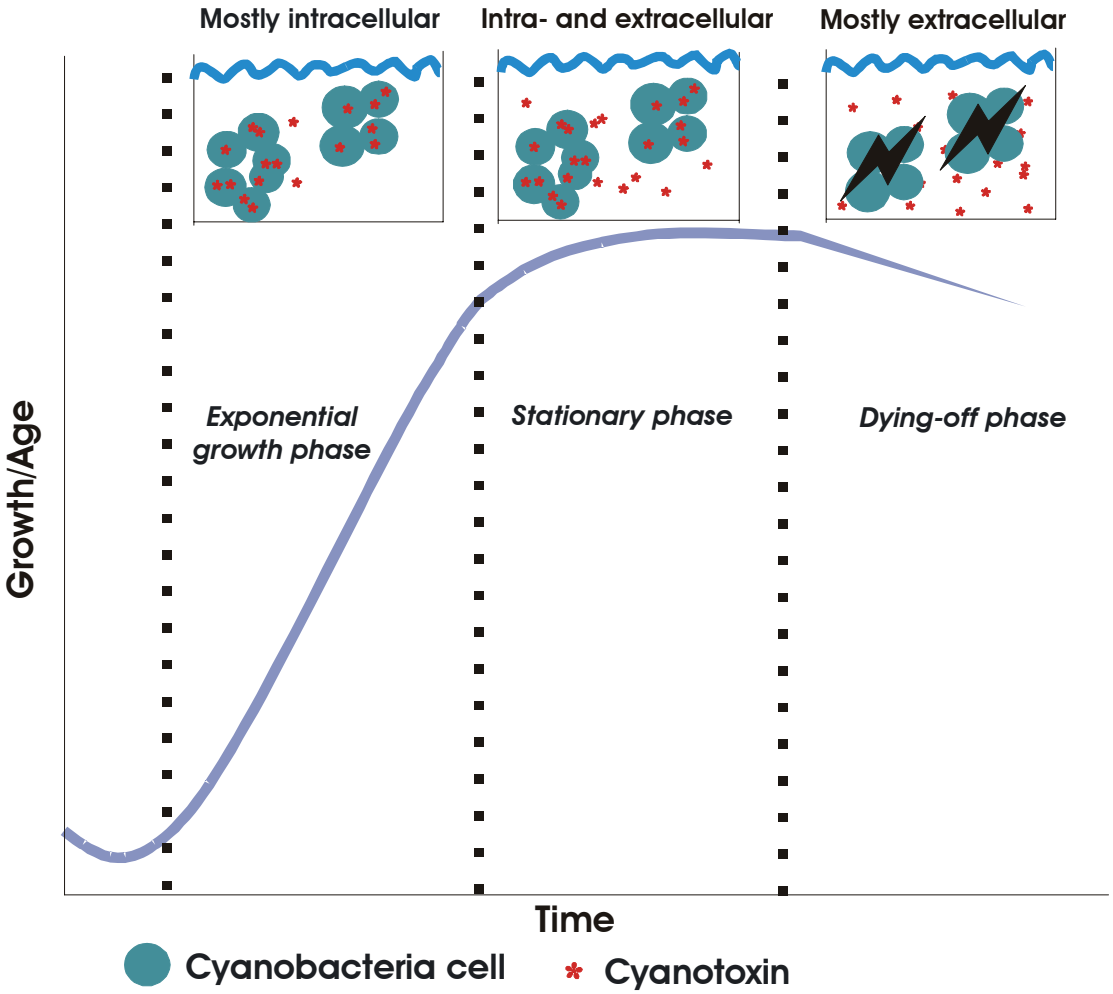

FIGURE 3.2: A theoretical growth curve for a cyanobacteria cell and the most likely location of the cyanotoxins during the growth phase.

It is important to stress that dissolved cyanotoxins (dissolved organic molecules) are much more difficult and expensive to remove than the cyanotoxins within the cyanobacteria, as the cyanobacteria themselves can be effectively removed if the treatment process is optimised. It is therefore much more cost-effective and beneficial to remove cyanobacterial cells "intact" (i.e. with

their cyanotoxins still inside the cells) from the source water than to risk breaking the cells, thereby releasing the cyanotoxins.

3.3 ACTIONS TO REDUCE THE RISK OF CYANOTOXINS IN DRINKING WATER

The actions that can be taken to reduce the risk of cyanotoxins occurring in drinking water can broadly be grouped into actions focusing on 1) the source water before abstraction, 2) the abstraction of the source water, 3) the optimisation of the conventional treatment process and 4) advanced treatment actions (Figure 3.3).

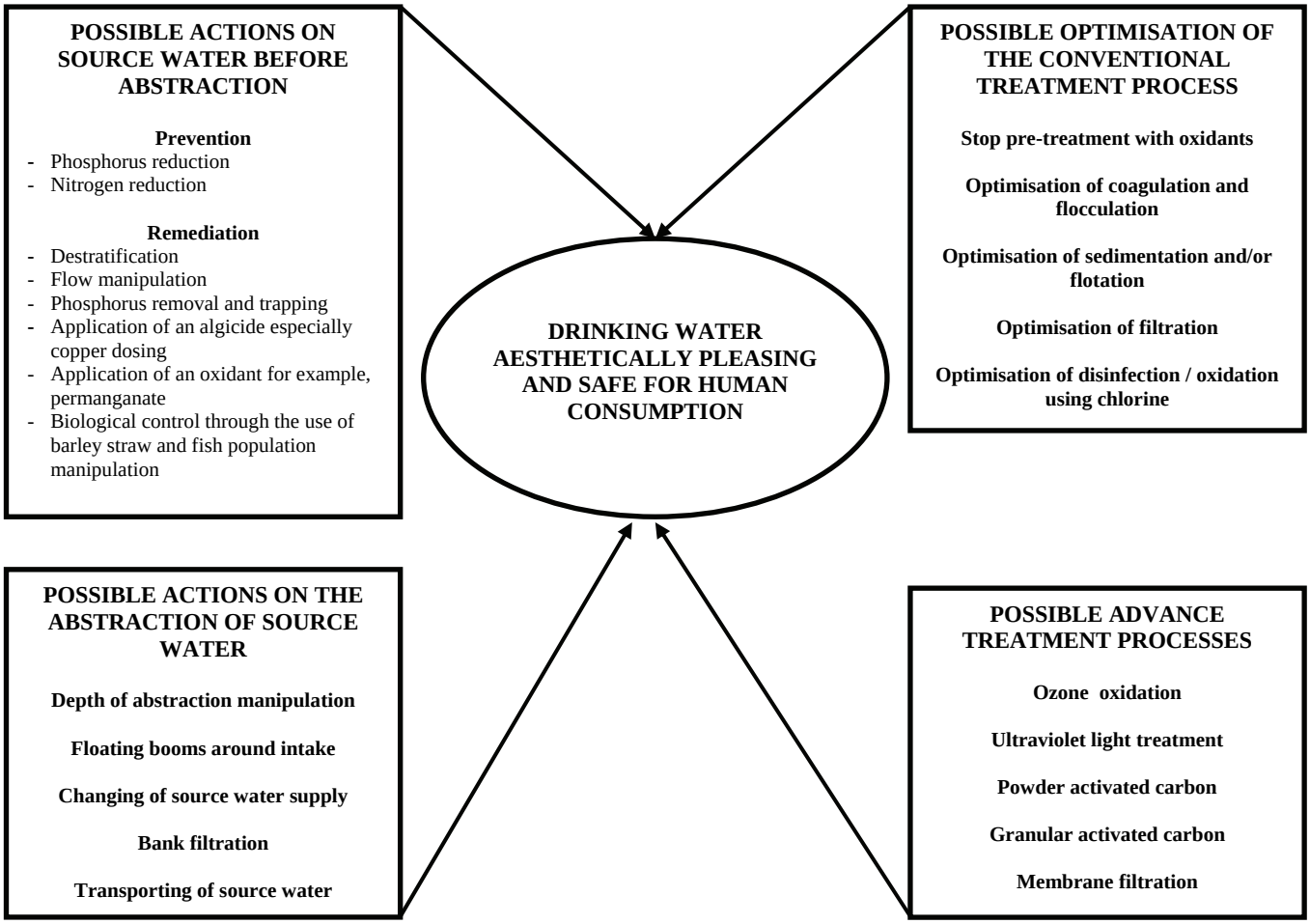

FIGURE 3.3: Actions that can be taken to reduce the risk of cyanobacterial effects on drinking water production (Chorus & Bartram, 1999; Falconer, 2005).

3.3.1 Actions on source water before abstraction

The main long-term strategy is to reduce the possibility of cyanobacterial growth, and specifically of bloom formation, through preventative actions. However, since many source waters experience excessive growths of cyanobacteria and subsequent bloom formation, this necessitates the consideration and implementation of remedial actions that will alleviate the immediate problem and, in some instances, will contribute to the long-term prevention of the formation of cyanobacterial blooms (Figure 3.3). It must be stressed that the legal framework within which a Water Utility operates will govern their role in implementing the preventative and remedial actions, as listed in Figure 3.3. In South Africa, the Department of Water Affairs is the custodian of surface water and

oversees the overall management of freshwater, and it must act as the Catchment Management Agency where one has not been established (Van Wyk, 2003; South Africa, 1998). Furthermore, the roles and responsibilities of Water Utilities regarding the protection of source water are limited, as defined by the Water Services Act (108/1997). The actions that a South African Water Utility can implement on source water before abstraction are therefore restricted.

In the South African context, two actions, namely the use of algicides and flow manipulation, require special mention. Algicides, specifically copper sulphate, are used to control algae in irrigation canals (Bruwer 1991, Du Plessis 1992a,b; Du Plessis & Davison, 1996) as well as to control benthic algae in sections of the drinking water treatment plant (Du Preez, 2002, personal observation). The application of copper sulphate to control algae and cyanobacterial blooms in source water has been, and still is, common practice albeit ecologically undesirable (Chorus & Bartram, 1999; Falconer, 2005; MHW, 2005). The dosage concentration of copper sulphate ranges from 0.5 to 2 mg/L copper sulphate (usually 1 mg/L copper sulphate is applied) and is calculated to be effective in the top 1 or 2m depth of the source water column. The application methods include spraying sulphate crystals from a boat, fixed aircraft or helicopter, spraying sulphate as a solution from a boat, or by spreading sulphate crystals from woven bags pulled behind a boat (Falconer, 2005). Although copper treatment is effective in killing off cyanobacterial cells and eliminating blooms, water treatment works can still experience an increase in taste and odour problems, as well as an increase in cyanotoxin and organic load in the source water. The release of cyanotoxins is primarily due to the lysis of the cyanobacterial cells after copper sulphate treatment, resulting in an increase in the concentration of dissolved cyanotoxins, which is more difficult to remove during the conventional treatment process. To minimise these problems, this treatment should be applied in the very early stages of cyanobacteria proliferation and should be repeated every two weeks for several months (Falconer, 2005). The above-mention used of copper to control cyanobacteria is not practised in South Africa.

Flow manipulation, especially pulse discharges and flushing, are most effective in destratification of the water column and bloom control (Falconer, 2005). Reservoir discharges containing cyanobacterial blooms can, however, have a major impact on downstream drinking water treatment works. Concentrated cyanobacteria, described as a cyanobacterial bloom (dense aggregation of cells), accumulated at the wall of the Hartbeespoort Dam were discharged and were deposited as a concentrated scum into the Crocodile River - the source water for several drinking water treatment works further downstream. Abstraction of this cyanobacteria-laden water by one of the downstream drinking water treatment plants resulted in their treatment capacity being exceeded, and therefore cyanobacteria as well as cyanotoxins appeared in the final drinking water (Geldenhuys *et al*., 2003). This incident could have been prevented if communication channels between the authority responsible for releasing water from Hartbeespoort Dam and the downstream drinking water treatment plants had been in place.

3.3.2 Actions regarding the abstraction of source water

During the abstraction of the source water several actions can be taken which will reduce the possibility of high concentrations of cyanobacteria occurring in the source water entering the drinking water treatment plant (Figure 3.3).

Depth of abstraction manipulation

Studies have shown that cyanobacteria are seldom uniformly distributed throughout the source water column except during polymixis. By regulating the depth from which the source water is abstracted (assuming that the impoundment in question is equipped with a variable drawoff depth outlet) at the intake tower, or is released via sluice gates situated at different depths (abstraction points), the intake

of cyanobacteria via the source water can be reduced (Falconer, 2005). A depth profile of the cyanobacterial cell concentration in the source water column must be determined beforehand, and thereafter a series of at least 4 profiles over a 24 hour period must be performed to optimise the abstraction, as the cyanobacterial cell concentrations may show diurnal depth variations. If no depth profile of cyanobacteria cell concentration exists (e.g. in shallow source waters), the alteration of abstraction depth would be meaningless. The optimal abstraction point (e.g. on occasion in the Inanda Dam, South Africa) can also be a trade-off between high cyanobacterial/algae cell concentrations at the surface and the poorer chemical water quality at greater depths (Harding & Paxton, 2001). During abstraction, vortex formation should be prevented so as to ensure that the abstractions at depth are effective. From the above it is evident that information regarding depth profile of the cyanobacterial cell concentration, the chemical water quality depth profile and an understanding of the physical flow dynamics during abstraction are required in order to be able to select the optimal abstraction point.

Floating booms around intakes.

Floating booms or barriers can be used to keep away floating cyanobacterial scums from intakes. This is usually effective in small reservoirs (Falconer, 2005) or in sheltered areas where wind and wave action will not disrupt the integrity of the boom.

Changing of source water supply

One of the options to consider when the main water source is contaminated by cyanobacteria is to utilise an alternative uncontaminated source. It is however important initially to assess the water quality of alternative sources with particular attention to both the presence of cyanobacteria and the chemical properties of the source water before implementation. Although this option has occasionally been effectively implemented in South Africa there are very few instances where it can be successfully applied to sustain bulk supplies of raw potable water.

Bank filtration

The drinking water treatment works are supplied from wells situated along the riverbank or reservoir margins or with water abstracted from below the riverbed. This technique for obtaining good quality water appears to be effective for the removal of taste and odours caused by cyanobacterial blooms, as some studies showed promising results in the removal of microcystins. Generally the effectiveness of the bank filtration process depends on factors such as the surrounding substrate, distance from the water body to the edge of the well and the abstraction rate, to mention only a few. The digging of channels between the source water and the well can however result in ineffective filtration (Falconer, 2005). This approach is only valid for small-scale, typically rural, supplies.

Transporting of source water

If source water containing cyanobacteria is transported in pipes under pressure over some distance the cyanobacteria will lyse (Dickens & Graham, 1995; Dickens *et al.,* 1996) with the subsequent release of cyanotoxins. Similarly, if there is a major height difference between the source water reservoir and the treatment works, the pressure reduction valves fitted to the pipes may cause the cyanobacterial cells to rupture (Falconer, 2005).

3.3.3 Optimisation of the conventional treatment process

Conventional treatment involves treating the source water by implementing pre-treatment measures, coagulation/flocculation, sedimentation, filtration and disinfection (Figure 3.3). Each of these

processes removes cyanobacteria and their associated cyanotoxins with different degrees of success. The removal of cyanobacteria can be enhanced by the optimisation of the conventional treatment process (MHW, 2005).

Stop pre-treatment with oxidants

Living cyanobacteria in the source water entering the drinking water treatment plant will contain most of their cyanotoxins within the cells (intracellular, see Figure 3.2). Pre-oxidation with chlorine causes cell death and cell lysis with a release of the intracellular cyanotoxins and a subsequent increase in the dissolved cyanaotoxin concentrations in the water. Ozone has a less damaging effect on the cyanobacterial cells and there is a reduced risk of liberating cell-bound cyanotoxins, while the dissolved cyanotoxins like microcystins are effectively destroyed. Potassium permanganate used as a pre-oxidant appears to reduce both cell-bound and dissolved cyanotoxins like microcystins in source water (Falconer, 2005). It important to stress that if chemical oxidation is applied it must be strictly controlled and monitored to ensure that sufficient oxidant is applied to destroy all the dissolved cyanotoxins, including those liberated from the cells as well as the organic load in the source water (Australian Water Quality Centre, 2005). As a general rule, it is thus advisable to **STOP** using oxidants for re-treatment, especially if chlorine is used.

Optimisation of coagulation and flocculation

The agglomeration (coagulation/flocculation) phase is one of the most important steps in algal removal. Coagulation can be described as the destabilization of charged (usually negatively) colloidal particles by compression of the double electrical layer surrounding these particles (reduction of zeta potential) by means of a coagulant. Flocculation refers to the aggregation of the destabilized particles into flocs (MHW, 2005). The ideal is for these flocs to grow large enough to settle easily and to be stable so as not to break into smaller particles, which are difficult to sediment. Cyanobacteria can influence this process, as they do not exhibit the typical characteristics of a colloidal particle, for which the process of coagulation/flocculation is primarily designed. An example of the deviation from this characteristic is the cell morphology of cyanobacteria, which can typically vary from long thin filamentous cells to small round cells in colonies, or thick layers of mucilage-surrounded cells and the ability to form gas vacuoles. The removal of these cells also presents a problem because of their small size, low specific gravity, low cell densities and negative surface charge (Tittlebaum & Holtman, 1982; Walters, 1992; Edzwald 1993; Johnstone, 1994; Whitton & Potts, 2000). These characteristics make cyanobacteria difficult to destabilize and flocculate. Available information regarding the lysis effect of the specific coagulants and flocculants on the cyanobacterial cells are contradictory and appears to be linked to the growth stage of the cyanobacterial cells as well as their general health (Australian Water Quality Centre, 2005). Nevertheless, if applied correctly alum coagulation and alum and ferric salt flocculation remove intact cyanobacteria cells effectively (Falconer, 2005).

The coagulation/flocculation process is thus considered to be the most cost-effective and important step during water purification in removing cyanobacterial cells *intact*. As stated above, it is important to remove the cells intact because most of the cyanotoxins are usually within the live cyanobacterial cells and would therefore be removed with the cells. The removal of cyanotoxins will thus be effective if the toxins are intracellular 'cell-bound" (e.g. > 80% if the microcystins are cell-bound), which is achieved by removing intact cyanobacterial cells (Hart *et al*., 1998; Chorus & Bartram, 1999). An increase in the retention times during the coagulation/flocculation process would thus allow for improved removal of intact cyanobacterial cells. It is important to note that the coagulation/flocculation process is not effective in removing extracellular (dissolved) cyanotoxins (Falconer *et al.* 1989; Jones *et al*., 1993; Rositano & Nicholson, 1994; Hart *et al*., 1998; Falconer, 2005).

Optimisation of sedimentation and flotation

Solid-liquid separation is one of the important processes in water treatment. In conventional treatment, clarification methods such as sedimentation or flotation are used. The most widely-used clarification method used in South African drinking water treatment plants is sedimentation. During sedimentation, gravity is used to settle flocs to the bottom of a sedimentation tank. For sedimentation to be effective the flocs must be stable and large enough to settle easily. Unfortunately, sedimentation is considered less effective with cyanobacterial cells because of their low density. Cyanobacterial cells also tend to form flocs that are not stable and which therefore are also difficult to settle (because of poor destabilization of surface charge, cell morphology, the ability of cells to move around in water, etc.). Many of the drinking water treatment plants in South Africa have found that many cyanobacterial cells can still photosynthesize in the sedimentation tanks, thereby producing oxygen, the bubbles attaching themselves to the outside of the cell or floc, making them less dense than water and thus causing the algae to float at the top of the sedimentation tank. Water with high cyanobacterial concentrations will sediment much better with low overflow rates and extensive flocculation periods, with increased coagulant and flocculent aid usage. An increase in the retention times during-sedimentation would thus allow improved removal of intact cyanobacterial cells. The removal of cyanotoxins will thus be effective if the toxins are intracellular 'cell-bound" (e.g. > 80% of cell-bound microcystins), which is achieved by removing intact cyanobacterial cells (Chorus & Bartram, 1999).

The flotation method using dissolved-air flotation (DAF) is widely used in South Africa, especially where cyanobacteria and algal blooms are experienced. The tiny bubbles produced in a DAF plant attach themselves to flocs, thereby lowering their density and floating them to the surface where they are 'skimmed' off. This method is effective in removing cyanobacterial cells and takes advantage of the natural tendency of some cyanobacteria to float or to form surface scums on water bodies (Edzwald & Wingler, 1990; Walters, 1992; Edzwald, 1993; Falconer, 2005). The morphology of the cyanobacterial cells (colony, filament or single cell) will however influence their removal. It has been shown that the filamentous *Anabaena* were removed better than the colonial *Microcystis*, which was parting turn better removed than the thin filamentous *Planktothrix* (Drikas & Hrudey, 1994). The removal of cyanotoxins will thus be effective if the toxins are intracellular 'cell-bound" (e.g. > 80% of cell-bound microcystins), which is achieved by removing intact cyanobacterial cells (Hart *et al*., 1998; Chorus & Bartram, 1999).

The sludge that is formed during the sedimentation and/or flotation process should be removed frequently as the trapped cyanobacterial cells will lyse and/or die, thus releasing their cyanotoxins into the water. If the sludge is de-watered, the supernatant should not be immediately returned to the process, as it may contain intact cyanobacterial cells but, more important, contain dissolved cyanotoxins. It is advisable to store the supernatant in holding dams until it has been biodegraded. The time frame for effective biodegradation is not well established but, in the presence of bacteria, it appears to range from 1 to 4 weeks (Australian Water Quality Centre, 2005; Falconer, 2005). It is however, advisable to monitor the cyanotoxin concentrations in the supernatant before it is returned to the treatment process (the costs of not being able to return washdown waters to the head of the treatment plant can be significant). Similarly, the cyanotoxin concentrations in the disposed sludge should be monitored to ensure that people handling the sludge are not exposed to the cyanotoxins.

Optimisation of filtration

Filtration is the removal of particles from water by some form of filter medium and a specific flow design. Typical media used are sand, crushed anthracite coal, diatomaceous earth, perlite and activated carbon. The filter acts as a mechanical screen and will therefore remove the larger cyanobacterial species more effectively than small species. The cyanobacterial species possessing

layers of mucilage and/or a firm sheath that surrounds the cells and supports the colony structure will have a tendency to clog the filter bed (MHW, 2005) and reduce the filter run times. Generally, shorter run times for sand filters are recommended during times of high cyanobacterial concentrations, in order to remove the cyanobacteria concentrated on filters and also to prevent dying cyanobacterial cells on the filters from releasing their cyanotoxins into the drinking water. The removal of cyanotoxins by rapid sand filtration will only be effective if the toxins are cell-bound (e.g. > 60% of cell bound microcystins), thus removing intact cyanobacterial cells. The same holds for slow sand filtration (e.g. 99% of cell-bound microcystins), although dissolved cyanotoxins may also be removed, but then the efficiency is likely to depend on biofilm formation and thus on filter run length (Chorus & Bartram, 1999).

Effective removal of the cyanobacterial cells will be enhanced if the operation of the filters is of a high standard and, to achieve this, special attention should be given to the following:

- Possible infrastructure deficiencies
  - Filters not cleaned
  - Optimal backwashing and fluidisation cannot be achieved
- Filter media not to specification
  - filter bed depth insufficient
  - formation of cracks
  - dead areas, mud patches and mud ball formation
  - uncontrolled “growth” of sand particles
- Operational deficiencies
  - filtration rate higher than the prescribed rate
  - procedures to ensure optimal backwashing and fluidisation not implemented or adhered to
  - procedures for bringing filters on-line after backwashing not implemented, especially when this is manually controlled

When toxin concentrations in the final water exceed 1 µg/L then the filter backwash water should not be reused in the treatment process, in order to reduce the risk of re-introducing cyanobacteria and possibly also dissolved cyanotoxins from the backwash water into the treatment process. It is advisable to store the backwash water in holding dams, to monitor the biodegradation of the cyanotoxins (biodegradation period 1 to 4 weeks) and only to re-use the backwash water once the cyanotoxins have been totally biodegraded.

Optimisation of disinfection/oxidation using chlorine

In South Africa, chlorine is primarily used for disinfection (post clarification) during the drinking water treatment process. When chlorine is used as an oxidation agent, after post clarification to destroy dissolved cyanotoxins, it important to note its the effectiveness would depend on factors such as the cyanotoxin species, pH of the water, dosage, contact time, chlorine demand of the water and the residual chlorine (Carlisle 1994; Nicholson *et al.* 1994; Hart *et al*., 1998; Chorus & Bartram, 1999; Hitzfeld *et al.*, 2000; Australian Water Quality Centre, 2005; Falconer, 2005). Aqueous chlorine and calcium hypochlorite generally remove more than 95% of microcystins or nodularin, as compared to sodium hypochlorite at the same dosage (≥1 mg/L). Current information suggests that the use of chlorine is not recommended for the removal of anatoxin-a and saxitoxins while chloramination was shown to be ineffective. Chlorine will generally be effective for the treatment of the cyanotoxins, microcystins (destroys > 80% dissolved microcystins) and cylindrospermopsin under the following conditions:

- pH range: 7 to 8

- Chlorine dosage: 3 to 4 mg/L but can be > 4 mg/L
- Residual chlorine: 0.5 mg/L after 30 minutes contact time

During a cyanotoxin incident, a cyanotoxin monitoring programme should be implemented to evaluate the effectiveness of the removal capacity under the operational conditions.

3.3.4 Possible advance treatment processes

Ozone oxidation

Ozone is one of the most powerful oxidizing agents and is used worldwide, especially in North America and Europe for primary disinfection, taste and odour control and target compound construction (Hitzfeld *et al.,* 2000; MHW, 2005). Typically, ozonation can be applied as pre-ozonation (at the beginning of the water treatment process), inter-ozonation (in the middle of the treatment process) or as post-ozonation (post clarification). During pre-ozonation there is a risk of cyanobacterial cell lysis, a subsequent release of intracellular cyanotoxins, and an increased ozone demand as DOC (dissolved organic carbon), which is typically oxidized first. The destruction of the cyanotoxins will be incomplete if the ozone demand is not met (Hitzfeld *et al.,* 2000; Newcombe, 2002). Furthermore, the oxidation of cyanotoxins by ozone is always in competition with that of other organic compounds in the water. As a result, naturally-occurring organic matter (including the presence of live cyanobacterial cells) is then one of the most important factors to consider in terms of the effectiveness of ozonation, because ozone demand generally increases with an increase in DOC. For this reason, it is usually better to use post-ozonation to oxidize cyanotoxins because most of the organic material should by then hace been removed from the water and its oxidation capacity mostly used for the cyanotoxins.

When using ozone as an oxidation agent after the clarification to destroy dissolved cyanotoxins, it is important to note that its effectiveness would depend on factors such as the DOC content of the water, the pH of the water, alkalinity, dosage, contact time, ozone demand of the water and the residual ozone required. Current information suggests that the use of ozone is effective in the removal of cyanotoxins and microcystins. However, the efficient removal of cylindrospermopsin, anatoxin-a and saxitoxins has not been studied in detail. Ozone will generally be effective for the treatment of the cyanotoxins and microcystins (destroys > 98% of dissolved microcystins) under the following conditions:

- pH range: 7 to 8
- Ozone dosage: > 2 mg/L
- Residual chlorine: 0.5 mg/l after 5 to 10 minutes contact time

During a cyanotoxin incident, a cyanotoxin monitoring programme should be implemented so as to evaluate the effectiveness of the removal capacity under the operational conditions.

Ultraviolet light

Ultraviolet light is widely used in water disinfection, especially of wastewaters, but its application in the disinfection of drinking water has gained momentum (MHW, 2005). Studies have shown that the destruction of cyanotoxins like microcystins and anatoxin-a (Carlisle, 1994; Rositano & Nicholson, 1994; Liu *et al.,* 2003) is possible by means of ultraviolet light irradiation. In the presence of titanium dioxide which acts as a catalyst, cyanotoxins such as microcysin-LR and cylindrospermopsin were also successfully destroyed by ultraviolet light irradiation (Robertson *et al.,* 1997; Robertson *et al.,* 1998). The conditions at which these treatments are effective are currently

outside the range of practical water treatment application (Newcombe, 2002). However, it is envisaged that as technology develops, photo-oxidation using ultraviolet light irradiation, with or without the presence of a catalyst, will be a feasible alternative for the treatment of dissolved cyanotoxins.

Powdered Activated Carbon (PAC)

Powdered activated carbon is formed through a process of carbonisation of raw materials (wood, coconut shell, lignite, bituminous coal, or anthracite), activation and sieving to form a porous carbonaceous substance (activated carbon particle size specification by AWWA, 1991: not less than 99% shall pass through a 149 μm aperture sieve, not less than 95% shall pass through a 74 μm aperture sieve; not less than 90% shall pass through a 44 μm aperture sieve; usually mean particle size: 20 μm to 50 μm), which has adsorptive properties (Linde *et al.*, 2001; MWH, 2005). Powdered activated carbon is used world-wide during the production of drinking water for the removal of taste and odour compounds as well as other micro-contaminants such as cyanotoxins (Falconer, 2005; MWH, 2005).

In South Africa, PAC is also only used intermittently for the removal of taste and odour compounds and infrequently for the removal of cyanotoxins. The addition of PAC can be incorporated at different points during the treatment process, for example before treatment (that is before coagulation and flocculation), in a slurry contactor or pipe during the rapid mixing phase and at the filter inlet (that is after coagulation) (MWH, 2005). The advantages and disadvantages (interference with preoxidation process; interference with coagulation process; filter clogging; increased turbidity due to filter breakthrough) of these options are summarised by MWH (2005), nevertheless the contact time should be as long as possible and the impact of natural organic matter should be minimised. Research has shown that the effectiveness of the PAC is dependent on factors such as 1) the type of PAC, 2) the adsorptive capacity of the PAC, 3) the PAC dosage, 4) the location of PAC addition, 5) the contact time, 6) the organic load of the water and 7) the presence of oxidants (MWH, 2005).

Drinking water treatment works must evaluate each batch of PAC to select the most suitable PAC product for their specific requirements and circumstances. Various tests have been developed to assist in the selection of this process including the determination of the 1) iodine number, 2) molasses number, 3) tannin number, 4) methylene blue number, 5) phenol number, 6) moisture content, 7) ash content, 8) density, 9) abrasion resistance, 10) particle size distribution and 11) by performing a jar test (Freese *et al.*, 2000; Linde *et al.*, 2001; MHW 2005). Various adsorption models, such as the homogenous surface diffusion model, can also be used to predict the adsorption rate of the target trace organic contaminant by the PAC (Freese *et al.*, 2000; Linde *et al.*, 2001). However, the jar test is very effective in determining the dose response relationship for a specific micro-pollutant (e.g. cyanotoxins) and a specific batch of PAC for the local conditions, thereby optimising the effective dosing of PAC at the drinking water treatment plant (Freese *et al.*, 2000; Linde *et al.*, 2001; MHW 2005).

Varying degrees of success were obtained when trying to remove cyanotoxins, which can most likely be attributed to the various factors stated above that will affect the effectiveness of the PAC in removing the cyanotoxins. Generally, relatively high dosages of PAC (20 to 30 mg/L) are required for effective reduction of cyanotoxins in drinking water (Chorus and Bartram, 1999), however, for many situations these dosage concentrations may be insufficient for removal at the required levels (Falconer, 2005). In cases where no dose response relationship data for the specific cyanotoxins and the available PAC for the local conditions have been derived, a dosage of 30 mg/L to 40 mg/L PAC should be applied to reduce a cyanotoxins concentration of < 5 μg/L to acceptable conditions. However, it must be stressed that in such cases the dose response data should be derived as a matter

of urgency in order to determine the most effective dose. Furthermore, during a cyanotoxin incident, a cyanotoxin monitoring programme should be implemented to evaluate the effectiveness of the removal capacity under operational conditions.

Granular Activated Carbon (GAC)

Granular activated carbon (mean activated carbon particle size: 0.5 mm to 3 mm) is used to remove dissolved organic substances and similar to PAC, also to remove micro contaminants. The GAC is usually operated as a fixed-bed system or as the upper or mixed layers of a dual filter system. GAC is usually applied after filtration, but before post disinfection (MHW, 2005). GAC has the advantage of lower activated carbon use and re-use of material. However, a major disadvantage is the considerable construction investment cost if contaminant and DOC removal are required only seasonally. A summary of the advantages and disadvantages of using GAC is given by MHW (2005).

GAC has been shown to effectively remove cyanotoxins like microcystins (> 90%) and anatoxins (Carlisle, 1994; Bernezeau, 1994; Chorus & Bartram, 1999; Newcombe, 2002) via adsorption. However, there is no published information on its removal efficiencies for nodularin, cylindrospermopsin or saxitoxins. It has been shown that many factors (see section on PAC) can determine the effectiveness of the GAC and the life span of the GAC bed (Hart and Stott, 1993; Jones *et al.,* 1993; Bernezeau, 1994: Craig & Bailey, 1995; Newcombe, 2002). For example, depending on the type of carbon used and the DOC of the water, the bed-life of GAC reached only approximately 30-45 days (Hart and Stott, 1993; Jones *et al.,* 1993; Craig and Bailey, 1995; Newcombe, 2002). In the GAC filters, cyanotoxins like microcystins (> 90%) can also be removed by biodegradation (Chorus & Bartram, 1999; Newcombe, 2002; Falconer, 2005). This process is however complex and requires further investigation (Newcombe, 2002).

From the preceding it is evident that GAC can effectively remove cyanotoxins, although the effectiveness of the GAC system in removing cyanotoxins will be dependent on various factors (as stated above also see Section on PAC). It is thus of critical importance to evaluate the effectiveness of the cyanotoxin removal of each batch of GAC (as for the PAC) as well as for the system as a whole. Furthermore, during a cyanotoxin incident, a cyanotoxin monitoring programme should be implemented to evaluate the effectiveness of the removal capacity under operational conditions. It is also advisable not to rely only on GAC for cyanotoxin removal, specifically that of microcystins (Newcombe, 2002).

Membrane filtration and reverse osmosis

The primary goal of membrane filtration (microfiltration and ultrafiltration) and reverse osmosis (nanofiltration and reverse osmosis nonopours) is to remove the target micro contaminants from the water (MHW, 2005). Although published investigations relating to the removal of cyanobacterial and cyanotoxins by these processes are limited, some promising results have been recorded. Microfiltration and ultrafiltration have been shown to be effective in the removal of cells of *Microcystis* (Panglisch *et al.* 1996; Chow *et al*., 1997), while nanofiltration was shown to remove the cyanotoxins microcystin and nodularin (Muntisov & Trimboli, 1996). Further research is required fully to evaluate the effectiveness of these processes in removing cyanobacteria and their cyanotoxins under different water quality and drinking water treatment scenarios.

3.4 CONCLUSIONS

Cyanobacteria produce organic compounds (offensive taste and odour compounds, cyanotoxins which can affect the health of people) that must be removed during the drinking water treatment process to ensure that the drinking water is aesthetically acceptable and does not pose a health risk to consumers. The Drinking Water Utility can reduce the risk of exposing consumers to cyanotoxins by optimising the extraction of source water, optimising their conventional treatment process and by implementing advanced treatment processes. Some understanding by plant operators of cyanobacterial cell and toxin characteristics will further aid in the selection of appropriate actions. To ensure that a Drinking Water Utility can timeously and effectively react to the presence of cyanobacteria and cyanotoxins in the source water, it is important for drinking water plant managers to develop, test and implement appropriate procedures and actions in a Cyanobacterial Incident Management Framework.

CHAPTER 4
CYANOBACTERIAL INCIDENT MANAGEMENT FRAMEWORKS

4.1 INTRODUCTION

The proliferation of cyanobacteria in many freshwater bodies (rivers, lakes, man-made reservoirs) that serve as source water for the production of drinking water is of concern to many Drinking Water Utilities. The concerns of Drinking Water Utilities are linked to the fact that cyanobacteria in the source water can have an effect on the conventional treatment process (ineffective coagulation, flocculation and sedimentation, penetration of sand filters, clogging of sand filters) and on the quality of the drinking water specifically, because of their ability to produce taste and odour compounds (e.g. geosmin, MIB: 2-methylisoborneol) and toxic compounds (e.g. microcystins, nodularin, cylindrospermopsin, anatoxins, saxitoxins, lipopolysaccharide endotoxins Beta-Methylamino L-alanine)). If the possible effects of the cyanobacteria are not addressed by the Drinking Water Utilities it would be impossible for them to achieve one of their main objectives, namely to supply to consumers drinking water that is aesthetically acceptable and that would not pose a health risk.

Drinking Water Utilities can implement various actions for example, 1) optimising of the extraction of source water, 2), optimising their conventional treatment process and 3) implementing advanced treatment processes to reduce the risk of exposing consumers to cyanotoxins. However, since the occurrence of cyanobacteria in the source water is seasonal, and in many cases sporadic, monitoring for cyanobacteria and their associated cyanotoxins does not form part of the routine water quality monitoring undertaken by the Drinking Water Utilities. Furthermore, many Drinking Water Utilities throughout the world (including South Africa) do not have skilled staff to monitor for cyanobacteria or cyanotoxins or have a sound knowledge of what actions can be taken if confronted with cyanobacteria in the source water. It is therefore necessary to develop a Cyanobacterial Incident Management Framework for Drinking Water Utilities in South Africa. This will guide water treatment managers to monitor proactively for cyanobacteria and cyanotoxins, to evaluate their current capacity to deal with a toxic cyanobacterial bloom and to document the actions that will be taken if cyanobacteria are present in the source water.

4.2 OVERVIEW OF CYANOBACTERIAL INCIDENT MANAGEMENT FRAMEWORKS

A Cyanobacterial Incident Management Framework (CIMF) is a monitoring and management action sequence that Drinking Water Utilities can and should use proactively to monitor the presence of cyanobacteria in the source water. It assesses the treatment's facilities to deal with cyanobacteria, develop action plans that can be implemented during the treatment of source water contaminated with cyanobacteria and to provide a graduated response to the onset and progress of a cyanobacterial bloom in source water.

Burch (1993) developed one of the first comprehensive management frameworks for cyanobacteria-rich water resources in Australia (Figure 4.1). The Burch model is based on cyanobacterial cell numbers in the source water that are set as triggers linked to a routine monitoring programme and three alert levels. Alert Level 1 is triggered when low numbers (500 to 2000 cells/mL) are detected in the source water, Alert Level 2 when there are moderate numbers (2000 to 15000 cells/mL) and Level 3 when there are persistently high numbers (> 15000 cells/mL), which are toxic. During the Alert Level 1 and Alert Level 2 phases the water supply is considered to be of acceptable quality, but at Alert Level 3 it is considered to be unsafe. The Burch model is further useful to Drinking Water Utilities as it also describes some operational actions (e.g. altering off-take depth, the deployment of booms, the use of PAC, etc.) that could be undertaken, the analyses (e.g. cyanobacterial

identification, cyanotoxins analysis) and the consultation (e.g. The Health Authorities) that should be undertaken (Figure 4.1).

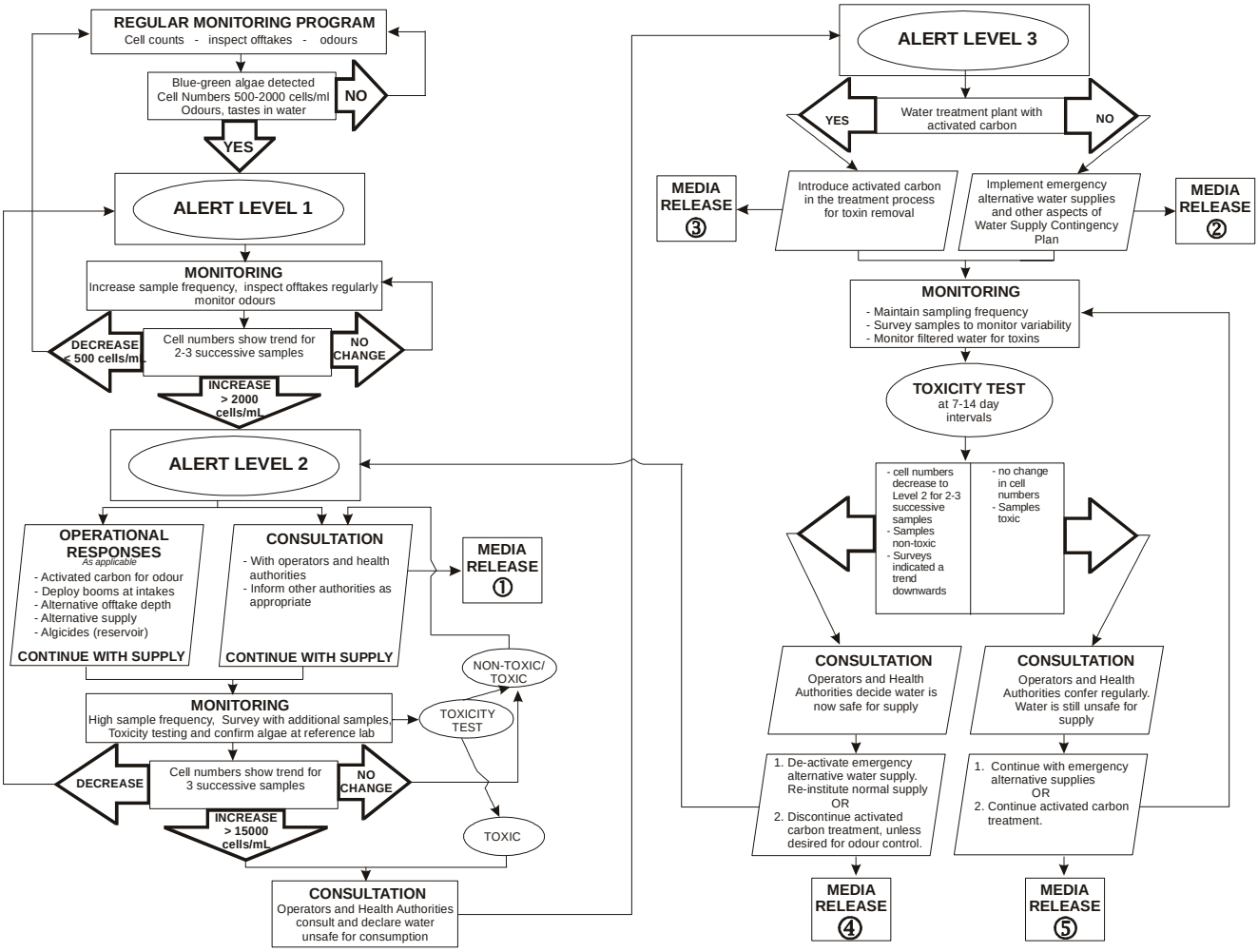

FIGURE 4.1: Burch Cyanobacteria Incident Management Framework using cyanobacteria biomass as trigger (Burch, 1993).

The Burch model thus formed a generic framework, which could be or has been adapted by many Drinking Water Utilities to include in their specific management and site-specific operational capabilities. Burch *et al.* (2003) also developed a national protocol for the monitoring of cyanobacteria and their toxins in surface fresh waters for use in Australia. This protocol is thorough and includes information on cyanobacteria, their toxins, sampling procedures, analysis procedures (cyanobacteria and toxin analyses) and Alert Levels framework for drinking water supply. The Alert Levels framework (Table 4.1) primarily uses the cyanobacterial biomass as trigger between the alert levels, ranging from a Detection Level (cyanobacteria > 500 cells/mL), to Alert Level 1 (cyanobacteria > 2000 cells/mL), to Alert Level 2 (cyanobacteria > 5000 cells/mL), and finally to Alert Level 3 (cyanobacteria > 50000 cells/mL). Biovolumes for the cyanobacteria are also included as trigger values should cell counts not be available. Cyanotoxin analyses are also required throughout the framework, as this is a requirement of the Australian Drinking Water Guidelines and isnecessary to assess the risk to the consumer.

In 1999 the World Health Organization (in Chorus and Bartram, 1999) proposed an Alert Levels framework for cyanobacteria (Figure 4.2), which is very similar to the Burch model. The WHO model is also triggered by different cyanobacterial concentrations in the source water, which are then

translated in to a Vigilance Level, an Alert Level 1 and an Alert Level 2, with appropriate actions and responses. The Vigilance Level is activated when cyanobacteria are detected at low concentrations and during this Level the main actions are an increase in monitoring and inspection of the source water at the intakes.

TABLE 4.1: Summary of the National Alert Levels framework for drinking water and the associated definitions developed by Burch *et al.* (2003)

LEVEL	THRESHOLD DEFINITION	ACTIONS
Detection Level	>500 cells/mL Cyanobacteria at low levels	**Have another look** • Regular monitoring • Weekly sampling and cell counts • Regular visual inspection of source water for scums around intakes
Alert Level 1	≥ 2000 cells/mL total cyanobacteria (Range: 1000 –3000 cells/mL) (Individual species or combined total) Trigger value can be adjusted for local conditions Levels indicate cyanobacteria population established and high numbers can occur	**Talk to the health regulators** • Notify agencies as required • Increase sampling frequency to 2x weekly at intake and representative locations in the reservoir. Establish population growth and special variability in source water • Monitor variability of the intake sample over time • Decide on requirement for toxicity assessment or toxin monitoring
Alert Level 2	≥ 5000 cells/mL total cyanobacteria *Microcystis aeruginosa or Anabaena circinalis* (Range: 5000 – 10000 cells/mL) Established bloom, potentially toxic If treatment not effective toxin concentration may exceed guideline	**Evaluate the significance of hazard in relation to guideline** • Advice from Health Authorities on risk to public. Health risk considering cyanotoxins data, sample type and variability and effectiveness of treatment • Consider if advice must be given to consumers if source water supply is not filtered • Continue monitoring as in Level 1 • Cyanotoxin monitoring of drinking water may be required by Health Authority.
Alert Level 3	≥ 50000 cells/mL total cyanobacteria *Microcystis aeruginosa or Anabaena circinalis* No treatment or ineffective treatment may cause an elevated risk of human health risks if advance treatment is not implemented or alternative water is not supplied	**Assess potential risk immediately if it was not done** • Notification of Health Authorities for advice on health risks • May require advice to consumers if the supply is unfiltered • Cyanotoxin measurement in source water and drinking water if not already carried out • Continue monitoring of cyanobacteria in source water as per Level 1 • In absence of treatment and depending on health risk assessment an alternative water supply may be required

Alert Level 1 is activated on the basis of cyanobacterial cell concentration (> 2000 cyanobacteria cells/mL), the presence of cyanotoxins at a concentration higher than the WHO guideline (1 µg/L microcystin equivalents) or the chlorophyll-*a* concentration of the source water (> 1 µg/L). At this alert level the actions focus on (1) an increase in monitoring to include cyanotoxins analysis, (2) an assessment of the feasibility to reduce the intake of cyanotoxins from the source water, (3) an assessment of the capacity of the drinking water treatment works to remove cyanobacteria and cyanotoxins and (4) possible early communications with Public Health Authorities. Alert Level 2 is activated when the cyanobacterial cell concentration exceeds 100000 cells/mL, the chlorophyll-*a* concentration of the source water exceeds 50 µg/L and the cyanobacteria are toxic. The main actions during this alert level include continuing with the monitoring programme and treatment optimisations, consideration of activating alternative water supply plans, increased communication with Health Authorities and more extensive media releases.

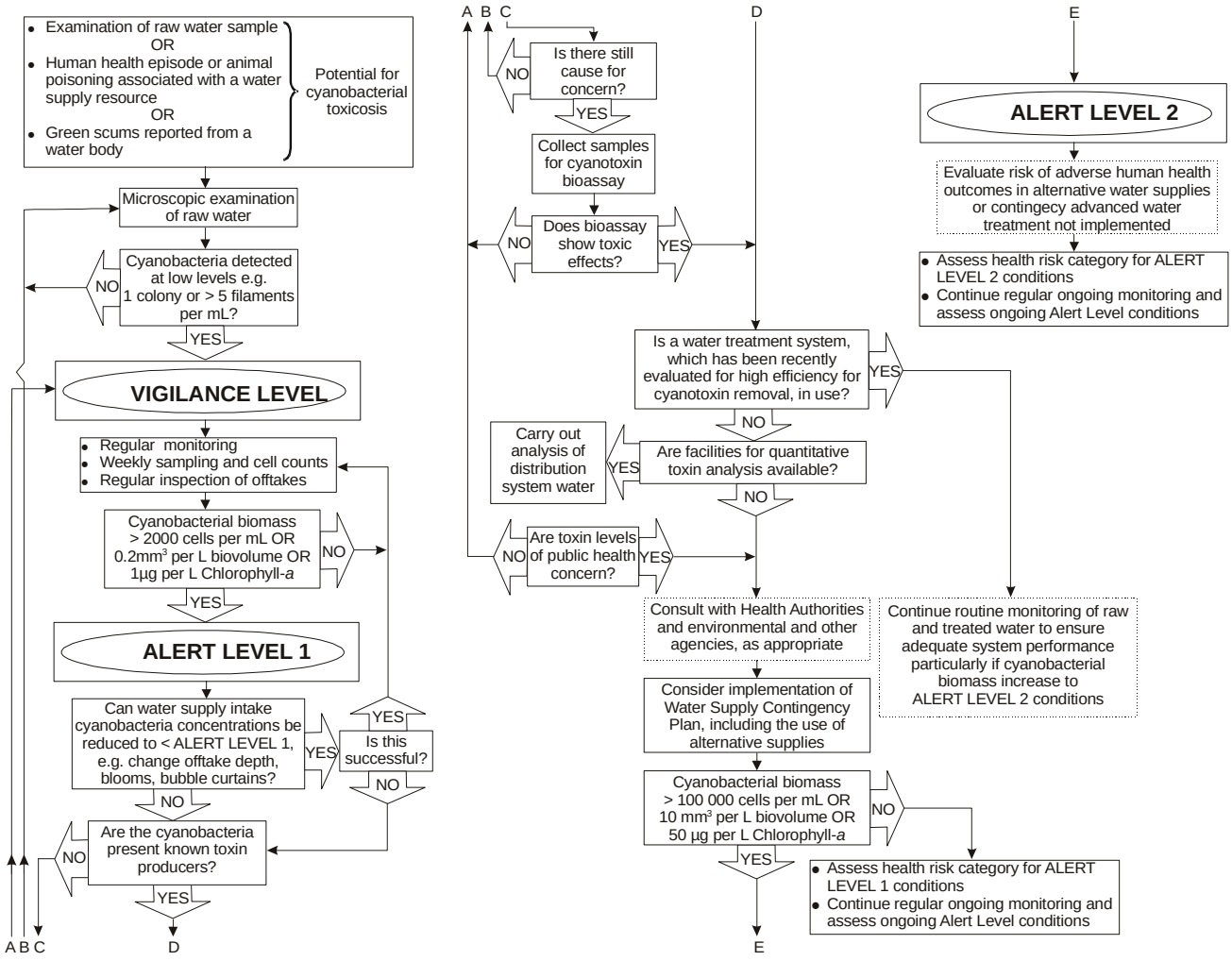

FIGURE 4.2: WHO Cyanobacterial Incident Management Framework using cyanobacteria as trigger (Chorus and Bartram, 1999).

In South Africa, Van Baalen & Du Preez (2001) developed a Cyanobacterial Incident Management Framework (CIMF) for Drinking Water Utilities based on the principles of the Burch (Burch, 1993; Burch *et al.*, 2003) and WHO models (Chorus & Bartram, 1999), but adding additional criteria to make it more practical for day-to-day application by drinking water treatment managers (Figure 4.3). The Van Baalen & du Preez CIMF model consists of various action levels, namely: Routine monitoring ↔ Vigilance Level ↔ Alert Level 1 ↔ Alert Level 2 ↔ Alert Level 3. Between each action alert there are primary triggers (phytoplankton identification and enumeration), secondary triggers (cyanotoxin concentration) and tertiary triggers (mouse bioassay test result), which allow for "movement" (step-up or step-down) between the action alerts. As in the Burch (Burch, 1993; Burch *et al.* 2003) and WHO models, each alert level describes the monitoring and actions that should be considered and undertaken by the drinking water treatment managers and the Drinking Water Utilities at large.

The Van Baalen & du Preez CIMF model is primarily based on an established routine cyanobacterial and algal biomonitoring programme. Therefore, each drinking water treatment plant must implement a routine monitoring programme to be able to activate the CIMF. This requirement is not emphasised in the WHO CIMF model. When cyanobacteria are detected at low concentrations during the routine cyanobacterial and algal monitoring (screening) programme, an alert is raised and the alert actions are activated or "stepped-up" to the Vigilance Level. During the Vigilance Level

there is an increase in the frequency of the monitoring activities, as well as an increase in the visual observation for cyanobacterial scum formation. Alert Level 1 is activated on the basis of a cyanobacterial cell concentration (> 2000 cyanobacteria cells/mL). At this alert level the actions focus on an increase in monitoring activities to include cyanotoxin analysis and the mouse bioassay, and communication and information transfer between the main role-players of the Response Committee. Alert Level 2 is activated when the cyanobacterial cell concentration exceeds 100 000 cells/mL (primary trigger), the presence of cyanotoxins at a concentration higher than 0.8 µg/L mycrocystins (secondary trigger) or when the mouse test is positive (tertiary trigger). The main actions during this Alert Level include treatment optimisations, continuation of the monitoring programme (daily monitoring of cyanobacteria and cyanotoxins), mouse test bioassays and Response Committee meetings (responsible for situation assessment, consideration of actions, communication etc). Alert Level 3 is activated when the cyanotoxin concentration is higher than 3 µg/L microcystins or when the mouse test is positive. The main actions during this alert level are the continued optimisation of the treatment actions, daily analyses for cyanobacteria and cyanotoxins as well as the performance of the mouse test. The Response Committee meets or communicates on a daily basis to ensure that any executive decisions made are implemented, while the appropriate crisis communication is carried out between Government Departments and the affected consumers. The Van Baalen model also stipulates that alternative drinking water should be supplied when the microcystin concentration in the drinking water exceeds 10 µg/L. An important action that is incorporated in this model is the closure of an incident by the Response Committee once it has ended and the water quality has improved to Alert Level 1 or the Vigilance Level.

The CIMF models mentioned above have all been developed as a decision tree consisting of alert levels. Each alert level has appropriate actions and responses linked to it based on threshold stages that can be directly translated into water quality in the terms of cyanobacteria. The alert levels follow each other sequentially, from an initial detection of cyanobacteria in the source water progressively to the highest alert level, which is a definite health risk posed to consumers. Most frameworks available use the type of cyanobacterial species and their concentration as indication of the level of risk to the consumer. This approach, however, is not always practical for a drinking water supplier because not all cyanobacterial blooms are toxic or hazardous. For a drinking water supplier the importance of cyanobacteria, in terms of risk to the consumer, is in the toxin concentration of the source and final water.

If a cyanobacterial bloom is present in the source water but it does not produce toxin, or it only produces low concentrations of cyanotoxins, or the drinking water treatment works is operating well and removing toxins during routine operation, then it would not be practical to step-up to higher alert levels which require additional costly operational interventions such as increased use of coagulation chemicals, activated carbon or increased backwashing frequencies. The Van Baalen & du Preez model overcomes this problem by adding additional criteria for determining the alert level under which a drinking water supplier should be operating during a cyanobacterial bloom. The cyanotoxin concentration present in the final water has been included as an additional criterion for determining the risk to the consumer. The advantage of adding cyanotoxin concentration in the final water to the cyanobacterial concentration is that a drinking water supplier is continuously aware of the potential risk posed by the cyanobacterial cells in the source water and the actual or current risk (in terms of toxin concentration) of the final drinking water. With this approach the operational changes can be implemented more appropriately thereby saving costs. However, the concentrations of the cyanotoxins at the different alert levels suggested by the Van Baalen & du Preez model are not operationally aligned.

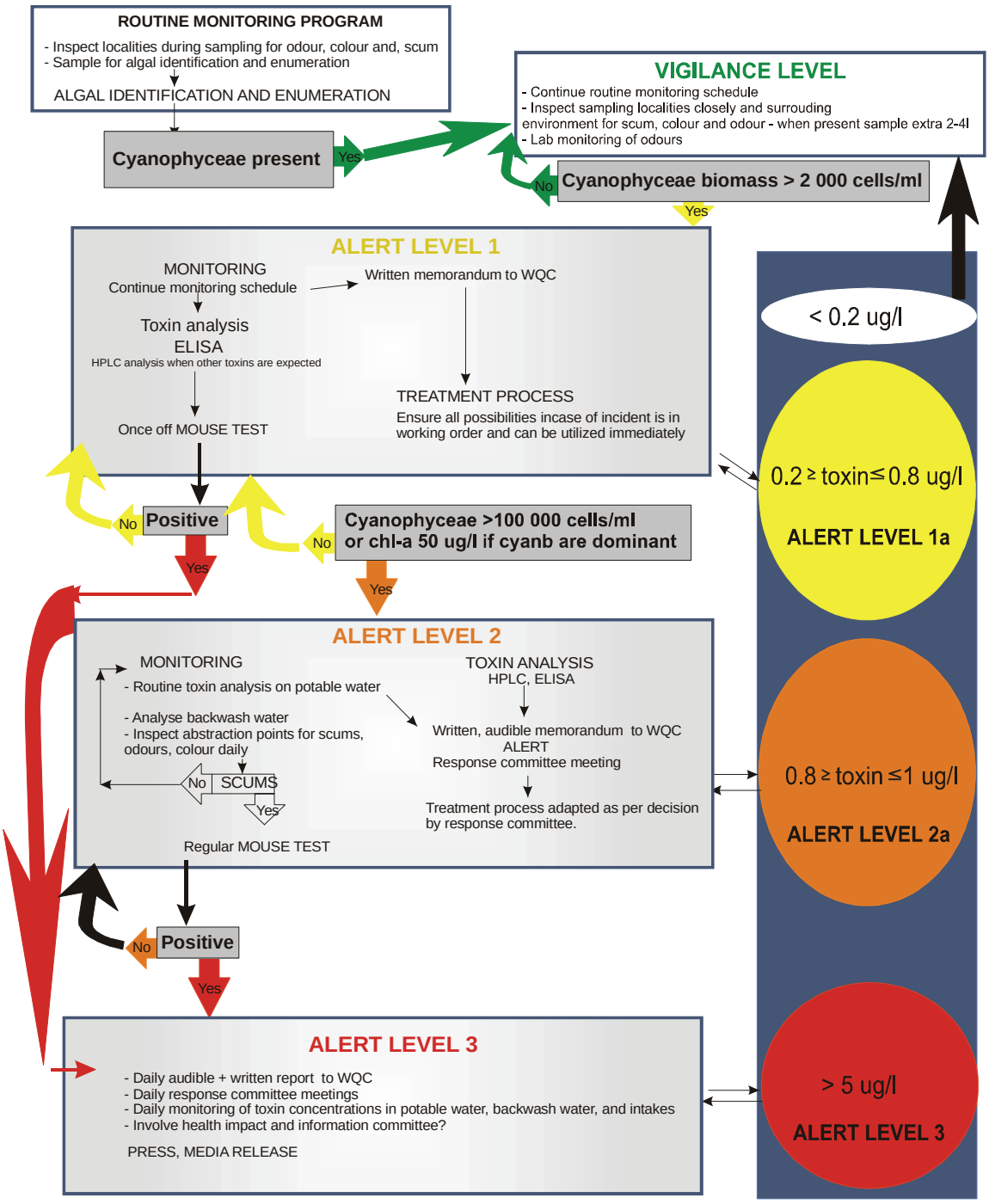

FIGURE 4.3: Van Baalen Cyanobacterial Incident Management Framework using cyanobacteria and toxin concentrations in drinking water as trigger (Van Baalen & Du Preez, 2001).

The application of the Van Baalen & du Preez model by drinking water treatment works in South Africa is currently limited to Rand Water, with the application of the concepts to crisis situations by suppliers of drinking water (primarily undertaken by Water Boards, but also by DWAF and

Municipality-operated drinking treatment plants) being performed on an *ad hoc* basis. This can be attributed to the fact that these drinking water suppliers differ significantly in their capacity (amount of funding, type of infrastructure, skills and know-how, capacity available to perform operational tasks) to monitor and deal with cyanobacteria and cyanotoxins. For example, the CIMF could provide two different variables (cyanobacterial cell identification and enumeration or chlorophyll-*a*) that can be used as primary triggers especially at the lower alert level. Because of the option given to drinking water suppliers to choose one of the two primary triggers to base their Incident Management Framework on (decision dependant on which of the two options the supplier has the capacity to perform/analyse routinely), it was therefore necessary to develop three different Incident Management Frameworks, one suitable for each primary trigger option available. These frameworks are exactly the same in principle, but differ in minor actions taken, especially in the lower alert levels. The CIMF using cyanobacterial identification and enumeration as primary trigger is the most comprehensive and recommended framework to use. One "step-down" from the cyanobacterial identification and enumeration CIMF is the management framework using chlorophyll-*a* as primary trigger. This framework is not as specific as the phytoplankton framework and acts more as a screening tool for the source water. The chlorophyll-*a* framework may involve the outsourcing of samples for phytoplankton analysis (i.e. if not able to analyse in-house) at specified times.

4.3 CYANOBACTERIAL INCIDENT MANAGEMENT FRAMEWORK USING CYANOBACTERIA AS PRIMARY TRIGGER

The Cyanobacterial Incident Management Framework (CIMF) based on the Burch, WHO and models (Burch, 1993, Burch *et al.* 2003, Chorus & Bartram, 1999; Van Baalen & Du Preez, 2001) consists of various stages of action alerts, namely: Routine monitoring ↔ Vigilance Level ↔ Alert Level 1 ↔ Alert Level 2 ↔ Alert Level 3 (Figure 4.4). Between the routine monitoring level and each action alert there are the primary (cyanobacterial identification and enumeration), secondary (cyanotoxin concentration) and tertiary (mouse test bioassay) triggers, which activate the next level and which allow for "movement" (step-up or step-down) between the routine monitoring level and the action alerts.

Routine Monitoring Level

Routine monitoring refers to monitoring of the variable chosen as the primary trigger for a specific drinking water supplier. The variable selected for this CIMF is cyanobacterial identification and enumeration analysis, which is performed on the source water sample from the abstraction point at least once every two weeks. If the analysis can be performed more frequently, that would be an advantage. When a drinking water treatment works is prone to experiencing cyanobacterial/algal related problems, or has a history of problems during summer and autumn months in their source water it is recommended that cyanobacterial identification and enumeration analysis is included in their routine source water monitoring program. Guidelines on sample taking, handling, storage, etc. can be found in the National Eutrophication Monitoring Programme publication (DWAF, 2002).

Analysis

Cyanobacterial identification and enumeration should be performed on the source water at least once every two weeks. It would be an advantage if this were performed more frequently.

Stepping – up activation

When cyanobacteria are detected during the routine cyanobacterial analysis then the alert is stepped-up to the Vigilance Level

Vigilance Level

Regular surveillance of source water

The reservoir (dam), lake or river from which the source water is abstracted should be surveyed for the development of colour and scum associated with a cyanobacterial bloom (excessive cyanobacterial growth). This process may be aided by information on the typical seasonal and/or daily wind patterns, and checking downwind shorelines for scum aggregation). The first site that should be examined is the area around the abstraction point. When a reservoir or lake is the source water used by a drinking water treatment plant it is a good practice to survey different areas in and around the dam (not just the abstraction area) for cyanobacterial bloom development. Areas close to the shore are usually good places to detect increased algal growth because of the concentration effect in shallow waters. The reason for "looking" for scum development in other areas of a reservoir is that many cyanobacterial species can concentrate in the top layers of water (because of the presence of gas vacuoles) and can quite easily be transported from one location in a dam to another by the wind. Therefore, even though cyanobacteria may not be spotted at the abstraction point, this situation can easily change over a short period of time (within hours) by a change in the wind direction whereby a bloom present in another area of the dam will concentrate in the abstraction area.

When abstracting from a river it is usually difficult to detect the development of a cyanobacterial bloom because the flow of most rivers restricts bloom development at one locality. Instead, the bloom develops as the water moves downstream and then appears at an abstraction point for a short period (pulse or plug flow). In some slow-flowing rivers frequent monitoring supports the detection of increases in cyanobacterial concentration over time. When a river has weirs or naturally-impounded areas it is more likely that any cyanobacteria and algal problems will occur there, if they are going to occur at all. People abstracting water along the rivers can also establish a network between companies, the Department of Water Affairs and the local community (when it is important to select a central coordinator), whereby the upstream users can notify the downstream users if a "pocket" of high cyanobacterial or algal biomass is seen moving downstream.

Analysis

Cyanobacterial identification and enumeration should be performed at least once per week on the source water.

Stepping – up activation

When the cyanobacterial concentration of the source water exceeds 2000 cells/mL then the alert must be stepped-up to Alert Level 1.

Stepping – down activation

When cyanobacteria are not detected for 14 consecutive days during the routine cyanobacterial analysis of the source water then the alert is stepped-down to the routine monitoring level.

Alert Level 1

Regular surveillance of source water

Increase the surveillance (as described under Vigilance level) of the reservoir (dam), lake or river from which the source water is abstracted to at least once a week for the development of colour and scum associated with a cyanobacterial bloom (excessive cyanobacterial growth).

Analysis

Cyanobacterial identification and enumeration analysis must be performed daily on the source water at the abstraction point.

Cyanotoxin screening/analysis

Cyanotoxin screening refers to the determination of cyanotoxins (Table 4.2) concentrations by using either the ELISA technique for microcystins or HPLC for the specific toxin standard available. It is important to perform a cyanotoxin analysis (the more comprehensive, the better, as appropriate management is more effective when the data are more representative) on the source and the final water. -Results from the source water will indicate if there are any cyanotoxins present and the final water will indicate how well the process is performing in removing these toxins (if at all) and also indicate the potential risk to the consumer.

The frequency of analysis should be at least once per week. If the Drinking Water Utility does not have the capacity to perform cyanotoxins analysis it is important to outsource the samples to laboratories that have that capacity. South African laboratories that have the capacity to perform cyanobacterial and cyanotoxin analyses are summarised in Table 4.3.

TABLE 4.2 Summary of cyanotoxins, and the cyanobacteria that produce them as well as of the recorded mammalian clinical symptoms of cyanotoxin exposure (adapted from NHMRC, 2004; Chorus & Bartram, 1999; Sivonen & Jones, 1999; Chorus, 2001; Falconer, 2005)

TOXIN	CYANOBACTERIAL GENERA	CLINICAL SYMPTOMS
Cyclic peptides		
Microcystins	*Microcystis, Anabaena, Oscillatoria, Planktothrix, Nostoc*	Gastro-enteritis, fever, pains in muscles and joints, nausea, vomiting, blistering around mouth, diarrhoea, swollen liver, death by liver failure
Nodularin	*Nodularia*	Gastro-enteritis, fever, pains in muscles and joints, nausea, vomiting, diarrhoea, swollen liver, death by liver failure
Alkaloids		
Cylindrospermopsin	*Cylindrospermopsis, Aphanizomenon, Anabaena, Raphidiopsis, Umezakia,*	Abdominal pains, vomiting, swollen liver, liver failure, pathological damage to the kidneys, spleen, thymus and heart
Anatoxin-a	*Anabaena, Planktothrix, Oscillatoria, Aphanizomenon*	Muscle weakness, respirator distress, exaggerated abdominal breathing, hyperactivity, hypersalivation, numbness around the lips, paralysis
Anatoxin-a(S)	*Anabaena, Aphanizomenon*	Muscle weakness, respirator distress, exaggerated abdominal breathing, hyperactivity, hypersalivation, numbness about the lips, paralysis
Saxitoxins	*Anabaena, Aphanizomenon, Lyngbya, Cylindrospermopsis*	Numbness around the lips, complete paralysis, death from respiratory failure
Lipopolysaccharides		
Lipopolysaccharides	All	Allergic reactions, inflammation, irritation, gastro-enteritis

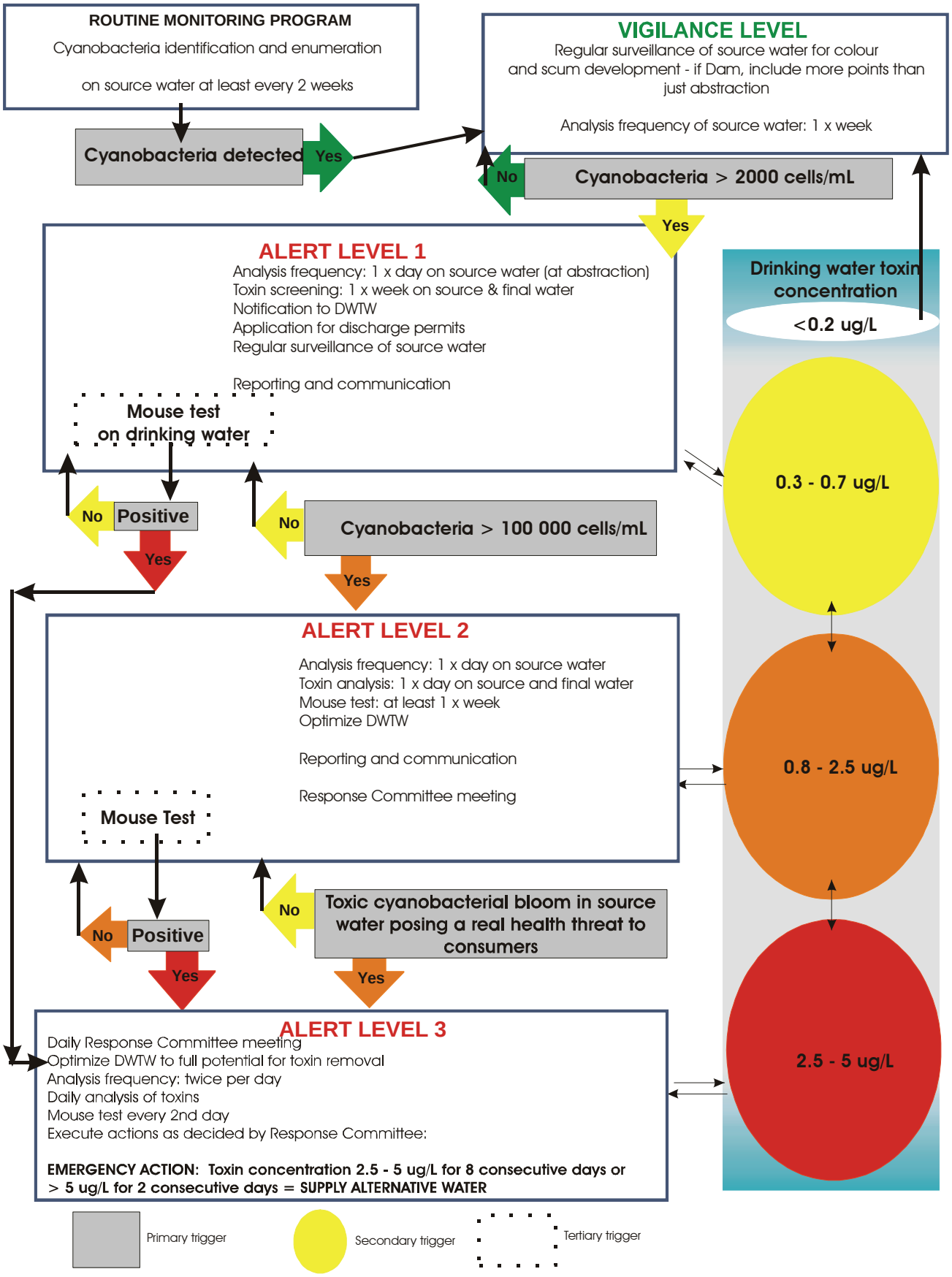

FIGURE 4.4: Cyanobacterial Incident Management Framework using cyanobacterial concentration as a primary trigger.

Mouse test bioassay

Mouse test bioassays are performed to establish whether a water sample has a toxic effect on a mouse. This effect is then translated to the effect that the water sample may have when consumed by humans. A mouse test bioassay should be performed at least on the drinking water during cyanobacterial dominance in the source water. Should the dominant cyanobacterial species in the source water change over time then it is important to run the mouse test bioassay again to confirm that no other cyanotoxins are present. **Note:** In South Africa the mouse test bioassays for cyanotoxins are done only at the Onderstepoort Veterinary Institute in Pretoria (Table 4.3).

Notification to drinking water treatment works (DWTW)

The manner in which the "Notification to DWTW" will be executed will be proactively defined by the Response Committee (see Section 4.6), which would in turn be–determined by the size and communication structures of the Drinking Water Utility. The notification should be documented and traceable and ideally should include the following:

- background information including historical data related to previous incidents
- current trends in the relevant water quality data related to the specific drinking water treatment works
- prediction in terms of immediate and short-term possibilities of cyanobacterial bloom formation
- recommendations for possible actions (e.g. ensure sufficient coagulant is available, ensure staff are aware and ready to react at short notice, ensure all steps in process are able to be optimised and are in working condition, etc.) that can be taken into consideration in order to prepare for a cyanobacterial incident
- reference to the CIMF that has been developed for the specific drinking water treatment works (see Section 4.6 for more information on notification and communication).

Discharge permits

Discharge permits from DWAF are necessary for the discharge of any waste into natural water systems. Should a cyanotoxin incident occur, it is likely that a decision will be taken not to recycle filter backwash water back to the head of the drinking water treatment works but to store the water on-site in holding dams or to discharge the filter backwash water into the river or reservoir/dam below the point of abstraction. No discharges are permitted without a valid permit. For more information it is recommended that the Department of Water Affairs and Forestry (DWAF) Regional Director in charge of the specific area be contacted for clarification on procedures and requirements. It is also recommended that the process of obtaining a discharge permit be initiated in a proactive manner (e.g. when the CIMF or the Water Safety Plan is developed), as this can be a very lengthy process.

Reporting and communication

The communication and reporting that must be initiated will have been defined proactively by the Response Committee (see Section 4.6), which would in turn be determined by the size and the communication structures of the Water Utility. It important that a Drinking Water Utility should have specified reporting and communication channels with regard to water quality problems (see Section 4.6 for a recommended structure for communication, which can either be adopted as is or slightly changed according to the needs and capacities of the specific Drinking Water Utility). Nevertheless, at this alert level there should already be some communication between the water quality coordinator, the specialist on cyanobacteria and drinking water treatment, the analytical laboratory staff and the drinking water treatment works manager (see Figure 4.6).

TABLE 4.3: Details of laboratories performing phytoplankton identification & enumeration, chlorophyll-*a* and cyanotoxin analysis

COMPANY	ANALYSIS	CONTACT TEL	CONTACT FAX	ADDRESS
Buffalo City Municipality	Chlorophyll-a Phytoplankton identification & enumeration	043 705 9366	043 743 2564	1 Reservoir Rd East London
Cape Metropolitan Council	Chlorophyll-a Phytoplankton identification & enumeration Microcystin by HPLC Anatoxin-a	021 637 9090	021 684 1000	Scientific Services Off Jan Smuts Ave Athlone, Cape Town
Directorate Resource Quality, Services (RQS), Department of Water Affairs and Forestry	Chlorophyll-*a* Phytoplankton identification Microcystin by HPLC & Microcystins by ELISA Cyanobacterial specialist	012 808 0377	012 808 2702	Moloto Road Roodeplaat Dam Pretoria, 0001
eThekwini Water Services (Durban Metro)	Chlorophyll-*a*	031 302 4911	031 302 4747	3 Prior Road, 4th Floor Durban
Johannesburg Water	Chlorophyll-*a*	011 728 7373	011 728 5444	75 4th Street, Houghton, Gauteng, 2198
Mhlatuze Water	Chlorophyll-*a* Phytoplankton identification & enumeration	035 902 1000	035 751 1145	Corner South Central Arterial Battery Bank Alton, Richards Bay
Midvaal Water Company	Chlorophyll-*a* Phytoplankton identification	018 482 1241	018 482 1110	Stilfontein, 2550
Namwater	Chlorophyll-*a* Phytoplankton identification & enumeration	264 61 71 2093	264 61 71 3093	176 Iscor Street Windhoek, Namibia
Nelson Mandela Metropolitan University	Chlorophyll-*a*, HPLC, ELISA Phytoplankton identification & enumeration,	041 504 2359	86 614 7129	Building 12, Department of Biochemistry and Microbiology, South Campus, University Way, Summerstrand, Port Elizabeth
North West University, Potchefstroom Campus	Phytoplankton identification & enumeration	018 299 2514	018 299 2203	Hoffman street JS van der Merwe Building Potchefstroom
Onderstepoort Veterinary Institute	Mouse test bioassay	012 259 9220		Toxicology Dept. Onderstepoort Veterinary Institute Pretoria, 0001
Rand Water	Chlorophyll-*a* Phytoplankton identification & enumeration Microcystin by HPLC & Microcystins by ELISA Cylindrospermopsin Nodularin Anatoxin-a Cyanobacterial specialist	016 421 5150	016 455 2055	Analytical Services Barrage Road Vereeniging, 1930
Sedibeng Water	Chlorophyll-*a*	0565 150 200	0565 150 381	Balkfontein Bothaville, 9660
Umgeni Water	Chlorophyll-*a* Phytoplankton identification & enumeration Microcystins by ELISA	033 341 1144	033 341 1349	310 Burger Street Pietermaritzburg, 3201

Stepping – up activation

When the cyanobacterial concentration in the source water exceeds 100 000 cells/mL then actions should be stepped-up to Alert Level 2.

OR

When the cyanotoxin (microcystins or nodularin or cylindrospermopsin) concentration in the drinking water exceeds 0.7 µg/ℓ then actions should be stepped-up to Alert Level 2.

OR

When the mouse test bioassay is positive for cyanotoxins in the drinking water then actions should be stepped-up to Alert Level 3.

Stepping – down activation

When the cyanobacterial concentration in the source water decreases to below 2000 cells/mL for at least 14 consecutive days, the cyanotoxins analysis (microcystins or nodularin or cylindrospermopsin) concentration in the drinking water is < 0.2 µg/L for 14 consecutive days and the mouse test bioassay is repeatedly negative for the drinking water then actions should be stepped-down to the Vigilance Level.

Note:

When stepping-up or -down from one alert level to the next it is important always to use the primary trigger (in this CIMF: cyanobacterial concentration (numerical density) in the source water) as default analysis to determine which actions to take. However, should the cyanotoxin concentration exceed the concentration limits of the alert level in which it is–operating (based on the primary trigger) then the secondary trigger (cyanotoxin concentration) over-rides the primary trigger and the actions should be performed at the alert level specified by the secondary trigger. Similarly, should the mouse test bioassay be positive, then the tertiary trigger (mouse test bioassay) over-rides the primary trigger and the actions should be performed at the alert level specified by the tertiary trigger. Should the concentration of the secondary trigger decrease to lower alert levels (or should the tertiary trigger be repeatedly negative) then actions should revert back to the appropriate alert level as dictated by the results of the primary trigger.

Alert Level 2

Regular surveillance of source water

Increase the surveillance see (see also Vigilance level) of the reservoir (dam), lake or river from which the source water is abstracted. This should be surveyed at least weekly at the abstraction point and surrounding area for the development of colour and scum associated with a cyanobacterial bloom (excessive cyanobacterial growth).

Analysis

Cyanobacterial identification and enumeration analysis must be performed daily on the source water at the abstraction point.

Cyanotoxin screening/analysis

Cyanotoxin analysis is performed daily on the source water and the drinking water (also see Section at Alert Level 1). If the Drinking Water Utility does not have the capacity to perform cyanotoxin analysis it is important to outsource the samples to laboratories that have the requisite capacity.

Laboratories in South Africa that have the capacity to perform cyanobacterial and cyanotoxin analyses are summarised in Table 4.3.

Mouse test bioassay

Mouse test bioassay is performed at least once a week on the drinking water (also see Section at Alert Level 1). **Note:** In South Africa mouse test bioassays for cyanotoxins are done only at the Onderstepoort Veterinary Institute, Pretoria (Table 4.3).

Optimisation of the drinking water treatment works

The optimisations that should be considered fall into the following broad categories: 1) actions on the abstraction of the source water (e.g. manipulation of the depth of abstraction), 2) optimisation of the conventional treatment process (e.g. stop pre-treatment with oxidants, optimisation of coagulation, flocculation, sedimentation, filtration and flotation processes, optimisation of disinfection with chlorine) and 3) the use of advanced treatment processes (e.g. ozone, powdered activated carbon). Additional information regarding these optimisation activities is described in Chapter 3 of this document. It is recommended that the possible optimisation process that could be implemented be identified and tested in a proactive manner during the development of the CIMF for the specific Drinking Water Utility. If this has already been done then the main focus would be to ensure that the actions are implemented and are functioning optimally to ensure that the Drinking Water Utility can effectively remove cyanobacterial and cyanotoxins from the source water as soon as the cyanobacterial concentrations (numbers) increase. This will also reduce the risk of reaching Alert Level 3.

Response Committee meeting

A meeting of the Response Committee is convened at Alert Level 2. The structure, roles and responsibilities of each member of the Response Committee would have been defined proactively during the development of the CIMF for that specific drinking water treatment works. However, this would be dependent on the size and the communication structures of the Drinking Water Utility (see Section 4.6 for more information on the roles and responsibilities of the Response Committee). At their first meeting it is important 1) to familiarize each member with the CIMF, 2) to clarify their roles and responsibilities and 3) to update contact information. The Response Committee discusses the current situation based on the available data, determines the appropriate actions that must be taken and identifies any problems that may hinder the implementation of those actions. Dates for feedback and follow-up meetings are set. Formal minutes of the meeting are kept.

Discharge permits

If the discharge permit has not been received from DWAF, the Response Committee decides on the course of action to obtain it (see comments at Alert Level 1).

Reporting and Communication

The reporting and communication focuses on internal reporting and communication to ensure that information is shared and any actions are speedily taken and implemented. Refer to Section 4.5 for the appropriate communications requirements.

Stepping – up activation

When the cyanobacterial concentration in the source water consistently exceeds 100 000 cells/mL, are toxic and cause scum to form in the source water then actions should be stepped-up to Alert Level 3.

OR

When the cyanotoxin (microcystins or nodularin or cylindrospermopsin) concentration in the drinking water is between 0.8 and 2.5 µg/L for more than 14 days then actions should be stepped-up to Alert Level 3.

OR

When the cyanotoxins (microcystins or nodularin or cylindrospermopsin) concentration in the drinking water exceed 2.5 µg/L for more than 4 days then actions should be stepped-up to Alert Level 3.

OR

When the mouse test bioassay is positive for cyanotoxins in the drinking water then actions should be stepped-up to Alert Level 3.

Stepping – down activation

When the cyanobacterial concentration in the source water decreases to below 100 000 cells/mL for at least 14 consecutive days, the cyanotoxins analysis (microcystins or nodularin or cylindrospermopsin) concentration in the drinking water is < 0.8 µg/L for 14 consecutive days and the mouse test bioassays is repeatedly negative for the drinking water then actions should be stepped-down to Alert Level 1.

Alert Level 3

Regular surveillance of source water

Surveillance (see also Vigilance level) of the reservoir (dam), lake or river from which the source water is abstracted should be undertaken at least daily at the abstraction point and surrounding area for the development of colour and scum associated with a cyanobacterial bloom (excessive cyanobacterial growth).

Analysis

Cyanobacterial identification and enumeration analysis must be performed twice a day (early morning and late afternoon) on the source water at the abstraction point. A depth profile of the cyanobacterial cell concentration in the source water column must be determined (e.g. when abstracting from a dam), and thereafter a series of profiles (at least 4) over a 24 hour period must be performed to optimise the abstraction, as the cyanobacterial cell concentrations may show diurnal depth variation.

Cyanotoxin screening/analysis

Cyanotoxin analysis is performed daily on the source water and the drinking water (also see Section at Alert Level 1). If the Drinking Water Utility does not have the capacity to perform cyanotoxin analysis it is important to outsource the samples to laboratories that have the requisite capacity. Laboratories in South Africa that have the capacity to perform cyanobacterial and cyanotoxin analyses are summarised in Table 4.3.

Mouse test bioassay

Mouse test bioassay is performed on the drinking water at least every alternative day (also see Section at Alert Level 1). **Note:** In South Africa mouse test bioassays for cyanotoxins are only done at the Onderstepoort Veterinary Institute in Pretoria (Table 4.3).

Optimisation of the drinking water treatment works

The drinking water treatment works should be optimised to its full potential for cyanobacteria and cyanotoxin removal. The following processes must therefore function at their optimal capacity: 1) the abstraction of source water (e.g. manipulation of the depth of abstraction or the use of an alternative source), 2) the conventional treatment process (e.g. stop pre-treatment with oxidants, optimisation of coagulation, flocculation, sedimentation, filtration and flotation processes; optimisation of disinfection with chlorine), 3) the use of advanced treatment processes (e.g. ozone and powdered activated carbon) and the discarding of filter backwash water. Additional information regarding these optimisation activities is given in Chapter 3 of this document. The ultimate aim is to reduce the cyanotoxin concentration in the drinking water to less than 1 μg/L.

Response Committee meeting

The Response Committee should meet daily during this alert level to evaluate the success of measures implemented and to decide if further actions must be implemented. Special attention is given to solving optimisation problems that are being experienced, alternative actions that can be implemented and to communication with external role-players (Department of Health, Department of Water Affairs and Forestry, customers and the general public). Formal minutes of the meeting are kept.

Discharge permits

If the discharge permit has not been received from DWAF, the Response Committee decides on the course of action to obtain this (see comments at Alert Level 1).

Reporting and Communication

Reporting and communication focuses on both internal (relevant role-players) and external role-players (Department of Health, Department of Water Affairs and Forestry, customers and the general public) to ensure that information is shared and any actions are speedily taken and implemented. Refer to Section 4.6 for the appropriate communication requirements.

Emergency action

When the cyanotoxin (microcystins or nodularin or cylindrospermopsin) concentration in the drinking water is between 2.5 and 5 μg/ℓ for more than 8 days then an alternative drinking water source must be supplied.

OR

When the cyanotoxin (microcystins or nodularin or cylindrospermopsin) concentration in the drinking water exceeds 5 μg/L for more than 2 days then an alternative drinking water source must be supplied.

Stepping – down activation

When cyanobacterial scum formation in the source water is not evident for at least 14 consecutive days, the cyanotoxin (microcystins or nodularin or cylindrospermopsin) concentration in the drinking water is less than 2.5 µg/L for 14 consecutive days–and the mouse test bioassays are repeatedly negative for the drinking water then actions should be stepped-down to Alert Level 2.

Closing procedure

When the conditions as described for Alert Level 1 occur after a cyanobacterial incident, then the Response Committee should close the incident. This would include a formal report describing the incident, the actions that were taken and the recommendations for improvements to the CIMF as well as preventative actions. All role-players must receive the final communication of the closure of the incident.

4.4 CYANOBACTERIAL INCIDENT MANAGEMENT FRAMEWORK USING CHLOROPHYLL-*A* AS PRIMARY TRIGGER

This Cyanobacterial Incident Management Framework (CIMF) is also based on the Burch, WHO and Van Baalen models (Burch, 1993; Burch *et al.* 2003; Chorus & Bartram, 1999; Van Baalen & Du Preez, 2000) and consists of various stages of action alerts, namely: Routine monitoring ↔ Vigilance Level ↔ Alert Level 1 ↔ Alert Level 2 ↔ Alert Level 3 (Figure 4.5). Between the routine monitoring level and each action alert there are the primary (chlorophyll-*a* concentration), secondary (cyanotoxin concentration) and tertiary (mouse test bioassay) triggers, which activate the next level and allows for "movement" (step-up or step-down) between the routine monitoring level and the action alerts**. It is thus important to note that this CIMF uses chlorophyll-*a* concentration as the primary trigger.**

Routine Monitoring Level

Routine monitoring refers to monitoring of the variable chosen as the primary trigger for a specific drinking water supplier. The variable selected for this CIMF is chlorophyll-*a* concentration, which is performed on the source water sample from the abstraction point at least once every week. If the analysis can be performed more frequently that would be an advantage. When a drinking water treatment works is prone to experiencing cyanobacteriall/algal related problems, or has a history of problems during summer and autumn months in the source water it is recommended that chlorophyll-*a* is included in their routine source water monitoring program. Guidelines on sample taking, handling, storage, etc. can be found in the National Eutrophication Monitoring Programme publication (DWAF, 2002).

Analysis

Chlorophyll-*a* analyses should be performed at least once per week on the source water. It would be an advantage if this were done more frequently.

Stepping – up activation

When the chlorophyll-a concentration detected during routine monitoring exceeds 5 µg/L then the alert is stepped-up to the Vigilance Level.

Vigilance Level

Regular surveillance of source water

The reservoir (dam), lake or river from which the source water is abstracted should be surveyed for the development of colour and scum associated with a cyanobacterial bloom (excessive cyanobacterial growth). The first area that should be examined is the area around the abstraction point. When a reservoir or lake is the source water used by a drinking water treatment plant, it is a good practice to survey different areas in and around the dam (not just the abstraction area) for cyanobacterial bloom development. Areas close to the shore are usually good places to detect increased algal growth because of the concentration effect in shallow waters. The reason for "looking" for scum development in other areas of a reservoir is that many cyanobacterial species can concentrate in the upper layers of the water (because of the presence of gas vacuoles) and can quite easily be transported from one location in a dam to another by the wind. Therefore, even though cyanobacteria may not be spotted at the abstraction point, ~~it~~ this can easily change over a short period of time (within hours) by a change in the wind direction and thereby concentrate a bloom present in another area of the dam and transport it to the abstraction area.

When abstracting from a river it is usually difficult to detect the development of a cyanobacterial bloom because the flow of most rivers prevents bloom development at a single locality. Instead, the bloom develops as the water moves downstream and then appears at an abstraction point for a short period. In some slow-flowing rivers, if frequent monitoring is done, it is possible to detect the increase in cyanobacterial concentration over time. When a river has weirs or some natural impounded areas it is more likely that any cyanobacterial and algal problems will occur there if they are going to occur at all. People abstracting water along the rivers should establish a network between companies, the Department of Water Affairs and the local community (important to select a central coordinator) whereby the upstream users could notify the downstream users if a "pocket" of high cyanobacterial or algal biomass seen is moving downstream.

Analysis

Chlorophyll-*a* analysis must be performed on the source water at least three times a week. If the analysis can be performed more frequently that would be an advantage.

Cyanobacterial identification and enumeration analysis should be performed on the source water sample if the chlorophyll-*a* concentration exceeds 10 μg/L. If the Drinking Water Utility does not have the capacity to perform the cyanobacterial identification and enumeration analysis, it is important that the sample be outsourced to a company that does have the requisite capacity. Laboratories in South Africa that have the capacity to perform cyanobacterial and cyanotoxin analyses are summarised in Table 4.3.

Stepping – up activation

When the chlorophyll-a exceeds 10 μg/L and the cyanobacterial concentration of the source water exceeds 2000 cells/mL then the alert must be stepped-up to Alert Level 1.

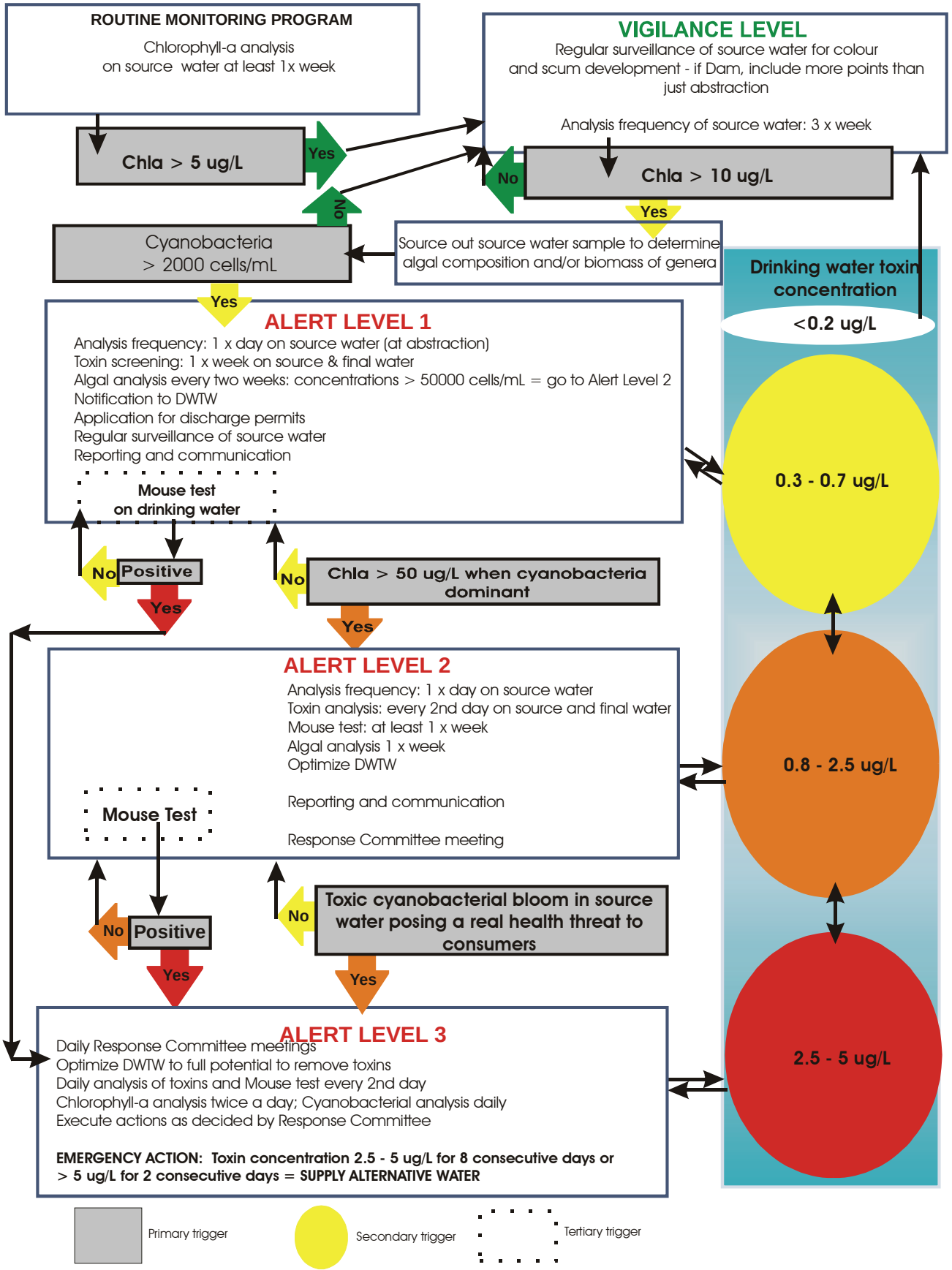

FIGURE 4.5: Cyanobacterial Incident Management Framework using chlorophyll-*a* concentration as a primary trigger.

Stepping – down activation

When the chlorophyll-a concentration detected in the source water is less than 5 µg/L for 14 consecutive days then the alert level is stepped-down to the Routine Monitoring Level.

OR

When no cyanobacterial concentration is detected in the source water sample then the alert level is stepped-down to the Routine Monitoring Level.

Alert Level 1

Regular surveillance of source water

Surveillance (as described under Vigilance level) of the reservoir (dam), lake or river from which the source water is abstracted should be conducted at least twice a week for the development of colour and scum associated with a cyanobacterial bloom (excessive cyanobacterial growth).

Analysis

Chlorophyll-*a* analysis must be performed daily on the source water at the abstraction point.

Cyanobacterial identification and enumeration analysis should be performed at least every two weeks on a source water sample. If the Drinking Water Utility does not have the capacity to perform the cyanobacterial identification and enumeration analysis, it is important to outsource the sample to a company that does have the requisite capacity (see Table 4.3)

Cyanotoxin screening/analysis

Cyanotoxin screening refers to the determination of cyanobacterial toxin concentrations by using either the ELISA technique for microcystins or the HPLC for the specific toxin standard available. It is important to perform a cyanotoxin analysis (the more comprehensive, the better, as appropriate management is more effective when the data are more representative) on the source and the final water. Results from the source water will indicate if there are any cyanotoxins present (which can be tested by a laboratory) and the final water will indicate how well the process is performing in removing these toxins (if at all) and will also indicate the potential risk to the consumer. The frequency of analysis should be at least once per week. If the Drinking Water Utility does not have the capacity to perform cyanotoxin analysis it is important to outsource the samples to laboratories that have the requisite capacity (see Table. 4.3)

Mouse test bioassay

Mouse test bioassays are performed to establish if a water sample has a toxic effect on a mouse. This effect is then translated to the effect that water sample may have when consumed by humans. A mouse test bioassay should be performed on the drinking water at least during cyanobacterial dominance in the source water. Should the dominant cyanobacterial species in the source water change over time then it is important to run the mouse test bioassay again to confirm that no other cyanotoxins are present. **Note:** In South Africa the mouse test bioassays for cyanotoxins are done only at the Onderstepoort Veterinary Institute in Pretoria (Table 4.3).

Notification to drinking water treatment works (DWTW)

The manner in which the "Notification to DWTW" will be executed will be defined proactively by the Response Committee (see Section 4.6), which would in turn be determined by the size and the

communication structures of the Drinking Water Utility. The notification should be documented and traceable and ideally should include the following:

- background information including historical data related to previous incidents
- current trends in the relevant water quality data related to the specific drinking water treatment works
- prediction in terms of immediate and short-term possibilities of cyanobacterial bloom formation
- recommendations for possible actions (e.g. ensure sufficient coagulant available, ensure staff are aware and ready to react at short notice, ensure all steps in the process are able to be optimised and are in working order, etc.) that can be taken into consideration in order to prepare for an cyanobacterial incident
- reference to the CIMF that has been developed for the specific drinking water treatment works

More information on notification and communication can be found in Section 4.5.

Discharge permits

Discharge permits from DWAF are necessary for any waste discharges into natural water systems. Should a cyanotoxin incident occur, it is likely that a decision will be taken not to recycle filter backwash water back to the head of the drinking water treatment works but to store the water on-site in holding dams or to discharge the filter backwash water into the river or reservoir/dam below the point of abstraction. No discharges are permitted without a valid permit. For more information it is recommended that the Department of Water Affairs and Forestry (DWAF) Regional Director in charge of the specific area be contacted for clarification on procedures and requirements. It is also recommended that the process of obtaining a discharge permit be initiated in a proactive manner (e.g. when the CIMF or the Water Safety Plan is developed), as it can be a very lengthy process.

Reporting and communication

The communication and reporting that must be initiated will have been defined proactively by the Response Committee (see Section 4.6), which would in turn be determined by the size and the communication structures of the Drinking Water Utility. It is important that a Drinking Water Utility has specified reporting and communication channels with regard to water quality problems (see Section 4.6 for a recommended structure for communication, which can be adopted as is or slightly changed according to the needs and capacities of the Drinking Water Utilities). Nevertheless, at this alert level there should already be some communication between the water quality coordinator, the specialist on cyanobacteria and drinking water treatment, the analytical laboratory staff and the drinking water treatment works manager (see Figure 4.6).

Stepping – up activation

When chlorophyll-a exceeds 50 µg/L and cyanobacteria dominant in the source water and their concentration exceeds 50 000 cells/mL then the alert must be stepped-up to Alert Level 2

OR

When the cyanotoxin (microcystins or nodularin or cylindrospermopsin) concentration in the drinking water exceeds 0.7 µg/L then actions should be stepped-up to Alert Level 2.

OR

When the mouse test bioassay is positive for cyanotoxins in the drinking water then actions should be stepped-up to Alert Level 3.

Stepping – down activation

When the chlorophyll-a concentration detected in the source water is less than 10 µg/L and the cyanobacterial concentration in the source water decreases to below 2000 cells/mL for at least 14

consecutive days, the cyanotoxin analysis (microcystins or nodularin or cylindrospermopsin) concentration in the drinking water is < 0.2 µg/L and the mouse test bioassays is negative for the drinking water then actions should be stepped-down to the Vigilance Level.

Note:

When stepping-up or -down from one alert level to the next it is important always to use the primary trigger (in this CIMF: chlorophyll-*a* concentration in the source water) as the default analysis to determine which actions to take. However, should the cyanotoxin concentration exceed the concentration limits of the alert level in which it is operating (based on the primary trigger) then the secondary trigger (cyanotoxin concentration) over-rides the primary trigger and the actions ~~as~~ should be performed at the alert level specified by the secondary trigger. Similarly, should the mouse test bioassay be positive, then the tertiary trigger (mouse test bioassay) over-rides the primary trigger and the actions should be performed at the alert level specified by the tertiary trigger. Should the concentration of the secondary trigger decrease to lower alert levels (or the tertiary trigger be negative repeatedly) then actions should revert back to the appropriate alert level as dictated by the results of the primary trigger.

Alert Level 2

Regular surveillance of source water

Surveillance (see also Vigilance Level) of the reservoir (dam), lake or river from which the source water is abstracted should be conducted daily at the abstraction point and surrounding area for the development of colour and scum associated with a cyanobacterial bloom (excessive cyanobacteria growth).

Analysis

Chlorophyll-*a* analysis must be performed daily on the source water at the abstraction point.

Cyanobacterial identification and enumeration analysis should be performed once a week on a source water sample. If the Drinking Water Utility does not have the capacity to perform the cyanobacterial identification and enumeration analysis, it is important to outsource the sample to a company that does have the requisite capacity (see Table 4.3).

Cyanotoxin screening/analysis

Cyanotoxin analysis is performed every second day on the source water and the drinking water (see also Section at Alert Level 1). If the Drinking Water Utility does not have the capacity to perform cyanotoxin analysis it is important to outsource the samples to laboratories that have the requisite capacity. Laboratories in South Africa that have the capacity to perform cyanobacterial and cyanotoxin analyses are summarised in Table 4.3.

Mouse test bioassay

Mouse test bioassay is performed at least once a week on the drinking water (see also Section at Alert Level 1). **Note:** In South Africa the mouse test bioassays for cyanotoxins are done only at the Onderstepoort Veterinary Institute in Pretoria (Table 4.3).

Optimisation of the drinking water treatment works

The optimisation that should be considered fall into the following broad categories: 1) actions on the abstraction of source water (e.g. manipulation of the depth of abstraction), 2) optimisation of the conventional treatment process (e.g. stop pre-treatment with oxidants, optimisation of coagulation, flocculation, sedimentation, filtration and flotation processes, optimisation of disinfections with chlorine) and 3) the use of advanced treatment processes (e.g. ozone and powdered activated carbon).

Additional information regarding these optimisation activities is provided in Chapter 3 of this document. It is recommended that the possible optimisation process be identified and tested in a proactive manner during the development of the CIMF for the specific Drinking Water Utility. If this has been done, the main focus would then be to ensure that the actions are implemented and are functioning optimally so that the Drinking Water Utility can effectively remove cyanobacterial and cyanotoxins from the source water whenever the cyanobacterial concentrations increase. This will also reduce the risk of reaching Alert Level 3.

Response Committee meeting

A meeting of the Response Committee is convened at Alert Level 2. The structure, roles and responsibilities of each member of the Response Committee would have been defined proactively during the development of the CIMF for the specific drinking water treatment utility. However, this would be dependent on the size and the communication structures of the Drinking Water Utility (see Section 4.5 for more information on the roles and responsibilities of the Response Committee).

At the first meeting it is important 1) to familiarize each member with the CIMF, 2) to clarify the roles and responsibilities and 3) to update contact information. The Response Committee discusses the current situation based on the available data, the appropriate actions that must be taken and identifies any problems that may hinder the implementation of the actions. Dates for feedback and follow-up meetings are set. Formal minutes of the meeting are kept.

Discharge permits

If the discharge permit has not been received from DWAF, the Response Committee decides on the course of action to obtain this (see comments at Alert Level 1).

Reporting and Communication

Reporting and communication focuses on internal reporting and communication to ensure that information is shared and actions are speedily taken and implemented. Refer to Section 4.5 for the appropriate communication requirements.

Stepping – up activation

When the cyanobacterial concentration in the source water consistently exceeds 100 000 cells/mL, are toxic and with scum forming in the source water then actions should be stepped-up to Alert Level 3.

OR

When the cyanotoxin (microcystins or nodularin or cylindrospermopsin) concentration in the drinking water is between 0.8 and 2.5 µg/L for more than 14 days then actions should be stepped-up to Alert Level 3.

OR

When the cyanotoxin (microcystins or nodularin or cylindrospermopsin) concentration in the drinking water exceeds 2.5 µg/L for more than 4 days then actions should be stepped-up to Alert Level 3.

OR

When the mouse test bioassay is positive for cyanotoxins in the drinking water then actions should be stepped-up to Alert Level 3.

Stepping – down activation

When the chlorophyll-a concentration detected in the source water is less than 50 µg/L and the cyanobacterial concentration in the source water decreases to below 50 000 cells/mL for at least 14 consecutive days, the cyanotoxin analysis (microcystins or nodularin or cylindrospermopsin) concentration in the drinking water is less than 0.8 µg/L and the mouse test bioassays are negative for the drinking water then actions should be stepped-down to the Alert Level 1.

Alert Level 3

Regular surveillance of source water

Surveillance (see also Vigilance level) of the reservoir (dam), lake or river from which the source water is abstracted should be conducted at least daily at the abstraction point and surrounding area for the development of colour and scum associated with a cyanobacterial bloom (excessive cyanobacteria growth).

Analysis

Chlorophyll-*a* analysis must be performed twice a day (early morning and late afternoon) on the source water at the abstraction point.

Cyanobacterial identification and enumeration analysis must be performed daily on the source water at the abstraction point. A depth profile of the cyanobacterial cell concentration in the source water column must be determined (if applicable, e.g. if water is abstracted from a dam), thereafter a series of at least 4 profiles over a 24 hour period must be performed to optimise the abstraction as the cyanobacterial cell concentrations may show diurnal depth variation.

Cyanotoxin screening/analysis

Cyanotoxin analysis is performed daily on the source water and the drinking water (see also Section at Alert Level 1). If the Drinking Water Utility does not have the capacity to perform cyanotoxins it is important to outsource the samples to laboratories that have the requisite capacity. Laboratories in South Africa that have the capacity to perform cyanobacterial and cyanotoxin analyses are summarised in Table 4.3.

Mouse test bioassay

Mouse test bioassay is performed at least every alternate day on the drinking water (see also Section at Alert Level 1). **Note:** In South Africa the mouse test bioassays for cyanotoxins are done only at the Onderstepoort Veterinary Institute in Pretoria (Table 4.3).

Optimisation of the drinking water treatment works

The drinking water treatment works should be optimised to its full potential for cyanobacteria and cyanotoxin removal. The following processes must therefore function at their optimal capacity: 1) the abstraction of source water (e.g. depth of abstraction manipulation or the use of an alternative source), 2) the conventional treatment process (e.g. stop pre-treatment with oxidants, optimisation coagulation, flocculation, sedimentation, filtration and flotation processes, optimisation of disinfections with chlorine), and 3) the use of advanced treatment processes (e.g. ozone and powdered activated carbon) and the discarding of filter backwash water. Additional information regarding these optimisation activities is provided in Chapter 3 of this document. The ultimate aim is to reduce the cyanotoxin concentration in the drinking water to less than 1 µg/L.

Response Committee meeting

The Response Committee should meet daily during this alert period to evaluate the success of measures implemented and to decide if further actions must be implemented. Special attention is given to solving optimisation problems that are being experienced, alternative actions that can be implemented and the communications with external role-players (Department of Health, Department of Water Affairs and Forestry, customers and the general public). Formal minutes of the meeting are kept.

Discharge permits

If the discharge permit has not been received from DWAF, the Response Committee decides on the course of actions obtain this (see comments at Alert Level 1).

Reporting and Communication

Reporting and communication focus on both internal (relevant role-players) and external role-players (Department of Health, Department of Water Affairs and Forestry, Customers and the general public)) to ensure that information is shared and any actions are speedily taken and implemented. Refer to Section 4.6 for the appropriate communications requirements.

Emergency action

When the cyanotoxin (microcystins or nodularin or cylindrospermopsin) concentration in the drinking water is between 2.5 and 5 µg/L for more than 8 days then an alternative drinking water source must be supplied.

OR

When the cyanotoxin (microcystins or nodularin or cylindrospermopsin) concentration in the drinking water exceeds 5 µg/L for more than 2 days then an alternative drinking water source must be supplied.

Stepping – down activation

When cyanobacterial scum formation in the source water is not evident for at least 14 consecutive days, the cyanotoxin (microcystins or nodularin or cylindrospermopsin) concentration in the drinking water is less than 2.5 µg/L for 14 consecutive days and the mouse test bioassays are repeatedly negative for the drinking water then actions should be stepped-down to Alert Level 2.

Closing procedure

When the conditions as described for Alert Level 1 after a cyanobacterial incident, then the Response Committee should close the incident. This would include a formal report describing the incident, the actions that were taken and recommendations for improvements to the CIMF as well as preventative actions. All role-players must receive the final communication of the closure of the incident.

4.5 RESPONSE COMMITTEE FOR THE CIMF

The establishment of a Response Committee is vital for the effective overall management of the CIMF. The Response Committee ensures that the role-players have a sound knowledge of the CIMF and are familiar with their responsibilities, that the actions as stipulated in the CIMF are implemented, that unforeseen problems/issues (technical; communication-related, etc) are speedily addressed, that all the necessary data and information are available and shared between the role-players, that there is effective internal and external communication and that the CIMF is updated as experience is gained. A typical Response Committee can comprise members with the following ability/authorization:

- Water Quality Coordinator (Coordinator of the CIMF)
- Management Representative from the Drinking Water Utility (authority to make highest level decisions)
- Person responsible for the day-to-day management of the Drinking Water Utility and who has authority to make decisions
- Person responsible for the sludge disposal plant and has who authority to make decisions
- The Drinking Water Utility chemist (to advise on water quality optimisation)
- Analytical laboratory representative (responsible for analysis of samples)
- Catchment management representative (responsible for discharge permits and catchment monitoring)
- Communication representative (responsible for external communication - media, other companies, Department of. Health, newspapers, etc.)
- Specialist on drinking water treatment
- Specialist on cyanobacteria and cyanotoxins.

It must be stressed that there is no fixed composition of representation on the Response Committee as it will depend on the size, reporting structure and the communication lines of the specific structures of the Drinking Water Utility. One representative can also fulfil more than one of the functions listed above.

Responsibilities – Water Quality Coordinator

The role of the Water Quality Coordinator (WQC) is to coordinate and communicate all information from the various sources to all the relevant stakeholders and to the Response Committee (See Figure 4.8). The responsibilities of the WQC can be summarised as follows:

- Summarise and organise all data and information and relate this to the CIMF to determine what actions should be taken.
- Initiate the appropriate actions by the relevant departments and/or persons identified in the CIMF. The notification of actions can be via the telephone followed by electronic or paper mail, to ensure and document the traceability of information and data.
- Keep all affected parties informed as to the progress of the cyanobacterial problem and give guidance on the application of the management framework.
- Initiate, convene and chair Response Committee meetings.

- During Response Committee meetings, give general feedback on the situation, actions taken and problems experienced.
- Ensure that minutes are taken and compiled during Response Committee meetings.
- Ensure that external communication *via* the media relation's representative has taken place. This communication must however first be authorized by the Response Committee.
- Ensure that all additional costs incurred by a cyanobacterial incident have been calculated and included in the final report.
- Ensure notification of the formal closure of an incident. The notification of actions can be telephonic followed by electronic or paper mail, to ensure and document the traceability of information and data.
- At the end of an incident compile and distribute a report that includes information on the actions taken, costs, effectiveness of various steps and probable improvements to the framework.

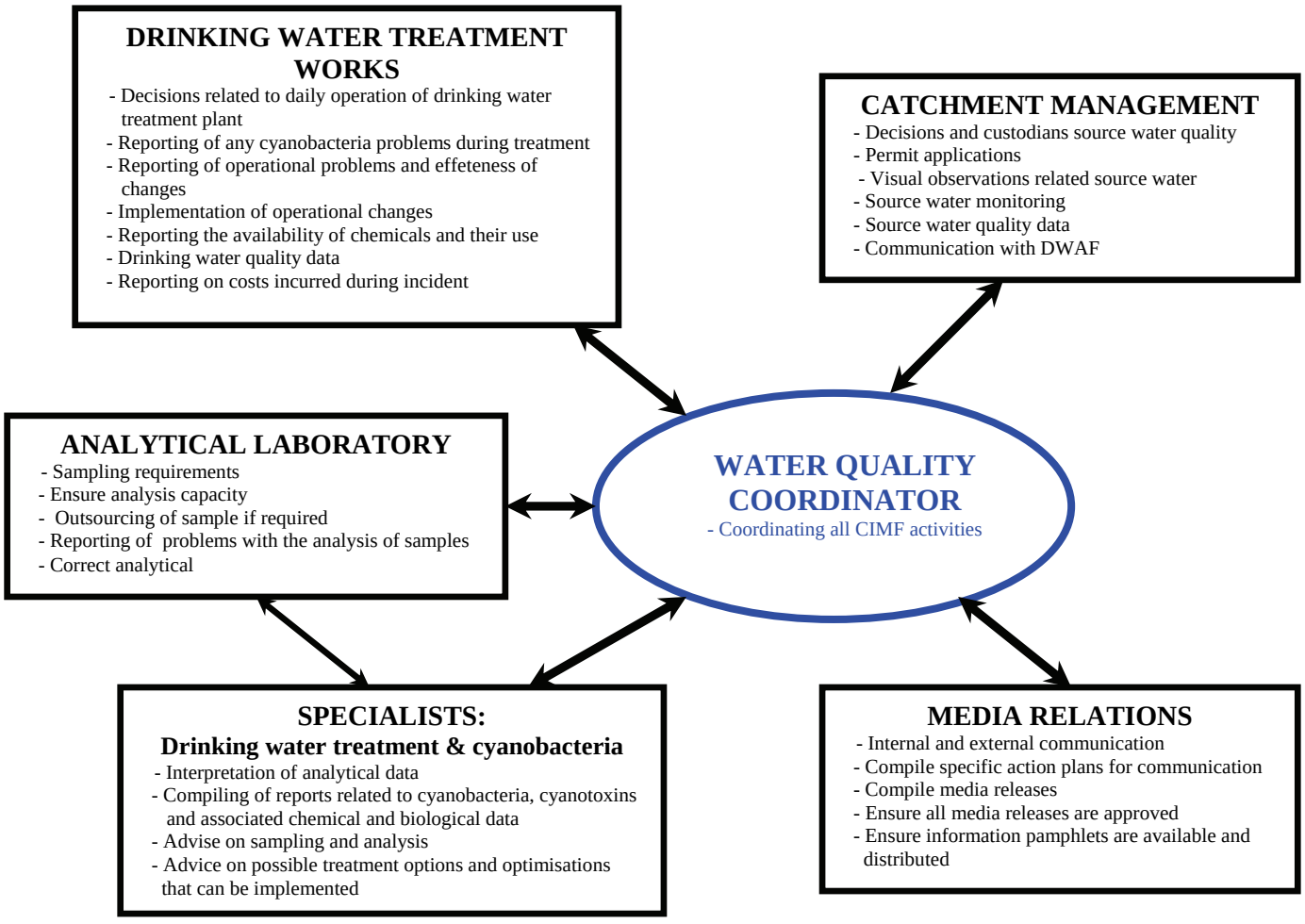

FIGURE 4.6 Possible communication channels for a CIMF

Responsibilities – Specialists

The specialists must have experience and knowledge of cyanobacterial ecology, cyanotoxins, drinking water treatment and the treatment of source water containing cyanobacteria and cyanotoxins. The responsibilities of the specialists can be summarised as follows:

- Interpretation of analytical data related to the cyanobacteria as they become available.

- Compilation of formal reports related to the cyanobacteria, cyanotoxins and associated chemical and biological data.
- Advise on occasional increases in the sampling frequency and sampling points.
- Ensure that the correct analyses are performed according to the specified requirements and procedures.
- Advise on possible treatment options and the optimisations that can take place.

Responsibilities – Analytical laboratory representative

The responsibilities of the Analytical Laboratory representative can be summarised as follows:

- Ensure that the analytical laboratory staff can perform the analyses according to the analytical requirements.
- Ensure that the samples are promptly processed.
- Ensure that analysis of the samples receives priority and that the data are promptly available to the specialists.
- Immediate notification of problems experienced with the receiving and/or analysing of the samples.
- Outsourcing of the samples if the analytical laboratory cannot perform the necessary analyses.

Responsibilities – Drinking water treatment works representatives

The representatives can include the treatment works operations manager, the drinking water treatment works chemist and the sludge disposal plant manager. Their responsibilities can be summarised as follows:

- Report on any cyanobacterial problems experienced at the drinking water plant to the Water Quality Coordinator.
- Ensure that the optimisation actions are communicated to operations staff members and are implemented.
- Report on the effectiveness of the optimisation actions that have been implemented.
- Advise on the improvement of the optimisation actions or alternatives that could be implemented.
- Report on the capacity of backwash storage, the toxicity of the backwash water and the disposed sludge.
- Ensure that all additional costs incurred because of a cyanobacterial incident are recorded and reported to the WQC.

Responsibilities – Catchment management representative

Depending on the company's structure and size it may or may not have a catchment management department. If there is no catchment management department, then the Drinking Water Utility must have a close relationship with DWAF for obtaining water quality information from the source water reservoir (dam), river or lake. Nevertheless, a specific staff member must be identified to have the following responsibilities:

- Be responsible for the application of the discharge permit. This permit is required if backwash water or water from the sludge plant must be retuned to the river or lake.
- Ensure that the visual observations stipulated in the CIMF are performed.
- Ensure that the source water monitoring is performed as stipulated in the CIMF.
- Ensure that source water quality data are available.

- Communicate the presence of a cyanobacterial bloom or cyanotoxin in source water, to the Resource Quality Centre of DWAF in Pretoria.

Responsibilities – Media Relations representative

The media representative will be responsible for communication with external parties and the general information sharing with internal staff members. The responsibilities of the media representative can be summarised as follows:

- Ensure that specified action plans are in place and used for communicating cyanobacterial water quality problems to governmental agencies (e.g. the Department of Health, Local authorities etc.), to clients, the general public and the media.
- Ensure that specific action plans are in place and used for communication with internal employees. Keep employees informed of the water quality, as they will probably be asked about the problems with the water in their circle of friends. It is good to have them trained as ambassadors for the company.
- Compile media releases and have them verified by the specialist (newspaper, magazines, radio, TV) and communicate them using the correct channels (stipulated by company) to the media of choice.

It is important to note that these communications cannot take place without the approval of the Response Committee.

Response Committee meeting agenda

A basic agenda for a Response Committee meeting are as follows:

- Welcome
- Brief situation summary by the WQC
- Brief overview of the Alert Levels framework
- Clarification of roles and responsibilities as required by CIMF
- Feedback by the Specialist on cyanobacteria
  - Graphs with cyanobacterial concentrations during the current season and graphs with concentrations of previous seasons (if available).
  - Prediction on cyanobacterial biomass/growth for the remainder of the season and the risk of the occurrence of cyanotoxins. Input from Catchment Management Representative.
  - Indication of the company's standing on the Alert Levels framework
- Water Quality Coordinator feedback
  - The company's standing on the Alert Levels framework
  - Feedback on measures that have been implemented to date. (Make sure that these are in line with recommendations provided in the Alert Levels framework)
  - Highlight problem areas.
- Feedback by the Drinking Water Treatment works representatives
  - Identification of envisaged optimisation problems
  - Recommendations on what should be done operationally to reduce the risk of going to a higher alert level.
- Open-floor discussion on:
  - The optimisation actions that should be applied, which must be in line with the CIMF
  - Alternative measures that are available but which are not included in the CIMF
- Feedback from the Media Relations representative

    - Clarification of communication channels as documented in the CIMF
    - Presentation of available communications documentation.
    - Identification of information needs (with sources and timing)
    - Confirm communication channels for the benefit of all.
- Summary by WQC of the main actions to be taken, and their links to the CIMF
- Date of the next meeting
- Closure

4.6 CONCLUSIONS

Cyanobacteria occur in many freshwater bodies that are also source waters for raw potable water. Cyanobacteria in the source water pose specific challenges to drinking water treatment managers as they have negative impacts on the conventional treatment process (i.e. ineffective coagulation, flocculation and sedimentation, penetration of sand filters, clogging of sand filters) and as the cyanobacteria produce cyanotoxins which can have an effect on human health. The drinking water utility can implement various actions, e.g. 1) optimising the extraction of source water, 2), optimising the conventional treatment process and 3) implementing advanced treatment processes to reduce the risk of exposing consumers to cyanotoxins. The seasonal, and in some cases sporadic, occurrence of cyanobacterial blooms in source water adds to the challenges to remove cyanobacteria and their toxins effectively during the treatment process. To assist drinking water treatment managers to meet these challenges several Cyanobacterial Incident Management Frameworks (CIMFs) have been developed; notably the Burch, WHO and Van Baalen models. These CIMF models describe monitoring and management action sequences that guide the Drinking Water Treatment Utility proactively to monitor the presence of cyanobacteria, to assess the treatment facilities capability to deal with cyanobacteria, to develop and implement action plans during the treatment of source water contaminated with cyanobacteria and to provide a graduated response to the onset and progress of a cyanobacterial bloom in source water. The CIMF models thus enable the Drinking Water Utility proactively to evaluate their capacity (skills, infrastructure, etc.) to deal with cyanobacteria and cyanotoxins and to develop their own CIMF to serve as guidance document to deal with cyanobacteria and cyanotoxins in the source water. The CIMF will also assist in improving the knowledge and understanding of cyanobacteria and cyanotoxins by the various role-players within the organisation.

CHAPTER 5
GENERAL CONCLUSIONS

In South Africa, as in many countries throughout the world, the proliferation of cyanobacteria (blue-green algae) in surface waters (e.g. reservoirs, rivers) plays a significant role in the production of drinking water, as many of these water bodies are sources for drinking water purification. The cyanobacteria in the source water can affect the drinking water treatment process (e.g. ineffective coagulation, flocculation and sedimentation, clogging of sand filters), as well as the quality (e.g. penetration of sand filters, the release of taste and odour compounds as well as toxic compounds) of water produced by the drinking water treatment plants. Although there are only a few recorded incidences of suspected human health effects caused by the toxic compounds (cyanotoxins) produced by the cyanobacteria, there are many incidences recorded of effects on animal health. The consequences of chronic exposure are unknown.

The possibility that drinking water is the cyanobacterial-exposure route has resulted in the development of drinking water guidelines and investigations into the effectiveness of the removal of cyanobacteria and cyanotoxins during the drinking water treatment process. These developments prompted many Drinking Water Utilities throughout the world to adopt the WHO provisional guideline for microcystin–LR (microcystin–LR 1 µg/L) or the derived guidelines based on their general approach. Many Drinking Water Utilities also implement various actions, e.g. 1) optimising the extraction of source water, 2), optimising the conventional treatment processes and 3) implementing advanced treatment process to reduce the risk of exposing consumers to cyanotoxins. However, in practice, drinking water treatment managers have found it difficult to implement these actions in a coordinated manner. The development of Cyanobacterial Incident Management Frameworks (CIMFs) notably the Burch, WHO and Van Baalen & du Preez models, bridges this gap and guides water treatment managers to deal pro-actively with cyanobacteria and their associated toxins in source water by using a step-by-step alert levels framework to ensure the provision of safe drinking water to the consumer.

In this report two CIMF models are described namely (1) a CIMF using cyanobacterial identification and enumeration as primary trigger, and (2) a CIMF using chlorophyll-*a* as primary trigger. These frameworks are based on the same principle but differ in minor actions taken, especially at the lower alert levels. The need for the CIMF based on the chlorophyll-*a* or colour is that drinking water suppliers in South Africa differ significantly in their capacity (amount of funding, type of infrastructure, skills and know-how, capacity available to perform operational tasks) to monitor and deal with cyanobacteria and cyanotoxins. It must however be stressed that the CIMF based on chlorophyll-*a* is not as specific as the phytoplankton CIMF and acts as more of a tool for screening the source water. Furthermore, there will be an increased risk of not detecting the cyanobacteria and their toxins at lower levels using the chlorophyll-*a* CIMF compared to the cyanobacterial identification and enumeration CIMF (Risk: chlorophyll-*a* CIMF > cyanobacteria identification and enumeration CIMF).

It is envisaged that the developed CIMFs would be the platform on which to evaluate the capacity to manage a cyanobacterial incident. Based on the requirements stipulated in the CIMFs and their assessment, the Drinking Water Utility would then develop and implement their customised CIMF. This process would not only ensure that the Drinking Water Utility has structures in place to deal with a cyanobacterial incident, but will also assist in improving the level of knowledge and understanding of cyanobacteria and cyanotoxins amongst the various role-players within the organisation.

Recommendations

The recommendations derived from this project are as follows:

- Development of technical courses in the field of identification and enumeration of cyanobacteria and phytoplankton in general. The target group should be the laboratory personnel associated with the Drinking Water Utilities.
- Development of a short training module on the monitoring, impacts and treatment of cyanobacteria and cyanotoxins as well as the development and implementation of CIMFs that can be incorporated in the formal training of drinking water plant operators or which could also be presented as short courses.
- Centres of excellence should be established at certain Drinking Water Utilities throughout South Africa that have the capacity 1) to identify and enumerate cyanobacteria, as well as phytoplankton in general, 2) to analyse cyanotoxins and 3) which have the technical knowledge to implement and manage CIMFs. This proposal is also contained in the WRC Strategic Plan for Algal Management in South Africa
- The implementation of a project on the screening for the production of Beta-N-methylamino –L-alanine (BMAA) by cyanobacteria in South African surface water..

CHAPTER 6
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