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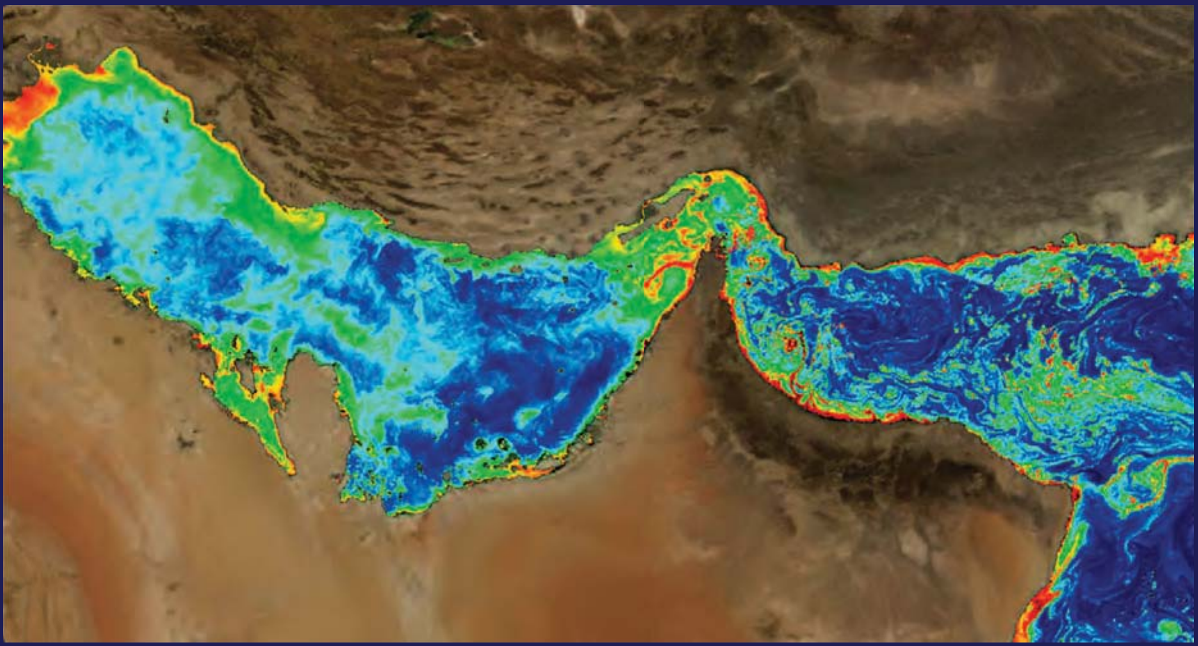
Harmful Algal Blooms (HABs) and Desalination: A Guide to Impacts, Monitoring, and Management



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8 WORLD HEALTH ORGANIZATION AND INTERNATIONAL GUIDELINES FOR TOXIN CONTROL, HARMFUL ALGAL BLOOM MANAGEMENT, AND RESPONSE PLANNING

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8.1 GUIDELINES AND STANDARDS

8.1.1 Drinking water guideline values for harmful algal bloom (HAB) toxins

8.1.1.1 Fresh- and brackish-water toxins

Drinking water guidelines are designed to protect public health and the safety of drinking water supplies by suggesting safe levels for constituents that are known to be hazardous to health. The World Health Organization (WHO) Guidelines for Drinking Water Quality (WHO 1996; 2004) represent a scientific consensus on the health risks presented by microbes and chemicals in drinking water and are often used to derive guideline values for individual countries, states or regions. The guideline values are to be used in the development of risk management strategies and are associated with guidance on monitoring and management practices.

Although no human deaths due to the consumption of cyanotoxins have been recorded, cyanobacteria and their toxins remain a significant issue for the WHO, since extended exposure may cause gastroenteritis, among other more serious health impacts (NHMRC/NRMMC 2011). In addition, cyanotoxins are suspected to have resulted in fatalities when introduced into the human body through routes other than ingestion, such as through the use of toxin-containing water for renal dialysis (Jochimsen et al. 1998).

Motivated by growing concern over the presence of cyanotoxins in drinking water, the WHO published an addendum to its Guidelines for Drinking Water Quality in 1998, which included a guideline value for microcystin-LR (MCLR), an acutely toxic cyanotoxin (WHO, 1998). The health-based guideline value for total (i.e., free plus cell-bound) concentration of MCLR was set at 1 µg/L; however, the WHO emphasizes that the guideline value is only provisional, since it only pertains to MCLR, and since the toxicity data for other cyanotoxins are still being collected (WHO, 2004). According to the WHO, not enough data exist to allow guideline values for other cyanotoxins to be developed (WHO 2004).

Concern over drinking water contamination by cyanotoxins has also grown among national regulatory bodies, due to the increasing impact of anthropogenic activity on water resources, as well as the improvement of analytical methods identifying and measuring cyanotoxins. For example, Australian drinking water authorities have set a guideline value of 1.3 µg/L for microcystins, expressed as MCLR. New Zealand has developed maximum allowable values (MAVs) for several cyanotoxins, including anatoxin and anatoxin-A, cylindrospermopsin, microcystins, nodularin, and saxitoxins. The US Environmental Protection Agency, on the other hand, has yet to set any firm, enforceable maximum contaminant levels (MCLs) for cyanobacterial toxins, and has only added cyanobacteria and their toxins to its candidate contaminant list (CCL), which prioritizes contaminants for setting MCLs. In Canada, a maximum acceptable concentration (MAC) of 1.5 µg/L has been developed for cyanobacterial toxins, expressed as MCLR. Canada’s guideline was derived using tolerable daily intake (TDI) values, determined using no-observed adverse effect levels (NOAEL), which are based on human or animal toxicity studies. Brazil has developed guidelines for three cyanobacterial toxins (microcystins, saxitoxins, and cylindrospermopsin), with guideline values being set as 1.0 µg/L, 3.0 µg/L, and 15 µg/L, respectively. Several other countries, however, still rely on the WHO provisional guideline of 1 µg/L MCLR.

A comprehensive summary of international guideline values for cyanobacterial toxins from various countries worldwide are summarized in Table 8.1.

8.1.1.2 Marine toxins

No toxin guidelines currently exist for drinking water produced specifically from the seawater that has been affected by HABs such as dinoflagellates and diatoms. As a result, operators must look to existing guidelines for drinking water produced from fresh water sources. In order to build knowledge of the potential for future guidelines, this chapter discusses the existing guidelines internationally for cyanobacterial toxins from fresh water. The WHO has a guideline specifically for microcystin-LR (1.0µg/L), a common analogue of microcystin, a toxin produced by several species of cyanobacteria. Other guidelines around the world (Table 8.1) have been determined in part by using this guidance. Relevant for seawater desalination are the guidelines for saxitoxin set by New Zealand (1.0 µg/L) and Brazil (3.0 µg/L). Outside the saxitoxin (STX) family, no guidelines exist as yet for other

Table 8.1. Guideline values or standards for cyanotoxins in drinking water from various countries. (From Newcombe et al. 2010, reproduced with permission from Water Research Australia and updated in 2015.)

Country	Guideline Value	Comments/Explanations
Argentina	Under revision	
Australia	1.3 μg/L total microcystins, guideline value	Australian Drinking Water Guidelines
Brazil	1.0 μg/L for microcystins; 3.0 μg/L for saxitoxins (equivalents); 15 μg/L for cylindrospermopsin	Guideline values for microcystins, saxitoxins and cylindrospermopsin, along with biomass monitoring programs. Guideline value for microcystins adopted as mandatory. Guideline values for equivalents of saxitoxins and for cylindrospermopsin included as recommendations. Use of algicides prohibited and toxicity testing/toxin analysis when cell counts exceed 10,000,000 cells/L or 1 mm^3 biovolume.
Canada	1.5 μg/L cyanobacterial toxins as MCLR MAC	Canada uses guidelines as the standard of water quality. The guidelines are expressed with the unit of Maximum acceptable concentrations (MAC). These are derived from tolerable daily intake (TDI), which in turn are derived from a calculated no-observed adverse effect level (NOAEL) from data from human or animal studies. To derive a MAC from a TDI, adjustments are made for average body weight and drinking water consumption, as well as other considerations. ln terms of health, the guidelines ensure that the MACs are far below exposure levels, at which adverse effects have been observed. For the case of cyanobacterial toxins, the guideline is considered protective of human health against exposure to other microcystins (total microcystins) that may also be present.
Czech Republic	1 μg/L MCLR	Value as national legislation, follows WHO provisional guideline value.
China	1 μg/L MCLR	WHO provisional guideline for microcystin-LR (MCLR)
France	1 μg/L MCLR	Drinking water decree
Italy	1 μg/L MCLR	WHO provisional guideline for MCLR used as a reference by local authorities.
Japan	1 μg/L MCLR	WHO provisional guideline for MCLR
Korea	1 μg/L MCLR	WHO provisional guideline for MCLR

Table 8.1 *(Continued)*

Country	Guideline Value	Comments/Explanations
New Zealand	MAV for cyanobactcrial toxins: - Anatoxin-a (S): 6.0 µg/L - Cylindrospermopsin: 1.0 µg/L - Microcystins: 1.0 µg/L - Nodularin: 1.0 µg/L - Saxitoxins: 1.0 µg/L	Maximum Acceptable Values (MAVs) for micro-organisms or organic determinants of health significance. MAVs are based on World Health Organization (WHO) Guidelines for Drinking Water Quality. They are the concentration of a determinant, which is not considered to cause any significant risk to the consumer over a lifetime of consumption of water. The method of derivation varies according to conditions and the way in that the determinant presents a risk. However, they are derived with the use of a TDI. The MAVs are standards in New Zealand. The standards provide compliance criteria and compliance is routinely monitored.
Norway	1 µg/L MCLR	Provisional WHO guideline for drinking water adopted
Oceana		Clean drinking water supply to all people main current focus
Poland	1 µg/L MCLR	National legislation for guideline value in drinking water
South Africa	0 to 0.8 µg/L for MCLR	Guideline levels for microcystins in potable water as a "Target Water Quality Range"
Spain	1 µg/L MCLR	National legislation, maximum permissible amount in drinking water
Thailand	No guideline currently	Awareness for need for guidelines
USA	None currently known	Maximum Contaminant Levels (MCLs) are the highest level of a contaminant that is allowed in drinking water. They are enforceable standards. Cyanobacteria and their toxins are listed as microbiological contaminants on the contaminant candidate list (CCL). This means that they are currently recognized as unregulated contaminants, but are known to occur in public water systems and may require regulation under the Safe Drinking Water Act. A new draft recommends Health Alert (HA) levels at or below 0.3 µg/L for microcystins and 0.7 µg/L for cylindrospermopsin in drinking water for children pre-school age and younger (less than six years old). For school-age children through adults, the recommended HA levels for drinking water are at or below 1.6 µg/L for microcystins and 3.0 µg/L for cylindrospermopsin.
Uruguay	Under revision	
WHO	1 µg/L MCLR	Refer to World Health Organization (WHO) Guidelines for Drinking Water Quality

commonly found seawater HAB toxins, such as the brevetoxins (BTX), okadaic acid (OA), and domoic acid (DA).

Some guidelines, such as the Australian Drinking Water Guidelines (ADWG) provide information and recommendations for several individual classes of toxins, but not necessarily a specific concentration of toxin. In this case microcystins, nodularin, saxitoxins, and cylindrospermopsin (NHMRC/NRMMC 2011). In the Australian case, a guideline value has been recommended only for total microcystins. The guideline recommends that the concentration of total microcystins in drinking water in Australia should not exceed 1.3 μg/L. No guideline values could be set for concentrations of nodularin, saxitoxins, or cylindrospermopsin in Australia due to the lack of adequate data. In relation to lipopolysaccharides (LPS) produced by cyanobacteria, there is currently insufficient information to carry out a critical assessment on occurrence and significance of LPS and so no fact sheet has been produced. The most recent review of the ADWG has now led to the recommendation that, although the strength of data is insufficient to establish a guideline value for cylindrospermopsin in drinking water, a range of information can be used to develop a 'Health Alert' value for cylindrospermopsin of 1 μg/L. The data used to develop this health alert came from a range of Australian toxicological studies, one of which provided sub-chronic oral doses of the toxin to mice and demonstrated responses to the toxins after an extended trial of 11 weeks (Humpage and Falconer 2002). The recommendation of a health alert acknowledges that health authorities should be notified if blooms of *Cylindrospermopsis raciborskii* or other producers of this toxin are present in water supplies.

Given that data pertinent to drinking water produced from the sea are very rare, it will take some time to establish guidelines for desalination. The process of establishing 'Health Alert' values could also be applied to relevant common seawater toxins or toxin families such as the brevetoxins, saxitoxins, okadaic acid, and domoic acid.

Further considerations to assist in establishing meaningful guidelines for HAB toxins in seawater desalination are the guidelines promulgated for shellfish harvesting based on acute toxicity following ingestion. Guidelines for toxins derived from marine HABs exist in Australia, New Zealand, and many other countries. The former are described by the Australian and New Zealand Food Authorities (ANZFA) (Todd 2011). ANZFA sets the following guideline values: paralytic shellfish poisoning (PSP or the saxitoxin family) 80 μg/100 g of edible shellfish, amnesic shellfish poisoning (ASP or domoic acid) 20 ppm, and diarrhetic shellfish poisoning (DSP okadaic acid and other toxins) 20 μg/100 g (Discussed further in Chapter 2). Although it is difficult to apply the latter values to drinking water, one could consider the minimum mass of shellfish consumed in a meal, and then compare that with a minimum volume of water consumed. For example, considering PSP, consuming a minimum of 10 g of shellfish would correspond to ingestion of 8 μg of saxitoxin. If one were to consume 100 mL of water containing the same 8 μg of saxitoxin, this would correspond to a concentration of 80 μg/L: however, guidelines for saxitoxins worldwide range from 1.0 to 3.0 μg/L, which suggests that it is far more prudent to work to these lower values when producing drinking water. The oral LD_{50} for humans is 5.7 μg/kg, so the average 80 kg person would need to ingest 456 μg of saxitoxin for the dose to be fatal. One would need to drink 5.7 L of water if guidelines for drinking water were based on shellfish guidelines or 456 L of water at the New Zealand drinking water guideline. Considering that small children are more susceptible to the toxin, as well as the fact that illness is common at far lower saxitoxin doses, 1.0 μg/L is a far more reliable guideline.

8.2 USING GUIDELINE VALUES

The guideline value is important for water supply authorities, as this value sets the concentration of toxin that is tolerable in drinking water, i.e. “at the tap”. For example, ADWG for cyanobacterial toxins in fresh or brackish waters are not mandatory standards; however, they provide a basis for determining the quality of water to be supplied to consumers in all parts of Australia. In this circumstance the guideline level is effectively a recommendation from the health authorities, although this situation is changing with the introduction of more prescriptive drinking water standards in some jurisdictions. For some water authorities in Australia the guidelines/standards become part of the *de facto* contractual standards. They are therefore required to comply with the guideline values as part of their standards of service.

For other countries the guideline level can be a standard that must be met and compliance monitoring may be required.

8.3 AUSTRALIAN DRINKING WATER GUIDELINES REGARDING MULTIPLE TREATMENT BARRIERS

8.3.1 What is the multiple barrier concept?

In the absence of guideline values for HAB toxins internationally, the best method for ensuring that toxin does not enter the drinking water distribution system is by employing the multiple barrier approach to treatment, which is well described in the Australian Drinking Water Guidelines (NHMRC/NRMMC 2011). The concept, which is widely recognized as the most effective approach for producing safe drinking water, aims to improve a water treatment train’s reliability by employing multiple treatment processes in series. Providing multiple treatment processes, or barriers, ensures that when one process fails or partially fails, the performance reduction can be compensated for by other processes in the treatment train. Ideally, all treatment barriers should be operating effectively to ensure that a water treatment plant is performing optimally. Since it is likely that individual barriers are not effective 100 percent of the time, however (NHMRC/NRMMC 2011), employing multiple barriers against contaminants ensures that produced drinking water remains of a high quality, even if one of the treatment barriers becomes compromised. In addition, using multiple barriers expands the range of contaminants removed by a water treatment train, also referred to as robustness, since individual barriers typically target different groups of contaminants (Crittenden et al, 2005). The number of barriers required, as well as the types of barriers employed, depend largely on how acute the source water contaminants are, with more acute contaminants requiring more barriers (Crittenden et al. 2005). In addition, understanding both the challenges that contaminants may present, as well as any vulnerabilities associated with the treatment barriers, plays an important role in barrier selection (NHMRC/NRMMC 2011).

Although the multiple barrier concept places a great deal of emphasis on treatment processes, other barriers that help ensure safe drinking water are equally important, such as source water selection and protection, as well as safe water transportation and storage (Bixio and Wintgens 2006). ADWGs recognize the importance of these barriers, stressing that “understanding a water supply system from catchment to consumer, how it works, and its vulnerabilities to failure” are an integral part of the multiple barrier concept (NHMRC/NRMMC 2011). Furthermore, ADWGs highlight the importance of including “mechanisms or fail-safes to accommodate inevitable human errors without allowing major failures to occur” when applying the multiple barrier concept (NHMRC/NRMMC 2011).

Seawater reverse osmosis (SWRO) plants are inherently a multi barrier treatment process for certain feedwater contaminants. As discussed in Chapter 9, pre-treatment processes provide an added barrier for toxin removal in addition to the core reverse osmosis (RO) treatment. This allows intracellular toxin removal upstream of the RO step and thus less dependence on this process as a sole toxin removal mechanism. In addition, many plants that commonly experience HAB blooms are in the Gulf and have a full or partial second pass. Chlorination of treated waters in the distribution system provides an added barrier for some toxins such as saxitoxin (Laycock et al. 2012).

8.3.2 Monitoring as a barrier

Once barriers are in place to protect public health, regulatory bodies need to ensure that those barriers are performing effectively. To this end, ADWGs identify drinking water quality monitoring as the ultimate test to confirm whether employed treatment barriers, or other preventative measures, are effectively protecting the public from consuming unsafe drinking water (NHMRC/NRMMC 2011). Additionally, ADWGs emphasize that drinking water quality monitoring should be performed on a frequent basis, so as to identify the failure of any treatment processes, or other measures, in a timely manner (NHMRC/NRMMC 2011).

In addition to monitoring drinking water quality, operational monitoring of treatment processes plays an important role in ensuring that safe water is delivered to consumers (refer to Section 8.4.3 below – HACCP). According to ADWGs, operational monitoring aims to ensure that all existing treatment barriers, and other water safety measures, are performing as desired (NHMRC/NRMMC 2011). For example, monitoring of RO permeate for conductivity can be used as a surrogate for failure of the RO (see Chapter 10). As with drinking water quality monitoring, operational monitoring should be performed regularly so that any detected process deficiencies can be corrected promptly. To this end, continuous, online monitoring is the most desirable form of operational monitoring, and should be implemented wherever practical (NHMRC/NRMMC 2011). This ensures that ineffective treatment barriers, such as a damaged membrane, can be recognized and addressed immediately, preventing unsafe drinking water from reaching the public. In the event of an emergency, such as the discovery of a ‘bloom’ event in the source water, monitoring frequency should be increased to ensure that barriers are effectively protecting consumers.

Validation monitoring is also vital to protecting the public from consuming unsafe drinking water. Unlike operational monitoring, validation monitoring aims to assess newly added treatment barriers, and ensure that they are performing effectively. For example, if a new activated carbon column were to be added to a water treatment train, the column’s effluent would need to be tested to confirm whether or not contaminants, such as toxins, are continually removed over time. Validation monitoring is particularly important when adding treatment processes that have not been implemented onsite previously, and have not been tested by the manufacturer (NHMRC/NRMMC 2011). In such cases, validation monitoring gives plant operators a chance to verify any assumptions regarding process performance, and to ensure that all desired contaminants are effectively removed. Where a treatment process has been tested by the manufacturer (i.e., pre-validated), validation monitoring should still be performed; however, the treatment process need not necessarily be tested before it is brought online in the water treatment plant, assuming that onsite water characteristics are not substantially different from those used in manufacturer testing (NHMRC/NRMMC 2011).

All forms of monitoring play a significant role in managing risk in a waters supply system. As a result, a monitoring strategy requires careful consideration of numerous factors, including which variables should be monitored, what data should be collected, and how collected data should be used to mitigate risk (NHMRC/NRMMC 2011). Furthermore, it is important that a monitoring strategy be developed with mechanisms in place to incorporate monitoring information into decision-making processes affecting the water supply system (NHMRC/NRMMC 2011). Finally, for all forms of monitoring, it is essential that monitoring data are compiled, analyzed, and reported in a timely manner to ensure that corrective measures can be taken before unsafe drinking water is delivered to the public (NHMRC/NRMMC 2011).

In summary, by checking that all treatment processes and other barriers are performing effectively, monitoring in and of itself represents an additional barrier, preventing unsafe drinking water from reaching consumers. Effective implementation of the multiple barrier concept thus requires integrating an effective monitoring program with a reliable, robust treatment train, along with sufficient preventative measures.

8.3.3 Multiple barriers in the context of HAB toxins

Employing multiple barriers against HAB toxins is a high priority, particularly due to their acute toxicity. Such barriers can be comprised of a wide range of treatment processes, preventative measures, and monitoring strategies.

In terms of treatment barriers, numerous processes have been developed to remove HAB biomass and their toxins from drinking water (Chapters 9,10). These aim to remove HAB cells (which can include cell-bound toxins), and can also remove dissolved (i.e., extracellular) toxins, depending on the treatment technology considered. For example, treatment using coagulation and dual media filtration removes a significant portion of cell-bound toxins from drinking water (Hrudey et al. 1999). Dissolved toxins, on the other hand, are not effectively removed using pre-treatment processes and are better targeted using reverse osmosis, oxidants, such as chlorine for some toxins, or activated carbon adsorption (Hrudey et al. 1999; Laycock et al. 2012). Where multiple treatment processes are employed, process interactions must be considered, since upstream treatment processes may result in cell damage, which leads to significantly higher levels of dissolved toxins. For example, chlorination of the intake will result in cell lysis and therefore higher concentration of dissolved toxins. Therefore, treatment processes leading to cell damage are not recommended unless a subsequent process is included to remove dissolved toxins (Newcombe et al. 2010).

A comprehensive monitoring strategy serves as the final barrier between HAB toxins and consumers. Monitoring toxins can, however, be challenging, since instrument-based analytical methods used to measure toxins are time expensive and consuming, required limits of detection are extremely low, and analytical standards used to quantify many toxins are lacking (WHO 2004). Consequently, analyzing toxins using sophisticated instruments such as liquid chromatography/mass spectroscopy (LC/MS) and high performance liquid chromatography (HPLC) is not likely for routine monitoring in desalination plants. On the other hand, source water monitoring using rapid screening methods for toxins (see Appendix 2) presents a practical alternative. Steps might include visually checking source water for indications that a HAB has occurred or may be imminent, or sampling of source waters to screen for potentially toxic or harmful species (Chapter 3).

8.4 RISK ASSESSMENT FOR THE PRESENCE OF HABS

Risk assessment is the process of using available information to predict how often identified hazards or events may occur and the magnitude of their consequences. Risk can be assessed at two levels: maximum risk in the absence of preventative measures and residual risk after consideration of existing preventative measures (Nadebaum et al. 2004).

8.4.1 Risk assessment

Formal risk assessment is often carried out under the auspices of official government agencies. Such risk assessment also typically draws on knowledge from a group of scientists, including chemists, toxicologists and statisticians. Risk evaluation is considered an iterative process and includes the following steps:

(i) Public call for data
(ii) Hazard identification
(iii) Exposure assessment
(iv) Hazard characterization
(v) Review of the status of detection and quantification methods
(vi) Review of toxicological and epidemiological data
(vii) Risk characterization
(viii) Recommendations for management and monitoring

In the case of new or emerging risks, it is common that an initial risk assessment is carried out, leading to a provisional management procedure. After some time, the effectiveness of this procedure is then reviewed and, possibly in combination with new toxicology and occurrence data, a new management procedure or trigger level may be put in place. Thus, risk assessment should be considered to be an iterative process.

Based on previous risk assessments and current knowledge of HAB occurrence, it is clear that algal toxins should be considered as an identified hazard in drinking water derived from seawater (Caron et al. 2010; Laycock et al. 2012; Boerlage and Nada, 2014; Berdalet et al. 2015). Thus, the main objective of this section is to discuss potential exposure and assess risk.

For several toxin groups described above, such risk assessments have been carried out by the European Food Safety Authority (EFSA 2008a, b, 2009a, b, c, d, e, f, g, 2010a, b, c, d; EFSA (EFSA Panel on Biological Hazards (BIOHAZ) 2012; FSAI 2006; Lawrence et al. 2011), in particular for exposure through the consumption of bivalve molluscs. Note that some discrepancies between current legislation and risk evaluation for several toxins groups in shellfish have been established in recent risk evaluation exercises by EFSA, as shown in the summary report (Table 8.2). For drinking water, so far only microcystin-LR has been formalized and regulated as a hazard by WHO (2004). This guide has also established 2 L as a maximum quantity of water that can be consumed as one portion in a day.

The maximum amount of a toxin or contaminant that a human may be exposed to without ill effects is referred to as the ARfD. ARfDs or *safe doses* have only been established for four marine toxins (saxitoxin, domoic acid, okadaic acid, and azaspiracids by EFSA) and for microcystin-LR (indirectly by WHO). Table 8.2 shows the current European Union (EU) limits for selected algal toxins in shellfish meat, ARfD and recommended maximum levels based on a representative portion of shellfish consumed. As not many reports are available for the occurrence of toxins in seawater, it was not possible to make probabilistic exposure assessments, so worst case assumptions of these five toxin groups used for assessment are provided here. The data used were collated from laboratory culture data on toxic HAB species described in Chapter 1, as well as from the studies described in Chapter 10 showing 99% rejection of dissolved toxins. The rationale for this approach is given below.

To assess risk, the amount of toxin that might be retained in treated water needs to be compared to the ARfD or safe dose values. The two components to be considered in this regard are the extracellular and intracellular toxins. Some studies report measurements of both categories of toxin in seawater, but most do not. For saxitoxin, a very polar compound, extracellular levels ranged from 12 to 31 µg/L in *Alexandrium* cultures studied by Lefebvre et al. (2008), who also reported a maximum extracellular STX level of 0.8 µg/L during an *Alexandrium* bloom in the field. Previous culture studies of cyanobacteria and dinoflagellates have reported extracellular STX levels of 50 to 75 µg/L (Hsieh et al. 2000; Velzeboer et al. 2001). For domoic acid, a toxin actively excreted by diatoms, a dissolved concentration of 3.3 µg/L has been reported (Liefer et al. 2013; Trainer et al. 2009), but much higher levels have also been observed. Kudela (pers. comm.) measured total and extracellular concentrations of 100 and 50 µg/L domoic acid respectively during a massive *Pseudo-nitzschia* bloom along the US west coast in 2014. Half of the measured toxin was extracellular. One study estimated extracellular okadaic acid concentrations during blooms of 0.2 µg/L (Takahashi et al. 2007), whereas another study measured only low background levels of okadaic acid in a coastal lagoon (Zendong et al. 2015). In contrast, Smith et al. (2012) reported that 60% of the okadaic acid produced by *Dinophysis* cultures was extracellular. Microcystin concentrations from terrestrial runoff in coastal water have been recently estimated to be around 1.4 µg/L (Kudela 2011; Miller et al. 2010).

These are just a few of the many studies that report toxicity values for HAB species cultures or for natural waters during blooms, and clearly there are many differences in the amounts of toxin that might be in intra- versus extracellular form. Given the large variability in these published data from different locations and conditions, the toxicity differences between strains of a given species, the variation in toxicity that occurs with different forms of nutrient limitation or environmental stress, and the different levels of population biomass achieved under varying growth conditions (see Chapter 1), simplifying assumptions are needed to constrain HAB risk assessments. Here a hypothetical approach is taken, in which laboratory-derived cellular toxicity data for the most toxic species producing the major HAB toxins are attributed to a dense bloom of those species. In Chapter 1 (Table 1.4), these calculations were performed for three possible bloom types – 100,000, 500,000, and 5,000,000 cells/L, representing moderate, large, and extreme HABs for most species. For this conservative analysis, the extreme bloom level is used to estimate maximum exposure levels and safety factors for treated water. For a bloom of this size, the highest calculated total toxin levels for saxitoxin, domoic acid, okadaic acid, and azaspiracid are 600, 335, 294, and 0.1 µg/L respectively (calculated in Chapter 2).

Chapters 2, 9, and 10 discuss the relative ease of removal of intracellular versus extracellular toxins. A variety of pretreatment steps like ultrafiltration and dissolved air flotation (DAF) will remove cells, and thus intracellular toxins, but they are not very effective in removing the dissolved or extracellular fractions. It is clear that on occasion, 50% or more of the toxin produced by HABs can be extracellular, and to this, one would add the toxin that is released by physical and chemical processes during pretreatment. Again, in order to err on the conservative side, it will be assumed that 100% of the toxin from a bloom of 5,000,000 cells/L will be dissolved and will reach RO membranes, where 99% removal will occur in a single pass. Results are tabulated in Table 8.3. A similar calculation could be made for thermal desalination systems, in which most cases there is no pretreatment and HAB cells will be degraded by temperature and pressure, releasing toxin (Boerlage and Nada 2014). A toxin removal of 99% in thermal systems could also be assumed for this calculation (toxin removal efficiencies are discussed in Chapter 10).

Table 8.2. Current European Union (EU) limits for selected algal toxins in shellfish meat (= total flesh), acute reference doses (ARfD) and recommended maximum levels based on a 400 g portion of shellfish consumed (adapted from (EFSA, 2009f)).

Toxin group	**Current EU limits in shellfish meat (SM) [a]**	**Exposure by eating a 400 g portion at the EU limit [c]**	**Exposure by eating a 400 g portion at the 95th percentile of the concentrations in samples currently on the EU market**	**Acute reference dose (ARfD[e])**	**Exposure corresponding to the ARfD by eating a 400 g portion [c]**	**Derived conc. in shellfish meat (B)**	**Ratio of B/A**
Okadaic acid (OA) and analogues	160 µg OA eq/kg SM[a]	64 µg OA eq/person (1 µg OA eq/kg b.w.)	96 µg OA eq/person (1.6 µg OA eq/kg b.w).	0.3 µg OA eq/kg b.w.	18 µg OA eq/person	45 µg OA eq/kg SM	0.28
Azaspiracids (AZA)	160 µg AZA eq[c]/kg SM	64 µg AZA1 eq/person (1 µg AZA1 eq/kg b.w.)	16 µg AZA1 eq/person (0.3 µg AZA1 eq/kg b.w.)	0.2 µg AZA1 eq/kg b.w	12 µg AZA1 eq/person	30 µg AZA1 eq/kg SM	0.19
Saxitoxins (STX)	800 µg STX eq/kg SM[b]	320 µg STX eq/person (5.3 µg STX eq/kg b.w.)	< 260 µg STX eq/person (< 4.3 µg STX eq/kg b.w.)	0.5 µg STX eq/kg b.w	30 µg STX eq/person	75 µg STX eq/kg SM	0.09
Domoic acid (DA)	20 mg DA/kg SM	8 mg DA/person (130 µg DA[d]/kg b.w)	1 mg DA/person (17 µg DA/kg b.w)	30 µg DA/kg b.w	1.8 mg DA/person	4.5 mg DA/kg SM	0.23

[a] SM whole uncooked shellfish meat, For OA, dinophysistoxins and PTX, current regulation specifies a combination; however the CONTAM Panel concluded that PTX should be considered separately.

[b] eq. = equivalents: In the Commission Regulation (EC) No 853/2004 a limit value of 800 µg PSP/kg SM is given. In the EFSA opinion, the CONTAM Panel adopted this figure as being expressed as µg STX equivalents/kg SM.

[c] the 400 g portion has been derived from the European consumption databases, it represents the 95 %ile; The CONTAM Panel assumed that AZA equivalent should refer to AZA1 equivalents.

[d] Applies to the sum of DA and epi-DA.

[e] ARfD = Acute reference dose

Table 8.3. Acute risk of poisoning from drinking desalinated water assuming 100% of the toxin in a major HAB is dissolved or extracellular.

Toxin	**Theoretical safe dose [a] (µg)**	**MPL [c] (µg/L)**	**Extracellular toxin concentration, (µg/L) [d]**	**Safety factor, raw intake water [e]**	**Safety factor after 99% rejection [f]**	**Concentration to detect in drinking water [µg/L] [g]**
Saxitoxin	30	15	600	0.025	2.5	0.15
Domoic acid	1,800	900	335	2.7	270	90
Okadaic acid (and DTXs)	18	9	577	0.016	16	0.9
Azaspiracid	12	6	0.1	60	6000	0.6
Microcystin [b]	2	1	1.4	0.7	71	0.1

[a] The theoretical safe dose is calculated based on the ARfD by EFSA (Summary Opinion, 2009); it refers to a 60kg person.

[b] Safe dose for microcystin separately derived from WHO guideline. Extracellular concentration estimated from Kudela 2011; Miller et al. 2010.

[c] MPL = Maximum permissible level; based on a consumption of a 2-L dose of desalinated water.

[d] Assumes that 100% of the total toxin from a dense bloom (5,000,000 cells/L) of the most toxic species producing each toxin is extracellular.

[e] The safety factor is the ratio of the MPL to the extracellular concentrations of each toxin. Safety factors greater than 1 indicate a safety margin. Safety factors below 1 indicate a higher risk.

[f] This assumes 99% rejection by the SWRO and thus considers only a single pass and no problems with the membranes.

[g] This concentration is arbitrarily set at 1/10th of the MPL or maximum permissible level

To explain the calculations in Table 8.3, a focus on saxitoxin is offered. The safe dose of STX that may be consumed (30 µg) has been established from a number of cases reported for shellfish poisoning (Table 8.2). Given the 2-L quantity of daily drinking water established by WHO, a maximum permissible level of STX in drinking water of ca. 15 µg/L (15000 ng/L) can be derived. (Note that some national guidelines have established lower, more conservative health alert guide for STX based on discrepancies in safety factors to convert a lowest observed adverse effect levels (LOAEL) to a NOAEL). If 100% of the toxin produced by a 5,000,000 cells/L bloom of a saxitoxin-producing species were to occur near a desalination plant, a safety factor of 2.5 can be calculated assuming that 100% of the toxin is extracellular, and that there is 99% toxin removal during treatment. Risk would thus be considered moderate. (Safety factors greater than 1 indicate a safety margin, safety factors below 1 indicate a high risk). A similar moderate-risk safety factor is calculated for okadaic acid, with other toxins at much safer levels. Given that many RO plants are two-pass systems, the calculated residual risk will all drop dramatically (~100-fold if the system is full two pass, care should be taken with partial two pass systems) after full treatment, giving some reassurance on the risks posed by algal toxins in desalinated drinking water; however, the uncertainty associated with these safety factor calculations is large.

The final column in Table 8.3 indicates the analytical levels of detection needed in order to detect the maximum permissible level (MPL) of these toxins in treated water. This can be helpful to plant operators in choosing analytical or screening

8.4.2 Assessing the likelihood of HABs in a water source

Information on the importance and interrelationship of environmental variables has been used in a range of ways to determine the likelihood of the growth of HABs and the development of blooms in particular areas. A range of approaches has been used to undertake risk assessments and these have been variously termed ‘susceptibility’ or ‘vulnerability’ assessments. For marine HABs, there have been assessments prior to the construction of plants as part of environmental impact statements and design risk assessments, but typically, these will be based on site-specific factors such as the prior history of HAB occurrence or the total phosphorous and nitrogen concentrations in the region. Another factor to consider is the transport pathway that might bring established blooms from elsewhere to the vicinity of a desalination plant. There is, however, no specific standard protocol or framework for risk assessments for HABS and desalination similar to those that exist for freshwater cyanobacteria. Each phytoplankton species has a different set of favorable conditions that promotes its growth and reproduction, and many different species can potentially cause problems with desalination operations (see Chapter 1). The two most important nutrients for phytoplankton growth are the elements nitrogen (N) and phosphorus (P), which are found naturally in aquatic environments in various concentrations. In freshwater, it has been possible to identify concentration levels at which the risk of cyanobacterial blooms is rare, infrequent, occasional, frequent and persistent, and frequent and persistent/strong. This risk assessment approach was developed in Australia to assess water bodies for their susceptibility to cyanobacterial contamination and is found in the National Health and Medical Research Council (Australia) ‘Guidelines for Managing Risks in Recreational Water’ (NHMRC 2006). This technique is based upon empirical observations in Australian reservoirs and from the range of literature studies on the variables influencing cyanobacterial growth. No such compilation exists for marine algae.

8.4.3 Hazard Analysis and Critical Control Point (HACCP)

The fourth edition of the World Health Organization (WHO) drinking water guidelines (WHO, 2011) advocates a risk management approach to water quality based on the multi-barrier approach and the development of Water Safety Plans based on the Hazard Analysis and Critical Control Point (HACCP) methodology, to assure safe drinking water. The HACCP system was developed for NASA in 1959 to ensure food safety for their manned space program as it was recognized that relying solely on end point testing was inadequate. Instead HACCP was developed to take a systematic preventative approach to addresses hazards through anticipation and prevention. Subsequently, HACCP evolved into a universally accepted risk management framework by the *Codex Alimentarius* Commission (Codex, 2003) established by the WHO and the United Nations Food and Agricultural Organization for the implementation of their food standards program. Since its codification, HACCP has been widely used in the food and beverage industry as a quality assurance management strategy.

Havelaar (1994) discussed the application of the HACCP methodology for drinking water supply. The HACCP system is now increasingly being incorporated into national drinking water guidelines and regulations to assure safe drinking water. In the drinking water context, Critical Control Points (CCP) are defined as process steps at which control can be applied and are essential in preventing or eliminating the water quality health hazard or reducing it to an acceptable level (WHO). For example, in surface water treatment, coagulation and media filtration may be defined as CCPs for the removal of *Giardia*. In drinking water treatment when the term ‘barrier’ refers to a CCP, it can be considered a critical barrier.

Due to the potency of the marine algal toxins, notably saxitoxin, there are clearly identifiable microbiological hazards in seawater desalination with a potential detrimental impact on human health. Boerlage and Nada (2014) described the use of HACCP in examining the fate of marine toxins in desalination plants and the potential (residual) risk in desalinated drinking water. The latter is also addressed in Chapter 9. The application of the HACCP framework for controlling marine toxins in SWRO and thermal desalination plants and preventing the risk of failure of CCP that may lead to toxins in the desalinated water is further described below.

Within the HACCP framework defined by *Codex Alimentarius*, five preliminary steps are detailed followed by the seven principles of HACCP, summarized in Figure 8.1. In conducting a HACCP assessment for a seawater desalination plant, a multidisciplinary team should be assembled covering a range of expertise including specialists in some of the following areas; water quality, public health, desalination process engineers, plant operators, maintenance managers, risk assessment specialists trained in HACCP, representatives from the plant owner. In areas where HAB are prevalent, a HAB specialist would be recommended. The team would be tasked to develop, verify and implement the HACCP plan. Ideally, the team would meet prior to the detailed design process and therefore include designers. A follow up workshop during commissioning and operation would help to continuously develop and improve the HACCP plan.

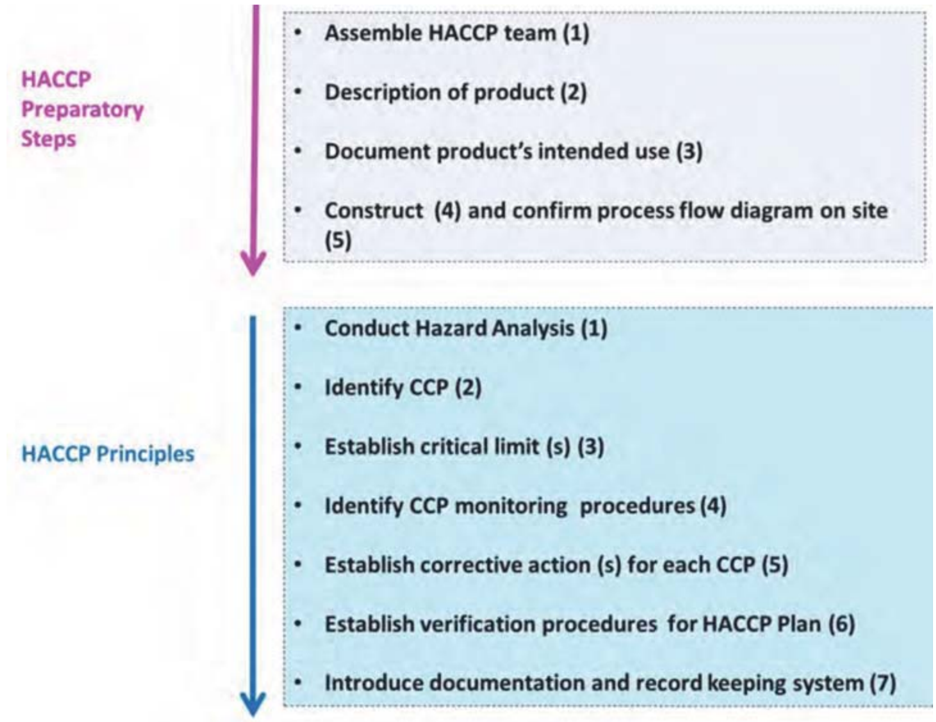

Figure 8.1. HACCP Framework comprising five preparatory steps and the seven principles of HACCP.

The drinking water (product) would then be described, examining the source raw water, specifications for chemicals used, treatment, storage and any standards the drinking water must meet – i.e. plant water quality specifications, national and/or international drinking water guidelines and its intended use – potable, industrial etc. For seawater desalination plants, the source seawater may have been characterized in a seawater quality study as described in Chapter 5 where the potential for HABs to occur would have been investigated.

In the final preparatory step, a process flow diagram (PFD) for the SWRO or thermal desalination plant would be developed which is critical in proceeding through the formal HACCP process. The process flow diagram would document the incoming raw seawater catchment and all entry pathways into the process that could lead to contamination (e.g., coagulant addition, storages, unit process steps to treat the seawater and produce desalinated drinking water, and waste treatment processes). The PFD needs to be verified as an accurate representation of the plant treatment process and modified as required during the life of the plant to document any changes.

In developing a HACCP plan, all potential chemical, physical and microbiological hazards and hazardous events which may impact on human health are identified, their fate in the plant process is determined using the PFD as a reference point and the hazards are inventoried. Focusing on a toxic marine algal bloom event and the release of toxins (a microbiological hazard), the risk associated with this event would be evaluated in the source water with controls and no controls in place through a typical risk assessment framework. Assessing the risk with no controls in place is essentially drinking seawater, which is highly unlikely, (carrying with it its own risk), but it allows the maximum risk to be determined.

The assessment would semi-quantitatively rate the likelihood of the occurrence of toxins in seawater based on categories, ranging from rare to almost certain, and their consequences, ranging from insignificant to catastrophic, each with a score increasing in severity from 1-5. A score of 1 for likelihood could be defined as a toxic HAB only occurring in ‘exceptional circumstances’ (at <1% or once in a hundred years), where ‘almost certain’ might represent a chance of >95%. A typical risk assessment matrix is shown in Table 8.4. The likelihood and consequences of a water quality hazard can be subjective and interpreted differently. In such a subjective case, the worse case scenario should be assumed.

As discussed above and in Boerlage and Nada (2014), it remains difficult to predict both the likelihood of marine toxins occurring at a desalination plant intake and then being entrained and thus their potential health consequences. Further, even if a bloom is detected at the intake by online monitoring of water quality parameters (Chapter 5), or through remote satellite sensing (Chapter 4), these methods cannot discriminate between toxic and non-toxic HABs. Algal identification, enumeration, and toxin analyses (Chapters 2, 3 and Appendix 2) would be required to confirm the toxicity of the bloom. Assessing the health consequences of a toxic bloom with or without controls in place is even more difficult, as the potency of each marine toxin varies. In addition, there are few water quality guidelines for marine toxins (see Section 8.1). Hence, it is difficult for an operator to assess human health consequences. Consequences considered in addition to human health in such risk assessments would typically include public perception, commercial, reputation, financial loss and legal. Other hazards and/or hazardous events for a desalination plant would be assessed, rated and risks prioritized for further evaluation. The net result of a water supply risk assessment would likely classify marine toxins as “moderate to very high” and a significant risk prior to treatment for plant operation and would therefore assigned priority for examination.

Table 8.4. Matrix scoring risk factors as low (L), moderate (M), high (H) and very high(VH).

		Consequences				
		Insignificant (1)	**Minor (2)**	**Moderate (3)**	**Major (4)**	**Catastrophic (5)**
Likelihood	Rare (1)	H	H	VH	VH	VH
	Unlikely (2)	M	H	H	VH	VH
	Possible (3)	L	M	H	VH	VH
	Likely (4)	L	L	M	H	VH
	Almost certain (5)	L	L	M	H	VH

In the second part of the risk assessment, the residual risk of marine toxins in desalinated drinking water with barriers (control measures) in place and the adequacy of these barriers are determined. SWRO desalination plants are typically multi-barrier schemes, and there are one or more barriers for algal cells and intracellular toxins (e.g., coagulation and granular media filtration) to reduce the risk. The efficiency of intracellular toxin removal and these barriers depends on: i) the effect of process parameters that may rupture the cell wall, such as mechanical shear, pressurization, or chemical oxidation (chlorination); and ii) the inherent nature and strength of the algal cell wall. Whereas, thermal plants typically only have screening prior to the multi-stage flash distillation (MSF) and multiple-effect distillation (MED) processes, and hence a single barrier. Should the HACCP team consider the residual risk as unacceptable, additional barriers would be required to mitigate the residual risk.

Critical control points are then identified amongst the barriers, defined, as above, where control can be applied at a step and which is essential in eliminating marine toxins or reducing their concentration to an acceptable level. Critical control points can be a process step, or a point in the system or procedure. Codex provides a decision tree approach (not mandatory) to consistently and logically identify CCPs through a sequence of questions shown in Figure 8.2.

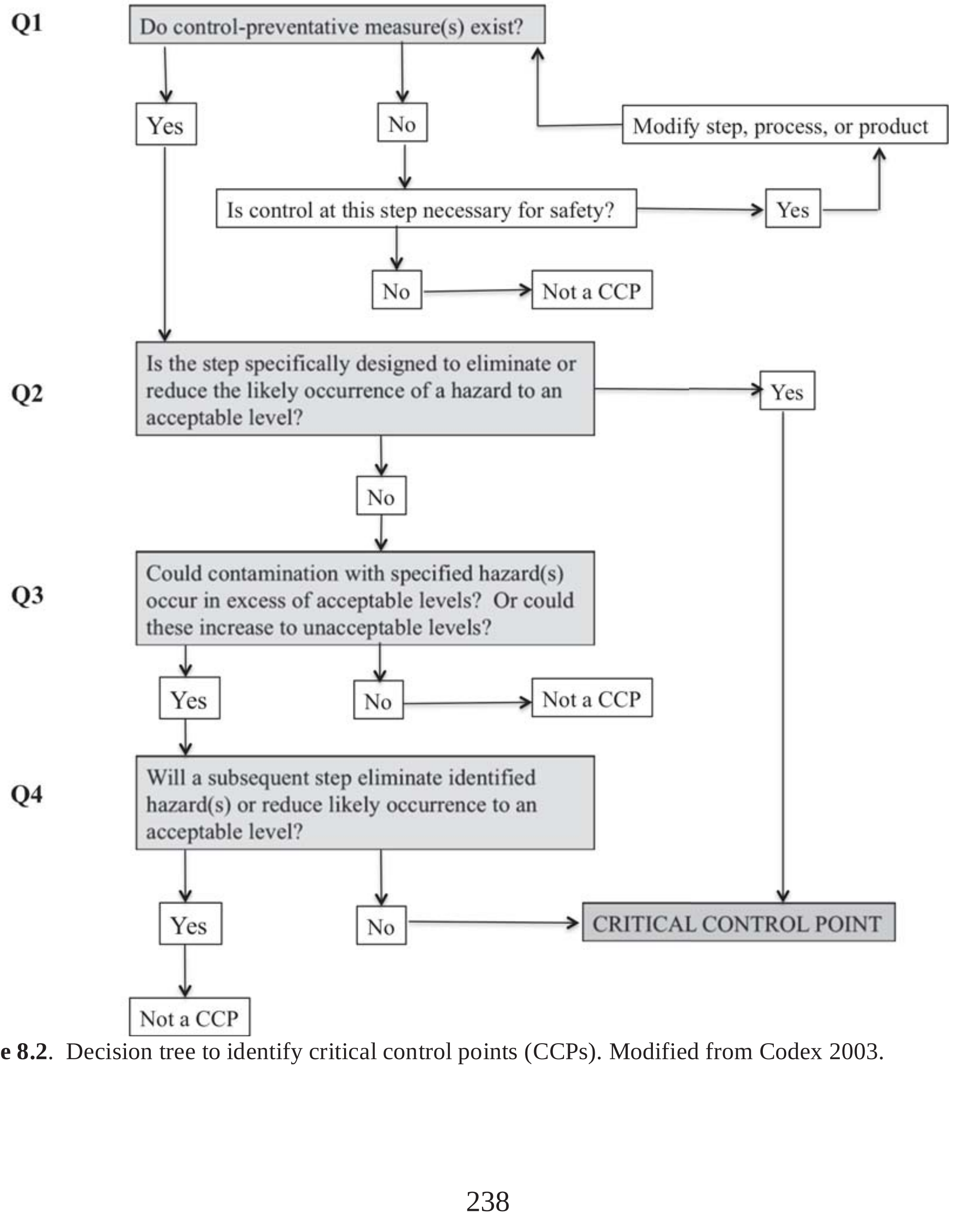

Figure 8.2. Decision tree to identify critical control points (CCPs). Modified from Codex 2003.

None of the pretreatment barriers in a typical SWRO desalination plant scheme (i.e., conventional pretreatment coagulation and flocculation, granular media filtration followed by cartridge filtration or ultrafiltration membrane pretreatment) would be deemed as critical control points when answering the four questions in the Codex decision tree. While these barriers may remove intact algal cells (and thus the intracellular toxins), none would act as a reliable barrier to remove extracellular algal toxins, nor meet the definition of a CCP.

Hence, following the decision tree approach, the RO step is the first critical control point in SWRO plants for removal of extracellular algal toxins. If a SWRO desalination plant operates a second-pass brackish water RO system to desalinate the water further, then this would be classed as the second critical control point. Similarly, for MSF and MED desalination plants, the thermal desalination step would be the critical control point to prevent algal toxins from contaminating drinking water.

Once CCPs have been determined, the HACCP framework requires the establishment of critical limits and monitoring to assess whether the CCPS are under control. Critical limits are defined as criteria that separate acceptability from unacceptability (i.e., safe and unsafe operating conditions at a CCP). Maintaining operation within the critical limits demonstrates a CCP is working and ensures safe drinking water. Breaches in a critical limit allow failures of a CCP to be detected which would result in an increase in the residual risk and trigger documented corrective actions, operating procedures etc. to bring the CCP back under control. Alerts can be set which are more conservative than critical limits, thereby allowing a timely response to rectify deviations prior to the critical limit being breached. Ideally, monitoring of the CCP and its critical limits should be continuous, using online measurements to allow monitoring of the CCP in real time and a rapid response by the duty operator in the control room. Further, parameters tending towards loss of control can be detected and provide an accurate record for verification.

Ensuring the integrity of both SWRO membranes and thermal desalination processes using critical control points is paramount for the removal of marine toxins. Integrity loss for SWRO membranes may occur due to membrane failure, defective interconnections, O-rings, etc. Membrane integrity would be continuously monitored in SWRO plants by conductivity as a surrogate for salinity to detect any leakage. Alert and critical limits, based on conductivity would be defined specific to a plant, its design, level of instrumentation and treated water storage. For example for a single pass system treating salinity of 35, an alert may be triggered when the conductivity of the RO permeate from a single RO train exceeds 400 µS/cm for more than 2 hours and an alarm when the combined RO permeate conductivity from several trains exceeds 400 µS/cm for more than 2 hours.

Similarly, in MSF and MED systems direct carry over from the seawater to the distillate must be limited to the greatest extent possible. Seawater and potential algal toxin carry over may occur due to possible joint leakage or tube failure allowing bypassing of the separation process or the displacement of demister pads (used to separate the entrained brine liquid droplets entrained with the vapor and to allow the vapor to pass through the mesh). The integrity of the tubes and joints can be checked and confirmed by hydro testing; however, failures are readily identified by rapid increases in distillate conductivity as the rejection of salts was demonstrated to be similar to marine toxins in the work of Laycock et al. (2012).

Should the conductivity increase in either a SWRO desalination or thermal plant approach, the alert, or critical limits, documented corrective actions would be taken in line with the fifth principle of the HACCP framework. Corrective actions would be established aimed at identifying and eliminating the cause of the deviation in conductivity to bring the CCP back under control. No unsafe desalinated water would be delivered should the CCP be out of control. With duty operators appropriately trained in HACCP, the processes and instruments would be directed to documented operating procedures associated with each alert and alarm. For a SWRO plant, corrective measures could include verification that RO permeate conductivity instruments were reading accurately using a handheld conductivity meter. Corrective measures could also include checking differential pressure, recovery and normalized flows. Should the conductivity reading be correct then conductivity profiling of RO modules may be amongst the corrective measures outlined and/or the RO permeate could be rejected and isolated and the RO train could be shut down. In the case of a prolonged HAB event, the alert and alarm levels could be reduced further to ensure a higher salt removal efficiency and corresponding removal of toxins. Corrective actions and reporting of CCP alarms may be integrated into the plant's incident and response plans.

The penultimate HACCP principle is to establish procedures to verify the HACCP system is working effectively. This encompasses a range of tools from internal and external auditing of procedures by qualified third parties, routine calibration checks of online CCP instrumentation (conductivity), operational checks, random sampling and analysis, recording CCP deviations, corrective actions, and follow up actions (Codex 2003).

The final HACCP principle requires accurate record keeping of HACCP documentation sufficient to verify that the HACCP controls are in place and being maintained. These include recording a hazard register, the risk assessment, determination of CCP, CCP monitoring activities, deviations, and associated corrective actions such as verification procedures performed and importantly modifications to the HACCP plan (Codex 2003). The HACCP plan would be integrated into the plant's operating systems.

8.5 ALERT LEVEL FRAMEWORKS

An 'Alert Level Framework' (ALF) is a monitoring and action sequence that operators can use for a graduated response to the onset and progress of HABs in a seawater source. All HABs should be treated with caution until the absence of toxicity in the treated water is confirmed, or advice based upon past local knowledge indicates the absence of hazard.

The ALF described here is a generic model; however, it is possible to translate the format for monitoring and management of HABs in waters used for other purposes such as recreation and agriculture. The level thresholds, indicators, and actions for each specific area or plant would be different and would need to be developed based upon appropriate local guidelines and risk assessment procedures. The following framework acts as an example and basis for further development by specific plant operations staff.

The ALF is a situation assessment tool based upon data from cell counts and other observations that can be used in conjunction with the relevant drinking water guidelines for toxins to assess the potential hazard from a bloom. The rationale for the use of cell counts to prompt management actions is that, for most practical purposes, cell counting is the fastest and most relevant way to detect algal-related water quality problems (Chapter 3). This is because cell counting is not too difficult for plant staff to undertake, and provides relatively rapid and cost-effective information. By contrast, reliable biotoxin testing is still sufficiently complex such that most desalination plants will not have a local capability. If samples are sent out for analyses, there can also be a slow turn-around time for results. Note, however, that highly sensitive antibody-based kits are now available for many of the algal toxins (see Appendix 2), so it is possible to do preliminary screening on site at a plant, with samples showing positive results being sent off site to qualified analytical facilities for confirmation.

The cell counts are regarded as an indicator or "surrogate" for a potential toxin or organic/fouling hazard. They do not replace toxin or organic carbon analyses, which are required for health risk assessment or for pre-treatment decisions, but rather are used as relatively conservative triggers in the management plan. The counts can be used to prompt toxin or biomass screening, which can then be assessed to determine the hazard and risk to plant operations. Cell counts are directly useful for determining the optimal operation of the plant and for implementing mitigation strategies to accommodate the higher volumes of biomass. If recorded properly and archived, they also provide useful information to guide future operational decisions on pretreatment strategies.

The framework given below is developed from the perspective of the plant operator. The circumstances and operational alternatives for use with the ALF will vary depending upon the source of supply and water treatment barriers available. The associated monitoring program for HABs will also be site- and season-specific. Further, the monitoring program will depend upon the level of expertise of the operators, and on the degree of access to cell counting, toxicity testing and analytical capacity for toxins, organic exudates, and other parameters. The progress through this sequence, particularly in relation to consultation and warnings, will vary depending upon the water source parameters such as the arrangement of the intake.

8.5.1 History of Alert Level Frameworks

The concept of the ALF was first developed for algal management in South Australia in 1991, and modified and adopted nationally in 1992. It was subsequently adopted and used internationally by the WHO as a model system for response to cyanobacterial blooms (Bartram et al. 1999), and has been adapted by other users to incorporate recreational and agricultural waters. The ALF given here is an updated version of the earlier Australian model which now references the Australian Drinking Water Guidelines for microcystin toxins in particular (NHMRC/NRMMC 2011). In this Chapter, the ALF concept has been adapted for use in seawater desalination systems and has been expanded to consider biomass as well as toxin. The generic Alert Level Framework described here was originally developed for tracking populations of potentially toxic *Microcystis aeruginosa* using cell counts as a surrogate for the toxin hazard. The use of ALFs in seawater desalination is a potential management tool, but requires optimization to be plant specific.

8.5.2 Using an Alert Level Framework

The ALF follows the development of a potentially toxic or disruptive HAB through a monitoring program with associated actions in four stages called Alert Levels. The actions accompanying each level include additional sampling and testing, operational interventions, consultation with health authorities and other agencies, and customer and media releases. The sequence of Alert Levels is based upon initial detection of HAB cells at the Detection Level, progressing to moderate HAB numbers at Level 1, where notification, operational readiness, additional sampling, and assessment of toxicity may occur. For the next stage at Level 2, the higher cell numbers can indicate the potential for the occurrence of toxins above guideline concentrations (or potential guideline values). Alert Level 2 represents the point where the operators may decide to take further action regarding operations within the plant to deal with biomass. This would follow a full health assessment and depend upon circumstances such as availability and performance of water treatment, consumption patterns, etc. It is possible of course that an operator may decide to issue advice or a notice at cell numbers lower than that equivalent to the guideline. The sequence can also continue to escalate to Alert Level 3 for very high biomass in the seawater. This level represents the situation where the potential risk of toxin in the seawater is significantly increased and treatment processes may break down due to heavy biomass loads. Alert Level 1 and 2 ideally require an assessment of toxicity and toxins in the seawater and assessment of both the drinking water and the performance of the treatment system for toxin removal.

8.5.3 Levels of the framework

8.5.3.1 Derivation and definition of the levels

Cell toxin quotas in natural populations will be highly variable and the relationship between toxin concentrations and cell numbers will not necessarily be valid for different species or populations (see Chapter 1, Table 1.4); however, the cell number assumptions below are regarded as reasonable for the purpose of preliminary hazard assessment in the absence of toxin testing.

8.5.3.2 Detection level

This level encompasses the early stages of bloom development, where HABs are first detected at low levels in raw water samples. The cell numbers for this level are somewhat arbitrary, and as an example may be $\underset{\sim}{}$ 100,000 cells/L.

Taste and odors may become detectable in the supply, although this does not necessarily indicate the presence of toxic HABs. If a routine monitoring program is not in place, this is the appropriate time to collect and deliver samples to a laboratory for confirmation of the presence of HABs. If there is no routine program the recommendation for monitoring is to commence weekly sampling and cell counts at representative locations in the water body. The presence of low population densities of HABs could still mean there is the potential for the formation of localized surface scums or subsurface accumulations, and operators should regularly inspect intake areas visually, or if not possible, inspect shoreline areas for scums or discoloured water.

Alert Level 1

Alert Level 1 represents the level at which the HAB population has become established, and localized high numbers may occur.

An example threshold for this level might be a cell number of 1,000,000 cells/L.

The definition for Level 1 is relatively conservative and has been chosen to indicate a point that represents a cell density providing a buffer, or time margin, of a few days before the guideline for toxin concentration in raw water might be exceeded (i.e. Level 2 conditions). This is based upon a population doubling rate of 4 days.

Alert Level 1 may require notification and consultation with health authorities and other agencies for ongoing assessment of the status of the bloom. Although contact with health authorities is recommended when this level is reached, it may not be required on a weekly basis if local conditions deem this unnecessary. For instance, if the dominant algal species present is not known to be a problem based on prior testing and experience, this alert level can be adjusted to suit the local situation.

The requirement for toxicity assessment at this level will depend upon advice and discussion with health authorities. It will also depend upon circumstances such as: whether the HAB is a known toxic species, cell concentrations that might be dangerous (see Table 8.3), past history of toxicity, nature of the supply and associated water treatment, local sensitivity in relation to this supply, or other factors. This consultation should be initiated as early as possible and continue after the results of toxicity testing and toxin analyses become available.

The water (if a potentially toxic species is present) should be sampled to establish the extent of the spread and patchiness of the bloom. Special samples (concentrated surface layers and/or plankton net tow samples representative of the raw water intake) should be collected and used for rapid toxin screening (Appendix 3), and/or dispatched for toxicity testing or toxin analysis.

In consideration of biomass, this level may warrant operational actions such as analysis of the pre-treatment performance or re-commissioning of the DAF system if this has previously been bypassed. Operators should be made aware of the situation and discussion regarding changes to pre-treatment made. Shock chlorination of the intake should be suspended where possible. Other plant-specific actions should be discussed that pertain to a readiness to act rapidly if Alert Levels escalate.

Alert Level 2

Alert Level 2 is the next stage at slightly higher cell numbers of potentially toxic HABs. The threshold for Level 2 (in the absence of toxin information) is cell numbers and/or biovolume that could indicate the potential for a toxin hazard at or above the guideline level in the seawater if the population was highly toxic, and all toxins were released from the cells and pre-treatment is ineffective for their removal. Some guideline values for this determination are given in Table 8.3.

This level is characterised in general terms by an established bloom with moderately high numbers showing a trend upwards over several successive samples at sampling frequencies of at least twice per week. The HAB population is likely to have developed to the extent that localised surface discoloration may be observed, though this does not always happen.

An example threshold for this level might be a cell number of 2,000,000 cells/L.

Alert Level 2 represents the point where the operators and health authorities may need to monitor the product water for relevant toxins to ensure toxin-free water is being delivered to customers. It is also possible that an operator may decide to issue advice or a notice at cell numbers lower than these thresholds, taking into account public safety.

It may be acceptable to continue to supply drinking water from the seawater even with a positive toxicity result, dependent upon a risk assessment by the health authorities that may recommend specific action to protect more susceptible population groups. As the removal of toxin should be in excess of 99% using RO, some health authorities may consider allowing continuation of supply. During this stage, direct toxin measurements are critical for the decision process, emphasizing the needs to develop a capability for reliable toxin screening by plant staff (Appendix 2), and to identify outside laboratories that can rapidly do toxin analyses.

When considering the effect of biomass on the plant, the operational interventions at this level are the same as those for Alert Level 1, with the addition of some minor changes to operating parameters, such as backwash frequency of DMF and UF units. Diurnal operation of the intake (off during the day and on at night) may provide some amount of protection from the bloom, depending on the depth of the intake, and the swimming or surface aggregation behavior of the HAB species (Chapters 1 and 6). Operation conditions should be discussed to allow for changes, but have some operational capacity in reserve to allow for Alert Level 3.

Alert Level 3

The cell number for Level 3 represents a minimum cell number that could produce ten times as much toxin as any international guidelines. This describes an established toxic bloom with high cell numbers and possibly localised surface accumulations. The sampling program outside the plant (Chapter 3) will have indicated that the bloom is widespread with no indication of a HAB population in decline in the short term. Conditions in Level 3 are indicative of a significant increase in the risk of adverse human health effects if water is treated by an ineffective pretreatment system.

An example threshold definition for Alert Level 3 is cell numbers of $\geq$ 5,000,000 cells/L.

The cell count at Level 3 can be a trigger for the immediate notification of health authorities, but this would only be in a situation where this has not occurred earlier (at Level 1 or 2). This would occur where there was no prior information from an ongoing monitoring program, treatment is limited, or its performance for toxin removal is untested. This could be a scenario where a one-off sample or result is the initial discovery of a major bloom in the source water. By definition, the circumstances for Level 3 are that there is potential for adverse public health outcomes if these high numbers are present in the source water or supply. When combined with failures of the treatment system, a single pass RO system or thermal system, the population sensitivity, and public water consumption patterns, a Level 3 incident has potential for serious public health issues. High cell numbers also mean there is potential for much higher localised concentrations, i.e. surface accumulations. Depending upon the position of the intake, this could then mean that very high cell numbers could be entering the supply for short periods and this may not be captured by the monitoring program.

In consideration of biomass removal, the full extent of the operational plan for HAB mitigation should be deployed at this point. At the selected cell concentration for Level 3, diurnal operation of the intake may no longer provide protection for the plant, again, depending on the vertical migration behavior of the HAB species. Shock chlorination should definitely be ceased, DAF should be fully operational where installed, and jar tests undertaken to establish conditions for maximum cell removal without damage to algae cells. If ultrafiltration is available, the backwash strategy should be reviewed and pre-coagulation used if possible to maximize time between backwashes, avoid algal organic material seeding biofouling on the RO, and to avoid irreversible fouling. If lower fluxes can be used by operating more UF units in parallel, this should be undertaken. Jar testing for GMF pre-coagulation should be undertaken and filter rates revised. Continual analysis of RO normalized permeate flux, normalized salt passage and differential pressure should be undertaken. The product water should be continually monitored at this Alert Level for the specific toxins to confirm their removal in the interest of public health.

In the unlikely event that seawater treatment barriers simultaneously fail and toxin removal is unsatisfactory, toxins present in the product water at concentrations significantly above suggested guidelines for Level 3 may result in the activation of a contingency water supply plan that is appropriate for the operator and the system. This may involve switching to an alternative drinking water supply for human consumption, or in some circumstances the delivery of safe drinking water to consumers by tanker or in bottles. More extensive media releases and provision of appropriate advice via direct contact with customers may be necessary. Where advice is provided to the public because of a toxin hazard to human health it may be appropriate to indicate that the water would be suitable for purposes such as washing, laundry, toilet flushing. Complete shutdown of a public drinking water supply because of a toxin hazard in source water is not likely to be justified since potential hazards from disruption of supply (public hygiene and fire-fighting, etc.) are likely to be worse than the toxin hazard.

Monitoring of the bloom in the intake and in coastal waters adjacent to the plant should continue, to determine when it is in decline, so that normal operation and supply can be resumed. Given the patchiness in marine HAB populations, monitoring at daily or every other day intervals is sometimes warranted. Experience suggests that the cell concentrations and thus the toxicity of a HAB population can change dramatically from day to day, but it will likely take a week or two, and sometimes more to dissipate completely.

The sequence of actions at Level 3 should follow through to deactivation of an emergency with advice and media releases to confirm the decline of a bloom. It is possible that the collapse of a bloom, or management action such as flushing and control of surface accumulations, could lead to a rapid decline from Level 3 back to Level 1 or beyond. Likewise, the sequence might escalate rapidly, bypassing Level 1 and 2, if adequate monitoring and early warning information is not available. The collapse of a bloom may be associated with the release of dissolved toxin into the water and the length of time for toxins to degrade is variable. Generally, times to avoid toxin contamination can vary from a minimum of several days to weeks depending upon the toxin and the seawater.

A summary of Alert Level Frameworks is provided in Figure 8.3.

8.5.4 Customer and media information dissemination

Providing information to consumers and the media is an important aspect of managing water quality problems associated with HABs. Information should be prompt and concise with details regarding reasons for changes to supply and explanation for any differences in water quality. It is important for all of the companies and agencies involved to provide coordinated and consistent advice. It is also useful to have guidance from a HAB expert, in order to address questions about the distribution and longevity of the bloom, or of the symptoms associated with consumption of certain of the toxins.

The Alert Level Framework suggests a number of points where media releases could be issued. These are in situations where consumers may experience changes in water quality, e.g. due to changes in source water quality, switching to another source water, changes in treatment, implementation of a contingency plan, or warning notices for recreational use of the source water. It is always advisable to have a single, well-informed individual as the spokesperson for the event. When too many people offer guidance to the media, the situation can become confusing and inaccurate guidance released.

The approach to release information will depend on the nature of the supply and the problem. For example, for SWRO plants with two passes and thus sophisticated multi-barrier treatment infrastructure, it may not ever be necessary to advise consumers, as water quality changes will not be evident in the product water. In those cases, however, it is important for the plant to be aware of the algal bloom situation in the event that the public, government officials, or journalists inquire about the safety of the drinking water after learning of the presence of a dangerous HAB through other impacts (e.g., dead fish, poisonous shellfish). It is far better for plant management to be able to say that they are aware of the situation and that tests have been run to assure water quality, rather than to be ignorant of the situation and presume that the RO and pretreatment processes are being effective. In circumstances with simple pre-treatment and a single pass RO, as is often the case with low salinity feedwaters, or if the bloom occurs in a multiple-use water resource (for instance those also used for recreation), it is important to inform consumers of the extent of the problem as part of the management strategy.

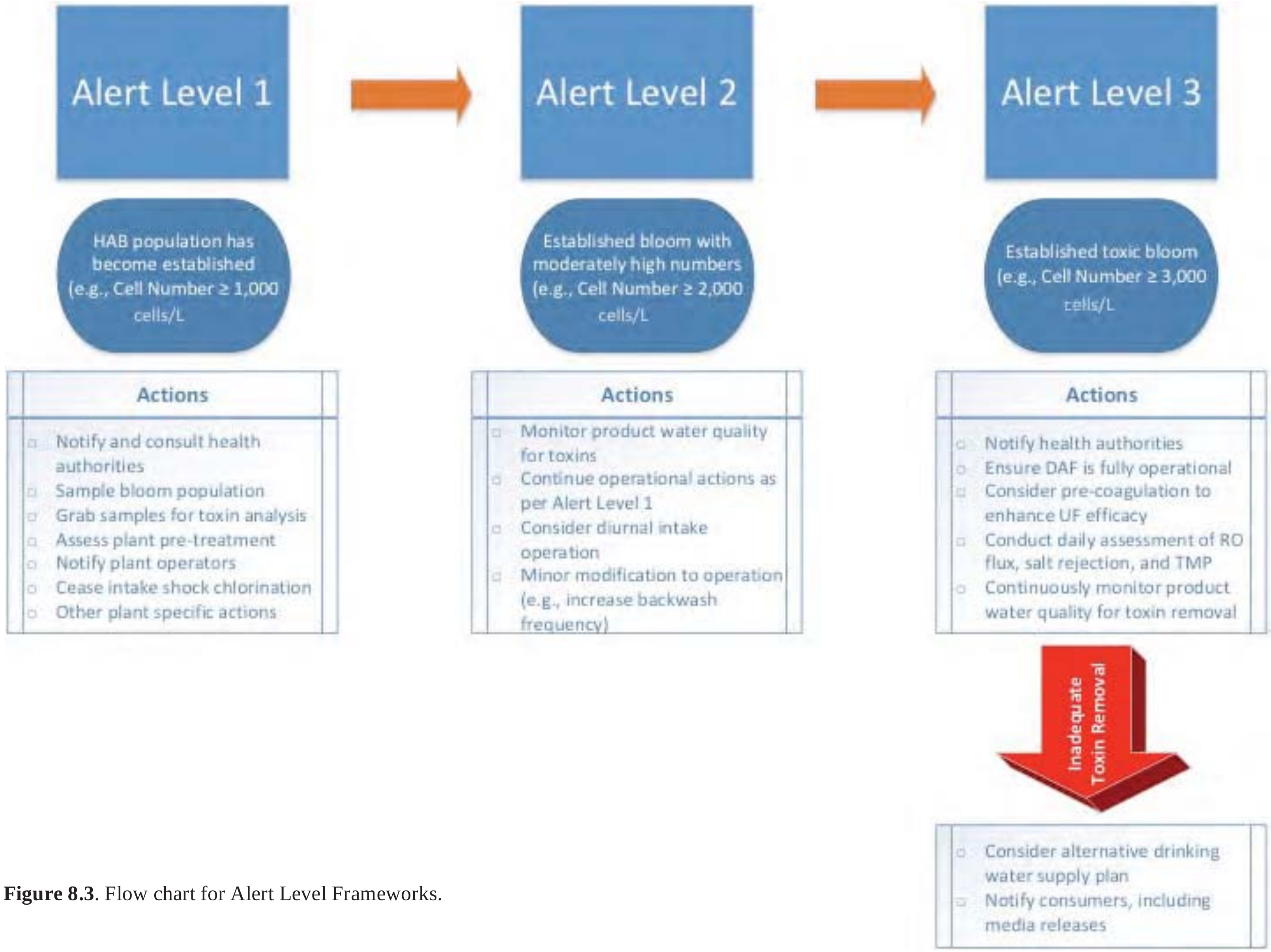

Figure 8.3. Flow chart for Alert Level Frameworks.

8.6 SUMMARY

This chapter has presented information regarding the risks presented by HAB toxins and how designers and operators could use tools to consider these risks and mitigate them appropriately. Many guidelines exist globally for HAB toxins in drinking water, although few countries have guidelines that consider seawater toxins, apart from New Zealand and Brazil that have guidelines for saxitoxin. To ensure complete removal of HAB toxins to a safe level in a desalination plant, designers can consider the multi barrier concept to mitigate the risk of unit process failure and toxin release into the distribution system. Risk assessments for HAB toxins can be undertaken by several methods, one of which is the HACCP process. This chapter also considered a practical assessment of toxin risks, calculating the residual risk after treatment for several common seawater toxins. Finally, this chapter describes an Alert Level Framework tool that can be used by operators to make rapid and effective decisions on how to operate a plant during a HAB bloom according to cellular concentrations in the seawater and thus react in an appropriate manner. By considering risks and mitigation options using the tools presented here, designers and operators can keep drinking water supplies safe and protect public health during toxic HABs.

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