Toxic Cyanobacteria in Water: A guide to their public health consequences, monitoring and management
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Chapter 10. DESIGN OF MONITORING PROGRAMMES

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Cyanobacterial blooms and cyanotoxins present a special challenge to monitoring programmes because the requirements are different from well-recognised monitoring designs both for pathogenic bacteria and for toxic chemicals. Pathogen concentrations are highest close to sewage outfalls or the inflow of agricultural runoff polluted by livestock faeces and they are diluted with increasing distance from such sources. In contrast, cyanobacteria multiply in the open water environment and scum-forming species are often dramatically concentrated by wind action. Furthermore, formation and dispersion of scums may change within days or even hours, making assessment of the associated hazard difficult. Toxic chemicals are dissolved in the water or bound to sediments. In contrast, at least while the producer cells remain intact, cyanotoxins are chiefly contained within the cells. Therefore, they may shift position in the water body with the cells and accumulate to hazardous concentrations. Consequently, monitoring strategies must encompass cell-bound toxins in addition to extracellular toxin pools.

Cyanobacterial distributions and their changes in space and time depend on the morphological, hydrological, meteorological and geographic characteristics of a given water body. Because the distribution of cyanobacteria is central to hazard assessment, the design of monitoring programmes should be specifically tailored for each water body to optimise the relation of information output to work input. Monitoring approaches also need to be more flexible than for many other parameters. Local knowledge of bloom history and a good understanding of the local growth conditions for cyanobacteria will greatly enhance the capacity to anticipate bloom formation. As knowledge and understanding of a given water body accumulate, regular patterns of Cyanobacterial growth may be noticed, so that in the long-term, monitoring may be focused upon critical periods and locations. To ensure efficiency of Cyanobacterial monitoring programmes, they should be reviewed regularly to provide the most cost effective use of resources and in order to continue to satisfy the primary needs for which they were established. Rapid evaluation and interpretation of results is important in order to achieve feedback into ongoing programmes and their adaptation to current needs.

Analytical quality assurance, as well as data analysis, interpretation and presentation are important aspects of monitoring programmes. These topics are covered in two of the companion volumes in this series: *Water Quality Assessments* (Chapman, 1996) and *Water Quality Monitoring* (Bartram and Ballance, 1996).

10.1 Approaches to monitoring programme development

10.1.1 Objectives of monitoring programmes

The objectives of a monitoring programme determine the approach, the design and the resources required. The aims and further applications of monitoring programmes focused on cyanobacterial populations and toxins may include, for example:

- Assessment of health hazards caused by cyanobacteria and their toxins.

- Identification of contaminated areas (e.g. in relation to drinking water intakes and recreational sites).

- Development of regulations concerning the development and use of recreational sites.

- Public education and information.

- Assessment of the causes of cyanobacterial problems (nutrient concentrations and other limnological data for understanding cyanobacterial growth).

- Development of a nutrient pollution control programme.

- Checking whether compliance with cyanobacterial cell (or biomass) and toxin level standards for the respective water use is being achieved.

- Prediction of levels and changes in cyanobacterial populations and toxins resulting from natural phenomena and human influence.

- Information of the effect of interventions, including lake and reservoir management and water treatment methods, on cyanobacterial cell and toxin levels.

- Wider contribution to the knowledge of cyanobacterial ecology, hydrobiology and the state of the environment.

The approach to monitoring programme development will differ for each of these aims. These examples would each require a programme with combinations of monitoring for cyanobacterial cells, cyanotoxins and growth conditions. Frequently, cyanobacterial monitoring will be connected to, or included in, other general purpose water quality monitoring programmes.

10.1.2 Monitoring strategies

Monitoring water bodies can be facilitated by using a structured approach which may significantly enhance efficiency of laboratory resource use, especially where resources are limited (see Figure 10.1). Because many commonly occurring cyanobacteria are more often toxic than non-toxic, the simplest approach is to assume toxicity and to monitor cyanobacteria rather than their toxins in the water body. Such an approach begins with simple visual inspection. If this indicates a possible cyanobacterial problem, the approach moves on to assessing which level of cyanobacterial development can be sustained by the nutrient concentrations available (i.e. the carrying capacity, which is most frequently determined by total phosphorus, see section 8.1.) If nutrient concentrations are high enough for cyanobacterial proliferation to be likely, cyanobacteria must be monitored at time intervals adequate to identify hazards (see section 7.5 for time intervals of monitoring).

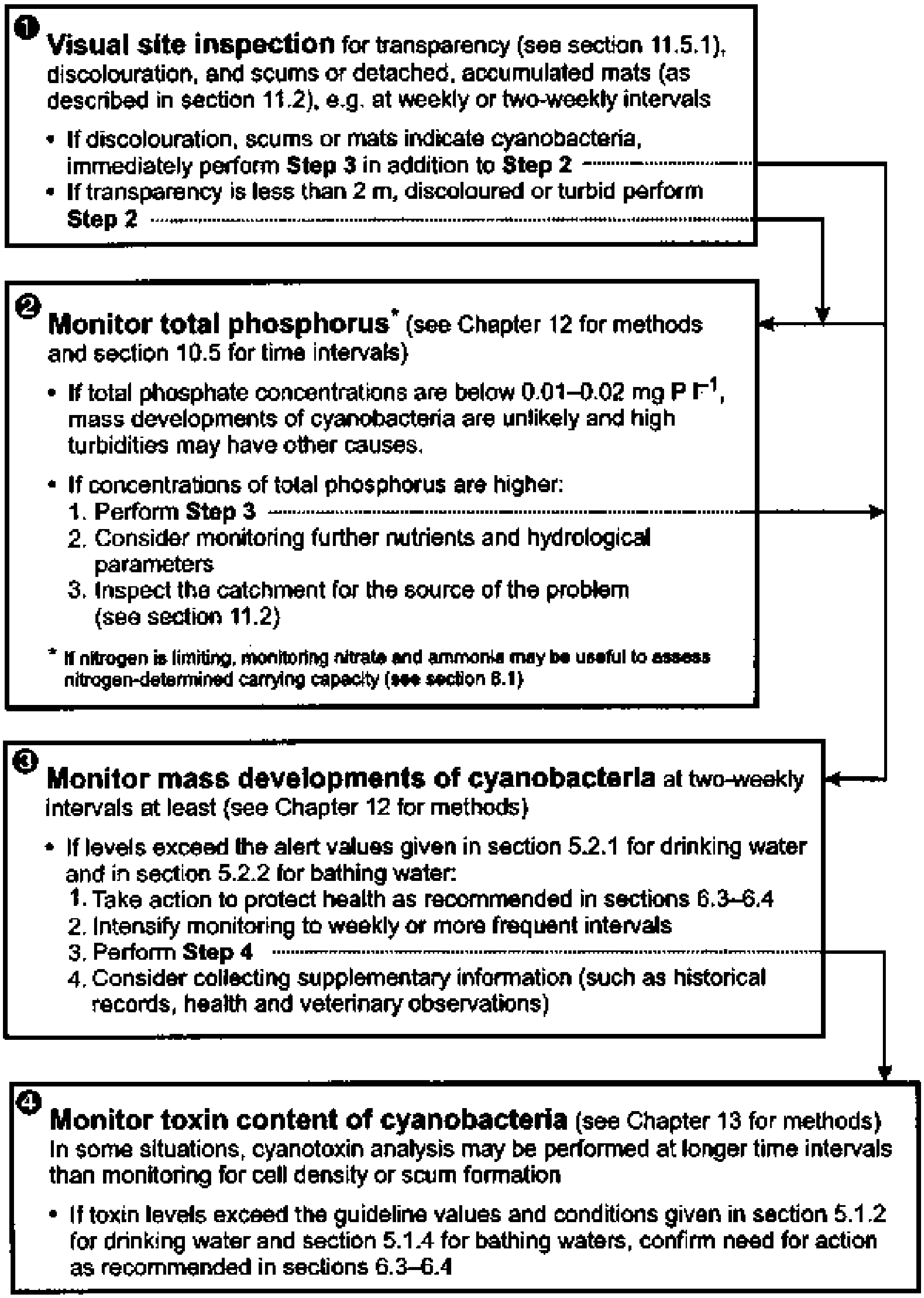
Monitoring may be supplemented with valuable information by collection of historical data on bloom occurrence and of health information, including veterinary records of animal poisonings (see Chapter 6).

10.1.3 Variable selection

Easy-to-assess visual indicators (Step 1 in Figure 10.1) may provide valuable information concerning cyanobacterial proliferation at low cost and often enable a high frequency of observation, especially if they are periodically supported by microscopy in order to ascertain that observed phenomena are due to cyanobacteria. If performed by local staff with alert and flexible observation skills as well as increasing experience, regular site inspection (including monitoring and recording of transparency, discolouration and scum formation) can provide much information in relation to the effort required. Including an assessment of land-based pollution in critical areas of the catchment may also provide information on nutrient pollution sources.

Monitoring of variables which enhance cyanobacterial growth and/or accumulation is valuable in recognising which water resources are at risk of bloom development and scum formation. In many regions, this may also assist substantially in ruling out resources unlikely to sustain major cyanobacterial populations. Monitoring of total phosphorus as a key factor for mass developments may be particularly relevant for setting priorities in monitoring recreational waters where short-lived minor surface scums are less of a problem. Total phosphorus data can further provide the basis for planning and assessing the success of measures to counter the causes of the problem (see Chapter 8). The collection of further environmental data on hydrological conditions (such as retention times and thermal stratification), light availability (as assessed by the relation of depth of light penetration to mixed depth, see section 2.2) as well as dissolved nitrogen (nitrate and ammonia) provides a basis for understanding why certain cyanobacterial genera or species dominate.

Figure 10.1 Example of structured, quantitative investigation approach to monitoring and surveillance for toxic cyanobacteria and their growth potential



Box 10.1 Limitations of assessing toxin risk from monitoring cyanobacterial populations

Although cyanobacterial identification and quantification provide a basis for estimating the toxic risk, the monitoring of cyanobacterial populations alone cannot be used as a surrogate for monitoring cyanobacterial toxins because:

- Toxin types and levels per unit cyanobacterial biomass can vary widely, ranging from undetectable to present at acutely toxic levels.

- Toxin levels per cell vary widely between individual strains and blooms of the same species.

- Individual cyanobacterial strains of the same species can contain more than one type of toxin.

- The toxins can persist in water bodies and water treatment plants in extracellular (soluble) form after release from the producer-cells upon cell lysis caused by biological, physical or chemical agents.

It thus follows that cyanobacterial toxins can be present in a waterbody or treatment facility in the absence of intact cyanobacterial cells or cell debris if the waterbody had recently contained cyanobacterial cells.

Monitoring cyanobacterial taxa and population densities (cell numbers or biomass) can provide an excellent basis for assessing risk, particularly if supported periodically with toxicity tests or toxin analysis. If data on toxin content of prevalent cyanobacteria are available for specific water bodies or regions, and have been found to remain fairly constant for the predominant taxa, a tentative prediction of toxin risks can be inferred from quantitative assessments of cyanobacterial taxa present using samples taken between the occasions of toxin analysis (see Box 10.1 for the limitations of this approach). Microscopy may also be used for monitoring finished drinking water prior to distribution, as well as different treatment steps, for breakthrough of potentially toxic cyanobacterial cells. The necessary laboratory equipment for monitoring cyanobacteria is limited to a microscope and some accessories (see Chapter 12). The training requirements for staff are lower than is frequently assumed (see Box 10.2).

In situations where the phytoplankton is largely dominated by cyanobacteria (e.g. they constitute more than half of the biomass seen through a microscope), measurement of the concentration of chlorophyll *a* can be used as an estimate of cyanobacteria present (see Chapter 12). A simple photometer is adequate for this approach.

Monitoring for cyanobacterial taxa, cell numbers and/or biomass may provide data which are of value for a variety of assessments, including:

- The occurrence, types, distribution and abundance of cyanobacteria, including potential toxin-forming types, in natural and controlled water bodies, water treatment and distribution systems and in potable water supplies.

• Spatial and temporal changes in cell populations, their composition, abundance and integrity.

• Relations between cyanobacterial populations and the types and levels of cyanobacterial toxins (if accompanied by toxin analysis), and associated water quality problems and health incidents.

• Warning systems to trigger contingency action plans in the event of cyanobacterial mass development in waters required for human or animal use.

• Responses of water bodies and water supplies to eutrophication control and strategies to destroy and/or remove cyanobacterial cells in water treatment.

Box 10.2 Adequate training for identifying important cyanobacterial taxa

A common misunderstanding is the assumption that the sophisticated taxonomic training, on a level adequate for ecological research, is necessary for practical monitoring of cyanobacterial hazards. This may be intimidating for beginners and practitioners. In practice, it may only be necessary to focus training on determining the taxa relevant in the region or waterbody to be monitored, frequently only to the level of genera (e.g. *Microcystis),* and down to the level of species only if these are easy to identify and if species differentiation is particularly important for indication of toxin content (e.g. *Planktothrix agardhii* and *Planktothrix rubescens).* Basic identification of cyanobacteria by local personnel should be supplemented by periodic quality control by experts (see the Alert Levels Framework Level 2 in section 6.3.3) to ensure adequate recognition of the important groups, especially after conditions in a water resource have been changed and other taxa may have proliferated.

Monitoring cyanotoxin concentrations and/or assessment of toxicity may be warranted to characterise the hazard presented by a given cyanobacterial population. The role of such monitoring is different in hazard assessment for drinking water and for recreational water use.

The increasing evidence of health outcomes due to unknown irritative cyanobacterial components may discourage the use of recreational sites with high cyanobacterial population densities for water contact-intensive activities, regardless of the concentrations of known toxins (e.g. microcystins, neurotoxins, cylindrospermopsin). Analysis of these toxins will not characterise the hazard of irritative effects (see section 5.2.2). However, monitoring of microcystins or other known toxins can assess whether specific blooms present hazards from the cyanotoxins which are of greater concern for public health. In particular, it may identify some blooms as not presenting high risk levels. This information may be particularly relevant for heavily used sites, such as those associated with holiday facilities and for which temporary closure might have a substantial economic and social impact.

Monitoring of recreational sites should emphasise bloom prevalence and the potential of bloom formation. Step 1 of the structured approach presented in Figure 10.1 is particularly important here. This approach can easily be communicated to the general public and to bathing site users, and can involve them in assisting with hazard assessment (in addition to providing a basis for their own decision-making on water contact activities) by encouraging reporting of scums or strong discolouration and turbidity to authorities.

Monitoring toxin concentrations is especially important in drinking water supply systems in order to detect toxins released from the cells into the water during treatment and to determine the level of risk associated with a specific bloom in the water resource. Monitoring for cyanobacterial toxins is necessary to provide data:

- On the occurrence, types, abundance and distribution of cyanobacterial toxins in aquatic environments, water treatment and distribution systems, potable supplies and food products which contain, or have been exposed to, cyanobacteria and their toxins.

- On relations between environmental conditions, cyanobacterial populations and cyanobacterial toxins.

- For use in alert levels schemes and in the activation of contingency action plans.

- On relations between cyanobacterial toxins and water quality and health, with reference to human and animal exposure levels and health effects.

- For the derivation of standards for drinking water quality, to enable compliance with these values to be achieved and to determine, in the longer-term, whether such standards remain appropriate or need to be changed.

10.2 Laboratory capacities and staff training

Monitoring for cyanobacterial health hazards makes a range of demands upon analytical resources, some of which are different from those required by water quality monitoring for other types of variables. An overview of the requirements for the monitoring approaches discussed in section 10.1 and their respective information return is given in Table 10.1. Proper interpretation of information concerning cyanobacteria and their toxins requires expertise from the health and water resource sectors. However, these areas of expertise occur within a single authority in a few countries. Multisectoral co-operation is therefore important. Planning of monitoring programmes should generally involve co-operation between the environmental and the health sectors, bringing in further agencies or organisations where appropriate (e.g. drinking-water suppliers and authorities responsible for tourism, for public education or for water management).

Table 10.1 Approaches to monitoring for cyanobacteria and analysis for cyanotoxins: requirements and options for their organisation

Monitoring type	Parameters/variables	Demands on equipment and skills	Who	Where
Basic		Minimal		
Site inspection for indicators of toxic cyanobacteria in waterbody	Transparency, discolouration, scum formation, detached mat accumulation	Secchi disc, regular site inspection by trained staff; skill requirement basic, training easily provided	Environmental or health officers, trained health staff or supervised local	Local
Background		Low to moderate		
Potential for cyanotoxin problems in waterbody	Total phosphorus, nitrate and ammonia, flow regime, thermal stratification, transparency	Photometer, boat, depth sampler, Secchi disc, submersible temperature/oxygen probe; skills basic but require specific training and supervision	Environmental officers or experts with limnological expertise	Local, regional
Cyanobacteria		Low to moderate		
In waterbody and drinking water	Dominant taxa (quantity): often determination to genus level only is sufficiently precise; quantification only as precise as needed for management	Microscope, photometer is useful; specific training and supervision is required, but quite easily achieved	Environmental or health officers (with occasional quality control by experts); consultants with limnological expertise	Local, regional
Toxicity assessment		Moderate		
In waterbody and drinking water	Toxicity	Demands on equipment are low, but rather high on skills	Toxicologists	Central
Toxin concentration		Moderate to high		
In waterbody and drinking water	Toxin concentration	New methods with lower financial demands presently in development for some cyanotoxins (e.g. immuno-assay); skill requirements vary widely from moderate to very high	Skilled analysts	Central

Monitoring for visual indicators of cyanobacteria focuses on critical site inspection and requires almost no facilities. Training of staff is necessary, but not difficult and experience leads to improved performance. However, much time in the field is required and this can be reduced substantially by involving local people who have been given specific training for visual inspection. Nevertheless, professional staff should exercise periodic quality control over their work.

Environmental monitoring of chemical and physical variables indicating bloom-forming potential, such as nutrient concentrations, hydrophysical conditions and transparency, make limited demands upon analytical resources (a submersible temperature and oxygen probe and a photometer with optical filters to provide the necessary wavelengths are the most complicated instruments required). Such analytical capacities may be readily decentralised. While laboratory analysis can be carried out by any capable chemical laboratory, some limnological expertise is necessary for the planning of field work, quality control of data and interpretation of results. The staff time required can be reduced once seasonal patterns of variation are known and sampling regimes can be adjusted to be most effective.

Health authority staff with experience in microscopy can learn to recognise the most important toxin-producing cyanobacteria in the water bodies under their responsibility, if training by experts can be provided (attention may need to be given to dampening the general taxonomic enthusiasm of some experts, in order to concentrate on the skills really needed for monitoring the cyanobacterial taxa relevant for the water resources in question, see Box 10.2). Cyanobacterial identification and quantification can be centralised or subcontracted because preserved samples can readily be transported (see Chapter 11). However, the development of local skills is recommended because this should enable more rapid identification of, and response to, current cyanobacterial problems.

Cyanotoxin analysis with customised immuno- or enzyme assays, or toxicity tests with simple bioassays (see Chapter 13), may make only moderate demands on equipment and can be performed potentially by local health or environmental authorities. However, these techniques require specific staff training and periodic quality control by comparing results with those of more elaborate methods. More advanced programmes addressing toxicity assessment and toxin analysis require developed analytical capacities and exacting quality control. Even in countries with extensive advanced analytical facilities it is unlikely that the demand for toxin analysis would justify establishment of widespread or local facilities and some form of co-operation on a broader scale of centralisation is therefore advisable. Methods for cyanobacterial quantification and toxin analysis should be standardised and a system of official accreditation for analytical laboratories should be implemented.

Several options may be available for conducting analyses of water samples. The agency responsible for the monitoring programme may have its own laboratory or laboratories, the facilities of another agency or of a government ministry may be available, or some or all of the analytical work may be done under contract by a private laboratory. Some analytical work may be done in the field using either field kits or a mobile laboratory. Regardless of the options chosen, the analytical services must be adequate for the volume of work expected. Furthermore, good communication between those planning and performing field work and the analytical laboratory is crucial for ensuring appropriate sample collection, preservation and transportation (see Chapter 11). Periodic quality control is highly recommended particularly with respect to the handling of samples from field to final analysis.

10.3 Reactive versus programmed monitoring strategies

Monitoring strategies can be regarded as either reactive or programmed, although these are not necessarily mutually exclusive. A reactive strategy is needed when an unexpected cyanobacterial bloom develops and affects, or has the potential to affect, water supplies, recreational water and human health. It can be triggered by an unanticipated bloom event, by health impairments reported to authorities and related to cyanobacterial proliferation, by results of routine visual site inspection, or if routine analysis in drinking water treatment facilities detects cyanobacteria or toxins in the raw water intake or in recreational areas. This response strategy can include a range of *ad hoc* assessments of cyanobacterial numbers, toxicity assessment and toxin analyses. Programmed monitoring strategies are being applied increasingly to the investigation of cyanobacterial population and toxin problems where cyanobacterial problems are ongoing, occur regularly, are anticipated or have occurred in the past. These structured programmes can provide additional preventative benefits by warning of necessary actions before a developing cyanobacterial population presents an operational, environmental, or health problem, or by triggering the implementation of preventive measures at the source of the problem (see Chapter 8).

The benefit and information obtained from reactive as well as from programmed monitoring strategies can be greatly enhanced by ensuring that samples of cyanobacteria or water from natural or controlled environments are supplemented by clinical observations and clinical samples in the event of associated human and animal health incidents. This can be assisted by heightening the awareness of medical practitioners, public health authorities and veterinarians through training and information programmes (see section 7.4).

The potential for community involvement in monitoring strategies is high, provided that adequate information is supplied using leaflets, publicity and educational campaigns (section 7.4.2). "Algae Watch" programmes, or "scum scouting" to report on the appearance of blooms and scums. Schools programmes and water sports associations in Australia, the USA and the UK have provided useful information to monitoring agencies, as well as having helped to promote community action and joint responsibility for the causes and cures of cyanobacterial bloom problems.

Programmed monitoring strategies have the potential to detect and anticipate changes in cyanobacterial populations and potential levels of toxins. Such strategies can thus provide information to trigger appropriate contingency plans. Alert Levels Framework (ALF) systems are finding application in some countries; these are systems of programmed monitoring which incorporate action sequences in the event of warning thresholds being exceeded. Alert Levels Frameworks may be used for the monitoring of cyanobacterial populations only, or cyanobacterial populations plus toxins, depending on monitoring objectives and resources (see section 6.3).

10.4 Sample site selection

The selection of sampling sites is a key factor in determining the value of the data to be sought from the subsequent sample examination and analysis procedures. Sample site selection should be tailored to meet the overall aims and objectives of the monitoring programme (or even a single sampling visit). Thus site selection must consider and take account of the following:

• The uses made of the water body must be considered (e.g. potable supply, recreation, animal watering). For recreational use, sampling will include shoreline areas particularly frequented by visitors and may focus on public bathing sites. It may also include offshore sites where immersion sports take place. For drinking water resources, sites at or close to the raw water intake are important, and sampling within a treatment plant might include sampling at different treatment steps.

• If sampling aims at assessing the total population size of the cyanobacteria and their scum-forming potential, or the nutrient concentrations which influence the maximum possible population size, it should cover a central reference site in open, mixed water (experience may indicate if this can be used as a representative site for the main water mass). Selection of adequate depths must consider stratification of organisms and nutrients using depth-differentiating or depth-integrating sampling techniques as described in Chapter 11.

• Morphometric and hydrophysical characteristics of the water body (e.g. exposure to wind or thermal stratification) may help identify sites which are prone to scum accumulation. These factors are likely to influence the development and fate of cyanobacterial populations and their subsequent location in parts of the water body.

• Current weather conditions, particularly wind direction, which lead to scum accumulation along certain shorelines may require flexible choices of sites, particularly if the aim is assessing the highest cyanotoxin concentrations by sampling maximum scum densities.

• Specific incidents, such as animal deaths or human illness, if these are suspected to be associated with exposure to cyanobacteria and toxins at a specific location in the water body concerned.

• The history, if available, of cyanobacterial population development and occurrence of toxins in the water body, because this information may indicate sites particularly likely to harbour scums.

• Local logistical resources, accessibility and safety factors (e.g. Secchi transparency should be measured from a pier or boat, offshore sampling requires access to a boat and to a site for launching it, and sampling from steep shores or reservoir dams might be dangerous).

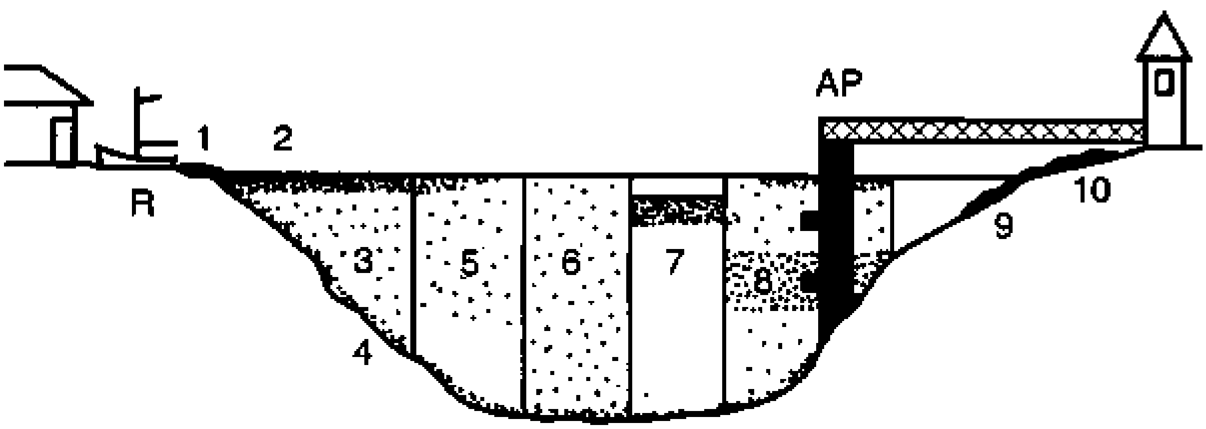
• Potential local sources of nutrient pollution (e.g. inlets or slopes affected by erosion).

For adequate sampling site selection it is of critical importance to consider the location and potential concentration of cyanobacteria in a water body, as described in Chapter 2 and in section 11.3.2. This site selection should account for accumulations of cyanobacteria as scums (usually quite unevenly distributed over the area of a water body), as subsurface maxima at some metres depth, as homogeneous distributions throughout the mixed strata of the water body, or growing on the sediment surface (from which they may become detached and driven onshore to present acutely toxic accumulations). Possible scenarios are shown in Figure 10.2.

The heterogeneous and dynamic nature of many cyanobacterial populations presents difficult problems for sample site selection. A flexible response to the current situation when choosing the sampling sites may, at times, be more appropriate than following a rigid programme. Alternatively, fixed sites always sampled within a broader monitoring programme may be supplemented with the sampling of sites currently harbouring cyanobacterial scums.

The horizontal and vertical heterogeneities in cell distribution are compounded by further variability in cyanobacterial toxin levels and distribution. Although the toxins are largely retained within the producer-cells during growth, they are released into the water during cell lysis due to natural agents, some algicides and pressure-induced disruption. Circumstances therefore arise where cyanobacterial toxins may be present in the absence of intact cyanobacterial cells. Sampling site selection for dissolved toxins may thus include locations such as the water close to decaying scums and in water treatment works and distribution systems, when it is suspected that cyanobacterial breakdown may have occurred.

Figure 10.2 Some locations of cyanobacteria in thermally stratified lakes or reservoirs. R, recreational area; AP, water abstraction point; 1, shoreline scum of planktonic cyanobacteria (often decaying); 2, planktonic cyanobacterial scum on open water during calm conditions; 3, dispersed cyanobacteria in epilimnion; 4, planktonic cyanobacteria on sediment; 5, upper mixed layer during autumn overturn; 6, spring and autumn conditions of complete mixing and in summer in shallow lakes in windy conditions; 7, scum under ice; 8, subsurface maximum of planktonic cyanobacteria (not apparent at surface); 9, mats of benthic cyanobacteria on sediment in shallow water; 10, shoreline accumulation of detached benthic cyanobacteria (Modified from Lindholm *et al.,* 1989 with additions)



10.5 Monitoring frequency

Cyanobacteria generally have fairly slow growth rates compared with many other micro-organisms. This helps to simplify monitoring frequency requirements. For those taxa which do not form scums but are dispersed in the water, weekly or even two-weekly monitoring intervals are often sufficient, even during their growing season, in order to monitor population development and to assess the cyanotoxin hazard. However, the ability of scum-forming cyanobacteria to change their concentration and position in the water body within very short time spans of only a few hours poses a specific challenge to the design of monitoring programmes.

Monitoring frequencies for cyanobacteria and cyanotoxins are suggested in the Alert Levels Framework given in Chapter 6. For example, monitoring may begin on a fortnightly or weekly basis and be increased to twice-weekly, or to daily, whilst alert levels are exceeded, and then be reduced again after values decline below alert levels and guideline values for cyanobacterial cells and toxins. The same principles should be applied to the monitoring of recreational waters, whether they are used on a year-round or seasonal basis (section 5.2.2). If a water body prone to cyanobacterial mass developments is used for water-contact sports on a seasonal basis, or for a single event, monitoring should begin not less than two weeks before the start of the season or the event. As monitoring is continued, frequency may be adjusted to enable decisions to be made on access to the facility throughout the season, or on whether to proceed with a special event.

Structured approaches to monitoring (e.g. Figure 10.1) introduce nutrients as a further variable for analysis. This may improve the information return for effort expended, particularly if each step in the structure is monitored at an appropriate frequency. Patterns of investigation may begin with longer time intervals and may be intensified as cyanobacteria begin to proliferate. As knowledge and understanding of a given ecosystem and the behaviour of its cyanobacterial populations accumulates, monitoring frequencies can be optimised to meet the demands of the specific situation. For this reason involving limnological expertise is particularly important in the planning of monitoring programmes, in the evaluation of the data, and in periodic reassessment of the adequacy of ongoing programmes. The following monitoring frequencies are suggested for the structured approach given in Figure 10.1:

- Visual site inspection may begin at weekly or two-weekly intervals, which can be increased to weekly or even more frequent intervals once cyanobacteria begin to proliferate.

- Assessment of the carrying capacity for cyanobacteria in terms of nutrients (phosphate and in nitrogen-limited systems, possibly also dissolved inorganic nitrogen) may be undertaken less frequently in many situations. This depends on prevalent nutrient levels and their rate of change. For example, in some water bodies, total phosphorus concentrations may show little seasonal change, or they may always be far too high to limit cyanobacterial biomass. In either case, occasional monitoring (in temperate climates once in spring and once in summer) may be sufficient. On the contrary, if the hydrological regime shows pronounced fluctuations, or if the total phosphorus concentration oscillates around levels critical for limiting cyanobacterial biomass (0.03-0.05 mg l^{-1} P), monthly or biweekly measurements may be necessary in order to assess the carrying capacity for cyanobacteria. Often it will be advisable to begin a programme with monthly sampling for one or two years. Evaluation of patterns may then enable a reduction of sampling frequency to be justified.

• Assessment of cyanobacterial cell numbers or biomass can be affected by the rapid changes discussed above, particularly if scum-forming taxa prevail. Knowledge of a water body's carrying capacity for cyanobacteria, of the taxa typically occurring, and of seasonal time patterns of their occurrence will help anticipate critical situations which require increased monitoring frequency. If the aim of monitoring is to check compliance with standards for drinking water or recreational use, and toxin levels in a given water body are in the borderline range or above, sampling and analysis may be necessary several times a week. Time patterns of water body use, particularly for recreation, may be a useful further criterion for determining the time patterns for sampling.

• Toxin analysis may be necessary less frequently than assessment of cyanobacterial cell numbers or biomass. Although toxicity of populations is variable, it does not appear to change within a few days. Assessment of toxicity is particularly recommended when situations in the water body change, e.g. when other taxa appear or if bloom lysis occurs.

Ideally, "real-time" information on the state of the cyanobacterial population and their toxins is desirable for scum-forming taxa. Some approaches to meeting this demand are currently being developed. The simplest approach is semiquantitative assessment of cyanobacterial cell numbers through a microscope. This can be performed within an hour or less of sampling, provided a microscope is available locally, and can be repeated frequently during problem phases provided the laboratory is close to the water body (which is often the case at drinking water supply reservoirs). Continuous automatic provision of fluorescence data indicating pigment concentrations has become possible by means of submersible flow-cell fluorescence spectrophotometers or by continuous water flow through laboratory fluorimeters and cytometers. These procedures are currently beginning to differentiate successfully between cyanobacteria and other components of the phytoplankton. Installation of such devices may be especially attractive for drinking water supply abstraction points, in order to adapt offtake levels to the current location of cyanobacteria (if offtake depths are flexible), or in order to have an immediate indication of the need to apply further treatment steps. Another approach currently investigated for acquisition of real-time data for chlorophyll distribution and levels, and potentially for cyanobacterial phycobiliprotein pigments in freshwaters, is remote sensing of the optical properties of the water body by high resolution airborne scanners (Cracknell *et al.,* 1990; Jupp *et al.,* 1994). However, flight times may be infrequent and data collection depends on factors beyond human control, e.g. cloud cover. Nevertheless, the remote sensing of cyanobacterial populations as a contribution to water body management has excellent potential particularly for the monitoring of scum locations. Remote sensing may become cost-effective for areas that have to monitor many recreational sites.

Further aspects to consider in determining monitoring programme frequencies are, as with site selection (section 10.4), the monitoring programme objectives, water-use, specific incidents associated with exposure to cyanobacteria and their toxins, historical evidence of blooms in the water body, local water body and catchment characteristics, and the wider knowledge of cyanobacterial ecology. Available resources, sampling and analytical logistics also need to be taken into account, for example, the time needed for sample transportation, processing and analysis, and for the interpretation and reporting of results.

Monitoring intervals should be timed to provide information for the following situations:

• To give warnings of developing cyanobacterial populations and toxin levels.

• On the duration of cyanobacterial populations and toxin levels which exceed guideline values.

• On the decline of cyanobacterial populations and toxins due to natural processes or the persistence or reduction in cyanobacterial populations and toxin levels due to intervention, such as eutrophication control and water treatment.

In subtropical and tropical latitudes where appreciable cyanobacterial populations can occur all year round, it may not be feasible or necessary to maintain high frequency sampling programmes throughout the year, particularly if the population density is subject to less change because there is little seasonal change in growth conditions. In this event, sampling of the natural or untreated water may need to be at less frequent intervals, e.g. monthly, with laboratory resources being directed towards higher frequency monitoring of treated drinking water.

10.6 References

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