Toxic Cyanobacteria in Water: A guide to their public health consequences, monitoring and management
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Chapter 1. INTRODUCTION

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"A pet child has many names". This proverb is well illustrated by such expressions as blue-greens, blue-green algae, myxophyceaens, cyanophyceans, cyanophytes, cyanobacteria, cyanoprokaryotes, etc. These are among the many names used for the organisms this book considers. This apparent confusion in use of names highlights the important position that these organisms occupy in the development of biology as a science. From their earliest observation and recognition by botanists (Linné, 1755; Vaucher, 1803; Geitler, 1932), and onwards to their treatment in modem textbooks (Anagnostidis and Komárek, 1985; Staley *et al.,* 1989), the amazing combination of properties found in algae and bacteria which these organisms exhibit, have been a source of fascination and attraction for many scientists.

The cyanobacteria also provide an extraordinarily wide-ranging contribution to human affairs in everyday life (Tiffany, 1958) and are of economic importance (Mann and Carr, 1992). Both the beneficial and detrimental features of the cyanobacteria are of considerable significance. They are important primary producers and their general nutritive value is high. The nitrogen-fixing species contribute globally to soil and water fertility (Rai, 1990). The use of cyanobacteria in food production and in solar energy conversion holds promising potential for the future (Skulberg, 1995). However, cyanobacteria may also be a source of considerable nuisance in many situations. Abundant growth of cyanobacteria in water reservoirs creates severe practical problems for water supplies. The development of strains containing toxins is a common experience in polluted inland water systems all over the world, as well as in some coastal waters. Thus cyanobacterial toxins, or "cyanotoxins", have become a concern for human health.

Prior to the first acute cyanotoxin poisoning of domestic animals documented in the scientific literature (Francis, 1878), reports of cyanobacteria poisonings were largely anecdotal. Perhaps one of the earliest is from the Han dynasty of China. About 1,000 years ago, General Zhu Ge-Ling, while on a military campaign in southern China, reported losing troops from poisonings whilst crossing a river. He reported that the river was green in colour at the time and that his troops drank from the green water (Shun Zhang Yu, Pers. Comm.). Codd (1996) reported that human awareness of toxic blooms existed in the twelfth century at the former Monasterium Virdis Stagni (Monastery of the Green Loch), located near the eutrophic, freshwater Soulseat Loch near Stranraer in south west Scotland. In more recent times, several investigators have noted that local people in China, Africa, North and South America and Australia, who use water from water bodies where green scums are present, will dig holes (soaks) near the water's edge in order to filter the water through the ground and thus prevent the green material from contaminating drinking-water supplies. This practice is similar to that of developing wells next to surface waters in order to use the filtering capacity of the soil to remove organisms and some chemicals from the surface waters - a technique known as bankside filtration.

1.1 Water resources

The hydrological cycle represents a complex interconnection of diverse water types with different characteristics, each subject to different uses. Recent developments have shown the importance of water resource management in an integrated manner and of recognising interconnections, especially between human activities and water quality.

Most of the world's available freshwater (i.e. excluding that in polar ice-caps, snow and glaciers) exists as groundwater. This ready supply of relatively clean and accessible water has encouraged use of this resource, and in many regions groundwater provides drinking water of excellent quality. However, in some areas, geological conditions do not allow the use of groundwater or the supplies are insufficient. Thus, where groundwater supplies are insufficient or of unsuitable quality, surface water must be used for purposes such as drinking-water supply. Compared with surface waters, groundwaters have a high volume and low throughput. Over-abstraction is therefore common.

This book is concerned principally with inland, surface freshwaters, and to a lesser extent with estuarine and coastal waters where cyanobacteria can grow, and under suitable conditions, form water blooms or surface scums. Cyanobacteria are a frequent component of many freshwater and marine ecosystems. Those species that live dispersed in the water are part of the phytoplankton whilst those that grow on sediments form part of the phytobenthos. Under certain conditions, especially where waters are rich in nutrients and exposed to sunlight, cyanobacteria may multiply to high densities - a condition referred to as a water bloom (see Chapter 2).

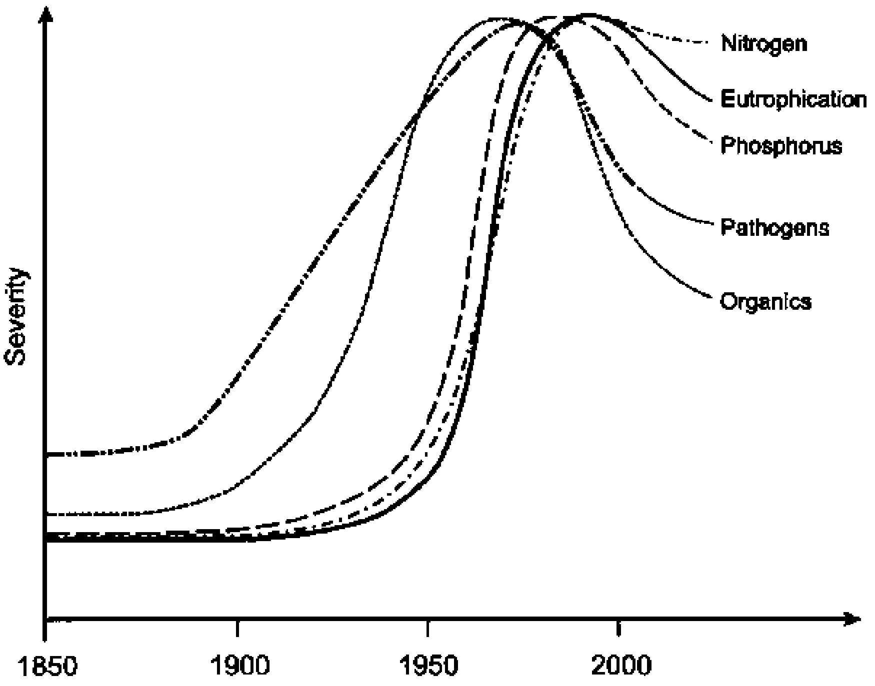
The composition of freshwaters is dependent on a number of environmental factors, including geology, topography, climate and biology. Many of these factors vary over different time scales such as daily, seasonally, or even over longer timespans. Large natural variations in water quality may therefore be observed in any given water system.

Eutrophication is the enhancement of the natural process of biological production in rivers, lakes and reservoirs, caused by increases in levels of nutrients, usually phosphorus and nitrogen compounds. Eutrophication can result in visible cyanobacterial or algal blooms, surface scums, floating plant mats and benthic macrophyte aggregations. The decay of this organic matter may lead to the depletion of dissolved oxygen in the water, which in turn can cause secondary problems such as fish mortality from lack of oxygen and liberation of toxic substances or phosphates that were previously bound to oxidised sediments. Phosphates released from sediments accelerate eutrophication, thus closing a positive feedback cycle. Some lakes are naturally eutrophic but in many others the excess nutrient input is of anthropogenic origin, resulting from municipal wastewater discharges or run-off from fertilisers and manure spread on agricultural areas. Losses of nutrients due to erosion and run-off from soils may be low in relation to agricultural input and yet high in relation to the eutrophication they cause, because concentrations of phosphorus of less than 0.1 mg l^{-1} are sufficient to induce a cyanobacterial bloom (see Chapter 8).

Hydrological differences between rivers, impoundments and lakes have important consequences for nutrient concentrations and thus for cyanobacterial growth. Rivers generally have a significant flushing rate. The term "self-purification" was adopted to describe the rapid degradation of organic compounds in rivers where turbulent mixing effectively replenishes consumed oxygen. This term has been applied, mistakenly, to any process of removing undesirable substances from water but does not actually eliminate the contaminants, including processes such as adsorption to sediments or dilution. Substances bound to sediments may accumulate, be released back into the water, and may be carried downstream. This process is important for phosphorus. Lakes generally have long water retention times compared with rivers, and by their nature lakes tend to accumulate sediments and the chemicals associated with them. Sediments therefore act as sinks for important nutrients such as phosphorus, but if conditions change the sediments may also serve as sources, liberating the nutrient back into the water where it can stimulate the growth of cyanobacteria and algae.

Surface water systems world-wide are now often highly regulated in efforts to control water availability, whether for direct use in irrigation, hydropower generation or drinking water supplies or to guard against the consequences of floods and droughts. Many major rivers (such as the Danube in Europe or the Murray in Australia) may be viewed as a cascade of impoundments. This trend in regulation of flow has an impact upon the quality and the quantity of water. It alters sediment transport and, as a result, the transport of substances attached to sediments, such as plant nutrients which may enhance cyanobacterial growth. By increasing retention times and surface areas exposed to sunlight, impoundments change the growth conditions for organisms and promote opportunities for cyanobacterial growth and water-bloom formation through modifications to river discharges. For many estuarine and coastal systems, human impact on hydrological conditions and nutrient concentrations is also now extensive.

Figure 1.1 Schematic representation of the development of surface water pollution with pathogens, oxygen-consuming organic matter, phosphorus and cyanobacteria in north-western Europe and in North America



Changes in the nature and scale of human activities have consequences both for the qualitative and quantitative properties of water resources. Historically, the development of society has involved a change from rural and agricultural to urban and industrial water uses, which is reflected in both water demands and water pollution as illustrated in Figure 1.1. The general trend has been an increase in concentrations of pollutants in surface waters together with increases in urbanisation. Construction of sewerage first enhanced this trend by concentrating pollutants from latrines (which can leak into groundwater or surface waters). After some decades, construction of sewage treatment systems began extensively in the 1950s. Originally these systems comprised only a biological step which degraded the organic material which otherwise had led to dramatic oxygen depletion in the receiving water bodies. Pathogens were also reduced to some extent, but phosphate remained unaffected. Upgrading treatment systems to remove phosphorus only began in the 1960s and also had the side-effect of further reducing pathogens. A resultant decline in eutrophication, and thus of cyanobacterial blooms, is lagging behind the decline of phosphorus inputs to freshwaters because phytoplankton growth becomes nutrient-controlled only below threshold concentrations (see Chapter 8).

It is unclear whether the historical shift in water demand from rural to urban will continue in the future, although a number of influences are apparent. The anticipated food crises of the early twenty first century will place increasing demands upon irrigated agriculture - a process that already accounts for about 70 per cent of water demand world-wide. By contrast, many industries have successfully developed processes with substantial water economy measures, and their demand upon water resources per unit of activity is now decreasing in some countries. Domestic water consumption tends to increase with population and affluence, but development of lower consumption appliances and control of losses from water mains may stabilise, or even reduce, demand in the future. Nevertheless, overall trends point to an increasing total demand for water, driven principally by global population growth.

1.2 Eutrophication, cyanobacterial blooms and surface scums

Eutrophication was recognised as a pollution problem in many western European and North American lakes and reservoirs in the middle of the twentieth century (Rohde, 1969). Since then, it has become more widespread, especially in some regions; it has caused deterioration in the aquatic environment and serious problems for water use, particularly in drinking-water treatment. A recent survey showed that in the Asia Pacific Region, 54 per cent of lakes are eutrophic; the proportions for Europe, Africa, North America and South America are 53 per cent, 28 per cent, 48 per cent and 41 per cent respectively (ILEC/Lake Biwa Research Institute, 1988-1993). Eutrophication also affects slow flowing rivers, particularly if they have extended low-flow periods during a dry season. Practical measures for prevention of nutrient loading from wastewater and from agriculture have been developed. In some regions preventative measures are being implemented more and more. During the 1990s, increasing introduction of nutrient removal during sewage treatment in North America and in north western Europe has begun to show success in reducing phosphorus concentrations; in a few water bodies, algal and cyanobacterial blooms have actually declined. Technical measures for reduction of nutrients already present in lakes are also available but have not been widely applied (see Chapter 8).

Wherever conditions of temperature, light and nutrient status are conducive, surface waters (both freshwater and marine) may host increased growth of algae or cyanobacteria. Where such proliferation is dominated by a single (or a few) species, the phenomenon is referred to as an algal or cyanobacterial bloom. Problems associated with cyanobacteria are likely to increase in areas experiencing population growth with a lack of concomitant sewage treatment and in regions with agricultural practices causing nutrient losses to water bodies through over-fertilisation and erosion.

There are important differences in algal and cyanobacterial growth between tropical and temperate areas. A characteristic pattern of seasonal succession of algal and cyanobacterial communities is, for example, diatoms in association with rapidly growing small flagellates in winter and spring, followed by green algae in late spring and early summer, and then by species which cannot easily be eaten by zooplankton, such as dinoflagellates, desmids and large yellow-green algae (in moderately turbulent waters also diatoms) in late summer and autumn. In eutrophic and hypertrophic waters, cyanobacteria often dominate the summer phytoplankton. As winter approaches, in most water bodies, increasing turbulence and the lack of light during the winter leads to their replacement by diatoms. In the tropics, seasonal differences in environmental factors are often not great enough to induce the replacement of cyanobacteria by other phytoplankton species. If cyanobacteria are present or even dominant for most of the year, the practical problems associated with high cyanobacterial biomass and the potential health threats from their toxins increase. High cyanobacterial biomass may also contribute to aesthetic problems, impair recreational use (due to surface scums and unpleasant odours), and affect the taste of treated drinking water.

Phosphorus is the major nutrient controlling the occurrence of water blooms of cyanobacteria in many regions of the world, although nitrogen compounds are sometimes relevant in determining the amount of cyanobacteria present. However, in contrast to planktonic algae, some cyanobacteria are able to escape nitrogen limitation by fixing atmospheric nitrogen. The lack of nitrate or ammonia, therefore, favours the dominance of these species. Thus, the availability of nitrate or ammonia is an important factor in determining which cyanobacterial species become dominant.

Cyanobacterial blooms are monitored using biomass measurements coupled with the examination of the species present. A widely-used measure of algal and cyanobacterial biomass is the chlorophyll *a* concentration. Peak values of chlorophyll *a* for an oligotrophic lake are about 1-10 µg l^{-1}, while in a eutrophic lake they can reach 300 µg l^{-1}. In cases of hypereutrophy, such as Hartbeespoort Dam in South Africa, maxima of chlorophyll *a* can be as high as 3,000 µg l^{-1} (Zohary and Roberts, 1990).

Trophic state classifications, such as that adopted by the Organisation for Economic Co-operation and Development (OECD), combine information concerning nutrient status and algal biomass (OECD, 1982). They provide a basis for the evaluation of status and trends for management and they facilitate international information exchange and comparison.

1.3 Toxic cyanobacteria and other water-related health problems

The contamination of water resources and drinking water supplies by human excreta remains a major human health concern, just as it has been for centuries. By contrast, the importance of toxic substances, such as metals and synthetic organic compounds, has only emerged in the latter half of the twentieth century. Although eutrophication has been recognised as a growing concern since the 1950s, only recently have cyanobacterial toxins become widely recognised as a human health problem arising as a consequence of eutrophication. The importance of such toxins, relative to other water-health issues, can currently only be estimated. A significant proportion of cyanobacteria produce one or more of a range of potent toxins (see Chapter 3). If water containing high concentrations of toxic cyanobacteria or their toxins is ingested (in drinking water or accidentally during recreation), they present a risk to human health (see Chapter 4). Some cyanobacterial substances may cause skin irritation on contact.

The relationship between water resources and health is complex. The most well recognised relationship is the transmission of infectious and toxic agents through consumption of water. Drinking water has therefore played a prominent role in concerns for water and human health. Diseases arising from the consumption of contaminated water are generally referred to as "waterborne". Globally, the waterborne diseases of greatest importance are those caused by bacteria, viruses and parasites, such as cholera, typhoid, hepatitis A, cryptosporidiosis and giardiasis. Most of the pathogens involved are derived from human faeces and the resulting diseases are generally referred to as "faecal-oral" diseases; however they can also be spread by means other than contaminated water, such as by contaminated food. Waterborne diseases also include some caused by toxic chemicals, although many of these may only cause health effects some time after exposure has occurred and may therefore be difficult to associate directly with the cause.

The second major area of interaction between water and human health concerns its role in personal and domestic hygiene, through which it contributes to the control of disease. Because hygiene is a key measure in the control of faecal-oral disease, such diseases are also "water hygiene" diseases. Other water hygiene diseases include skin and eye infections and infestations, such as tinea, scabies, pediculosis and trachoma. All of these diseases occur less frequently when adequate quantities of water are available for personal and domestic hygiene. It is important to note that the role of water in control of water hygiene diseases depends on availability and use, and water quality is therefore a secondary consideration in this context.

"Water contact diseases" are the third group of water-related diseases and occur through skin contact. The most important example world-wide is schistosomiasis (bilharzia). In infected persons, eggs of *Schistosoma* spp. are excreted in faeces or urine. The schistosomes require a snail intermediate host and go on to infect persons in contact with water by penetrating intact skin. The disease is of primary importance in areas where collection of water requires wading or direct contact with contaminated surface waters such as lakes or rivers. The water contact diseases also include those diseases arising from non-infectious agents in the water, that may give rise, for example, to allergies and to skin irritation or to dermatitis.

The fourth principal connection between water and human health concerns "water habitat vector" diseases. These are diseases transmitted by insect vectors that spend all or part of their lives in or near water. The best-known examples are malaria (transmitted by mosquito bites and caused by *Plasmodium* spp.) and filariasis (transmitted by mosquito bite and caused by microfilaria).

The classification of water-related disease into four groups (waterborne disease, water hygiene disease, water contact disease and water habitat vector disease) was originally developed in order to associate groups of disease more clearly with the measures for their transmission and control and has contributed greatly to furthering this understanding. Because of its importance to the global burden of disease, the classification is based upon infectious disease. Nevertheless, the principal groups of diseases related to chemicals occurring in water may also be categorised in a similar way. However, there are a number of water-health associations that fall outside these categories. These include deficiency-related diseases and recreational uses of water. For recreational water use, the principal area of concern relating to faecal-oral disease transmission may be classified reasonably alongside other waterborne disease transmission. However, concern related to transmission of, for example, eye and ear infections does not readily fit into the classification system, nor does the increased transmission of diseases arising from the effect of immersion compromising natural defence systems (such as those of the eye).

Public health concern regarding cyanobacteria centres on the ability of many species and strains of these organisms to produce cyanotoxins. Cyanotoxins may fall into two of the four groups of water-related diseases. They may cause waterborne disease when ingested, and water contact disease primarily through recreational exposure. In hospitals and clinics, exposure through intravenous injection has led to human fatalities from cyanotoxins (see Chapter 4). These toxins pose a challenge for management. Unlike most toxic chemicals, cyanotoxins only sometimes occur dissolved in the water - they are usually contained within cyanobacterial cells. In contrast to pathogenic bacteria, these cells do not proliferate within the human body after uptake, only in the aquatic environment before uptake.

Cyanotoxins belong to rather diverse groups of chemical substances (see Chapter 3), each of which shows specific toxic mechanisms in vertebrates (see Chapter 4). Some cyanotoxins are strong neurotoxins (anatoxin-a, anatoxin-a(s), saxitoxins), others are primarily toxic to the liver (microcystins, nodularin and cylindrospermopsin), and yet others (such as the lipopolysaccharides) appear to cause health impairments (such as gastroenteritis) which are poorly understood. Microcystins are geographically most widely distributed in freshwaters. Recently, they have even been identified in marine environments as a cause of liver disease in net-pen reared salmon, although it is not clear which organism in marine environments contains these toxins. As with many cyanotoxins, microcystins were named after the first organism found to produce them, *Microcystis aeruginosa,* but later studies also showed their occurrence in other cyanobacterial genera.

The hazard to human health caused by cyanotoxins can be estimated from toxicological knowledge (see section 4.2) in combination with information on their occurrence (see section 3.2). However, although the information clearly indicates hazards, there are few documented cases of human illness unequivocally attributed to cyanotoxins (see section 4.1). In a number of cases, investigation of cyanobacteria and cyanotoxins was carried out only several days after patients had been exposed and had developed symptoms. This was because diagnosis moved on to considering cyanobacteria only after other potential causative agents had proved negative, or even years later when knowledge of cyanobacterial blooms in a water body was connected with the information on an outbreak of symptoms of unidentified cause.

The number of quantitative surveys on cyanotoxin occurrence is low, and the level of cyanotoxin exposure through drinking water or during recreational activities largely unknown. Surveys on cyanobacteria and cyanotoxins have been primarily ecological and biogeographical. Early surveys in a number of countries including Australia, Canada, Finland, Norway, South Africa, Sweden, the UK and the USA involved toxicity testing of scum samples by mouse bioassay. Surveys during the 1990s have tended to employ more sensitive and definitive methods for characterisation of the toxins, such as chromatographic or immunological methods (see Chapter 3). These studies provide an improving basis for estimating the range of concentrations to be expected in a given water body and season. However, monitoring cyanotoxin concentration is more difficult than many other waterborne disease agents, because variations in cyanobacterial quantities, in time and space, is substantial, particularly if scum-forming species are dominant (see section 2.2). Wind-driven accumulations and distribution of surface scums can result in concentrations of the toxin by a factor of 1,000 or more (or even result in the beaching of scums) and such situations can change within very short time periods, i.e. the range of hours. Therefore, discontinuous samples only provide a fragmentary insight into the potential cyanotoxin dose for occasional swimmers and into the amount entering drinking water intakes.

Very few studies of cyanotoxin removal by drinking water treatment processes have been published (see Chapter 9), although some water companies have carried out unpublished studies. Thus, a reliable basis for estimation of cyanotoxin exposure through drinking water is lacking. In regions using surface waters affected with cyanobacteria as a source for drinking water, actual toxin exposure will depend strongly on method of water abstraction and treatment.

In comparing the available indications of hazards from cyanotoxins with other water-related health hazards, it is conspicuous that cyanotoxins have caused numerous fatal poisonings of livestock and wildlife, but no human fatalities due to oral uptake have been documented. Human deaths have only been observed as a consequence of intravenous exposure through renal dialysis. Cyanotoxins are rarely likely to be ingested by humans in sufficient amounts for an acute lethal dose. Thus, cyanobacteria are less of a health hazard than pathogens such as *Vibrio cholerae* or *Salmonella typhi.* Nevertheless, dose estimates indicate that a fatal dose is possible for humans, if scum material is swallowed. However, swallowing such a repulsive material is likely to be avoided. The combination of available knowledge on chronic toxicity mechanisms (such as cumulative liver damage and tumour promotion by microcystins) with that on ambient concentrations occurring under some environmental conditions, shows that chronic human injury from some cyanotoxins is likely, particularly if exposure is frequent or prolonged at high concentrations.

1.4 Present state of knowledge

Research into developing further understanding of the human health significance of cyanobacteria and individual cyanotoxins, and into practical means for assessing and controlling exposure to cyanobacteria and to cyanotoxins, is a priority. A major gap also lies in the synthesis and dissemination of the available information.

Information concerning the efficiency of cyanotoxin removal in drinking water treatment systems is limited. Especially, simple, low-cost techniques for cyanobacterial cell removal, such as slow sand filtration, should be investigated and developed further. More information is also needed on the capability of simple disinfection techniques, such as chlorine, for oxidising microcystins and cylindrospermopsin (Nicholson *et at.,* 1994). If this is found to be applicable, or if "conventional" treatments are found to be effective if properly operated, these approaches would provide a practical tool for removing cyanotoxins in many situations.

Whilst cyanobacterial blooms remain sporadic or occasional events, most emphasis is still placed upon the protection of drinking water supplies through the preparation of contingency plans and their activation when appropriate. Early warning systems and predictive models can facilitate this and should be based upon available information on the conditions leading to cyanobacterial bloom development and on occurrence, localisation and movement of scums.

Epidemiological evidence is of particular value in determining the true nature and severity of human health effects (and therefore the appropriate response) but is generally lacking in relation to human exposures to cyanobacteria. The limited studies undertaken to date in relation to recreational exposure require further substantiation. Opportunistic studies into exposures through drinking water may provide further valuable insights. Information from experimental toxicology also needs to be strengthened. In particular, long-term exposure studies (of at least one year or longer) should be carried out to assess the chronic toxicity of microcystins and cylindrospermopsins. Uptake routes (e.g. through nasal tissues and mucous membranes) require further investigation.

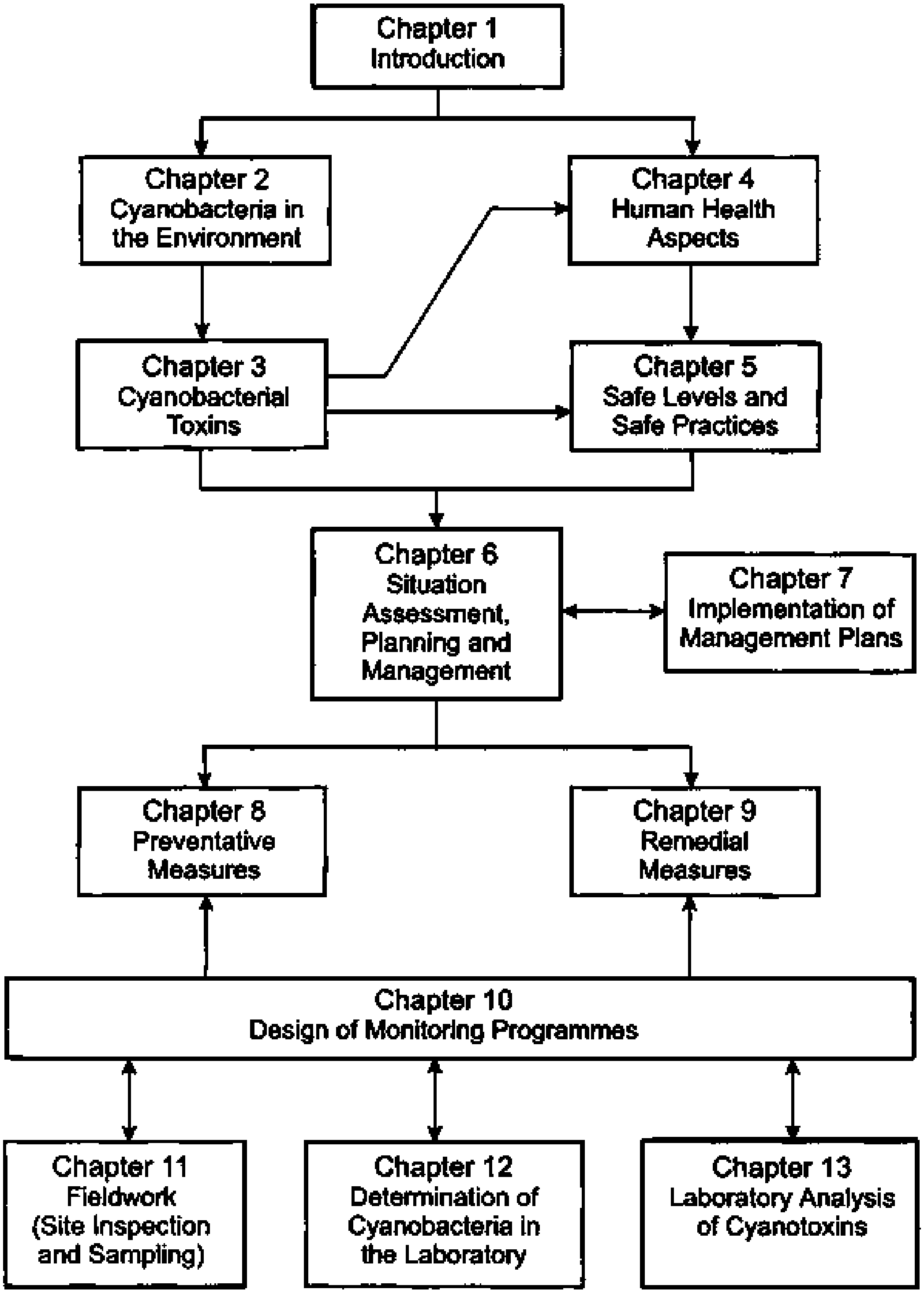
Further systematic studies are also required into the suggested tumour-promoting effects of some cyanotoxins, particularly in the dose range of potential oral uptake with drinking or bathing water.

Lipopolysaccharide (LPS) endotoxins from cyanobacteria pose a potential health risk for humans, but knowledge of the occurrence of individual LPS components, their toxicology, and their removal in drinking water treatment plants, is so poor that guidelines cannot be set at present. Further bioactive cyanobacterial metabolites are also identified frequently and the health significance of these requires investigation.

1.5 Structure and purpose of this book

The structure of this book follows a logical progression of issues as outlined in Figure 1.2. Because of the lack of comprehensive literature in the field of cyanotoxins, this book aims to give background information as well as practical guidance. Some parts of the text will mainly be of interest to particular readers. Chapters 2 and 3 provide the background for understanding the behaviour of cyanobacteria and their toxin production in given environmental conditions. Chapter 4 reviews the evidence regarding health impacts, primarily for public health experts establishing national guidelines or academics identifying and addressing current research needs. Chapters 5-7 provide guidance on safe practices in the planning and management of drinking water supplies and recreational resorts. Readers who access the book with specific questions regarding prevention of cyanobacterial growth or their removal in drinking water treatment will find Chapters 8 and 9 of direct relevance. Guidance on the design and implementation of monitoring programmes is given in Chapter 10, and Chapters 11-13 provide field and laboratory methods for monitoring cyanobacteria, their toxins and the conditions which lead to their excessive growth. As far as is possible, individual chapters have been written to be self-contained and self-explanatory. However, substantial cross-referencing, particularly between Chapters 10 to 13, requires that these chapters should be used jointly. Where chapters call upon information presented elsewhere in the text, this has been specifically noted.

Figure 1.2 Aspects of monitoring and managing toxic cyanobacteria in water as discussed in the various chapters of this book



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