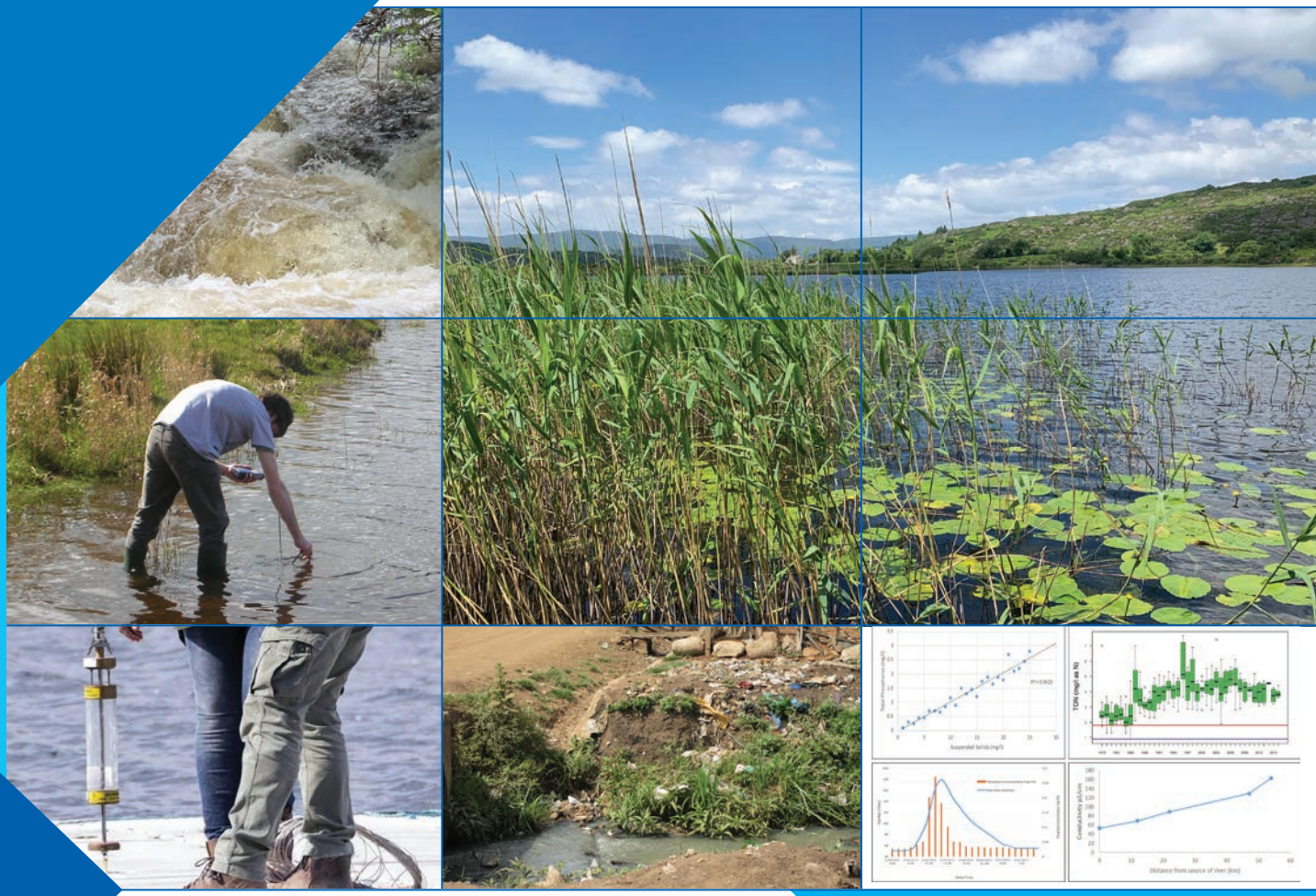
UN environment programme



INTRODUCTION TO FRESHWATER QUALITY MONITORING AND ASSESSMENT

Technical Guidance Document

Prepared by UNEP GEMS/Water Capacity Development Centre for the
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FOREWORD

This technical guidance document is intended as a basic introduction to water quality monitoring and to guide readers to the most relevant detailed guidebooks in this series. It is intended for scientists and technicians who do not have specialised knowledge or experience in water quality monitoring and need a general overview of the key aspects and complexities of establishing a water quality monitoring programme. It highlights the need for understanding the hydrological and ecological functioning of water bodies when planning a sampling and analysis programme. Brief guidance is given for choosing monitoring approaches and water quality parameters that will provide meaningful and useful data for management and policy making. It is intended and strongly recommended that this guidebook is read in conjunction with the accompanying guidebooks in the series, particularly "*Water Quality Monitoring and Assessment in Rivers, Lakes and Reservoirs*", "*Water Quality Monitoring and Assessment of Groundwater*", "*Quality Assurance for Freshwater Quality Monitoring*" and "*Water Quality Data Handling and Assessment*".

In addition to this document, the full set of guidance documents in the series that address various aspects of monitoring and assessment of freshwater are:

- Water Quality Monitoring and Assessment of Groundwater
- Water Quality Monitoring and Assessment in Rivers, Lakes and Reservoirs
- Quality Assurance for Freshwater Quality Monitoring
- Freshwater Quality Monitoring with Biota
- Freshwater Quality Monitoring using Particulate Matter
- Water Quality Data Handling and Assessment

LIST OF ABBREVIATIONS

ANZACC	Australian and New Zealand Environment and Conservation Council
ARMCANZ	Agriculture and Resource Management Council of Australia and New Zealand
BOD	biochemical oxygen demand
COD	chemical oxygen demand
EC	electrical conductivity
GEMS	Global Environment Monitoring System
GIS	Geographic Information Systems
GPS	Global Positioning System
ISO	International Organization for Standardization
PCBs	polychlorinated biphenyls
PM	particulate matter
QA	quality assurance
QC	quality control
SDG	Sustainable Development Goal
SOP	standard operating procedure
TOC	total organic carbon
TSS	total suspended solids
UN	United Nations
UNEP	United Nations Environment Programme
WHO	World Health Organization

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CHAPTER 1

INTRODUCTION

Freshwater of adequate quality and quantity is an absolute necessity for all life and for sustainable development. Freshwater quality is threatened globally by a variety of pollutants arising from human activities (e.g., domestic sewage, industrial effluents, agricultural runoff). At the same time there is an increasing global demand for water for domestic and industrial use, agricultural irrigation, and environmental services. These demands place increasing pressure on the finite freshwater resources available in all countries, with each demand having specific water quality requirements. Water of the highest quality is required to protect human health, such as for drinking water. Aquatic ecosystems and the aquatic organisms within them also have requirements for water quality that support their "health" and growth. Without monitoring, it is not possible to know whether water quality requirements for human health and the ecosystem are being met. Data from monitoring programmes are therefore necessary for effective management that can protect and restore water quality.

By 2030, target 6.3 of UN Sustainable Development Goal (SDG) 6 aims to "improve water quality by reducing pollution, eliminating dumping, and minimizing the release of hazardous chemicals and materials", with the aim of "halving the proportion of untreated wastewater, and substantially increasing recycling and safe reuse globally" (United Nations [UN] 2015). To determine whether water quality is improving and the aims of SDG 6 are being met, it is necessary to monitor water quality and water quantity. In the context of the SDG 6, water quality is measured by SDG Indicator 6.3.2 "The proportion of bodies of water with good ambient water quality". This indicator is calculated using typical water quality monitoring data from rivers, lakes and groundwaters at national scale.

Water quality monitoring can be defined as the acquisition of quantitative and representative information about the physical, chemical and biological characteristics of a water body over time and space. There is an urgent need for water quality to be monitored at national, regional and global scales in order to identify where water quality is inadequate or under threat. Monitoring enables assessment of the current state of water quality and trends over time, and whether targets and guidelines are being met. It can identify actual and emerging problems of water pollution and estimate the flux of substances from rivers to oceans, or across boundaries in shared waterbodies. Targeted monitoring can provide a rapid assessment of the influence of an environmental incident (e.g., chemical spill) on a water body and regular monitoring can provide an insight into the development and implementation of water quality management plans and the setting of priorities. Finally, it enables evaluation of the effectiveness of management and remediation activities and provides information on the efficiency of operational activities (**Box 1.1**).

Water quality monitoring is carried out at many different scales and by many different organisations, including national agencies (e.g., Environmental Protection Agencies), water resources departments or organisations, local authorities (e.g., state and regional water authorities), non-governmental organisations,

BOX 1.1 EXAMPLES OF QUESTIONS THAT CAN BE ADDRESSED WITH WELL-DESIGNED WATER QUALITY MONITORING ACTIVITIES

- Is water quality acceptable for human use or contact (drinking water source, irrigation, recreation, etc.)? How might the water quality affect certain populations, especially women and children?
- What are the major sources of pollution to a water body?
- How far downstream does the impact of an effluent discharge reach?
- Has a new policy resulted in the intended effect and has it been cost effective?
- When did this water quality problem start and what changes in human activities have made it better or worse?
- Has a water quality management plan worked?
- Could the catchment benefit from an educational programme for all stakeholders?

industry (for compliance and operational monitoring), private companies (e.g., consultancies, on behalf of clients), research individuals and institutes, and citizens and communities. The monitoring data generated by one or more organisations may be used by a wide range of other organisations and individuals for many different purposes, such as national organisations for local/national management and policy; regional agencies to assess status and trends and transboundary issues with international agencies for global status and trends, international conventions, etc.; and research projects and programmes.

1.1 The keys to successful monitoring programmes

Scientists with appropriate expertise should be involved in the design of a monitoring programme to ensure that scientific understanding and principles are applied to the design. All stakeholders should be consulted, with gender balance representation, including the communities served by the water bodies, to ensure their concerns and observations are taken into consideration in the monitoring programme design. It is particularly important to consult the women and children who often have the main responsibility for obtaining water for domestic use.

Good foresight and understanding of the aquatic system being monitored can produce monitoring data with enduring value. This involves looking ahead to anticipate the potentially important environmental problems of the future and then selecting key measurements that are likely to be sensitive to the resulting changes and that generate high quality data that will remain useful for decades. Water scientists can ensure that methods are appropriate and accessible, that the data generated are of the highest possible quality and will be useful and relevant, and that the programme is cost-effective. In order to enable the maximum possible use of data, liaising with other scientists is necessary to create harmonised monitoring networks that facilitate sharing of data across sites, boundaries and even different disciplines.

Understanding the aquatic system enables scientists to choose the most relevant parameters among the many that could potentially be measured. Some parameters are important to measure because they represent critical processes (e.g., primary production, nutrient budgets, river discharge), and others are useful because they are known to have an impact on the whole ecosystem (e.g., phosphorus). Monitoring key parameters improves the likelihood that a dataset will be useful in the long term and will contribute to the study of future environmental issues.

The complexity of a monitoring programme can range from simple field measurements of a limited number of parameters at one or more locations to complex programmes with multiple samples taken at each location followed by advanced laboratory analysis techniques. Different levels of monitoring have different associated costs and requirements for resources. The complexity of a programme is governed by its objectives. The monitoring programme design team is responsible for selecting the appropriate complexity of monitoring to ensure that the programme objectives

BOX 1.2 THE KEYS TO A GOOD MONITORING PROGRAMME

- Well defined, clear and realistic objectives.
- Appropriate monitoring programme design.
- An appropriate level of quality assurance for all steps leading to, and maintaining, the data.
- Careful interpretation of results.
- Successful application in water resources management and policy development

are met (**Box 1.2**). The objectives of the monitoring programme must be clearly defined in order to aid this process (see section 1.2).

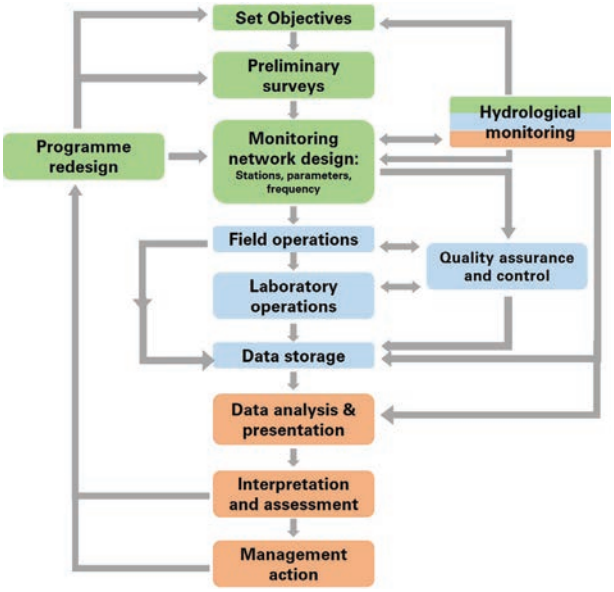
Monitoring programmes can be expensive to implement but the savings made by making evidence-based management decisions, together with the relative value of the water resources themselves and the services they provide, can match or out-weigh these costs (Damania *et al*. 2019). Government agencies should evaluate their monitoring programmes in the light of national needs, and they should take steps to ensure that critical programmes are not sacrificed when resources are limited. There should be a commitment to funding freshwater quality monitoring ensuring that it is done to the highest possible standard and that data are appropriately stored and archived. Resource managers must make the commitment to maintain and expand long-term monitoring programmes under their control and the programmes need to be designed to survive times when budgets may become restricted. This can be helped by securing and maintaining a minimum funding commitment, having a core set of inexpensive monitoring parameters, and having a group of people dedicated to collecting, interpreting and using the data. This will provide an invaluable legacy of information for future scientists and citizens.

Historically, there has been a tendency to carry out monitoring programmes and then to archive large amounts of water quality data without making full use of them. This common practice in many disciplines led to the expression "Data rich - information poor" (Bell, 2006). Data generated from monitoring programmes must be used and not just accumulated in databases, otherwise the resources used to carry out the programme have been wasted. Some reasons why data are stored and not used fully include inaccessibility to all but a few people, poor quality or inadequate documentation, and storage in an incompatible or non-exchangeable format. In some situations, data may have been collected solely to fulfil a legal requirement and sharing may not be permitted.

There is no single, best model for structuring a monitoring programme but success is more likely if a logical sequence of steps is followed. There are three main phases in the design and implementation of a water quality monitoring and assessment programme (**Fig. 1.1)**:

- Phase 1 Setting of objectives for the monitoring programme and design of the programme.
- Phase 2 Implementation of the monitoring programme.
- Phase 3 Assessment, reporting and management action.

Figure 1.1 The chain of activities in designing and implementing a freshwater quality monitoring programme showing phase 1 in green, phase 2 in blue and phase 3 in orange (adapted from Chapman, Meybeck and Peters 2005)



Access to hydrological information needs to be considered at all three phases and, if necessary, it should be included in the monitoring programme design. An indication of the relevant hydrological information required for different levels of complexity of monitoring programmes is given in **Table 1.1**. Relevant quality assurance procedures must also be planned and implemented in order to ensure the monitoring data are reliable and credible (see accompanying guidebook on *"Quality Assurance for Freshwater Quality Monitoring Programmes"*). An overview of phases 1 and 2 is given in the following chapters, and all three phases are covered in more detail in the accompanying guidebooks in this series: *"Water Quality Monitoring and Assessment of Groundwater"* and "*Water Quality Monitoring and Assessment in Rivers, Lakes and Reservoirs*".

1.2 Setting monitoring programme objectives

The success of a monitoring programme is dependent on having clearly defined objectives prior to commencing the programme. Well-defined objectives are essential to identifying the information that must be produced from the monitoring activities. Setting objectives is the first step in the design and implementation of a monitoring programme (Fig. 1.1). End user(s) of the monitoring data and all stakeholders, including local communities, women and children, should be involved to ensure the objectives are complete and correct. Several attempts may be needed to clarify and agree the final objectives amongst all stakeholders.

Some pitfalls to avoid when specifying objectives include targeting the wrong problem as a result of not understanding the underlying issues or the functioning and behaviour of the water body, complicating the issue so that no solution is possible, and using information that is incorrect or irrelevant. Examples of objectives are given in **Box 1.3**.

Monitoring objectives may be either single i.e., addressing one problem area only (normally involving a simple set of parameters, such as pH, alkalinity, nutrients, chlorophyll, etc.) or multiple i.e., covering several water issues and providing information that feeds into a number of management processes including drinking water supply, industrial

Table 1.1 Hydrological information required for different levels of water quality monitoring programme complexity

	Rivers	Lakes and Reservoirs	Groundwater
All programmes	Map of catchment	Depth at sample site Residence time Thermal regime	Type of aquifer Direction of groundwater flow
	PLUS	*PLUS*	*PLUS*
Basic programmes	Water level at time of sampling	Lake level at time of sampling Depth of thermocline (if present)	Piezometric level
Advanced programmes	River discharge at time of sampling	As above *PLUS* vertical profiles of dissolved O_2 and temperature at time of sampling	Piezometric level between sampling Aquifer map
Complex programmes	Continuous measurement of river discharge	As above *PLUS* rate of inflows to lake and patterns of water movements	Full knowledge of groundwater hydrodynamics

Source: Adapted from Kuusisto (1996)

BOX 1.3 EXAMPLES OF OBJECTIVES FOR FRESHWATER QUALITY MONITORING PROGRAMMES

- To identify the causes of algal blooms in a lake.
- To determine whether surface waters are suitable for drinking or recreational use.
- To determine the effects of long-term temperature changes on the aquatic ecosystem.
- To identify river basins at national scale that require additional controls on wastewater discharges.
- To determine the extent and impacts of an accidental discharge of toxic compounds.
- To provide advanced warning of a possible change in water quality for sensitive water abstraction points.
- To assess the biological productivity of lake or reservoir and its ability to support a commercial or recreational fishery.
- To validate a water quality model

manufacturing, fisheries and ecosystem protection, etc. These objectives must also reflect the use of the resultant data and will determine whether the focus is on spatial variations in water quality (high station number), on trends (regular sampling over long time frames) or on specific parameters (e.g., targeting contaminants).

Once the objectives have been clearly defined, it is important to carry out a full preliminary survey (see chapter 2) that will provide information to ensure the monitoring programme and its associated network of monitoring stations provide the information required to meet the objectives.

1.3 Monitoring for water quality assessments

A monitoring programme should be designed and implemented in relation to the programme objectives, which should specify the nature of the intended water quality assessment. For example, if the objective is to check whether surface water quality is suitable for drinking without treatment, the assessment will be made by comparing the monitoring data with national or international drinking water standards or guidelines, e.g., World Health Organization [WHO] (2022). The level of detail and accuracy of the monitoring data required to perform the assessment should also be considered, so that appropriate methods can be selected. Any supplemental information needed to prepare an assessment should also be considered and the availability of the necessary information should be investigated as part of the preliminary survey. For example, a water quality assessment of the impact on the aquatic environment arising from a particular wastewater discharge would require the following information in addition to the results from an appropriately designed monitoring programme:

- A list of the compounds present in the discharge, preferably with an indication of the range of their concentrations and the frequency, volume and location of discharge,
- Other potential sources of the same compounds,
- Known or likely toxicity to aquatic organisms, and
- Potential for bioaccumulation of any of the compounds likely to be discharged.

Without this information the monitoring programme is unlikely to be designed appropriately and the impacts are unlikely to be fully, or accurately, assessed.

A water quality assessment of the fluxes of heavy metals to the coast from a river basin or across the national boundary of a transboundary river would require water quality monitoring data, hydrological data, and catchment characteristics. The use of Geographic Information Systems (GIS) is appropriate for this type of assessment because it lends itself well to the incorporation of catchment characteristics (see chapter 6).

Assessment of status and trends in surface waters may require a combination of physical, chemical and biological information, or it may rely on the use of a biological index alone. Biological indices are widely

used to assess trends in national river quality status (see guidebook on *"Freshwater Quality Monitoring with Biota"*), where water quality is assigned categories such as excellent, good, fair or poor. This type of assessment is particularly useful to convey information to non-experts, such as policy makers and the public, and to identify hotspots and regions of poor water quality.

1.4 Monitoring programme review, evaluation and redesign

Monitoring programme review, evaluation and redesign is an important step in a monitoring programme and is necessary to identify how the monitoring programme could potentially be improved. The goals of reviewing and refining the monitoring programme are:

- Refocus the objectives of the monitoring programme.
- Address resource issues (personnel, laboratory facilities, etc.).
- Increase the effectiveness of staff and laboratory resources.
- Identify where additional data or complementary data are needed to aid assessment and data interpretation.

All aspects of the programme should be examined and their efficiency, suitability and adequacy reviewed, including field activities, laboratory procedures and data management (**Box 1.4**).

Evaluation of a monitoring programme is important to consider whether things may be done differently to generate reliable data in a cost-efficient way. The results of the evaluation should then be used to repeat the process of monitoring programme design using the same steps as for the original programme design (Fig. 1.1) and making adjustments where necessary. When redesigning a monitoring programme it is critically important to ensure continuity and comparability of data obtained before and after redesign. If necessary, a period of overlap between the original and revised monitoring programmes might be necessary to compare the results obtained. This is particularly important if methods and/or instruments are changed because they may have different limits of detection or levels of accuracy.

BOX 1.4 QUESTIONS TO BE ASKED WHEN REVIEWING A MONITORING PROGRAMME TO ENSURE OBJECTIVES ARE STILL BEING MET AND THE PROGRAMME IS BEING IMPLEMENTED EFFICIENTLY

- Does the monitoring programme meet the programme objectives?
- Are the field operations adequate to generate the necessary data?
- Are field notes adequate and accurate enough to explain possible unexpected variations in data?
- Are the monitoring results obtained of sufficient accuracy and are effective Quality Assurance procedures and laboratory quality controls in place and implemented?

The results from the programme, up to the point of programme review, can help inform the decisions to some of the appraisal questions.

CHAPTER 2

THE PRELIMINARY SURVEY

It is important that new monitoring programmes do not merely become repeat studies. The information gained in previous monitoring programmes should, therefore, inform new monitoring programmes by identifying gaps in knowledge. The preliminary survey should bring together all available information and data from all relevant sources, including monitoring information from different national agencies and institutions, research studies and scientific publications. It may involve a review of relevant information or data already available, identification of gaps in required information, review of historical monitoring data for the site(s) of interest and other relevant locations, an assessment of land use and human activities in the catchment of interest, a comprehensive literature review, and a review of interviews or observations recorded by local community members and field personnel. Additionally, it should determine the time and space variability of the aquatic environment to be monitored in order to identify possible sampling locations and sampling frequency, and to define the essential parameters to be measured. Finally, it should provide information that will support the design of the monitoring programme, including feasibility and costs. Inadequate preliminary surveys may lead to costly deficiencies, or overspending, during many years of the monitoring programme.

There are three main components to preliminary surveys:

- review of existing information and data,
- field surveys to validate site locations and/or collect baseline water quality information, and
- selecting, testing and refining sampling and laboratory methods.

2.1 Review of existing information and data

Existing data provide information on spatial and temporal variations in the past (which aids selection of sampling sites and sampling frequency), areas of natural and/or possible human influences on water quality (which aids site selection sampling and the parameters to be included), and the ranges of measurements obtained for any particular water quality parameters (which assists selection of analytical and field methods).

Reviewing the available geological, topographical and land use maps provides information on natural influences on water quality such as from different geological formations, potential influences on water quality from human activities such as agriculture, urban development and wastewater discharges, and areas where runoff may affect water levels and water quality.

Reviewing applicable guidelines and standards and identifying relevant stakeholders provides information on parameters that may be essential for the monitoring programme, the level of accuracy that may be required for analysis of essential parameters, and people or organisations that may contribute to the monitoring programme (design or implementation) or who may be interested in the results.

2.2 Field surveys

Preliminary field surveys determine whether sampling sites identified on a map are actually accessible and safe to access (**Fig. 2.1**). They may also identify where permission to access sampling sites may be required from adjacent landowners. Visiting potential sampling sites prior to commencing their use also provides information on activities in the locality, such as regular or intermittent wastewater discharges or agricultural run-off, that might affect the interpretation of the water quality data (**Fig. 2.2**). Where available at sufficient resolution, satellite imagery such as that available from Google Earth (https://earth.google.com/web/), may reduce the need for preliminary site visits by field personnel.

The width and depth of the river at proposed sampling sites should also be measured and the influence of meteorological conditions on discharge determined, i.e., does the discharge respond to rainfall within hours or days. Locating the nearest gauging stations will assist with this, especially if they are automatically providing data or can be accessed to take manual readings. Sampling locations should also be checked to ensure the water is well mixed, especially if the intention is to use a single representative sampling station. A short intense sampling survey analysing a basic parameter such as temperature or conductivity at different depths and points across the width of the river, will indicate the degree of variability.

Figure 2.1 **A preliminary field survey of potential sampling locations can help to identify whether they are accessible and safe to access. © Deborah Chapman**

Figure 2.2 **Potential sources of influence on the water quality at potential sample sites, such as this highly turbid drainage, can be determined during a preliminary field survey. © Deborah Chapman**

Depending on their size and geographical location, lakes may exhibit variation in water quality horizontally and vertically that depends on their bathymetry and catchment (see guidebook on *"Water Quality Monitoring and Assessment in Rivers, Lakes and Reservoirs"*). If the bathymetry is not already known, a bathymetric survey may be necessary. Lakes may also show strong temporal variations that are a response to seasonal variations in climate. A preliminary sampling programme with a high density of sampling stations can check this variability. In shallow temperate lakes it is also necessary to determine whether the lake stratifies with depth and, if so, the depth of the thermocline. This provides information that assists decisions on the depth, number and type of samples to be collected, e.g., integrated or composite samples (see section 4.1.2).

Drilling new wells for groundwater monitoring programmes is not always possible due to financial constraints. Therefore, the preliminary survey should establish the locations of existing wells and their suitability for inclusion in the programme. Wells may exist on farms, commercial or industrial premises,

and individual households where permission to access them may be necessary. The construction of wells selected for inclusion should be checked to determine whether the well casing is perforated or not. If it is perforated it may be allowing access to water from more than one aquifer. Wells may also be open to contamination from the surface and therefore samples may only represent the immediate locality of the well and not represent the overall quality of the aquifer. The direction of flow and depth to water table or piezometric level should also be determined. Further information on selection and construction of wells for monitoring in available in the accompanying guidebook on *"Water Quality Monitoring and Assessment of Groundwater"*.

2.3 Selecting, testing and refining sampling and analysis methods

For a new monitoring programme, it may be necessary to test the intended methods or to run trials of different approaches in order to select the most appropriate methods that will meet the expectations of the programme objectives in relation to cost, precision and accuracy. This applies to both field and laboratory methods. The intended laboratory must be sufficiently close to the sampling stations to ensure that samples are received from the field within the timeframe required for analysis and before any deterioration in the samples occurs. If existing field or laboratory equipment and facilities are not adequate, new equipment may need to be considered, or new methods developed, or existing methods refined. It may also be necessary to consider the services of an external laboratory. Whatever laboratory arrangement is chosen, it is imperative that procedures are established for quality control of the analytical work (see section 5.5). Alternative approaches may also be explored and tested, such as monitoring with biota (see chapter 3 and guidebook on *"Freshwater Quality Monitoring with Biota"*). Staff may require relevant training in any new methods prior to the commencement of the monitoring programme.

CHAPTER 3

SELECTION OF MONITORING MEDIA AND PARAMETERS

Water quality can be considered as the combined physical, chemical, and biological characteristics of the water. Examples of these are:

- *Physical* - colour, transparency, pH, temperature, electrical conductivity, total suspended solids (TSS).
- *Chemical* - major ions, nitrate, nitrite, orthophosphate, toxic compounds.
- *Biological* - species diversity and abundance, total coliforms, faecal coliforms, chlorophyll.

Traditionally, freshwater quality monitoring has been based on the determination of the physical and chemical properties of water samples. However, when designing a monitoring network, consideration should be given to using any of the three media that comprise a water body: water, aquatic organisms and particulate matter. Each medium has specific characteristics that might be relevant for particular monitoring objectives, such as:

- Applicability to a type of water body.
- Possibility for providing additional information, such as fluxes.
- Sensitivity to types of pollutant, e.g., whether the pollutant is lipid or water soluble which may lead to the possibility of amplification of the concentration in biota and particulate matter.
- Sensitivity to sample contamination during collection and analysis.
- The potential for time-integration of environmental impacts, thereby reducing the required frequency of sampling.

The availability or requirements for skilled personnel, as well as suitable storage facilities for the types of samples (e.g., refrigeration, amount of space, risk of contamination) should also be considered. Ultimately, the available budget may influence final decisions because some media may provide an adequate level of information at low cost while others may require expensive analytical facilities.

Water is the most commonly-used monitoring medium in all types of water body and is the only medium that can be used for groundwater. It can be readily analysed for a wide range of parameters and is the most appropriate medium for sampling and analysis when the water is going to be used for a purpose with specified quality criteria, such as for drinking. It is also most appropriate when it is necessary to know the concentrations of water-soluble substances that can affect the aquatic ecosystem, such as nutrients (e.g., nitrogen and phosphorus), or some toxic compounds when it is anticipated that they will occur at the sampling location. Water samples can be analysed without filtration to measure total concentrations of dissolved and particulate fractions of a parameter or filtered and the dissolved and particulate fractions analysed separately.

The biological characteristics of a surface water body reflect the condition of the aquatic ecosystem and the impact of human activities on the ecosystem (see accompanying guidebook on *"Freshwater Quality*

Monitoring with Biota"). There are many definitions of biological monitoring or biomonitoring, but in the context of water quality monitoring it means the use of biological responses to assess changes in the aquatic environment. It is commonly used to track long-term trends in surface water bodies and to illustrate impacts on aquatic ecosystems. Biomonitoring methods integrate responses to all contaminants present in their location together with other environmental stressors during the lifetime of the organism. By contrast, physical and chemical analyses of a water sample give a measurement that is valid only for the instant in time when the sample is collected. Biological monitoring can also offer a quick and cheap method to determine water quality when compared with some physico-chemical analyses (**Table 3.1**).

Particulate matter (PM) comprises mineral matter and organic particles, such as microscopic organisms or decomposing organic matter, suspended in water and deposited on the bottom of a water body. Particulate matter in the water column is often referred to as suspended solids. Particulate matter is defined as particles greater than 0.45 µm and dissolved matter includes all particles finer than 0.45 µm. Mineral PM is derived primarily from rock weathering processes. Erosion and run-off transfers sediments or soil particles from their point of origin to the point of deposition at the bottom of a receiving water body. Sediments may become resuspended during storm events and transported even further afield. The ultimate sink for particles is usually the deepest part of lakes, hollows and sheltered backwaters in rivers, or the river delta or coastal zone. Further information on including particulate matter in monitoring programmes is available in the accompanying guidebook on *"Freshwater Quality Monitoring with Particulate Matter"*.

Particulate organic matter may have associated nutrients (e.g., phosphorus) bound to the organic particles or incorporated within living or dead biota. These nutrients can actively exchange between particulate matter and water, depending on environmental conditions. Toxic inorganic pollutants, such as some heavy metals, may be subject to adsorption, deposition and recycling by particulate matter. Toxic organic pollutants that have an affinity for lipid material, such as organochlorine compounds, hydrocarbons, etc. may be associated with organic particles. Hence, chemical analysis of suspended

Table 3.1 **Strengths and weaknesses of chemical and biological approaches to monitoring water quality**

	Strengths	Weaknesses
Chemical monitoring	Valid for all water bodies. Very fine temporal resolution possible, including continuous monitoring for some parameters. Possible to determine precise pollutants and their concentrations. Standardised methods available for most parameters. Wide range of potential methods available with the possibility for *in situ* measurements for some parameters.	Detection limits for some micropollutants may be inadequate or may be possible only with specialised laboratory facilities. High costs associated with most analyses. Limited options for continuous monitoring and temporal integration. Possibility of sample contamination for some pollutants.
Biological monitoring	Provides long term indication of water quality. Good spatial and temporal integration. Potential for amplification of some parameters occurring in water at very low concentrations (bioaccumulation, biomagnification). Good response to chronic, minor pollution events.	Only valid for surface water (not groundwater). Standardization difficult and precise cause of response detected often unknown. Not valid for pollutant flux studies. General lack of temporal sensitivity.

particulate matter can provide information on the total concentrations of nutrients and pollutants in the water column and the rate of vertical settling of pollutants and nutrients in still or slow flowing waters. Chemical analysis of deposited particulate matter can provide information on sinks of pollutants and, by analysing vertical depth cores of sediments, it can provide information on past concentrations of pollutants.

3.1 Physico-chemical parameters

Many physical parameters are included as basic measurements in water quality monitoring programmes because they may influence other measurements or they may be important for the normal functioning of the aquatic ecosystem (**Box 3.1**).

Temperature affects the rate of biological and chemical processes and has an influence on other physical parameters. It is, therefore, a fundamental measurement for all water bodies. Temperature varies geographically and with season. Freshwater bodies exposed to solar radiation show the greatest variation in temperature. It can be measured *in situ* using a thermometer or temperature sensor. Some sensors designed to measure dissolved oxygen, conductivity or pH, can also measure temperature.

Box 3.1 EXAMPLES OF BASIC PARAMETERS FOR INCLUSION IN MOST AMBIENT WATER QUALITY MONITORING PROGRAMMES

	Rivers	Lakes	Groundwater
Temperature	✓	✓	
Dissolved oxygen	✓	✓	
pH	✓	✓	✓
Nitrogen	✓	✓	✓
Phosphorus	✓	✓	
Electrical conductivity	✓	✓	✓
Faecal bacteria			✓
BOD and/or COD	✓		
Chlorophyll *a*		✓	

Figure 3.1 A Secchi disc for measuring the transparency of the water (Department of Environment and Science [DES] 2018) By State of Queensland, Licenced under CC BY 3.0 AU

The colour of water varies naturally due to geological and biological influences in the catchment and can sometimes be indicative of the presence of dissolved substances, such as humic acids and microscopic organisms, particularly microalgae. It is rarely included as a basic parameter for routine monitoring but may be noted on a field record sheet as an observation of the condition of the water. Together with colour, turbidity and transparency determine the depth to which light is transmitted in water, which in turn controls the growth of macrophytes and algae in the water body column. Transparency gives an indication of the depth to which light can penetrate into the water and is usually measured in the field using a simple Secchi disc (**Fig. 3.1**). Turbidity is affected by the density of phytoplankton and other particles and, therefore, turbidity measurements can give an indication of the nutrient or trophic status of the water body (see *"Water Quality Monitoring and Assessment of Rivers, Lakes and Reservoirs"*). Turbidity is a

measure of dissolved and suspended material in the water column. It can be measured in the field with a simple turbidity tube (**Fig. 3.2**) or an electronic turbidity meter. It can be useful to measure the impact of wastewater discharges, or sediment resuspension or transport events. It should be measured immediately after the sample is collected to avoid any settlement of suspended particles that might occur leading to a lower value. A more accurate and standardised measure of turbidity is total suspended solids (TSS), which is the non-filterable residues retained on a standard filter (usually a glass fibre "GF/C" grade) dried to constant weight at 103–105 °C (International Organization for Standardization [ISO] 1997).

Figure 3.2 **A simple graduated turbidity tube is filled with water directly from the water body until the coloured base is no-longer visible from above. © Deborah Chapman**

The pH influences many biological and chemical processes within a water body and it is therefore usually included as a basic parameter. It can be influenced by the presence of effluent discharges and by changes in the balance between carbon dioxide, carbonate and bicarbonate ions. Photosynthesis and the respiration cycles of freshwater plants and algae, particularly in nutrient rich waters, can also affect pH levels through their use and release of carbon dioxide. The carbon dioxide dissolves in water to produce carbonic acid, which in turn dissociates to release hydrogen ions. Reduced levels of carbon dioxide resulting from photosynthesis lead to lower hydrogen ions in the water and a higher pH. Ideally, pH should be measured in the field or immediately after the sample is taken, because natural processes in the water can continue to influence the pH value after the sample is taken. There are many field and laboratory pH sensors available, as well as indicator solutions and paper indicator strips. The sensors provide the greatest accuracy, but they must be calibrated before each use.

Oxygen is essential to all forms of aquatic life and the availability of oxygen influences nearly all chemical and biological processes in water bodies. Measuring dissolved oxygen is, therefore, fundamental for any water quality monitoring programme in surface waters. The amount of oxygen dissolved in water varies naturally with atmospheric pressure, temperature, dissolved mineral salts and the atmospheric exchange due to turbulent mixing. Warm water holds less dissolved oxygen than cold water and, in addition, the respiration of all living organisms, including microorganisms responsible for biological degradation of organic waste material, can reduce oxygen levels. Therefore, dissolved oxygen concentration can be useful as an indication of pollution by organic matter in surface waters. However, the photosynthetic activity of aquatic plants during daylight can increase dissolved oxygen concentrations and high phytoplankton populations near the surface of lakes can lead to supersaturation with oxygen.

Dissolved oxygen can be measured using a hand-held sensor and meter (usually in mg l^{-1} or as percentage saturation) or by using the Winkler titration method (ISO 1983). In freshwater at sea level, dissolved oxygen concentrations range from 15 mg l^{-1} at 0 °C to

8 mg l^{-1} at 25 °C. Concentrations below 5 mg l^{-1} may affect the survival and functioning of biological communities in freshwater, and most fish cannot survive at 2 mg l^{-1} or less. Very low oxygen concentrations may suggest the presence of biodegradable organic matter, such as sewage. Anoxic conditions, i.e., where there is no detectable oxygen, can occur where decomposition rates are high, such as at the sediment-water interface in still waters, in the hypolimnion of nutrient rich lakes and close to wastewater discharges in rivers.

Electrical conductivity (EC) is a measure of the ability of an aqueous solution to conduct an electric current, which in turn depends on the concentration of ions in solution. It is sensitive to variations in dissolved solids, mostly mineral salts, and can be useful to characterise a water body. Values in freshwaters range from 10 to 1,000 µS cm^{-1} (microsiemens per centimetre) and can change naturally, especially during periods of increased flow in rivers (**Table 3.2**). Deviation from normal ranges can indicate pollution, such as from wastewater inputs or run-off from land, and saltwater which may arise from excess irrigation, road de-icing or intrusion into groundwater from coastal waters. Conductivity is commonly measured with a sensor and the recording unit may also provide derived values for salinity and total dissolved solids. Electrical conductivity is temperature dependent and if the sensor and meter are not equipped with automatic temperature correction, the temperature of the sample should be measured and recorded to enable correction of the values obtained.

3.2 Chemical parameters

The list of chemical parameters that can be measured in freshwater is extremely long and some of them are very expensive to measure at low concentrations and/or to a satisfactory precision and accuracy. Therefore, the selection of chemical parameters in a monitoring programme should be considered very carefully in relation to the objectives of the programme and the information required. Some of the more common parameters and reasons for including them in a monitoring programme are described briefly below (see also Box 3.1) and details of methods can be found in Rice, Baird and Eaton (2017) and in the individual methods published by the International Organization for Standardization (ISO).

3.2.1 Nutrients

Nutrients are essential for all living organisms. In the aquatic environment the main nutrients are nitrogen and phosphorus compounds. Other nutrients, such as silica, can be important to specific groups of organisms. Nitrogen compounds arise from rock, land drainage and plant and animal debris. Phosphorus compounds arise mostly from rocks and the decomposition of organic matter. Nutrients are recycled in the aquatic environment and their availability can influence the growth of aquatic algae and plants that form the base of the aquatic food chain. Additional nutrients can reach water bodies with agricultural runoff from land, wastewater inputs and atmospheric deposition.

Table 3.2 Examples of electrical conductivity values in different types of water

Water source	Approximate electrical conductivity (µS cm^{-1})
Distilled water	0.5 – 3
Rainwater	10 – 20
Drinking water	50 – 500
Freshwater river	150 – 500
Industrial wastewater	10,000
Seawater	55,000

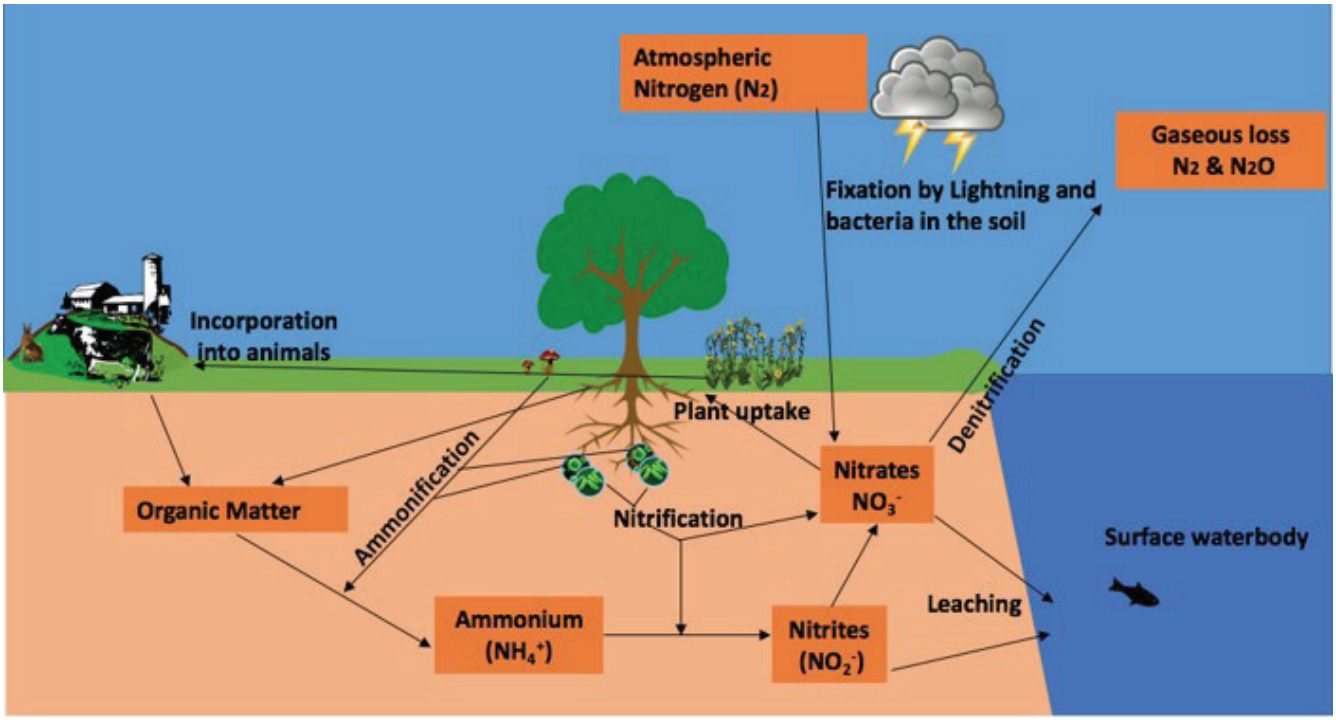
Sources: Hickin (1995); ANZECC and ARMCANZ (2000)

Nitrogen is an essential nutrient for living organisms as an important constituent of proteins, including genetic material. It undergoes biological and non-biological transformations in the environment as part of the nitrogen cycle (**Fig. 3.3**). Inorganic nitrogen occurs in a range of oxidation states as nitrate (NO_3^-) and nitrite (NO_2^-), the ammonium ion (NH_4^+) and molecular nitrogen (N_2). Ammonia exists in ionised (NH_4^+) and unionised (NH_3) forms; NH_3 is toxic at very low concentrations to fish (Camargo and Alonso 2006). The relative proportion of ionised and unionised ammonia in water depends on temperature and pH, and to a lesser extent on salinity (for further information see the accompanying guidebook on *"Water Quality Monitoring and Assessment in Rivers, Lakes and Reservoirs"*). Nitrate is highly soluble and often reaches surface water and groundwater with run-off from agricultural activities (e.g., application of inorganic nitrogenous fertilizers and organic manures), in discharges from wastewater treatment plants, and following oxidation of nitrogenous waste products in human and animal excreta.

There are many methods for measuring different forms of nitrogen in a water sample in the laboratory. There are also several kits and sensors available for measuring nitrate in the field but these vary in their accuracy, precision and limits of detection. The main consideration when selecting the method should be whether the limit of detection is adequate for the anticipated concentrations in the water samples, because some field kits are not sensitive enough to measure nitrate at low concentrations that may be required for the objectives of a monitoring programme.

Phosphorus is an essential nutrient for living organisms and exists in water bodies in both dissolved and particulate forms. It is generally the limiting nutrient for algal growth in freshwater ecosystems and, therefore, influences the maximum potential growth of

Figure 3.3 The nitrogen cycle



aquatic plants and algae in a water body. Phosphorus enters water bodies in a number of ways (**Fig. 3.4**):

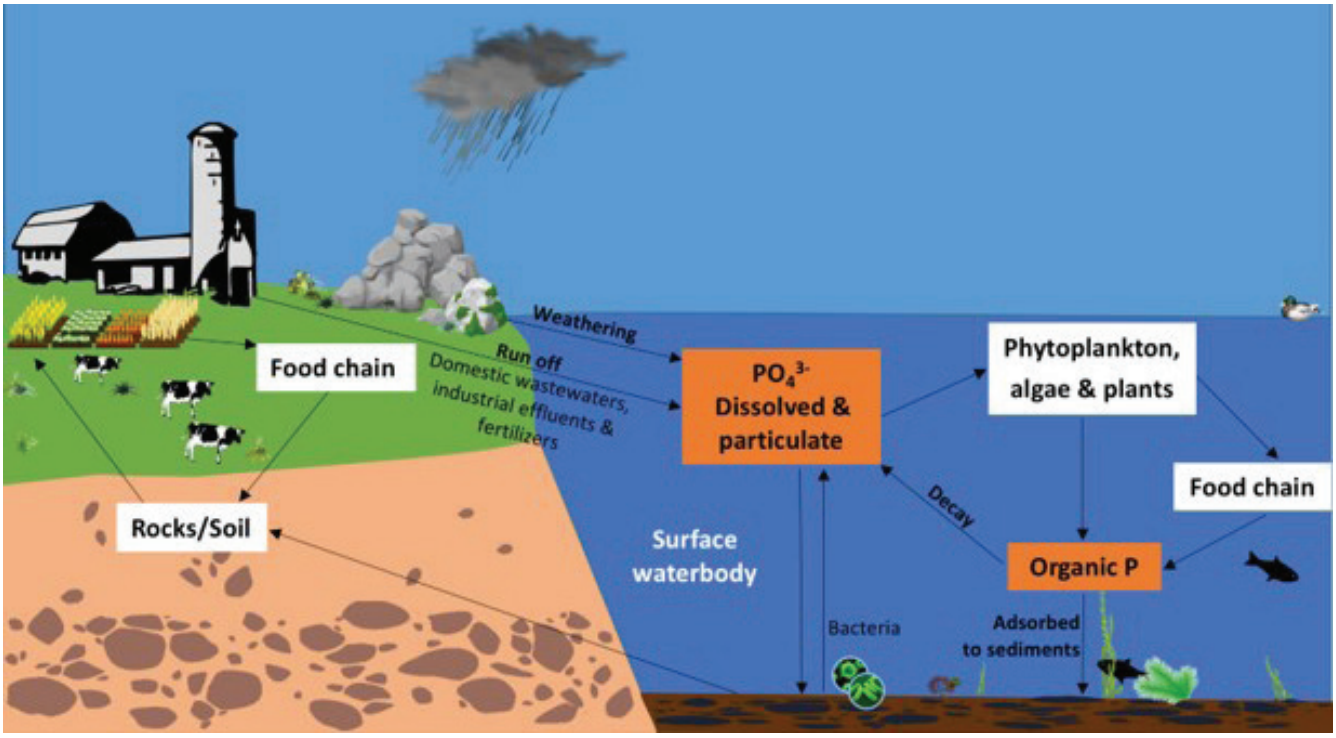
- Naturally, by the weathering of phosphorus-bearing rocks and the decomposition of organic matter.
- With domestic wastewaters.
- With industrial effluents.
- With run-off from inorganic fertiliser and manure.

Phosphorus associated with organic and mineral constituents of sediments in water bodies can also be mobilised by bacteria and released to the water column.

Orthophosphate is the bioavailable, dissolved, inorganic form of phosphorus and is rarely found in high concentrations in freshwaters because it is actively taken up by plants and algae. As a result, there can be considerable fluctuations in concentrations in surface waters associated with the seasonal growth and decline of plants and algae at most latitudes. In most natural surface waters, orthophosphate ranges from 0.005 to 0.020 mg l^{-1} PO_4-P. Concentrations as low as 0.001 mg l^{-1} PO_4-P may be found in some pristine waters and as high as 200 mg l^{-1} PO_4-P in some enclosed saline waters. Average groundwater levels are about 0.02 mg l^{-1} PO_4-P. High concentrations of total phosphorus (i.e., dissolved and particulate forms combined) can indicate additional inputs from human activities.

There are many methods for measuring different forms of phosphorus in a water sample in the field and in the laboratory. Total phosphorus is commonly measured where water quality is influenced by human activities. Orthophosphate is often measured in lakes because of its role in driving the growth of phytoplankton populations and the potential for algal blooms. There are field kits and sensors available for measuring dissolved phosphorus as orthophosphate in water samples but, as for nitrates, they vary in their accuracy and precision. The main consideration when selecting the method should be whether the limit of detection is adequate for the anticipated concentrations in the water samples, because

Figure 3.4 Sources and pathways of phosphorus into freshwater bodies



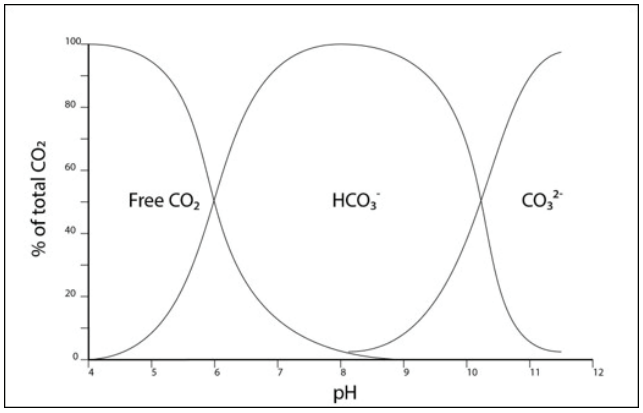
some field kits are not sensitive enough to measure phosphorus at low concentrations.

3.2.2 Major ions

Major ions (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, Cl^{-}, SO_4^{2-}, HCO_3^{-}) are naturally very variable in surface and groundwater due to local geological and climatic conditions. They are commonly measured in groundwater because they are important for providing information about the origins of groundwater recharge and of the mixing of water flows (see the accompanying guidebook on *"Water Quality Monitoring and Assessment of Groundwater"*). Sodium (Na^{+}) concentrations are particularly of interest when the water is used for drinking or irrigation. Concentrations of potassium (K^{+}) in natural waters are usually very low except in hot springs or brine waters, or when they are polluted with inorganic fertiliser or industrial effluents. Calcium (Ca^{2+}) is an essential element for living organisms and is incorporated into bones and into the hard tissues and shells of invertebrates. Calcium can precipitate in water when carbon dioxide levels drop, for example due to photosynthetic activity, which in turn influences pH values. Magnesium (Mg^{2+}) is common in natural waters and contributes to water hardness, along with calcium. Natural levels are rarely influenced significantly by industrial effluents. Chloride (Cl^{-}) levels are usually low in surface waters but can be increased due to deposition from oceanic aerosols, industrial and sewage effluents, agricultural runoff, and runoff from roads treated with salt in the winter.

Industrial discharges and atmospheric precipitation can add significantly to the natural levels of sulphate (SO_4^{2-}) in surface waters. High concentrations (> 400 mg l^{-1}) can make water unpleasant to drink. Some bacteria use sulphate as an oxygen source and convert it to hydrogen sulphide (H_2S) under anaerobic conditions, as may occur at depth in stratified lakes. Hydrogen sulphide is a colourless gas with an unpleasant smell of rotten eggs, which is often indicative of the presence of anaerobic conditions. Carbonates (CO_3^{2-}) and bicarbonates (HCO_3^{-}) influence the hardness and alkalinity of the water and arise mostly from the weathering of rocks or from the atmosphere. Their concentration is also related to the pH of the water (**Fig. 3.5**).

Figure 3.5 The relative concentration of free CO_2, HCO_3^{-} and CO_3^{2-} changes with pH in water



3.2.3 Metals and organic contaminants

Very low concentrations of metals are always present in freshwater from the weathering of rocks and soil. Elevated concentrations usually arise from wastewater discharges and mining activities. Very low concentrations, particularly manganese (Mn), iron (Fe) and zinc (Zn) are essential for aquatic life but at high concentrations many elements can be toxic to both aquatic life and humans. Metals can be present in water in dissolved, colloidal and particulate forms. The behaviour, toxicity and sedimentation potential of metals in freshwaters depends on these forms. Organic contaminants do not usually occur naturally in freshwaters and many are toxic to aquatic life and humans even at low concentrations. They include mineral oils, phenols, pesticides, polychlorinated biphenyls (PCBs), pharmaceutical residues and many thousands of individual organic compounds manufactured, used and released to the environment. Such compounds are not usually monitored routinely in water bodies because the analysis is often complex and expensive, requiring sophisticated instrumentation, hence they may be included with a less frequent sampling regime than other key parameters. They are more often included in monitoring programmes specifically to assess the presence of pollution and its potential risk to the aquatic ecosystem or human health.

3.2.4 Total organic carbon

Total organic carbon (TOC) is a convenient, non-specific, indicator of general water quality, particularly organic matter contamination. Organic carbon arises from the presence of living material and is also present in waste materials and wastewaters in dissolved and particulate forms. It can be measured continuously with automatic analysers which are convenient for water intakes and wastewater discharges. Concentrations of TOC in surface water are generally less than 10 mg l^{-1}, and in groundwater they are less than 2 mg l^{-1}.

3.2.5 Chemical oxygen demand and biochemical oxygen demand

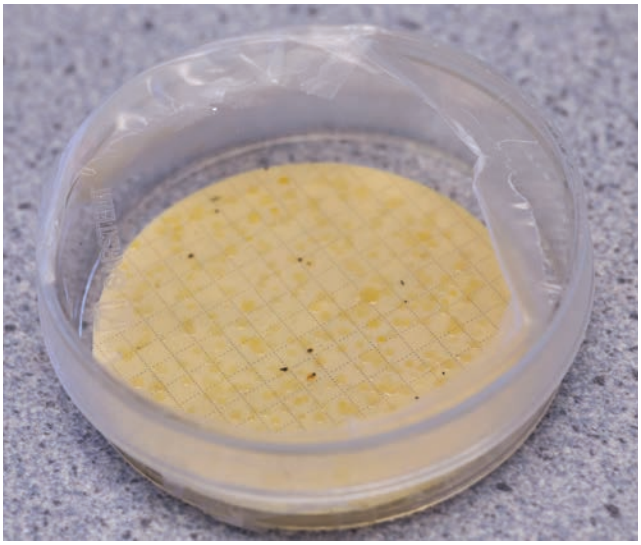
Chemical oxygen demand (COD) is a measure of the oxygen equivalent of the organic matter in the water that is susceptible to oxidation by a strong oxidant, such as dichromate. The test is non-specific and does not differentiate between organic and inorganic material present in the water sample. It is widely used as an indicator of the presence of sewage or industrial effluents because it can be measured rapidly in the laboratory. In surface waters COD typically ranges from 20 mg l^{-1} of O_2 or less in unpolluted waters to more than 200 mg l^{-1} O_2 in water receiving effluents. Industrial wastewaters may have COD values ranging from 100 mg l^{-1} O_2 to 60,000 mg l^{-1} O_2.

Biochemical oxygen demand (BOD) is a measure of the biochemically degradable organic matter present in the water and is defined as the amount of oxygen necessary for the aerobic microorganisms in a water sample to oxidise the organic matter to a stable inorganic form. Despite the possible interferences in the method (e.g., toxic compounds in the water sample inhibiting the action of the microorganisms), it is widely used to determine the efficiency of sewage treatment and as a general indication of pollution of surface waters by organic matter. The most common standardised analytical procedure requires incubation of the water samples for five days, hence the method is commonly referred to as BOD_5. Results are expressed as the amount of oxygen used during the incubation period. Unpolluted surface waters usually have a BOD of about 2 mg l^{-1} O_2 and polluted waters may have values of 10 mg l^{-1} O_2 or more. For comparison, raw sewage has a BOD of about 600 mg l^{-1} O_2.

3.3 Faecal pathogens

The most common risk to human health associated with water comes from the presence of pathogenic (disease-causing) microorganisms. Monitoring for the presence of pathogenic bacteria is an essential component of any water quality assessment where there is a potential for human ingestion, such as through drinking, personal hygiene, food preparation or recreational use. Increasingly, microorganisms and other faecal markers are being included in monitoring programmes for the detection and location of domestic and livestock wastewater inputs, and for diffuse sources (Hagedorn, Blanch and Harwood 2011). Indicator organisms which are normally present in faeces from warm blooded animals are used to detect the presence of faecal material, e.g., thermotolerant coliforms, *Escherichia coli* (**Fig. 3.6**). The presence of faecal material can suggest the possible presence of waterborne pathogenic organisms that are transmitted through

Figure 3.6 Colonies of *E. coli* (yellow patches) growing on a membrane filter after filtration of a river water sample and incubation on a culture plate containing a special culture medium. © Patrick Cross



the faecal-oral route, such as *Vibrio cholerae, Salmonella*, *Campylobacter* and *Cryptosporidium*. Specific pathogens are usually more complex to detect and quantify in water samples, requiring special methods and associated microbiological laboratory facilities. Particular care must be taken during sampling and sample preparation in the laboratory to avoid potential contamination and incorrect results (see accompanying guidebook on *"Quality Assurance for Freshwater Quality Monitoring"*).

Municipal raw sewage can contain 10–100 million coliform bacteria per 100 ml whereas surface waters that do not receive effluents from human settlements or livestock may contain 10–100 coliform bacteria per 100 ml. Drinking water should contain zero coliforms per 100 ml.

3.4 Biological characteristics

Macroinvertebrates, fish and algae, are the most commonly used aquatic organisms in biological monitoring of freshwater environments. Microbiological monitoring for faecal bacteria and pathogens is considered separately from biological monitoring. A bioindicator is a living organism that responds in defined ways to particular changes in water quality. However, such changes may arise from both natural and/or anthropogenic impacts and therefore the life cycles, habitat and environmental preferences of any particular organism used for biological monitoring of the health of freshwater systems should be known and understood. Ideally, bioindicator species should demonstrate most of the characteristics listed in **Box 3.2.**

The presence or absence, abundance, health and condition of biota, for example, can provide information on activities that affect water quality, such as agricultural runoff and wastewater discharges, persistent pollutants in the water body (giving rise to bioaccumulation and biomagnification), hydrological control regimes (e.g., impoundments), and the effectiveness of catchment management programmes (e.g., wetland restoration). However, it can often be difficult to link observed changes in biota to specific environmental changes or impacts because the observed changes in bioindicator organisms could be a result of seasonal or other natural cycles, such as life stage and reproductive conditions or natural disease prevalence, rather than ecosystem degradation linked to water quality decline. Monitoring programmes based on biological methods should be designed so that impacts due to natural changes in the water body can be separated from those resulting from anthropogenic activities. This may require a detailed knowledge of the ecology, life history and sensitivity of the species being used, combined with complimentary physical and chemical monitoring.

BOX 3.2 CHARACTERISTICS OF AN IDEAL BIOINDICATOR SPECIES FOR MONITORING WATER QUALITY

- Can be easily recognised by non-specialists
- Is highly sensitive to environmental stressors
- Has a wide distribution
- Has very limited mobility and therefore indicates water quality at the sample site
- Has well-known ecological characteristics
- Is suitable for laboratory trials
- Lends itself to quantification and standardisation.

Figure 3A **The freshwater mussel is widely used as a bioindicator species. By NOAA Great Lakes Environmental Research Laboratory. Licenced under CC BY-SA 2.0**

Therefore, an experienced biologist is needed to guide the development of the monitoring programme (such as appropriate timing of sampling campaigns) and the interpretation of the data.

Living organisms can be used for monitoring in four main ways:

1. Ecological surveys of species diversity and abundance, or enumeration of indicator organisms (e.g., macroinvertebrate diversity or bacterial counts).

2. Ecotoxicological assays using one or several species to determine the presence of toxic compounds.

3. Histological and enzymatic studies in selected organisms to indicate environmental stress.

4. Chemical analysis of body tissues for selected compounds.

More detail on these specific approaches is available in the companion guidebook on *"Freshwater Quality Monitoring with Biota"*.

3.4.1 Chlorophyll *a*

Chlorophyll *a* is a green pigment that is involved in photosynthesis in plants and algae. It is commonly included in lake monitoring programmes as an indicator of algal biomass in the water column. Nutrient rich water bodies generally support high levels of algal growth and have associated high chlorophyll concentrations.

Chlorophyll pigment (typically chlorophyll *a*) concentrations can be inferred *in situ* with a portable fluorometer or measured with greater accuracy in the laboratory after filtering the water sample and trapping any algae in the sample on the filter. The chlorophyll is extracted using a solvent and the intensity of the colour in the solvent is measured with a spectrophotometer. The results are usually expressed as $\mu g\ l^{-1}$ or $mg\ m^{-3}$. In surface waters, values can range from < 5 $mg\ m^{-3}$ in water bodies with low nutrient inputs to > 100 $mg\ m^{-3}$ in water bodies with excess nutrient inputs.

CHAPTER 4

SAMPLING LOCATION AND FREQUENCY OF SAMPLING

The choice of sampling approach, location and frequency all have a major influence on the reliability and relevance of the data obtained and their ability to address the objectives of the monitoring programme. A thorough understanding of the functioning and behaviour of the water body is essential for ensuring that the most appropriate sampling regime is used. This topic is covered in more detail in the companion guidebooks on *"Water Quality Monitoring and Assessment of Rivers, Lakes and Reservoirs"* and *"Water Quality Monitoring and Assessment of Groundwater"*.

The most appropriate approach to sampling and the associated equipment depends on the type of water body, access and safety for field personnel and spatial and temporal requirements for water quality information specified in the monitoring programme objectives. Specific requirements associated with the parameters that will be analysed in the samples after collection may also dictate the type of sampling equipment, such as samples intended for heavy metal analysis in the laboratory may need to be collected with samplers constructed with specific materials, such as Teflon™, or in acid-washed polyethylene containers. Advice on how to ensure correct sample collection and handling is available in the accompanying guidebook *"Quality Assurance for Freshwater Quality Monitoring"*.

Grab samples are discrete samples collected at single points in space and time and can be cheap and easy to obtain using a variety of devices, ranging from a simple jug or bucket to samplers that can be triggered to collect water from discrete depths (**Fig. 4.1**). Composite samples are made up by combining a number of grab samples of a given volume over a given period of time. Integrated samples are either made up by combining samples from different depths or across different locations, or by using special sampling techniques that collect water between two points in depth or space. Specific approaches for surface and groundwaters are discussed in the accompanying guidebooks on *"Water Quality Monitoring and Assessment in Rivers, Lakes and Reservoirs"* and *"Water Quality Monitoring and Assessment of Groundwater"*.

Analysis of grab samples of water provide an indication of water quality at that particular point in space and time.

Figure 4.1 **Left – a simple dip sampler on an extendable pole. Right – emptying a sample taken from a discrete depth with a Ruttner sampler. © Deborah Chapman**

Increasing the temporal frequency of grab sampling (i.e., decreasing the sampling interval) provides a better characterisation of water quality over time but requires increased resources for sampling and analysis, such as using *in situ* automated continuous sampling and monitoring techniques and technology. Automatic water samplers enable the frequency of sampling to be selected and in some cases modified remotely. Samples may be collected at a constant rate (time-proportional sampling) or change with discharge (flow-proportional sampling) or, more recently, adjusted based on the values of other measured paraments (dynamic or burst sampling). The major advantage of automatic composite sampling is that it allows representative water conditions to be characterised with far fewer analyses than would be required by manually collecting grab samples, and it enables sampling at times when it would be difficult or undesirable, e.g., during storm conditions or in remote locations.

4.1 Sample site location

The choice of location for sampling in freshwater bodies is often based on the judgemental sampling approach where the location is selected with the aid of existing knowledge on the type of water body, its behaviour and variability. Probability sampling, which is based on statistical probability theory can also be used in some situations where sites are selected at random across the surface of the water body or selected randomly within smaller areas which are considered to be homogeneous. Where sufficient water quality data are available over a long time series, various statistical techniques, e.g., O'Hare *et al*. (2020), can also be applied to optimise existing sampling locations in order to reduce monitoring costs.

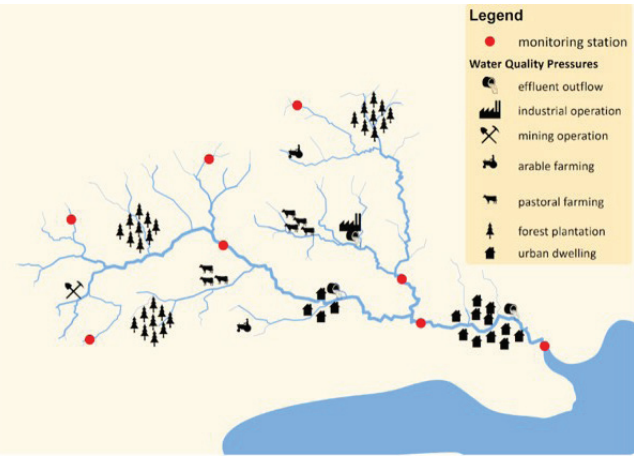
4.1.1 Rivers

When selecting sample locations in rivers, access and safety are very important considerations. Checking for safe access to a water body is part of the preliminary survey. A well-designed monitoring programme to observe status and trends in water quality in a river basin should have sampling sites located throughout the catchment. Typically, monitoring sites would be in the headwaters, where the river drains different types of geology and land-use (e.g., just below the confluence of tributaries), below major sources of impact such as urban or industrial areas, where the river leaves a defined basin or jurisdiction (e.g., regional or national boundary), and just before the river enters a lake or the sea (**Fig. 4.2**).

Ideally headwater sites should not be impacted by diffuse or point-sources of pollution and can, therefore, provide baseline water quality information. Sample sites located where the river drains to an estuary or lake reflect the total accumulated suspended material, nutrients and contaminants from upstream and can be used to calculate the total transport of material (fluxes) from the river basin. Flux calculations are only possible when water discharge values are available from the same locations.

A sample station is the precise point in space (vertically and horizontally) from which the water sample is taken at a given sample site. Sample stations in rivers should be located where water is well mixed so that a single sample is representative of the site. Complete mixing of different water masses (tributaries, discharges and effluents) may not occur for some distance downstream. Complete mixing in a river can be verified by taking several samples across the width and depth of the river and measuring temperature, conductivity or suspended solids. A sampling station can be established at the point where the results from these samples do not vary significantly. Further

Figure 4.2 **Examples of potential sampling locations (red dots) in a small river catchment with multiple activities within the catchment**



guidance is available in *"Water Quality Monitoring and Assessment in Rivers, Lakes and Reservoirs"*.

Sampling locations and/or sample stations should be clearly identifiable with a description and geographical coordinates, to ensure that results are comparable for repeated sampling occasions. A bridge is an ideal location to sample because it is easy to access, clearly identifiable, and enables a sample to be taken mid-stream without a boat.

Figure 4.3 **Sampling for plankton from a pontoon on a lake © Patrick Cross**

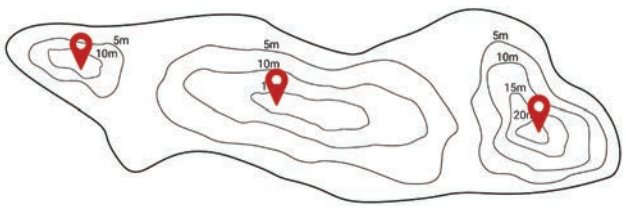
4.1.2 Lakes and reservoirs

A boat is usually required to collect representative samples from lakes and reservoirs unless there are structures present that allow access to the deeper water beyond marginal vegetation, such as abstraction towers or pontoons (**Fig. 4.3**). Safety considerations are very important, especially when sampling from a boat or pontoon in deep water. A life jacket (personal flotation device) or buoyancy aid is recommended for all personnel in these situations.

Bathymetry and thermal structure must also be considered when choosing sample locations within lakes or reservoirs. Bathymetry affects whether the lake or reservoir behaves as a uniform single water body, or whether basins with restricted mixing of the water may have different water qualities. If the lake or reservoir is well mixed, a single sampling location near the centre, or at the deepest part of the lake, would normally be sufficient. Where a lake has many bays or inlets, or contains a number of deep basins in which water quality may vary naturally or be influenced by different catchment activities (such as human settlements) or inflowing rivers, several sample points are usually necessary (**Fig. 4.4**). See "*Water Quality Monitoring and Assessment in Rivers, Lakes and Reservoirs*" for more details.

Before finalising the sampling regime for a lake or reservoir, it is important to determine whether the water column stratifies and when the stratification is likely to occur. This should be a part of the preliminary survey for the monitoring programme. When a lake is stratified, samples may need to be collected through the depth of the water column in order to obtain a representative assessment of water quality. An integrated depth sample can be collected by taking samples from regular depth intervals with a discrete depth sampler (Fig. 4.1) and mixing them, or by collecting a single integrated sample (e.g., with a long tube or a pump). If the lake stratifies regularly, sampling from a fixed depth within the epilimnion would enable comparability

Figure 4.4 **Possible sample locations in a lake with several basins that may behave differently and have different water quality**



over all seasons when carried out over a long time period. Further details on sampling approaches are given in the accompanying guidebook "*Water Quality Monitoring and Assessment in Rivers, Lakes and Reservoirs*".

4.1.3 Groundwater

Sampling for groundwater quality data is complicated by the three-dimensional nature and potential heterogeneity of groundwater bodies. There is often a lack of basic hydrogeological information to aid the selection of the appropriate location and depth of monitoring wells. In practice, existing wells or springs are often used to sample groundwater and the information obtained from these wells can be used to aid decisions regarding new sampling well locations for a monitoring programme. If a well is known to be in a high-risk area for contamination by local activities (e.g., from mining or waste disposal), the water from that well may not represent the quality of the groundwater resources in that area. In these situations, it is recommended to use nearby wells from the same aquifer or to drill a new sampling well. For further information see "*Water Quality Monitoring and Assessment of Groundwater*".

4.2 Sampling frequency

The frequency with which it is necessary to take samples from a water body depends on the objectives of the monitoring programme and the human and financial resources available, together with the natural variability of the water quality, which is driven mostly by climatological factors such as rainfall, wind, solar radiation and temperature. Relatively high frequency sampling may be necessary initially over a full year to characterise seasonal or rainfall-driven variability. The frequency can then be adjusted according to the acceptable level of variability and the need to ensure that necessary events (e.g., pollution emissions) are captured. More detailed information is available in the accompanying guidebook on "*Water Quality Data Handling and Assessment*". A very minimum of once per season, or ideally once a month, is recommended for surface waters. In general, the quality of groundwater fluctuates much less than surface waters and a single sample per year may be adequate for status, trends and uses that do not directly affect human health. If large variations in quality are observed in these samples, the sample frequency should be increased. If water is abstracted for a specific use, frequent or continuous sampling at the point of abstraction may be necessary to manage water treatment processes or to protect human health. For further information see "*Water Quality Monitoring and Assessment in Rivers, Lakes and Reservoirs*" and "*Water Quality Monitoring and Assessment of Groundwater*".

4.2.1 *In situ* and near real-time monitoring

Autonomous *in situ* monitoring involves collecting water quality information directly from the sample point of a water body without the need to remove and transport water samples enabling real-time (or usually near real-time) data collection. *In situ* monitoring requires the use of sensors or probes that can be immersed in water and can transmit the value obtained to a meter from which the results can be manually recorded (**Fig. 4.5**), downloaded to an electronic recording device such as a smart phone or computer, or transmitted telemetrically (via satellite, cellular networks or radio) to the laboratory. Sensors may be deployed from a floating platform or buoy using solar or battery power for the sensors and the data transmission (telemetry) system (**Fig. 4.6**). The telemetry system must be chosen and tested as part of the preliminary survey. Network coverage in the area where the equipment is deployed is critical because sporadic availability or overloading of cellular networks at peak times may interrupt communications. Data may also be collected continuously by diverting water from the water body through a tank containing sensors (physical, chemical or biological), and by diverting water directly through an analytical instrument that performs analyses at a very high frequency. Continuous monitoring facilitates rapid management responses and is particularly useful for early warning monitoring, such as may be required for a drinking water abstraction point.

Development of robust sensors that can measure a wide range of parameters *in situ* is progressing

Figure 4.5 **Measuring electrical conductivity *in situ* using a sensor and recording the values manually from a digital meter. © Deborah Chapman**

Figure 4.6 **An anchored buoy with continuous monitoring sensors suspended at depth underneath. Solar panels provide power for the sensors and telemetry system. © Timothy Sullivan**

rapidly. Some of the most common commercially-produced sensors can measure:

- pH
- Electrical conductivity and total dissolved solids
- Dissolved oxygen
- Temperature
- Depth/Pressure
- Turbidity
- Photosynthetic pigments (chlorophyll or phycocyanins for algae or cyanobacteria).

All sensors should be fully calibrated following manufacturer's instructions before monitoring begins and their accuracy validated in the laboratory or by comparison with other instruments. Regular maintenance and calibration is usually critically important to maintain accuracy and to keep the equipment functioning within the required specifications. Maintenance intervals are largely dependent on environmental conditions at the site (e.g., high suspended solids) and other parameters, such as the potential for biofouling (unwanted biological growth, e.g., algae and invertebrates, on immersed surfaces), water temperature, seasonal fluctuations and cost. Many different types of organisms find the surface of a suspended sensor a convenient location to settle and grow and *antifouling* coatings or other mechanisms may be necessary to keep the optical "windows" to the sensors very clean. Common calibration and preventative maintenance intervals are weekly, bi-weekly or monthly and these should be factored into the monitoring programme design and allocation of resources. If not correctly maintained, the instruments may provide incomplete or inaccurate data.

CHAPTER 5

GOOD PRACTICE IN THE FIELD AND LABORATORY

The implementation of a monitoring network comprises four activities that are closely linked and should occur concurrently: field measurements and sampling, laboratory analyses, hydrological measurements and quality assurance (see Fig. 1.1). This chapter highlights some important general considerations for implementing a monitoring programme, and specific detail on different aspects mentioned above are provided in the accompanying guidebooks on "*Water Quality Monitoring and Assessment of Groundwater*", "*Water Quality Monitoring and Assessment in Rivers, Lakes and Reservoirs*" and "*Quality Assurance for Freshwater Quality Monitoring and Assessment*".

5.1 Before going into the field

Fieldwork (work conducted on site within the environment) contributes a significant component of the cost of the monitoring programme, and should be carefully planned to ensure that efforts are not wasted. The two main components of field operations are preparation before going into the field and actual field activities while on-site at a monitoring location. Adequate planning before going to the field ensures that the field sampling trip goes efficiently and takes the minimum time necessary. The route between sampling sites needs to be optimised to ensure that samples are in transit for the minimum time possible. Some analyses must be performed within a certain period of time after collection of the sample, e.g., thermotolerant coliforms, and this must be taken into account when planning travel routes and the order in which sites are visited. Field personnel should be fully aware of the monitoring programme objectives so that they understand the reasons for specific procedures and the need to take samples from precise locations. They also need to be fully trained and competent in sampling and handling of the different types of samples they may need to collect.

It is good practice to have a checklist to ensure that everything is prepared in advance to complete the field work successfully. It can also act as a memory aid during the field sampling trip. It should list all sampling and monitoring equipment required, the chemicals for sample preservation or stabilisation, data recording instruments or notebooks that will be used in the field, as well as personal safety items and clothing.

Full and due consideration of field safety is critically important. Aside from the natural hazard associated with close proximity to water bodies, field personnel can encounter a wide range of additional hazards during field work, such as water contaminated with sewage, chemicals, sharp wire, glass, slippery surfaces, and wildlife or livestock. It is important that field personnel are appropriately trained to recognise and deal with any hazards as they are encountered. The minimum training should include water safety and first aid. Depending on national Health and Safety legislation, a Risk Assessment may also be required before commencing the field sampling. A comprehensive guide to risks and hazards in fieldwork is available from the University of Wollongong (undated). Field technicians should carry first aid kits with them at all times during fieldwork.

Different sample container types are sometimes recommended for specific parameters that will be analysed in the laboratory. Where possible, plastic sample containers are preferred because they are less likely to break than glass containers. **Table 5.1** gives some examples of the sample containers for different parameters.

Ideally sample containers should be provided by the laboratory to ensure that the sample bottles are of sufficient volume and prepared correctly, including the addition of chemical preservatives where necessary. It is often more convenient to add chemical preservatives to sample containers in the laboratory than in the field. If chemical preservatives are added in the laboratory, it is important that sample containers are labelled with the name, volume and concentration of the chemical preservative. If chemical preservatives are not added to sample containers in the laboratory, clear instructions need to be provided for the field personnel to ensure that a correct volume of the chemical preservative is added to the sample container.

Each sample container needs to be carefully labelled with a unique sample identifier, such as a code or number. The following information should also be included on the sample bottle or on a sample submission sheet that accompanies the samples to the laboratory:

- Name of study
- Sample station number
- Sample depth
- Date and time of sampling
- Name of field operator who collected the sample

Table 5.1 Examples of different types of sample container for specific parameters

Parameter(s) for analysis	Sample container
Aluminium, barium, cadmium, cobalt, copper, iron, lead, manganese, nickel, zinc	Polyethylene
pH, hardness, turbidity	Polyethylene
Ammonia, nitrate, nitrite, total nitrogen	Polyethylene
Mercury	Glass
Total phosphorus	Glass

5.2 In the field

Prior to collecting a sample, a field operator should ensure that samples are collected from the correct sampling station. This can be determined by visually checking for landmarks, and/or with a Global Positioning System (GPS) device. In lakes, sampling stations should be marked by placing an anchored floating buoy.

Variations in sampling procedures can have a marked effect on the results of analysis. Procedures for sampling operations should be carefully documented in a field sampling manual together with precautions to be taken while sampling. Samples may be affected such that they no longer represent their original condition. Collection, preservation, transportation and storage can lead to incorrect measurement results for some parameters. Sources of error can include carryover of analyte from sampling equipment, incomplete decontamination of equipment between samples and sampling trips, cross contamination between samples and absorption of volatile chemicals from the air during transportation and storage. Quality assurance of sampling can be achieved by strict adherence to standard operating procedures (SOPs) for sampling, ensuring all equipment is clean and in working order, recording all conditions which applied during sampling, and taking strict precautions to avoid contamination (see *"Water Quality Monitoring and Assessment in Rivers, Lakes and Reservoirs"*).

When taking depth samples or groundwater samples, it is important to avoid disturbing the bottom sediment or including any detritus such as leaves. If vertical profiles are needed by taking a series of discrete samples, the samples should be taken in sequence, starting at the surface and finishing at the bottom, so that the sampler causes minimum disturbance to the water as it descends though the water column.

If samples are collected directly into the sample bottle, it should be rinsed three times with water close

to the sampling station but not at exactly the same point from which the actual sample is taken. When a sampling device is used to collect samples, the sample bottles used to transport or store samples should be rinsed three times with portions of the sample before being filled and capped. However, this does not apply to sample bottles which contain preservative chemicals.

Sample temperature and dissolved oxygen can be measured *in situ* at the sampling station or by immediately pouring a portion of the sample into a beaker large enough to submerge the sensor. This avoids any potential contamination of the actual sample that will be returned to the laboratory for analysis.

Special precautions are needed when sampling for bacteriological analysis because samples can be easily contaminated. Samples should be collected in pre-sterilised sample bottles. The sample bottle lid should be removed for the minimum time possible and the sampler should wear a fresh pair of clean sterile gloves at each sample location.

All measurement taken in the field need to be recorded in the field notebook before leaving the sampling station, together with observations on the field conditions (e.g., weather, colour of the water, presence of livestock or waste) because they may help in data interpretation. Details recorded in the field notebook should also include sample IDs (as noted on the sample bottles), and the methods used and the results obtained for any field measurements. If the field record sheet is in electronic form, it must be secure with regular copies of all records made for backup purposes.

5.3 Sample handling

Once the sample has been collected, it is important that the sample is stored correctly during transportation and in the laboratory. Samples should be stored in a clean, cool, dark environment and protected from recontamination. Depending on the analysis to be completed, additional sample preservation may be necessary including freezing, solvent extraction and the addition of chemical preservatives. Correct handling of samples, and the delivery of samples to the laboratory in as short a time period as possible, is essential to ensure that results are representative. Samples begin to deteriorate as soon as they are removed from their environment.

All sample bottles should be stored in a container or crate for transportation to avoid spillage or breakage. As a general rule, samples should be transported in a cool box that maintains the temperature of the water body from which they were collected, unless the samples have been chemically preserved. Field personnel need to liaise with the laboratory regarding when the samples will be arriving, the number of samples, and the analyses to be completed so that the laboratory can prepare quantities of reagent chemicals.

It is important that samples reach the laboratory within the timeframe recommended for the analysis to be completed. This is particularly relevant for bacteriological analysis because delays in analysis can affect the true representation of the bacteriological quality of the water. Most chemical analyses of samples should be completed within 24 hours after collection, although some parameters (e.g., hardness and chloride) are stable for two to three weeks.

5.4 The laboratory

It is good practice for a member of the laboratory to sign for receipt of the samples and to record the time of arrival and the location of storage.

Laboratory personnel should also carry out some basic checks on the samples when they arrive:

- Are all samples correctly labelled?
- Are samples contained in the appropriate bottle for analysis (e.g., polyethylene, glass)?
- Have samples been treated with the necessary chemical preservatives?
- Have samples been stored at the appropriate temperature during transport to the laboratory?

As soon as the samples arrive at the laboratory they should be logged in the laboratory record system and transferred to a refrigerator (4°C). If laboratory personnel are not available to receive the samples, then someone other than laboratory staff should be instructed to transfer the samples to the refrigerator, and to take note of the time the samples were received and the condition of the samples. Laboratory personnel should then be notified accordingly. Samples that have been inappropriately treated or stored may need to be discarded because they will not give accurate results when analysed.

The entire sample ID, analysis procedures and all related forms, notes, calculations, test reports and chain of custody reports need to be held in a secure, limited-access, storage location, in electronic and/or hardcopy format. Hard copies should be kept in folders and filed using the following suggested guidelines: by year, by analytical parameter, and by assigned laboratory number. If data are to be stored electronically there should be written procedures defining where the data will be stored, how many copies will be made, and how the database will be secured.

Laboratory records should have a designated minimum retention time. These must comply with the appropriate legislative requirements. Before releasing data from the laboratory for sharing with other users, or for permanent storage in a database, they should be checked by the relevant laboratory personnel for obvious errors, dubious and unreliable readings, and that they have been reported to the appropriate decimal places.

When all analyses on a sample have been completed, and the laboratory report issued, the authorized individual should dispose of the sample in a safe manner in accordance with laboratory waste disposal procedures. Occasionally, some analyses may need to be repeated using the original samples. Therefore, samples are normally disposed of only when it is certain that further analyses will not be required, or when the sample has deteriorated and will no longer give viable results.

5.5 Laboratory quality assurance and control

Time and effort put into collecting samples and analysing them is wasted if the data produced are not credible and defensible. If data are going to be shared with other laboratories, organisations or databases they must also be comparable and compatible. Credible data can be ensured by using recognised or standard methods, such as those published by the International Organization for Standardization (ISO), applying quality assurance, and demonstrating confidence in the data with statistical techniques (standard deviations/confidence limits), and rigorous data checks. Ensuring data are credible involves the application of quality assurance. Quality assurance is the maintenance of a desired level of quality in a service or product, especially by means of attention to every stage of the process of delivery or production. It should be applied to field operations, laboratory operations and data storage, and should be considered at the network design

BOX 5.1 THE ELEMENTS OF A QUALITY ASSURANCE PLAN

- Description of the plan.
- Organisation and responsibilities.
- Required levels of precision and accuracy.
- Sampling procedures.
- Sampling custody.
- Calibration procedures and frequency.
- Analytical procedures.
- Data manipulation/validation/reporting.
- Internal quality checks and frequency.
- Performance and system audits and their frequency.
- Procedures for assessing data accuracy/completeness and any necessary corrections.
- QA reporting and management procedures.

phase so that adequate resources are made available. Confidence in the standards and output of a laboratory can be enhanced by achieving and maintaining the ISO standard for laboratory competence, ISO/IEC 17025:2017 (ISO 2017). Approximately 10–20% of the total resources needed for a monitoring programme should be devoted to quality assurance, i.e., financial, technical and personnel.

Every monitoring programme should have an associated quality programme. The quality programme minimizes errors in environmental data acquisition but cannot totally prevent them. It may also help quantify errors in measurement. Quality control (QC) consists of a series of technical activities to control the quality of the data generated. Quality assurance (QA) is the management system that ensures that quality control is working as intended. A formal QA/QC programme is written as a Quality Assurance Plan (**Box 5.1**). a detailed description of the elements of a Quality Assurance Plan is available in the companion guidebook on "*Quality Assurance for Freshwater Quality Monitoring*":

CHAPTER 6

DATA MANAGEMENT

Proper data management is essential for all monitoring programmes because the effort and resources put into collecting the data are wasted if the data are not managed correctly. Full coverage of this topic is available in the companion guidebook on "*Water Quality Data Handling and Assessment*". The "data rich, information poor" situation, where data are collected but not used in any form of assessment, should be avoided. Management of data is vital to maximize the effective use and value of data and information and to improve data quality, including data accuracy, integrity, integration, timeliness of data capture and presentation, relevance, and usefulness. It is also necessary to ensure appropriate use of data and information, to facilitate data sharing and reuse, and to ensure sustainability and accessibility for long term reuse of data.

Errors can occur in many steps of the storage and manipulation process, particularly if data have to be transcribed from instruments to notebooks, notebooks to record books, and record books to computer databases. Transcribed data should be checked against the original records immediately after transfer and databases should be checked periodically for unusual or unlikely values.

Before reporting the results of a monitoring programme, the data must be examined to determine whether the results are fit to report. Information which may have a bearing on interpretation of the data, such as field observations, should be stored with the data and included in the report, together with information relating to the type of sample and the analytical procedure which was applied. Reports should also include reference to all calibration and quality control data and any problems that were encountered during data collection (e.g., rejected analytical batches, loss of sample, etc.).

When sharing data, it is important to provide accurate information about the analytical results generated to avoid misinterpretation. Shared results must be comparable between the organisations and databases that are sharing the data, i.e., the techniques used must provide similar types of data or facilitate their conversion. For example, the units of measurement must also be compatible or convertible to an agreed unit, e.g., $\mu g\ l^{-1}$ or $mg\ m^{-3}$ or $mg\ l^{-1}$. Only significant figures should be reported even though the spreadsheet or database might generate more decimal places!

Data must be documented with sufficient metadata to enable its use by third parties without reference to the originator of the data. It is important to use a consistent naming convention for everything that can be used to group data (parameter names, locations, water body types etc.). Ideally, there should be a centralized data storage system with regular backups. Access to the database should be restricted, preferably to users who enter the data.

Quality control during data storage is crucial to preserve the meaningfulness of the data, and to detect and clean-up data contamination. Standards should be defined and enforced for data entry (formats, codes, measurement units, metadata) and a person should be assigned responsibility for data quality; this is usually the person entering the data.

6.1 Data use

Data analysis and presentation are necessary to provide the information required by the objectives of the monitoring programme, to determine whether the objectives of the monitoring programme are being met, and to convert the raw data into a format which is accessible and understandable to different groups of people. Data analysis is also used to check efficacy of quality assurance and quality control procedures, to inform the monitoring programme review process by checking whether the collected data are fit for purpose, to identify trends in the data, and to understand the relationship between the different parameters.

Before monitoring data are used for any analysis or presentation procedures, it is critical to undertake some preliminary data checks to ensure that the data have been validated and are comparable. This is especially important when data are being collated from more than one source (see **Box 6.1**). Initial data checks include: limits of detection, units of measurement, and significant figures.

Further checks on the data before the analysis and presentation of the data include data outliers, metadata, data irregularities, and quality assurance. Data outliers (**Fig. 6.1**) can be introduced during many steps of the monitoring programme implementation. Outliers are values which do not appear to belong to the measurement group. If outliers are noticed, they should be investigated to check whether they are due to a natural event, or an error in the analytical or data handling processes. Outliers due to natural events often appear in multiple parameters for a particular sample event. Metadata are critical to help understand patterns in the data and are collected along with the water quality samples, e.g., sample location, flow conditions of a river and weather conditions. They should be checked for obvious impacts on water quality results, such as abnormal flow conditions when the sample was collected caused by heavy rain. Data irregularities can affect the interpretation of results if they are not accounted for appropriately. For example, samples collected from a different location for practical reasons on one or more occasions may not be suitable to include in the time series of the intended site. Quality assurance checks on monitoring data should be performed as part of the laboratory quality assurance procedures.

Before applying any statistical analysis of a data set, it is often useful to prepare some basic visual representations of the data. Simple graphs can often

BOX 6.1 PRELIMINARY CHECKS ON WATER QUALITY MONITORING DATA THAT SHOULD BE CARRIED OUT BEFORE USE IN AN ASSESSMENT

Limits of detection of the methods used (LODs)

This refers to the lowest quantity of a substance that can be confidently determined in the samples. Different laboratories or methods may have different limits of detection. For example, the limit of detection of a method using field apparatus may be higher than a method performed in a laboratory for the same parameters. A field method may not be sensitive enough to measure a very low concentration of a particular parameter, whereas it could be measured if a sample was analysed in the laboratory.

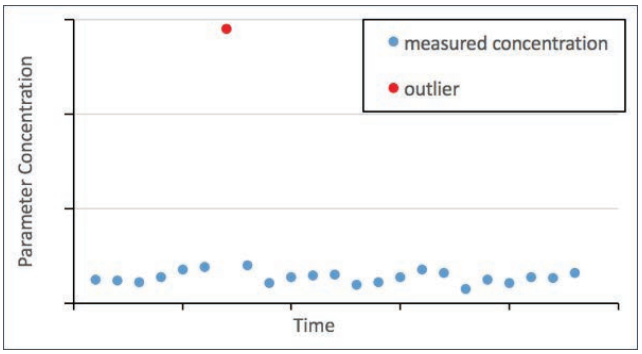
Units

The units of measurement used for some parameters can vary from one organization to another. Hence it is important that the units reported by all contributors to a water quality data set are consistent throughout. For example, orthophosphate can be reported as milligrams of phosphate phosphorus (mg l^{-1} PO_4–P) or milligrams of phosphate (mg l^{-1} PO_4). A reported concentration of 0.02 mg l^{-1} PO_4–P is equivalent to 0.06 mg l^{-1} PO_4 and a conversion may need to be applied to ensure consistency.

Significant figures

The significant figures used for values when reporting data can vary between different laboratories or organisations. Too few or too many significant figures may be applied automatically by data manipulation software, if they are not specified. For example, a pH data value recorded as 6.4824, may be beyond the accuracy of the instrument. Conversely, a recorded value of 6, may not provide enough detail for subsequent analysis.

Figure 6.1 **Example of an outlier (red dot) in a series of analyses over time**

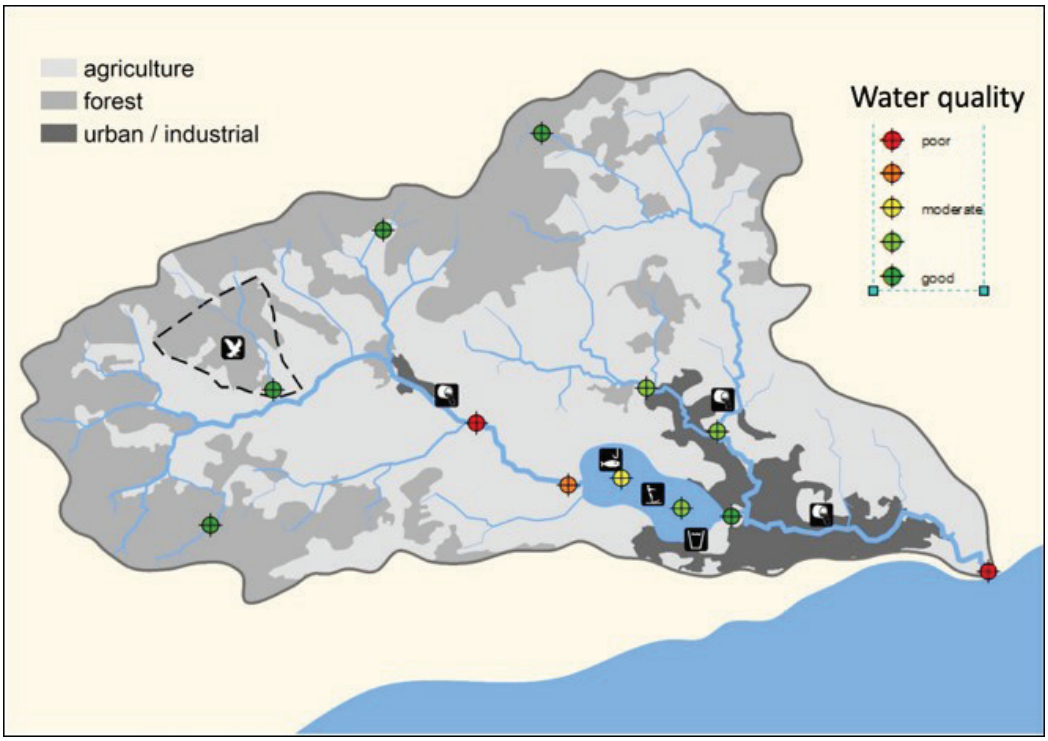


give a quick impression of fluctuations, trends, inter-relationships between parameters, and potential flaws in the dataset due to sampling or analytical errors, or other unforeseen natural events. The intended audience and mode of dissemination should be kept in mind when performing analyses and presenting results. For example, a more technical audience will expect and require greater detail and scientific analysis, than a non-technical or public audience.

Carefully chosen graphs can easily convey information to non-specialists and are an important component of a water quality assessment report. Examples are used throughout the accompanying guidebooks in this series.

Maps are a powerful method to illustrate water quality patterns and trends spatially. Additional data can be provided along with the water quality data to help the viewer interpret the information. Geographical Information Systems (GIS) facilitate the collection, management, analysis and presentation of spatial information on maps. They are now widely used in the water sector by government departments, utility companies, health services, environmental protection agencies, engineering companies and many more. One of the most important uses of GIS in water quality monitoring is for data interpretation by combining water quality data with ancillary information but they can also aid in the design of monitoring networks. Monitoring stations can be selected based on factors such as land use, population density, or known pollution sources that are mapped in a GIS (**Fig. 6.2**).

Figure 6.2 **Example of a map showing different influences on water quality in a hypothetical catchment together with an assessment of the water quality at various monitoring stations**



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