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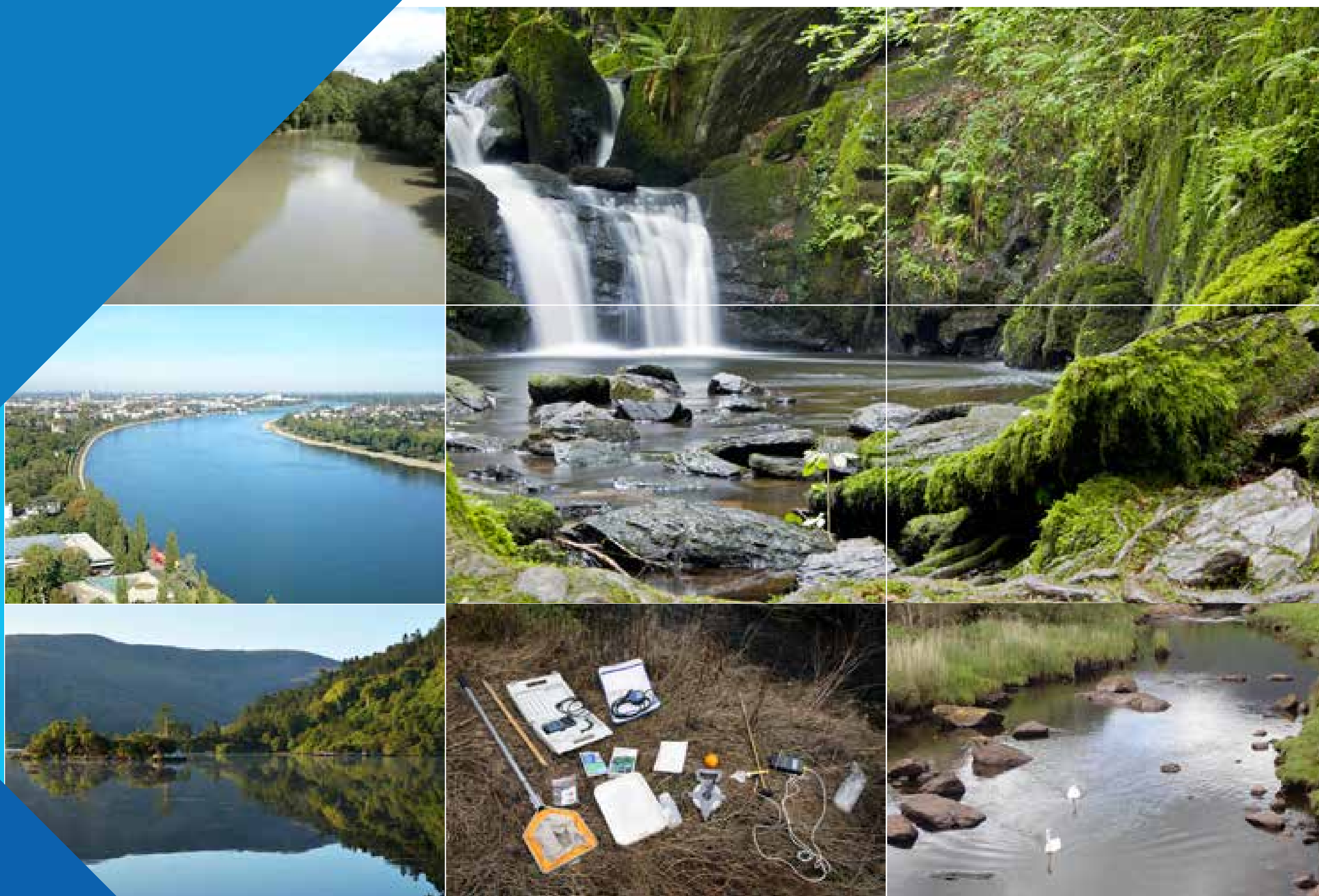

# WATER QUALITY MONITORING AND ASSESSMENT IN RIVERS, LAKES AND RESERVOIRS

## Technical Guidance Document

Prepared by
UNEP GEMS/Water Capacity Development Centre
for the United Nations Environment Programme

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# FOREWORD

This technical guidance document is intended for scientists and practitioners who are involved in planning and implementing water quality monitoring in rivers, lakes and reservoirs but who do not have specialist knowledge or experience. It provides an introduction to the key aspects of these waterbodies that can influence the design, development and implementation of a monitoring network, and the interpretation of the monitoring results as part of a water quality assessment. It then goes on to describe the different approaches and methods that can be used to monitor water quality in rivers, lakes and reservoirs and gives some examples of typical water quality assessments in these environments. It is strongly recommended that this quidebook is read in conjunction with the accompanying guidebooks in the series, particularly *"An Introduction to Freshwater Quality Monitoring and Assessment" and "Quality Assurance for Freshwater Quality Monitoring"*.

Other guidance documents in the series that address various aspects of monitoring and assessment of freshwater are:

- Introduction to Freshwater Quality Monitoring and Assessment
- Water Quality Monitoring and Assessment of Groundwater
- Quality Assurance for Freshwater Quality Monitoring
- Freshwater Quality Monitoring with Biota
- Freshwater Quality Monitoring using Particulate Matter
- Water Quality Data Handling and Assessment

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| | |
|---|---|
| AOA | Algae Online Analyser |
| CPOM | Coarse particulate organic matter |
| DES | Department of Environment and Science |
| DO | dissolved oxygen |
| DOC | dissolved organic carbon |
| DOM | dissolved organic matter |
| EDI | equal-discharge increment |
| EPA | Environmental Protection Agency |
| EU | European Union |
| EWI | equal-width increment |
| FIB | Faecal indicator bacteria |
| FPOM | Fine particulate organic matter |
| GIS | geographic information systems |
| GPS | global positioning system |
| ICOLD | International Commission on Large Dams |
| ICPDR | International Commission for the Protection of the Danube River |
| IISD | International Institute for Sustainable Development |
| ISO | International Organization for Standardization |
| JDS | Joint Danube Survey |
| NASA | National Aeronautics and Space Administration |
| NOAA | National Oceanic and Atmospheric Administration |
| PAR | photosynthetically active radiation |
| PCBs | polychlorinated biphenyls |
| PPE | personal protective equipment |
| SDG | Sustainable Development Goal |
| SOP | Standard Operating Procedure |
| TDS | Total dissolved solids |
| TNMN | TransNational Monitoring Network |
| TSS | Total Suspended Solids |
| UN | United Nations |
| UNEP | United Nations Environment Programme |
| USEPA | United States Environmental Protection Agency |
| USGS | United States Geological Survey |
| VOCs | Volatile Organic Carbons |
| WFD | Water Framework Directive |
| WHO | World Health Organization |

# Chapter 1

## INTRODUCTION

Rivers, lakes and reservoirs play an important role for livelihoods and economic development. The water is used for many purposes, including drinking water supply, agriculture and food production, industrial processes, hydropower, wastewater disposal, navigation, commercial fisheries and recreation (swimming, angling, boating, etc.). Some of these activities have specific water quality requirements, and many of them lead to a gradual decline in water quality through the return of wastewater, or due to the direct introduction of contaminants. In addition, aquatic ecosystems have requirements for water quantity and quality in order to function properly and to provide the ecosystem services on which many communities rely (Keeler *et al.* 2012). In highly populated areas, freshwater bodies are under increasing pressure to meet human needs, in term of both quantity and quality, in order to support all the increasing demands that global development creates. Attaining good water quality in all water bodies is an essential element of sustainable development, as highlighted by the inclusion of a specific target in Agenda 21 and the Sustainable Development Goals (United Nations [UN] 2015). Local communities are particularly affected by degraded water quality, with women and children facing significant impacts arising from physiological differences and women's domestic gender roles, and the smaller body size of children which makes them more susceptible following consumption of contaminated water. Managing these potential human impacts, and protecting and preserving waterbodies, require an understanding of past and present water quality. This information can only be obtained through water quality monitoring programmes that are designed to answer specific questions about current status and trends (e.g., Chapman, Meybeck and Peters 2005; United Nations Environment Programme [UNEP] 2021; Chapman and Sullivan 2022).

All monitoring programmes must have well defined objectives that guide the design, development and implementation of the programme (**Fig. 1.1**). These objectives may be related to quality requirements for water use (such as abstraction for drinking water) or to establishing status and trends, or to determining the impacts of known or anticipated contamination. The monitoring methods selected and the locations and frequency of sampling are informed by the objectives. They may also be informed by an understanding of the functioning of the water body, i.e., its hydrology and ecology and any other relevant information that is found during a preliminary survey, such as known or potential influences on water quality. To assess water quality using the data obtained from monitoring activities, it is also important to have information relating to the water quality as it should

**Figure 1.1** The chain of activities in designing and implementing a freshwater quality monitoring programme (adapted from Chapman, Meybeck and Peters 2005)

be, in the natural state unaffected by human activities. This baseline water quality, or reference state, is often difficult to obtain now that many water bodies worldwide are already affected by human activities, but it may be inferred from historical monitoring and from similar water bodies elsewhere. A reference condition is an essential element of monitoring water quality for SDG indicator 6.3.2 (UNEP 2021; Irvine 2022).

This guidebook begins by introducing the key characteristics of rivers, lakes and reservoirs that inform better monitoring programme design and assist in interpreting the data for water quality assessments. It briefly introduces some other types of surface water bodies that are also important in some areas, i.e., estuaries and deltas, and others that have been created by alteration of rivers and lakes to support human needs. The final two chapters give guidance and examples for approaches and methods for monitoring activities and for interpretation and assessment of the monitoring data. Further information related to the design of a monitoring programme is available in the companion guidebook on *"An Introduction to Freshwater Quality Monitoring and Assessment" and "Quality Assurance for Freshwater Quality Monitoring*". Guidance specifically for groundwaters is available in "*Water Quality Monitoring and Assessment of Groundwater".*

When planning or redesigning a water quality monitoring and assessment programme, it is important the hydrology of the water body is taken into consideration for both selecting the location and frequency of sampling activities, and for the interpretation of any water quality measurements (see **Fig. 1.1**). In an ideal situation, hydrological data is collected simultaneously with water quality data, or at the time of sample collection.

## 1.1 Water quality issues in rivers, lakes and reservoirs

Surface waters are vulnerable to inputs from the land, the atmosphere, direct discharges from human activities and, in some situations, from groundwater. Wastewaters arising from treated or untreated sewage, are high in organic matter and have been a major source of degradation in water quality in rivers for centuries. Their impacts on the chemical quality and the biological communities of rivers caused by the reduced oxygen concentrations due to the microbial decomposition of the organic matter, have been well documented for decades (e.g., Hynes 1960). These changes have formed the basis of some of the most established approaches to using biota for water quality assessment (see the companion guidebook on *"Freshwater quality Monitoring with Biota")*. Another common water quality issue for surface waters worldwide is the increase in levels of nutrients above those that would normally be present without anthropogenic influence, particularly the nutrients phosphorus and nitrogen. They are essential for primary producers, i.e., plants and phytoplankton, and therefore have a key role in the functioning and balance of aquatic ecosystems. A gradual enrichment with nutrients can occur in lakes and reservoirs over centuries but does not normally occur in rivers and streams. Excess nutrients enhance primary production which leads to eutrophication and its associated changes in water quality (see section 5.2). The additional inputs of nitrogen and phosphorus come mostly from the discharge of domestic and industrial wastewaters and agricultural run-off of inorganic and organic fertilisers. Harvesting of forests and clearing of land for buildings, roads and urban development accelerates land run-off, potentially adding more nutrients to rivers. The key driver of eutrophication is phosphorus and the main impact is usually visible as dense growths of phytoplankton and aquatic plants. This makes the water less suitable for many uses without extensive treatment. The decay and decomposition of the phytoplankton creates additional water quality deterioration by using the available oxygen.

Changes in the natural chemical water quality of rivers, lakes and reservoirs (see chapters 3 and 5) can be caused by direct addition of elements and compounds, such as minerals, organic micropollutants and metals, and indirectly by alterations in pH, dissolved oxygen concentrations and sediment composition. Salinisation is the increase in mineral salts above natural levels. Sources of increased mineral salts can arise from mining waste, certain industrial wastewaters, and increased evaporation and evapotranspiration. Domestic wastewater, atmospheric pollution, road de-icing salts and fertiliser run-off can also increase salt concentrations (particularly $Ca^{2+}$, $Na^{+}$, $Cl^{-}$ and $SO_4^{2-}$ ions), especially at local level (Kaushal *et al.* 2018). The pH of freshwater in peat-dominated catchments (due to organic acids), or in certain geological formations, can be naturally low (Tolkkinen 2015). However, acidification can be caused by human activities, such as the direct inputs of acidic wastewaters from mining and other industries, diffuse sources of acidic mining wastes, and indirect inputs from acidic atmospheric deposition. Afforested catchments, particularly those of conifer plantations, can have more acidic streams than those in unforested areas. The decrease in pH associated with acidification can cause the release of metals into the water column making them more available for accumulation by biota.

Trace element pollution with heavy metals arises from many human activities that discharge directly or indirectly to surface waters. The main sources of trace element pollution include:

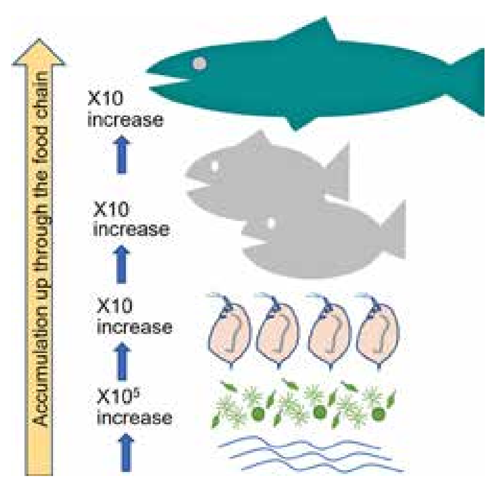
- industrial wastewaters (e.g., from chlor-alkali plants which can release mercury),
- mining and smelter wastes (arsenic, lead, cadmium, zinc),
- urban run-off,
- agricultural run-off (e.g., copper from pesticides or fungicides),
- atmospheric deposition, and
- leaching from solid waste dumps (i.e., landfills).

Trace elements are often readily adsorbed onto particulate matter and are deposited in the sediments, where they can accumulate in bottom living organisms (O'Callaghan, Fitzpatrick and Sullivan 2022). Deoxygenation of the sediment or sediment disturbance can release and recirculate these toxic metals back into the water column. Once in the river or lake, heavy metals and trace elements can bioaccumulate in the food chain (**Fig. 1.2**) (see also "*Freshwater Quality Monitoring with Biota*"). Where fish are used as a food source by local populations, the bioaccumulation of mercury, for example, could pose a serious risk to the health of the fish consumers (World Health Organization [WHO] 2017), especially pregnant women and indigenous children in populations that heavily rely on fish.

Organic micropollutants have become a major issue globally for water quality in recent decades (Schmidt 2018). These organic micropollutants are mostly synthetic chemicals manufactured, used, and then released to the environment. They are often toxic, persistent and bioaccumulate in organisms. Examples of organic micropollutants are pesticides, hydrocarbons, solvents, detergents, cosmetics and pharmaceutical products. They enter water bodies from:

- point sources from sewers and domestic, urban and industrial effluent discharges (most wastewater treatment plants are not equipped to remove these organic micropollutants),
- diffuse releases from agricultural run-off,
- leaching from industrial and municipal waste dumps, and

**Figure 1.2** Some trace elements and organic compounds in water can accumulate in biota, in which their concentrations are magnified with each step in the food chain.



- long-range atmospheric transport and deposition.

Microplastics are another form of micropollutant reaching water bodies from similar sources and becoming ubiquitous in all water bodies (Cárdenas *et al.* 2022). Their presence and impacts on aquatic life have been well documented in recent years but work is still ongoing to develop standardised monitoring methods (e.g., Eriksen *et al.* 2013; UNEP 2020; Cárdenas *et al.* 2022).

Human and animal faeces can reach rivers and streams via surface run-off, soil leaching and wastewater effluents. Faecal contamination from human and animal excrement poses a potential human health risk if contaminated water is used for drinking water directly or with inadequate treatment, for food preparation or for recreational activities (e.g., Jacob *et al*. 2015; Gitter *et al*. 2020; Lin, Yang and Xu 2022). Although both men and women use surface waters for bathing, women are at particular risk because of their frequent use of water from rivers and lakes for cleaning clothes and collecting water for cooking and drinking in the household. Children are also at particular risk because of their play activities in local surface waters and also because they often have the task of collecting water for the household. The pathogenic organisms in the faeces can cause gastrointestinal infections after ingestion, or infections of the upper respiratory tract, skin, ears, eyes and nasal cavity. Diseases causing gastroenteritis, with symptoms such as vomiting and diarrhoea, can be caused by bacteria (e.g., *Salmonella, E. coli*), protozoa (e.g., *Giardia, Cryptosporidium*) and viruses (norovirus, rotavirus and adenovirus). The problem can be widespread in large, fast-growing cities where population growth far exceeds the construction of wastewater treatment facilities with sufficient capacity for the growing population (Koop and Leeuwen 2017). The time for which many disease-causing pathogens can survive in water can be quite long (months for some organisms) and thus the health risks can remain even after the source of contamination has been removed or controlled. Faecal indicator bacteria (FIB) are typically monitored to determine the presence of faecal contamination in water bodies (see other technical guidance documents in this series, particularly *"Freshwater Quality Monitoring with Biota"* for further information).

Morphological changes to surface water bodies to control or enhance water supplies to meet human needs, such as canalisation, artificial embankments and the construction of dams, lead to changes in physical characteristics that in turn affect water quantity and quality. These are discussed in more detail in section 2.5. Human activities like agriculture, deforestation and the use of river water for cooling, can affect the physical characteristics of water bodies. In particular, total suspended solids can be increased locally where there is over-grazing or deforestation within the catchment. When water is used as cooling water in industry, the higher temperature of the discharged water may lead to chemical and biological changes in the receiving water body (Policht-Latawiec, Kanownik and Jurek 2016).

# CHAPTER 2

# MORPHOLOGY AND CHARACTERISTICS OF RIVERS AND STREAMS

Rivers naturally form on high ground and flow downwards towards the sea due to the effect of gravity. They drain areas of land known as river basins and as a river progresses towards the sea its gradient and features change. A network of smaller rivers may drain into the main river within the main drainage basin, forming a number of sub-basins with their own defined catchment areas (**Box 2.1**).

There are huge variations in precipitation in different climatic zones, and the amount, intensity and temperature of the rainfall influence the behaviour of rivers. Rivers in regions with a temperate, oceanic climate with frequent rainfall events, show high levels of rain-fed discharge throughout the year, with rare periods of low flow. In contrast, regions with a tropical climate often have less frequent precipitation, and rivers may have more distinct seasonal variations in flow that alternate between dry and wet seasons. The quantity of runoff is also related to biophysical factors, such as vegetation cover and terrain characteristics like elevation, rock and soil types; slope characteristics (steepness and length); and landscape modifications produced by human land use (McGuire *et al.* 2005).

Rivers generally exhibit one of three flow regimes: ephemeral, intermittent or perennial. Ephemeral streams flow only for a short time, usually after heavy rainfall when there is an increase in water runoff. These are generally small and the channel is always above the water table, resulting in a dry channel at times during the year. The Ugab river in Namibia is an ephemeral river because it only flows a few days or weeks of the year after heavy rainfall, but is still an

## BOX 2.1 TERMINOLOGY RELATING TO RIVERS

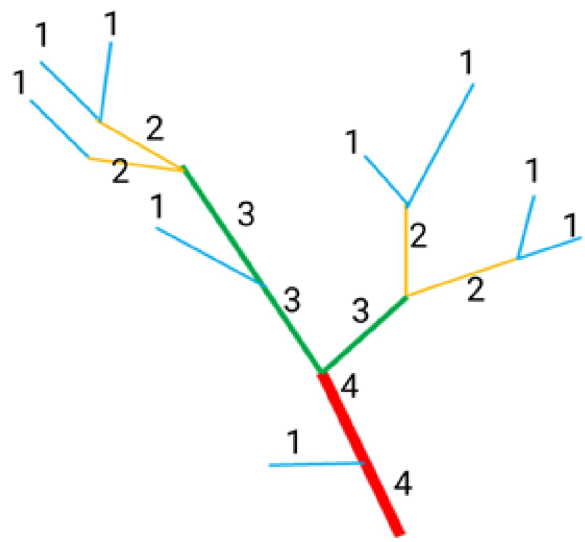
Drainage basin - the area of land that is drained by a river and all of its tributaries.
Catchment area - the area within the drainage basin.
Watershed - the edge of highland surrounding a drainage basin which marks the boundary between two drainage basins.
Source - the beginning or start of a river.
Confluence - the point at which two rivers or streams join.
Tributary - a stream or smaller river which joins a larger stream or river.
Mouth - the point where the river comes to an end, usually when entering the sea.

**Figure 2A** A single river with major tributaries may be divided into several river basins, as shown here in different colours

important water source. Intermittent streams have a seasonal flow, and only flow at certain times of the year. More than half the total length of rivers in the USA, Greece and South Africa are intermittent (Larned *et al.* 2010). Perennial, or permanent rivers have water flow throughout the year, where the base flow is maintained by groundwater influx. The Zambezi, Amazon and Nile are all examples of perennial rivers. Rivers that are classified as ephemeral or intermittent are more likely to be flashy, i.e., water levels rise and fall quickly, because rainwater reaches the river very quickly. The flow regime of a river can be changed by impoundments (e.g., dams), abstraction and other constructions such as canals (see section 2.5).

Rivers can also be classified by their discharge. River size categories can be related to their average annual discharge, their drainage area, and river width (**Table 2.1**). The area drained by a river (i.e., the drainage basin) influences its discharge and width. The size classifications of this approach are arbitrary, and the annual variability is also not accounted for. Discharge is discussed in more detail in section 2.1. The stream order is a means of measuring the relative size of streams and rivers. The first, second and third tributaries of a river system are considered as headwater streams. Streams classified from fourth-order through to sixth-order are medium streams, while seventh-order or larger constitute a river. For context, the Mississippi and the Nile are tenth-order rivers, while the Amazon is a twelfth-order river. First-order streams are single, unbranched streams, second-order streams are formed when two first-order streams meet, third-order streams are formed when two second-order streams meet, and so on (**Fig. 2.1**).

**Figure 2.1** Example of stream order numbering




## 2.1 Stream and river discharge

The discharge of rivers (also referred to as streamflow) is influenced by climatic conditions, geology and size of the drainage basin. River

**Table 2.1** River size classification by average discharge

| River size | Average discharge ($m^3\ s^{-1}$) | Drainage area ($km^2$) | River width (m) | Stream order |
|---|---|---|---|---|
| Very large rivers | >10,000 | >$10^6$ | >1,500 | >10 |
| Large rivers | 1,000–10,000 | 100,000–106 | 800–1,500 | 7 to 11 |
| Rivers | 100–1,000 | 10,000–100,000 | 200–800 | 6 to 9 |
| Small rivers | 10–100 | 1,000–10,000 | 40–200 | 4 to 7 |
| Streams | 1–10 | 100–1,000 | 8–40 | 3 to 6 |
| Small streams | 0.1–1.0 | 10–100 | 1–8 | 2 to 5 |
| Brooks | <0.1 | <10 | <1 | 1 to 3 |

*Source: Adapted from Meybeck et al. (1996)*

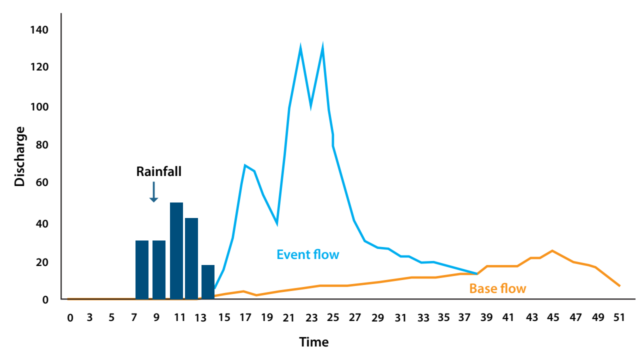
discharge is simply the volume of water that flows through a certain section of the river in a given unit of time (usually given as $m^3\ s^{-1}$). It is typically calculated by multiplying the cross-sectional area of the river by the average velocity of the water passing the point of measurement. The calculated river discharge indicates the quantity of water in a river that is available for different water uses.

When precipitation falls on a drainage basin it can either run-off the surface downhill or be absorbed by the soil/bedrock. When run-off (overland flow) occurs, the soil is either already saturated with water, or dry and hardened and unable to absorb moisture. Surface run-off from rock surfaces occurs when the rock is impervious. Overland flow then travels down into streams and rivers. At a certain depth below the surface, the ground becomes saturated with water. This is known as the water table. If a river cuts into this layer, some of the underground water will feed into the river. This supply of groundwater to streams and rivers is called baseflow. Perennial (permanent) rivers are sustained by the baseflow which keeps water in the river throughout the year.

In cold latitudes and high mountainous areas, the processes of freezing and thawing cause changes in the amount of water flowing downstream. Low river discharge occurs during the glacial freezing of the winter and high discharge during the thaw in the summer months. Urbanisation and the converting of forestry or agricultural land to impermeable surfaces hinders its ability to absorb precipitation, leading to more overland flow. During periods of heavy rain, water may be diverted to storm drains, which often flow directly into rivers. River discharge can also be severely affected by major abstractions of water. The most common reasons for abstracting water from rivers are irrigation, industrial cooling waters and drinking water supply. Abstraction of large amounts of water reduces the discharge of a river resulting in changes in the river ecosystem and sediment accumulation. Groundwater abstractions also affect river discharge through changes in baseflow. This is especially important during low flows (hot, dry weather conditions) when the baseflow contribution is dominant (de Graaf *et al.* 2014).

The sudden increase in run-off with precipitation can be observed as increases in discharge when plotted as a hydrograph. Hydrographs show the discharge over time at a certain point in the river and are often used to predict whether a river will flood. In the theoretical stream hydrograph shown in **Fig. 2.2**, the run-off from a heavy rainfall event appears as a sharp rising curve, while the baseflow discharge reacts by increasing more gradually. There is usually a delay between the peak rainfall and the peak discharge in a receiving river.

**Figure 2.2** Hydrograph showing the peak discharge in a stream (blue line) lagging behind the peak rainfall. The baseflow (orange line) responds more slowly.



### 2.1.1 The impact of discharge on water quality

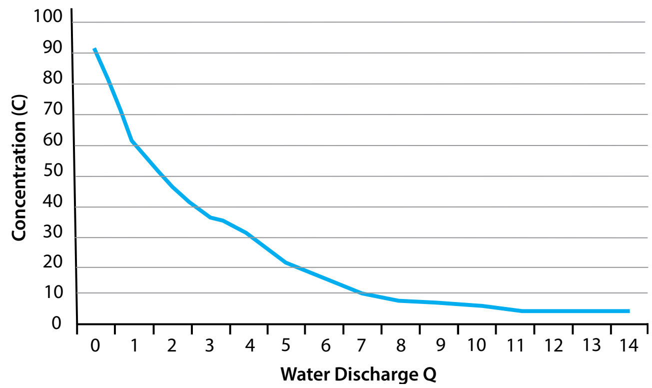
Erosion of the land surface, often exacerbated by land use change such as deforestation, leads to sediment being carried to rivers with run-off. When discharge levels are low, the sediment is deposited on the river bed, but as the quantity of water rises in a river, and its velocity and discharge increase, erosion of the banks and river bed occur. As a result, previously sedimented material may also be resuspended. Hence total suspended solids (TSS) and turbidity increase during periods of high discharge (**Fig. 2.3**).

Water quality variability within a river may be related to the discharge variability, i.e., the number of floods per year. Water quality changes markedly during flood events as a result of inputs to the river from different origins. The water entering a river during a heavy rainfall event can come from surface run-off, soil water (sub-surface run-off), and groundwater discharge, each carrying many different elements:

- Surface run-off is usually highly turbid with high levels of suspended solids, nutrients and other land-based contaminants such as hydrocarbon run-off from roads and pesticides from agricultural land.

**Figure 2.3** River Findhorn from Dulsie Bridge showing highly turbid water due to high levels of suspended solids carried by the river during a high discharge event. By Steven Brown. Licensed under CC BY-SA 2.0

**Figure 2.4** The relationship between concentration and discharge when the substance is entering the river at a fairly constant rate, e.g., from a point source.




- Sub-surface run-off carries leached dissolved organic carbon and nutrients (nitrogen and phosphorus) from soils.
- Groundwater carries elements resulting from rock weathering.

The major sources of elements and substances in a river can be determined by comparing the changes in discharge with the simultaneous changes in chemical concentrations. **Fig. 2.4** shows a decrease in concentration with increasing river discharge, which implies enhanced dilution of a substance. The substance must be entering the river at a steady rate, such as from a point source discharge. **Fig. 2.5** shows an increase in concentration as the discharge increases. This can be associated with soil constituents coming from run-off, such as organic matter and nitrogen compounds. In **Fig. 2.6**, the curve shows an exponential increase in concentration with increased discharge. This may occur for total suspended solids (TSS) and with all substances bound to particulate matter as a result of sheet erosion (removal of soil in thin layers over a wide area by the forces of raindrops and overland flow) and river bed remobilisation. Phosphorus, heavy metals and organic pollutants like pesticides and herbicides, are examples of substances that may be bound to particulates.

Total suspended solids will not always produce an exponential curve with increased discharge. If there is a series of storms one after the other, the sediments

**Figure 2.5** An increase in concentration with increased discharge may indicate a major contribution of substances from land run-off.

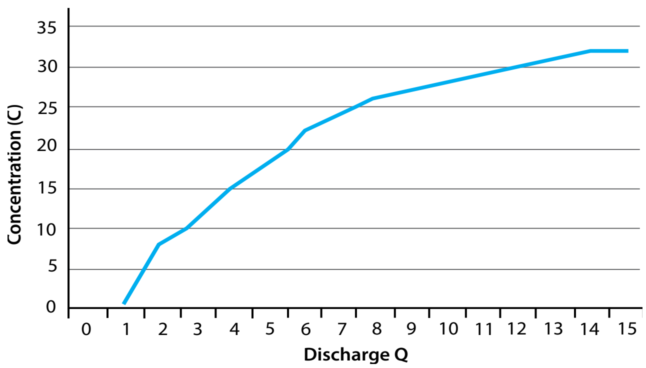
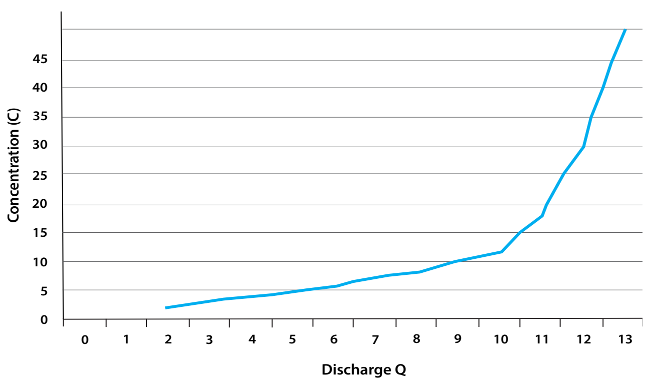



**Figure 2.6** An exponential increase in concentration with discharge is often associated with substances bound to particles.




may be "exhausted". This means there is less sediment available in the river bed to be remobilised after each storm event.

These examples are simple relationships to illustrate the diagnostic capability of discharge concentration curves in determining major sources of pollutants. However, a substance can often come from many sources which makes the determination of its origins more difficult.

## 2.1.2 Measuring river discharge

Discharge is an essential component of most monitoring programmes in rivers. Ideally, discharge should be recorded frequently and at the same time and in the same location as water quality samples are collected. Discharge measurement at the time of water quality sampling facilitates the calculation of loads using the measured concentrations of water quality parameters. This is particularly important for pollutants and for the fluxes of pollutants between water bodies. Regular measurement of discharge can also provide early warning of potential damage to the river ecosystem that may be caused by reduced streamflow arising from abstraction. Storm event sampling for water quality is particularly advisable in small river basins (roughly less than 100,000 $km^2$) because the chance of sampling during high discharge events when using a regular sampling frequency (e.g., monthly) is reduced. In larger river basins (greater than 100,000 $km^2$) regular frequency sampling is adequate. Nevertheless, if a major storm event is forecast, sampling should be carried out over this period because the heavy rain may cause changes in water quality in the river basin.

River discharge (*Q*) in cubic metres per second ($m^3\ s^{-1}$) is calculated by multiplying the cross-sectional area of the river (*a*) in $m^2$ by the average velocity (*v*) in $m\ s^{-1}$ of the water passing that point:

$$Q = v \times a$$

A simple method for measuring discharge ***in situ*** is described in Appendix A. An important point to remember for monitoring programme design is that when sampling stations are located at different river stages, the cross-sectional area of the river must be determined at each sampling station because it will vary with river stage.

Where a permanent or long-term water quality monitoring station is established, or where it is important to have frequent measurements of discharge for flood and abstraction management, a mechanism for continuously recording discharge can provide valuable information. The discharge values can be inferred from rating curves. A rating curve shows the relationship between stage (elevation of the water surface) and discharge (**Fig. 2.7**). To establish a rating curve, hydrologists record discharge manually at frequent intervals at the gauging station, including during periods of extremes, such as droughts or

**Figure 2.7** A rating curve showing the relationship between river stage (water level) and discharge

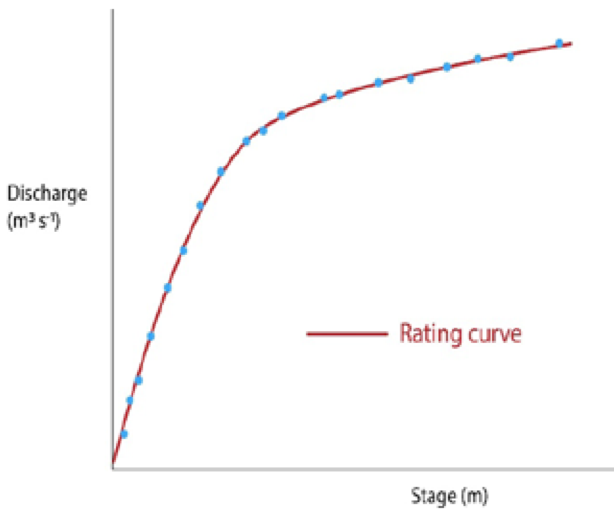



**Figure 2.8** A simple staff gauge for measuring water level © Patrick Cross

floods. Water levels can be read manually from a simple staff gauge comprising a graduated length of metal, plastic or other water resistant material (**Fig. 2.8**) or recorded by an automated gauging station that records water level continuously and sends the information directly to a computer. Providing the relationship between water level and discharge has been established, discharge can be computed using the data from these automated water level (stream gauge) recorders. For further information on how to set up, maintain and obtain reliable data from automatic guaging stations see World Meteorological Organization [WMO] (2010). Many countries have a combination of manual and automated gauging stations distributed throughout their major river basins as part of a national hydrometric network (e.g., Ireland, Environmental protection Agency [EPA] 2022). These stations are used to monitor and manage river flow and can provide valuable information for water quality monitoring programmes, especially if located at sampling locations.

## 2.2 Erosion and deposition

The movement of water in a river channel leads to erosion and deposition. Erosion and deposition constantly change the physical nature of a river. Human modification of rivers, such as by the introduction of flood barriers, can also alter erosion and deposition patterns. These affect water quality and also the riverine habitats that support the biota. There are four main types of erosion in river systems.

- Hydraulic action is the erosion that occurs when the motion of water against a rock surface produces mechanical weathering. During this process, air becomes trapped in the crevices of the river bank and bed, and causes the rock to break apart.
- Abrasion occurs when material being transported in a river wears away at a surface over time, i.e., the process of friction caused by scraping, grinding and rubbing away of the two surfaces.

## BOX 2.2 ORGANIC MATTER IN THE RIVER ECOSYSTEM

*Coarse particulate organic matter (CPOM)* is defined as any organic particle larger than 1 mm in size (Cummins 1974) and comes from the riparian ecosystem adjacent to the river where it either falls, get blown, or washed into the river channel. Leaves are an important source of CPOM in temperate and tropical forested rivers, while flowers, twigs, wood, fruit and pollen also contribute. The death of macrophytes and aquatic animals in the river or stream also adds to coarse organic detritus.

*Fine particulate organic matter (FPOM)* is defined as organic particles in the size range of > 0.5 μm to < 1000 μm (1 mm), and is primarily formed by the breakdown of CPOM by the activity of shredders (a group of organisms that break material into smaller pieces), microbial processes and physical abrasion. It can also enter the system from wind transport, surface run-off, and river bank erosion. Macroinvertebrate faeces and soil are also significant sources of FPOM.

*Dissolved organic matter (DOM)* comprises organic particles smaller than 0.45 μm in size and represents the largest pool of organic matter in aquatic ecosystems. DOM is very diverse in composition including organic molecules such as sugars, lipids and amino acids as well as larger humic molecules and colloids. The majority of DOM comes from terrestrial decomposition processes and enters rivers from the land. Soil organic matter input is typically greatest from grassland catchments, intermediate from forested catchments and lowest from desert catchments. As DOM is readily transported downstream, the concentration of DOM increases with increasing stream order.

- Attrition occurs when rocks that are transported downstream along a river bed collide against each other, breaking apart to become smaller and more rounded and smoother fragments.

- Solution erosion occurs when the water itself dissolves certain types of rocks, e.g., acid waters eroding limestone.

Through these processes, erosion can lead to the river bed becoming deeper (vertical erosion), the banks becoming wider (lateral erosion), and the channel becoming longer (headward erosion). Deposition is the process of the transportation of eroded material downstream, that settles elsewhere in the system due to a reduction in river velocity. Velocity decreases with depth in a river channel with laminar flow, because bottom friction from the bed decelerates the flow. The energy released by the deceleration is transferred into moving coarse sediment particles along the river bed.

Substrates, comprising both inorganic and organic particles, vary from river to river, across a river channel, and along the length. Inorganic particles are mineral and are classified by their size, i.e., mud, sand, gravel, pebbles, and cobbles. Coarse substrate is heavy and requires a high hydraulic force to move it. Hence, these substrates tend to be more stable. As substrate stability increases, so too does the abundance and diversity of organisms present. Organic particles in the substrate may comprise lumps of wood and debris as well as flocculated organic molecules carried by the river system and deposited on the river bed. Organic matter can be classified into three forms which play an important role in the overall river ecosystem (**Box 2.2**).

The substrate influences the biota that can be found there, so if the organic matter (detritus) content increases, the abundance and diversity of biota will increase because many organisms have more food available. Allochthonous organic matter arises externally to the riverine system and is not broken down as easily as autochthonous organic matter that is formed from within the river system. The process of decomposition of organic matter in rivers can release nutrients to the water column. The relative contribution of allochthonous and autochthonous organic matter can change from one river segment to the next.

## 2.3 Mixing processes in rivers and streams

The changes in velocity of water and how it moves through different channels must be understood in order to design monitoring programmes appropriately and to interpret the results obtained. Water flowing in rivers and streams can exhibit two main types of flow pattern:

- *Laminar flow* Typically smooth, slow flow in deep rivers, that allows suspended material to settle to the river bed. Laminar flow results in different velocities throughout the water column: the maximum velocities occur in the middle of the channel where there is less friction. The bank and bottom of the river exert frictional forces on the water flowing past, thereby reducing the flow rate.
- *Turbulent flow* Typically rough, fast flow in shallow rivers, that keeps particles in suspension. Turbulent flow leads to complete mixing throughout the water column.

Velocity gradients in the water column affect how inflowing waters, tributaries or point-source effluents, mix with the river. Initially influent streams and discharges are forced to flow along the side of the river in which they enter until mixing occurs between the layers of water. Mixing can occur at bends in the river, at rapids and at waterfalls. Rapids and waterfalls cause turbulent mixing, whereas mixing induced by bends is often by vertical circulation. The type and location of mixing is relevant for appropriate sample site selection.

**Figs. 2.9** and **2.10** illustrate laminar flow at a river confluence where a tributary joins the main river channel. In Fig. 2.9 the force of the laminar flow in the main channel, with the maximum velocity in the middle, causes the inflowing water (dark colour) to flow along the side of the channel. This continues until mixing occurs at the bend. This process can happen with any inputs such as point-source effluents from municipal wastewater treatment and industrial waste.

**Figure 2.9** The influence of laminar flow in the main river on the mixing of water from a tributary.

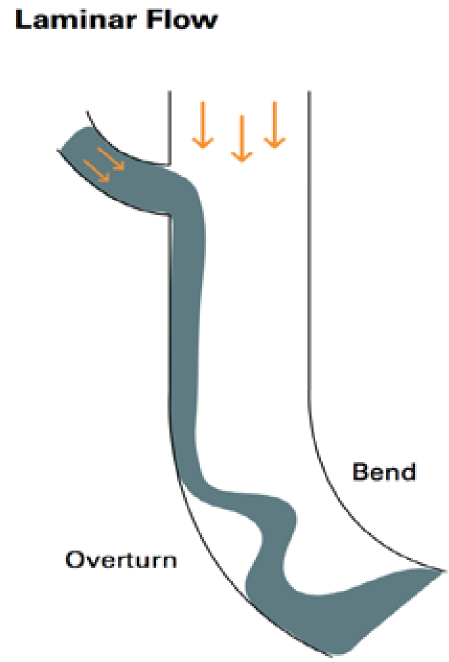



**Figure 2.10** Confluence at Mtskheta, Georgia showing laminar flow to the left. © Deborah Chapman

Incomplete mixing can cause variations in concentrations of water quality parameters across a river channel. Thus, the mixing processes affect how sampling campaigns need to be carried out to ensure representative samples are taken. A single sampling site is not adequate to describe the distribution and abundance of chemical constituents in a river system, so the homogeneity of the parameters of interest in a river should be checked prior to the establishment of a monitoring station. Sampling sites are often chosen at a sufficient distance above and below any confluences of streamflow or point-sources to avoid sampling a cross-section that is not mixed or not unidirectional. The variations in concentrations downstream of a confluence as a result of the lack of mixing may persist for several kilometres.

## 2.4 Deltas and estuaries

Rivers ultimately flow into the oceans, or into a lake through a zone where the river may be influenced by the receiving water body, especially if the level of the receiving water body can be elevated by tidal cycles or wind driven water movements. Suspended material carried by rivers may be deposited at the river mouth, creating a delta. The changing topography caused by deposited sediments in a delta leads to the development of wetlands and many smaller river channels. Deltas and estuaries receive the accumulated sediments, nutrients and contaminants from the whole river catchment and are, therefore, vulnerable to water quality and ecosystem degradation. However, they are also important areas for human settlements, enabling agriculture and providing fisheries and other ecosystem services. Therefore, deltas and estuaries require management and protection to ensure the ecosystems and the services they provide remain sustainable. Part of this management strategy should include monitoring of water quality and quantity on a regular basis in order to detect change and inform appropriate management upstream.

### 2.4.1 Deltas

As a river flows towards its mouth, the velocity slows and allows sediments to settle out onto the bottom of the river. Deltas are a feature of this deposition found at a river mouth where it reaches the sea (**Fig. 2.11**), an estuary, a lake, or very occasionally empties into land. River deltas are distinguished by being low-lying and are often highly productive with diverse ecosystems. They can offer a variety of ecosystem services including sea defence, drinking water supply, recreation, fisheries and highly productive soil for agriculture (Reader *et al.* 2022).

Dams and other forms of river management affect the morphology and ecology of deltas, together with the associated water quality. For example, the Nile delta has experienced reduced flooding and thus less alluvial silt deposition following the construction of the Aswan Dam, because the silt is now confined behind the dam. As a result, the agricultural land of the Nile delta is now much more reliant on fertilisers and irrigation, with consequences for water quantity and quality (e.g., Abu Zeid 1989; Abd-El Monsef, Smith and Darwish 2015).

A continuous monitoring programme designed to aid management of the San Francisco Bay and Delta was established by United States Geological Survey in 1988 to explore the spatial and temporal variability of water quality and sediment transport and to provide

**Figure 2.11** The Ganges-Brahmaputra Delta seen from space. Credit: NASA Public Domain

**Figure 2.12** Sierra Leone River estuary. Credit: European Space Agency. Contains modified Copernicus Sentinel data (2015) Licensed under CC BY-SA 3.0 IGO

decision makers, resource managers, and the public with the most up-to-date data and information. The monitoring programme continuously monitors suspended-sediment concentration (SSC), turbidity, dissolved oxygen, temperature, salinity, and the water level at many sites throughout the San Francisco Bay and the Sacramento-San Joaquin Rivers Delta (United States Geological Survey [USGS] undated).

### 2.4.2 Estuaries

An estuary is the mouth of a large river where the freshwater mixes with seawater as it flows into the sea (**Fig. 2.12**). The tidal and saline influence makes the water quality of estuaries complicated because they have very diverse conditions and transient states of vertical and horizontal circulation. An estuary can have a gradient of salinity from fully saline at the mouth to freshwater at the landward end, and this

#### BOX 2.3 TYPES OF ESTUARIES BASED ON THEIR MIXING PROCESSES

*Salt wedge estuaries* occur when river water is discharged into a very calm sea making the river input more important than the tidal effect. Freshwater that is less dense than seawater floats on top in a layer that gradually spreads out over the surface of the sea water. The denser seawater moves up the estuary along the bottom of the estuary forming a salt wedge. There is a distinct halocline, i.e., the separation zone between layers of water with different salinities. The salt wedge can move further up the estuary if the freshwater input is low, such as during a drought.

*Partially mixed estuaries* occur when a river discharges into a sea with a medium tidal range. The tidal currents are stronger than the rivers output. This means the water is moved up and down the estuary with the tide. The mixing caused by the shear stress between the salt and freshwater layers is compounded by the turbulence caused by the friction with the bed of the estuary. The saltwater is mixed upwards and the freshwater is mixed downwards. The halocline in this type of estuary is less pronounced.

*Well mixed estuaries* occur where tidal forces are strong, and the tidal range is high. The river discharge is weak in comparison and the result is a well-mixed water column. The salinity is mostly uniform throughout the depth and there is no halocline. However, there may be horizontal variations in salinity even if there are no vertical variations. Due to Coriolis forces, the sea water flows upstream on the left-hand side while the freshwater tends to flow out on the right-hand side in the Northern Hemisphere and in the reverse in the Southern Hemisphere (facing seaward).

*Negative circulation estuaries* occur when evaporation is greater than the incoming freshwater. High evaporation rates at the head of the estuary produce hypersaline waters which sink and flow seaward drawing in a surface flow of seawater. Surface water salinity is therefore increased. This causes a distortion of salinity gradients to seaward in the bottom waters. This occurs in areas like the Arabian Gulf.

*Source: Dobson and Frid (1998)*

gradient is influenced by the topography of the estuary, the tidal regime and the circulation pattern. The salinity gradient also moves up and down the estuary with the tides. There are four types of estuaries classified by their different distributions of salt and freshwater and the mixing processes occurring in the estuary (**Box 2.3**). Water quality, especially salinity fluctuations, can be complex in estuaries due to the influence of freshwater, saltwater and the tidal cycle. This needs to be understood in order to select appropriate sampling sites and to assess water quality data. For further information on estuaries see Kennish (2016).

**Figure 2.13** Artificial banks along the urban stretch of the Dâmboviţa river as it passes through Bucharest © Deborah Chapman

## 2.5 Modified rivers

Human settlements along the length of rivers have created many demands, such as abstraction and diversion of water for municipal use and irrigation, access along the river channel for navigation and transport, and impoundment for hydropower generation. As a result, many rivers around the world have been subject to some form of modification that completely alters the hydrology and associated ecology. These include artificial banks in sections of a river to avoid erosion or overtopping during floods (**Fig. 2.13**), canalisation or channelling through pipes and open drains, weirs and dams. Changes in hydrology, water quality and ecology can arise during and after the modification of a river (**Fig. 2.14**). Impacts arising during the modification process may be temporary, but in some situations the river ecology may take many years to recover. Examples of impacts during construction can be high suspended sediment loads (**Fig. 2.14**) arising from digging and reforming banks and river beds, altered flow rates due to temporary dams and diversions, the creation of ponds behind temporary dams, and the creation of temporary channels during diversion of flow.

Permanent modifications of rivers usually result in changes in the river's hydrological regime. Flow

**Figure 2.14** Channelisation works on the Bandon River, Ireland for flood prevention (left) and the resultant high suspended solids and enhanced microalgal growth in the river water downstream of the flood prevention works (right) © Patrick Cross

rates may increase or decrease depending on the nature of the modification. For example, widening a river channel may decrease the velocity of the water, and impounding water behind a dam will reduce the discharge below the dam. These changes in the hydrological regime will also impact on water quality, transport of particulate matter, and riverine ecology, as well as providing a physical barrier to the movement of migratory species.

### 2.5.1 Canals

Artificial rivers, commonly known as canals, are waterways that have been specially created where no previous waterway existed, e.g., the Panama Canal. Some are dug and allowed to mature with natural banks, while others are completely or partially constructed from stone, brick and concrete. Canals are usually constructed either (a) to allow the passage of boats and ships (**Fig. 2.15**) or (b) to transport water for irrigation, drainage and other purposes (known as irrigation canals or aqueducts) (**Fig. 2.16**). Canals enable transport between two points, regardless of the terrain. Sections of a waterway at different elevations are connected through locks. Each section of the canal typically has little or no downward flow, other than that created by the water exchanged between sections when the lock gates are opened and closed to enable the passage of boats. The amount of water exchanged depends on the size of the lock and its frequency of use. The water may become stagnant with very low oxygen concentrations and anoxic sediments. Canals are also subject to the accumulation of nutrients from land-based sources together with organic matter from sewage, oil residues from ship engines, high suspended matter from sediment disturbance by the ships, and abundant growths of planktonic organisms.

Irrigation canals take diverted water from a main river or stream to areas where it is required to water crops. In regions where irrigation is essential for agriculture, the volume of water diverted into canals may exceed that remaining in the natural river or stream. Irrigation canals therefore make an important contribution to the hydrological regime of a watershed and should be included in a monitoring network as part of an integrated river basin management plan. They often show different hydrological regimes from the main rivers and streams, depending on their size and the intensity of abstraction for irrigation (Carlson *et al.* 2019).

In arid regions, groundwater is used for irrigation, and the run-off from this irrigation is collected in drainage canals. The water of these canals is often of very poor quality; it can be high in salts and nutrients, and

**Figure 2.15** The Manchester Ship Canal By John Eyres - https://www.flickr.com/photos/32865578@N02/3418179672/, Licensed under CC BY 2.0

**Figure 2.16** Irrigation canal near Fira Shia, Iraq. By Christopher Ellis, U.S. Army. Public Domain

low in oxygen. Such drains also accumulate other wastewater, including sewage, adding to the poor water quality. In recent years, due to the increasing depletion of groundwater resources, efforts are being made to remediate the quality of drainage waters to re-use them for agricultural purposes. An example of this is the extensive water quality monitoring of the drainage network of the Nile delta in Egypt (Fleifle and Allam 2016).

### 2.5.2 Weirs and dams

Weirs are usually built to slow the flow of water in a river, to raise the water level upstream behind the weir, or as a point at which water flow can be measured (**Fig. 2.17**). The changes in flow lead to physico-chemical changes upstream and downstream, that consequently affect the biota. An example of a negative impact of a weir can be clearly shown from tropical regions where the increased aeration of the water flowing over the weir, combined with a suitable substrate to which they can attach, favours the growth of the larvae of biting Blackfly, which can transmit diseases such as River Blindness (WHO 2022a). A discussion of the role and impact of weirs upstream and downstream is available in Rickard *et al.* (undated).

A dam is a physical structure across a river that holds back most of the river flow (**Fig. 2.18**), creating a reservoir upstream of the dam. Dams are extremely common worldwide and numbers have been increasing steadily, particularly hydropower dams (Lehner *et al.* 2011; Zarfl *et al.* 2015). Dams are also built to create a reservoir for irrigation, to regulate river flow and prevent flooding, to supply water for domestic and industrial use, for recreation and fish farming, and to facilitate inland navigation by ships. A large dam is defined as having a height of 15 metres or greater from lowest foundation to crest, or a dam between 5 metres and 15 metres in height impounding more than 3 million cubic metres (ICOLD 2011).

The creation of a dam changes the nature of the river above and below the dam. A reservoir or lake is formed immediately behind the dam, but where the river meets the reservoir there is a transitional zone. The morphology, hydrology, physical, chemical and biological characteristics of the three zones are different (Thornton *et al.* 1996). The main impacts on the river upstream and downstream resulting from the construction of a dam are shown in **Table 2.2**.

**Figure 2.17** The Rodington hydrometric gauging weir on the River Roden with fish and eel pass installed to the left. By Gary Bywater, Environment Agency, UK. Licensed under Open Government Licence v3.0

**Figure 2.18** The hydropower dam on the River Lee, Ireland, built in the 1950s © Patrick Cross

**Table 2.2** Main physical and environmental impacts associated with dams

| Upstream of dam | Downstream of dam |
|---|---|
| Transition from river to a lake behind a dam | Scouring of river bed at dam face |
| Reduced flushing leading to sediment and nutrient accumulation in the river behind the dam | Reduced flow and discharge |
| Eutrophication | Reduced nutrient supply |
| Increased water temperature and reduced oxygen | Lower suspended particulates |
| Increases in the occurrence and severity of stagnant water diseases | Increased light availability through water column |
| Irretrievable water loss through evaporation and groundwater seepage | Reduced impacts of heavy rain and run-off |
| Changes in plant and animal communities<br>a) Increased plankton growth with reduced flushing<br>b) Soft sediment benthic communities<br>c) Altered river sediments affecting fish spawning grounds | Changes in plant and animal communities<br>a) Isolation from remainder of population, food sources or breeding grounds<br>b) Interruption of migration routes<br>c) Habitat fragmentation |

When a dam is completed, the reservoir behind the dam undergoes a series of changes in water quality and it may be many years before the water quality and biological conditions stabilise. This needs to be taken into consideration when planning a monitoring programme or assessing the water quality monitoring data from a recently created reservoir. An example is Lake Kariba, Zimbabwe which was formed after the closing of the Kariba Dam (Thornton *et al.* 1996). It experienced initial high productivity supported by the decomposition and release of nutrients from vegetation that was flooded in the river valley. The productivity stabilised after approximately six years and water quality improved.

River flow and discharge below a dam may be related to the purpose of the dam. For hydropower dams, the operation of the turbines affects discharge as the water passes through the turbines. Water extracted from deeper parts of the reservoir and discharged through turbines may be cold and anoxic, and the impacts can extend many kilometres downstream (Ling *et al.* 2016). For the safety of any dam, water may be spilled over the dam or via a spillway if the water level gets too high (as in **Fig. 2.18**). This can create a scouring effect immediately below the dam, which can change the physical habitat and carry away aquatic organisms. The quality of the water downstream is also affected by the sudden flux of reservoir water, which may have different physical, chemical and biological characteristics. Some dams incorporate mechanisms for fish to continue their migration upstream, such as a special channel called a fish pass. The fish below the dam are attracted by the outflowing water of the fish pass channel (**Fig. 2.19**).

**Figure 2.19** Fish pass at the dam on the Moselle River at Koblenz, Germany. The fish are attracted to the outflowing water from the gate at the side of the fish pass © Deborah Chapman

CHAPTER 3

# CHEMICAL AND BIOLOGICAL CHARACTERISTICS OF RIVERS AND STREAMS

Sources of elements and chemical compounds can be either natural or anthropogenic. The natural chemical characteristics of rivers are independent of any human impact on the chemical composition and arise solely from natural sources, and these natural sources can vary hugely from one river to the next. Anthropogenic sources come from human changes to the landscape or from human activities. The catchment of a river may comprise different types of rock, natural land cover and human land use. Thus, along its path a river may receive solid materials and dissolved substances arising from rock weathering, run-off and infiltration from many types of land-use, point source pollutant inputs, and direct precipitation.

## 3.1 Natural chemical characteristics

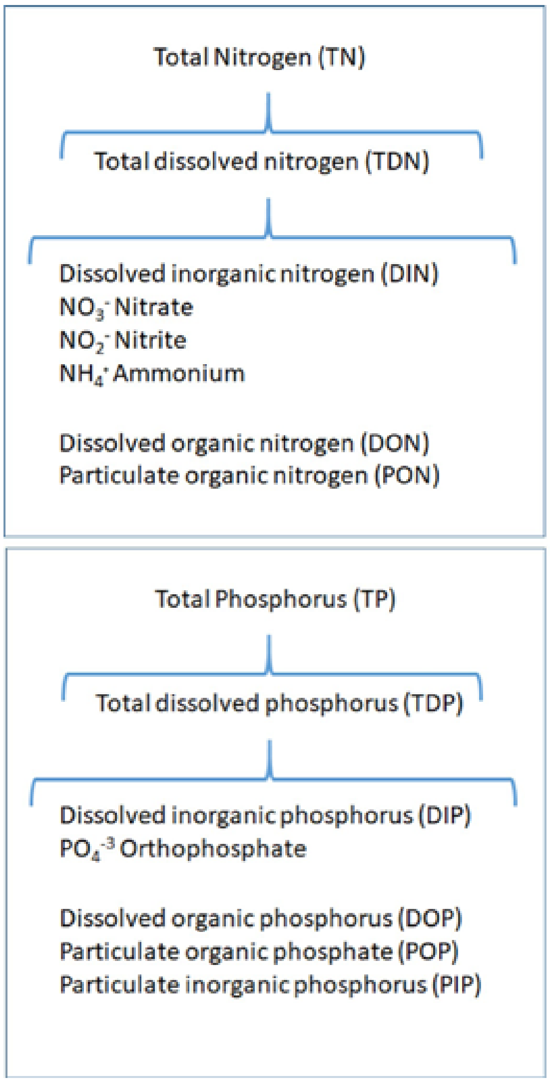
Natural inputs of chemicals into a river can arise from a number of pathways. Groundwater infiltration (baseflow – see section 2.1) into rivers brings dissolved minerals from the aquifer rocks. The chemical composition of the baseflow depends on the type of rock and whether it is highly soluble. Run-off after rainfall brings organic and inorganic material from the drainage basin. Leaching of organic soils can lead to dissolved organic carbon and nitrogen entering groundwater and/or surface water. Tributaries may contribute different chemical characteristics that depend on the nature of their individual catchments. Atmospheric inputs depend on the location of the river. Rivers situated near the coast can have elevated concentrations of sodium, chloride, magnesium and sulphate ions from oceanic aerosols. Volcanic fall-out (HCl, $H_2SO_4$) can also be deposited onto the drainage basin and into rivers.

Carbon dioxide ($CO_2$) and oxygen ($O_2$) are almost at saturation point in turbulent and unpolluted streams, whereas larger rivers that are less turbulent have lower concentrations. This is because the surface area is lower in a large river relative to the total volume, reducing the amount of molecular diffusion. Dissolved oxygen can control the speciation of some metals and their solubility and toxicity, for example, reduced cations such as $Fe^{2+}$ and $NH_4^+$ (ammonium) or the oxidised species $Fe^{3+}$ and $NO_3^-$ (nitrate). Dissolved oxygen concentrations can increase as a result of oxygen released from photosynthesis by aquatic vegetation (algae and macrophytes) and can be used up by plants, bacteria and other organisms during respiration. Photosynthesis is limited to the areas of the river receiving sunlight.

Oxygen levels generally decrease downstream, because the upper reaches of a river tend to be more turbulent, have lower temperatures, and have a greater surface area to volume ratio for diffusion of oxygen from the atmosphere. A fast-flowing, turbulent, unpolluted stream is usually saturated with oxygen. Conversely, pools and stagnant areas, especially with a high organic load, e.g., due to dead and decomposing leaves, can have low levels of oxygen. Extremely low levels of oxygen usually only occur in heavily polluted streams and rivers, or as a result of a combination of low-flow, high temperature and dense vegetation.

The nutrients, nitrogen (N) and phosphorus (P), are the main limiting nutrients for growth of algae and macrophytes in a river. Different forms of nitrogen (nitrate, nitrite and ammonium **Fig. 3.1**) occur naturally, but usually at low concentrations in rivers.

**Figure 3.1** Major forms of N and P in natural waters




Processes such as denitrification (conversion of nitrate to nitrous oxide or free nitrogen which is released back to the atmosphere), organic matter burial in sediments, sediment sorption, and plant and microbial uptake, can remove nitrogen from the river. Nitrogen levels can also decrease in turbulent water, for example by volatilisation of ammonia.

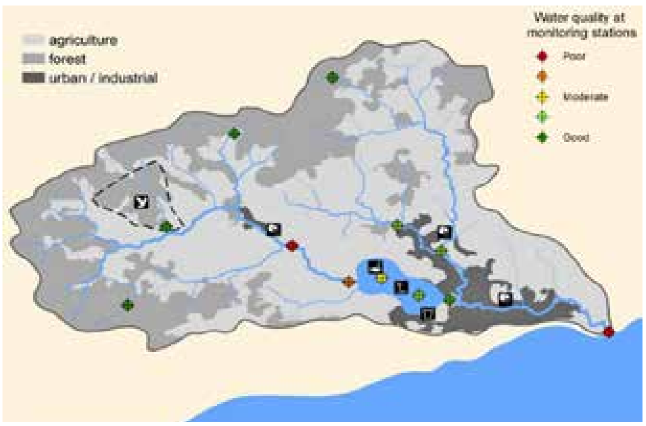
Phosphorus (**Fig. 3.1**) arises naturally from weathering and from run-off with precipitation. It is taken up by plants and can become adsorbed (attached) to particulate matter and sediments from which it may be released (desorbed) under certain environmental conditions. Dissolved phosphorus can combine with metal oxides and hydroxides to form insoluble precipitates. In areas of slow flow, particles with bound phosphorus can settle on the river bed, and under anoxic conditions the phosphorus may be released from river sediments, increasing the concentrations in the water column.

Total dissolved solids (TDS) include all the inorganic salts (major ions), and some organic matter, dissolved in water. High levels of TDS reflect the dominance of carbonate minerals in sedimentary rocks (such as limestone) within the river catchment. Common inorganic salts that can be found in rivers include the cations calcium ($Ca^{2+}$), sodium ($Na^+$), magnesium ($Mg^{2+}$) and potassium ($K^+$), and the anions bicarbonate ($HCO_3^-$) and sulphate ($SO_4^{2-}$). The majority of these salts are derived naturally via the weathering of rocks, but some can come from bacterially-produced $CO_2$ dissolved in soil and groundwater (i.e., bicarbonate), while others can result from precipitation in coastal areas (e.g., sodium). The levels of these salts would also typically increase with high levels of evaporation. More than half of TDS in rivers is composed of bicarbonates, chlorides and sulphates. The quantity of carbonates in a river determine whether it is hard water or acidic water. Acidic water has low levels of carbonate ions and this influences the species of flora and fauna.

### 3.1.1 Spatial and temporal variability

Differences in natural ionic chemistry resulting from river basin lithology are greatest in smaller river basins because the lithological composition of larger river basins tends to be more homogeneous. River chemistry can be quite constant over ranges of 100-1,000 km in regions with homogeneous rock type such as the Canadian, Brazilian and African shields, or in large sedimentary basins such as the central Congo or Amazon basins. However, there is no global "natural" water quality for river water that could be used as a baseline or reference point against which it can be determined whether a river is polluted or not. It may be necessary, therefore, to use another river or tributary within the same catchment as a baseline (**Fig. 3.2**), or one from nearby that has similar geological conditions, but without any (or with very little) human influence in the catchment. In reality, this approach is often very difficult to achieve.

**Figure 3.2** Potential water quality monitoring stations in a hypothetical river basin. The good water quality locations where the land is forested would be typical locations to determine the background water quality



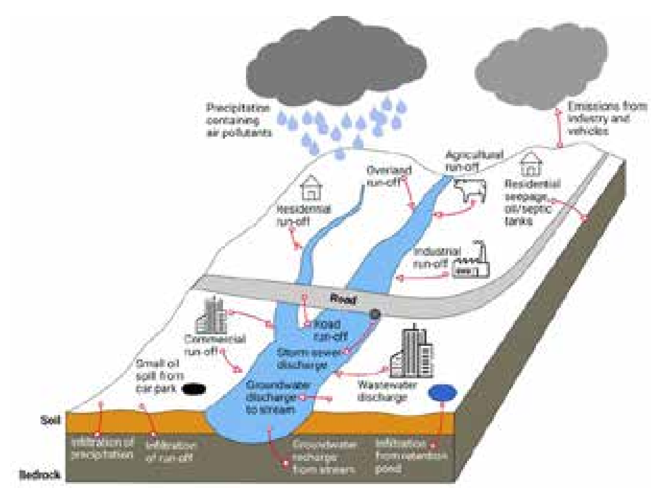

The variation in chemical composition of rivers often reflects the precipitation pattern. Seasonal variation also reflects the importance of the groundwater contribution to the streamflow. The major ions that are in high concentrations in groundwater are most influential to river chemistry when discharge is low and baseflow dominates. The climate and associated vegetation growth in different world regions affects run-off. Run-off from tropical rain forest areas is commonly low in dissolved solids, e.g., the Amazon River, whereas in arid climates the high evaporation rates from the soil, give rise to high dissolved solid concentrations in run-off and river water, e.g., the Colorado River, USA. Regions where climate is characterised by alternating wet and dry seasons have seasonal differences in the chemical composition of streams and rivers. In the wet season, large variations in discharge lead to a wide range in chemical composition with the increased run-off. Cold weather climates inhibit geological weathering reaction rates because of low temperatures and run-off is mostly low in solute concentrations.

### 3.1.2 Influence of human activities on chemical characteristics

Changes in chemical water quality in rivers as a result of human activities may lead to the water becoming no longer suitable for agricultural, industrial and recreational uses; and the river ecosystem may also be affected (see also section 3.2). There are many sources and pathways of potential contaminants from human activities (**Fig. 3.3**). Treated or untreated sewage and industrial effluents mostly enter rivers from point-sources. Municipal sewage and industrial effluents can contain a wide range of organic and inorganic substances, including heavy metals, organic compounds, salts and minerals. Human activities within the catchment, such as agricultural practices, tourist and recreational activities can cause seasonal changes in the quantity and composition of inputs to rivers. Very large temporal variability in water quality usually indicates human impacts rather than natural changes due to seasonal fluctuations.

Indirect impacts from human activities occur as a result of increasing natural processes such as erosion and soil leaching, and by adding compounds to the land that are carried with run-off into rivers. Such compounds include mineral salts and inorganic fertilisers, and synthetic compounds such as solvents, pesticides and aromatic hydrocarbons. Nitrate is more soluble than phosphate and therefore the concentrations of nitrogen in fertiliser run-off are often higher than phosphorus because the phosphorus

**Figure 3.3** Sources and pathways of contaminants to rivers arising from human activities. Skyscraper icon designed by "freepik", factory icon designed by "srip", cow icon designed by "monkik" from Flaticon



binds to soil particles. However, in heavy rains and storms that lead to soil erosion, the concentration of both N and P can increase. Air pollution can also cause rainwater to contain N and P which are added to river systems with precipitation and run-off. Oil residues can also wash off roads into streams, or into storm-sewers which are often released into streams.

The resultant impacts of human activities on the chemical characteristics of rivers are usually characterised by:

- changes in average concentrations or time and space variability in substances,
- changes in ionic assemblages and nutrient ratios, or
- the presence of synthetic compounds that do not normally occur in ecosystems.

## 3.2 Biological characteristics of rivers

The flow rate of the water in a river affects the nature of the river substrate and the exchange of gases at the water surface. The concentration of oxygen in the water, together with the substrate and presence of vegetation, can influence the types of organisms, and even the species, that can live in a river. Seasonal variations in flow rate may also lead to seasonal changes in the plants and animals. High velocity flows keep more particles in suspension, which reduces the amount of light penetrating the water column. The amount of light available affects the photosynthetic organisms that can successfully colonise the river, i.e., macrophytes, algae and microalgae (phytoplankton). These primary producers, or autotrophs, produce their own nutritional requirements through photosynthesis. Secondary producers, or heterotrophs, are organisms that must consume organic matter from other organisms. Macroinvertebrates (**Fig. 3.4**), zooplankton, fungi and bacteria are secondary producers in river systems. Many organisms find it difficult to colonise fast flowing rivers and streams, but some organisms have adapted to survive the flowing water, to exploit the habitats that are available, and to swim against the current or avoid being carried away by it.

Understanding the natural plant and animal communities in a river is useful for detecting any disturbance in the system, such as changes in water quality. The river biota can be used to monitor change, and even provide evidence of pollution. The principles and key approaches to using biota for water quality monitoring are presented in the accompanying guidebook: "*Freshwater Quality Monitoring with Biota*".

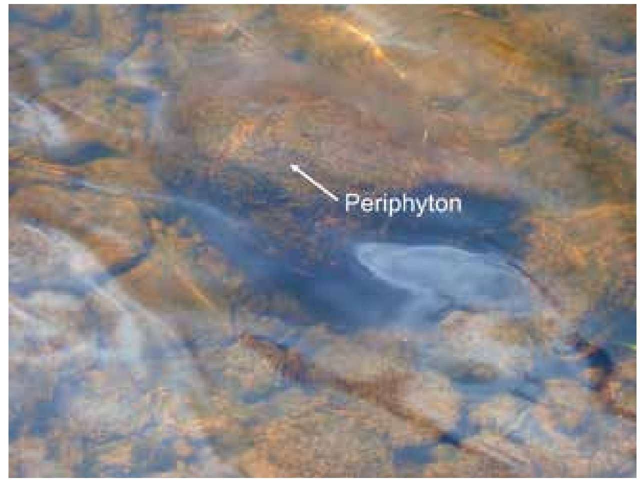
There are two main zones in a river system that incorporate the majority of river biota, i.e., the pelagic

**Figure 3.4** Typical macroinvertebrates found in good (left) and poor (right) water quality rivers and streams. © Patrick Cross

and benthic zones. The pelagic zone is inhabited by organisms that can swim or float in the water column and comprise mostly plankton and fish. Phytoplankton are primary producers, comprising mainly diatoms, cyanobacteria and green algae (Belcher and Swale 1979). They can only survive in areas of slow flow in rivers because they are often washed downstream before they have time to multiply and achieve significant populations. Cyanobacteria (also referred to as blue-green algae) can produce cyanotoxins which can be harmful to human and animal health. Dense populations of cyanobacteria usually only occur in static or extremely slow flowing waters. Zooplankton are small, sometimes microscopic, animals that graze on phytoplankton, organic detritus or other zooplankton. They are also more likely to form significant populations where river flow is very slow. Fish can exploit all accessible river habitats but specific environmental conditions are often needed for spawning, because some fish attach their eggs to stones or plants, or deposit them in shelters constructed on the river bed. These requirements mean the breeding success of fish is sensitive to changes in river velocity and erosion. Migratory fish moving upstream to spawn may have their passage blocked by weirs, dams, locks and even stretches of river with highly toxic or anoxic water.

The benthic zone is inhabited by organisms that grow in, on, or in association with, substrates. Macroinvertebrates (**Fig. 3.4**), periphyton and macrophytes make up most of the benthic community. The presence or absence of benthic organisms is sometimes used to assess whether there has been a change in the habitat or environmental quality because they have limited ability to escape from any undesirable change in their environment, including water quality. Periphyton are microscopic plants that are attached to the substrate or cling to plants just above the sediments, where they can form biofilms (**Fig. 3.5**). Light is essential for periphyton to photosynthesise, and therefore increased turbidity or the blocking of light penetration by phytoplankton blooms, can hinder their growth. Macrophytes are aquatic plants that either float or grow in, or attached to, the substrate depending on the availability of light and the nature of the substrate (see **Fig. 5.4**). They provide a substrate for macroinvertebrate filter feeders and grazers. They also provide food for herbivorous

**Figure 3.5** Periphyton forming a biofilm on the surface of stones in a shallow stream. © Deborah Chapman




invertebrates, fish, birds and mammals. Shallow rivers and streams, that have clear, non-turbid water allowing light to penetrate to the river bed, support the growth of benthic algae and rooted macrophytes. The absence of light, or reduced light caused by riparian vegetation or high concentrations of suspended material can lead to an absence, or reduced growth, of macrophytes.

Temperature affects the rate of physiological processes of organisms, such as respiration and the growth rate. For example, the reduced oxygen concentrations associated with warmer water can affect the ability of some species to thrive and reproduce, leading to reduced diversity of species. Temperature usually increases from the source of a river to its discharge to a lake or the sea, resulting in associated changes is species diversity and abundance. In shallow streams, water is well-mixed due to turbulence, creating a relatively uniform temperature in most parts of the stream. Only in deep, slow-moving rivers can significant temperature differences be found between the surface and bottom waters.

Vegetation can increase oxygen concentrations during the day as a result of photosynthesis, but concentrations decrease significantly during the night due to respiration, resulting in increased carbon dioxide levels at night. Different aquatic species have different abilities to cope with varying oxygen concentrations. Some species have adapted their respiratory ability and oxygen requirements to tolerate situations with low oxygen. Approximately 5 mg $l^{-1}$ of dissolved oxygen is generally considered to be the lowest safe level for fish populations, especially in warm tropical rivers (Welch and Lindell 2004).

# CHAPTER 4

# MORPHOLOGY AND CHARACTERISTICS OF LAKES AND RESERVOIRS

A lake is a body of water surrounded by land and with no direct access to the sea. Freshwater lakes can occur anywhere in a river basin. Natural lakes are formed by processes on, or at, the Earth's surface resulting in, for example, glacial lakes, fluvial lakes and volcanic lakes. Artificial lakes are formed by impounding rivers with dams, or by constructing reservoirs. Lakes and reservoirs provide water for many different purposes, such as for drinking water, irrigation, and industrial uses (including hydropower and cooling water). Some uses have defined water quality criteria, such as for drinking water (WHO 2022b) and irrigation (Ayers and Westcot 1985), hence water quality monitoring is essential to ensure that the quality is adequate for the intended uses. Lakes and reservoirs are also important freshwater ecosystems that provide many other services, such as fisheries, aquaculture and recreation. Monitoring provides valuable information on water quality status and trends that can inform sustainable management of the lake or reservoir ecosystem.

This chapter focusses on the important characteristics of lakes and reservoirs that influence water quality and are important for the appropriate planning and implementation of monitoring activities and for the interpretation and assessment of water quality monitoring data. These characteristics include residence time, mixing in the water column, nutrient cycling and biological productivity.

## 4.1 Morphology

A lake forms in a depression in the Earth's surface (**Fig. 4.1**), in which water accumulates more quickly than it is lost. The origin of a lake can influence its shape, depth and water chemistry (Wetzel 2001).

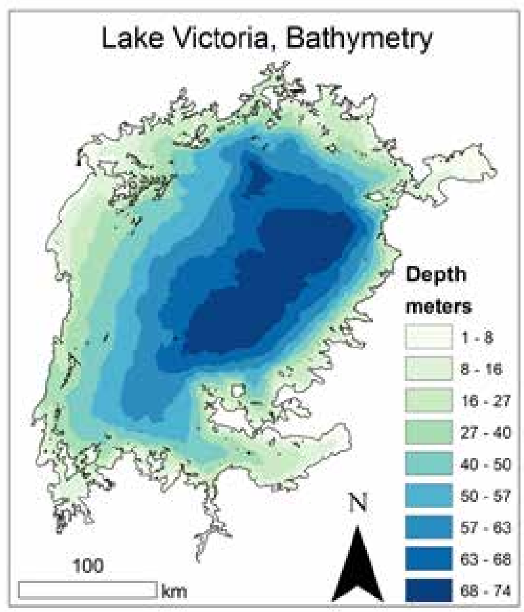
**Figure 4.1** A small lake in a hollow created by a glacier in the mountains of southern Ireland. The outflow is small stream at the right. © Deborah Chapman

Reservoirs are water bodies that are modified or formed by humans for specific purposes, in order to provide a reliable and controllable water resource. Natural lakes can be used as reservoirs by creating a controllable abstraction point from which water is diverted for specific uses. Most reservoirs are formed by damming rivers and streams, creating an impoundment behind the dam (**Fig. 4.2**). The other major types of reservoirs are off-river, bunded or embanked reservoirs, which are constructed by enclosing a basin with water-proof banks (**Fig. 4.3**). Impoundments can be very large, and are more sinuous and dendritic than embanked reservoirs. The main difference between a lake and a reservoir is that the outflows, and sometimes also the inflows, are carefully managed in a reservoir to maintain the desired water volume. As a result, reservoirs can control flooding downstream by storing water and releasing it in a controlled manner and also

**Figure 4.2** Raystown dam and spillway creating the impoundment of Raystown Lake, Huntingdon County, Pennsylvania, USA. © Deborah Chapman.

**Figure 4.3** Embanked reservoirs built to supply drinking water to London. © Deborah Chapman

**Figure 4.4** A bathymetric model of Lake Victoria by Stuartehamilton. Licensed under CC BY-SA 4.0.




improve water quality conditions downstream by trapping sediments and allowing natural processes to attenuate nutrients and contaminants, e.g., Lake Mead, USA (Prentki and Paulson 1983).

Very few lake basins are uniform in shape and depth This variability in topography can lead to differences in water quality (physical, chemical and biological) in different areas of a lake. It is important, therefore, that the topography is known and taken into consideration when planning a monitoring programme and especially when selecting monitoring locations. The underwater topography can be visualised by a bathymetric map of the lake floor (**Fig. 4.4**). A bathymetric map is prepared from depth readings at known positions in order to create depth contours. Modern techniques, such as the use of SONAR, satellite imagery and geographic information systems (GIS), enable three dimensional visualisations of lake bathymetry (Dost and Mannaerts 2008; Sherstyankin *et al.* 2005). Bathymetric maps are used to highlight areas within a lake that may act as separate water bodies due to restrictions in water movements resulting from the topography of the lake bed. They can also highlight deep basins which may be areas of sediment deposition and accumulation.

## 4.2 Water volume and hydraulic retention time

Water in a lake[1] generally appears to be static, even though there is some movement of water into and out of most lakes. The water level and volume are influenced by precipitation and direct run-off in the lake basin, together with river run-off to the lake from precipitation occurring within the river catchment. Water movements within the lake are influenced by wind strength and direction, together with lateral flow between the lake inflow and outflow. The temperature of the water is influenced by the ambient air temperature and solar radiation reaching the surface of the lake.

Water entering a lake or reservoir from a river flows into the depth layer that is most similar to its own density. This process is governed by temperature and dissolved and particulate substances. River water entering a lake may flow at the surface of the lake (known as overflow, where the river water is less dense), along the bottom (known as underflow, where the river water is more dense), or at an intermediate depth (known as interflow, where river water is of the same density as lake water). Gradual mixing of the inflows occurs, unless the density differences between the inflows and the lake are quite large. When sampling close to an input in a lake or reservoir, care should be taken to ensure the sampling location and depth are representative of the lake water after full mixing has occurred.

The water balance of a lake is the result of:

| *Inputs* | *minus* | *Losses* |
|---|---|---|
| Water received from precipitation | | Water lost by evaporation |
| Surface inflows from rivers and streams | | Outflow to rivers and streams |
| Groundwater inflows | | Seepage to groundwater. |

Inputs from, and losses to, groundwater can be difficult to measure. In small lakes, and in temperate climates, evaporation is considered to be negligible and approximately equivalent to direct inputs from precipitation. Hence, the water balance may be approximated from inflows and outflows from rivers and streams. Nevertheless, rainfall and solar heating can lead to seasonal variations in water level. The period of time water spends in a lake is known as the hydraulic retention time, or residence time. This is the time it takes for water (and any dissolved or suspended pollutants) to be flushed through the lake. Retention times can vary from a few hours to years, e.g., Lake Biwa, Japan, to decades, e.g., Lake Garda, Italy, and even to hundreds of years, e.g., Lake Baikal, Russia. The differences in residence times of the Great Lakes of North America are shown in **Table 4.1**. Most very shallow lakes (< 5 m deep) have short residence times of one year or less. Many estimates of residence time are based on the theoretical residence time, which is the mean volume ($m^3$) divided by either the mean rate of inflow or mean rate of outflow ($m^3 s^{-1}$). Lake volume has traditionally been estimated by approximating the lake basin to the shape of a cone, but today GIS is a useful tool for estimating lake volume more accurately (Hollister and Milstead 2010).

The residence time governs how long it takes for any compounds in solution entering the lake to be eliminated with water exchange. Residence times are therefore important for indicating how long a lake might take to recover from a pollution incident (Soares *et al.* 2008). Residence time also has an important influence on the types of organisms that can develop substantial populations in the open water of the lake. When residence times are long and the water exchange is slow (weeks or more), many planktonic species are able to multiply before they are washed out of the lake. Provided sufficient nutrients are available, dense growths of phytoplankton may occur, known as algal blooms. Thus, managing the residence time in a nutrient-rich reservoir, by controlling inflows and outflows, can help to prevent the development of dense growths of planktonic organisms that may adversely affect water quality.

[1] Throughout the remainder of this chapter, descriptions relating to lakes also apply to reservoirs unless specifically stated otherwise

**Table 4.1** Residence times of the Great Lakes in North America

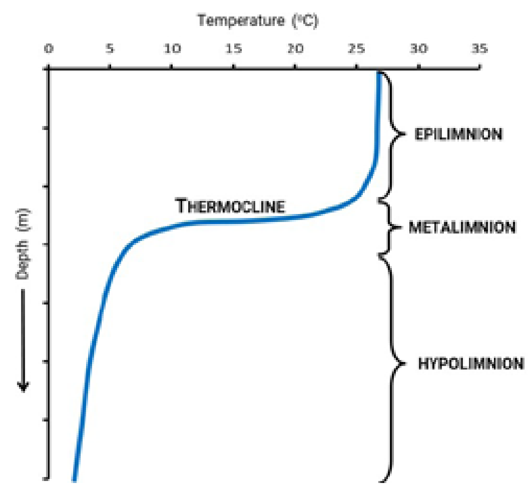
| Lake | Rank in world lakes | | Residence time (years) |
|---|---|---|---|
| | by area | by volume | |
| Superior | 2 | 4 | 191 |
| Michigan | 4 | 6 | 99 |
| Huron | 5 | 7 | 22 |
| Erie | 11 | - | 2.6 |
| Ontario | - | 12 | 6 |

*Source: Adapted from McBean and Motiee (2008)*

## 4.3 Heat and thermal stratification

The density of water is dependent on its temperature. Water is heated at a lake or reservoir surface by solar radiation. The warmer surface water is less dense than the deeper, colder water. When there is very little wind action on a lake surface, physical separation of water masses of different density can occur, and this process is known as thermal stratification. Shallow lakes (i.e., lakes less than 10 m in depth) may not stratify when the water is warm, or they may show very weak stratification. However, they may stratify when the water is very cold. The upper layer of a stratified lake is known as the epilimnion (**Fig. 4.5**). It has relatively freely circulating water, with a small and variable temperature gradient. This lies over a deep, generally undisturbed, cold layer known as the hypolimnion, which has a gentle vertical fall in temperature that is roughly exponential. The plane of the most rapid temperature change is known as the thermocline and the layer above and below the thermocline, where temperature is changing most rapidly, is known as the metalimnion (**Fig. 4.5**). Destratification occurs when the epilimnion and hypolimnion mix. This is known as lake overturn. In temperate lakes, overturn occurs when the temperature of the surface water decreases due to falling ambient temperature and reduced solar radiation. The density difference between the water layers becomes too small to remain stable and is easily disrupted by wind action.

**Figure 4.5** Typical temperature profile from a stratified lake in the temperate zone




Climate conditions and the depth of the lake can produce different patterns of stratification and mixing. Seasonal patterns can be represented by plotting isotherms (lines of equal temperature) on a depth-time graph. In order to plot isotherms, temperature readings are required throughout the depth of the lake or reservoir, at regular intervals over time, e.g., weekly. The example in **Fig. 4.6** shows fully mixed water (indicated by vertical isotherms) between January and late May, when the process of stratification begins (indicated by horizontal isotherms). The lake remains fully stratified until late September when the thermocline begins to break down, eventually leaving the lake fully mixed until the following summer. In tropical lakes, like Lake Victoria, in which there are only very small differences in water temperature, there may be a more permanent but weak stratification. Polar lakes do not have time to undergo a summer stratification when the ice melts, so they have one mixing period in the summer before the inverse stratification is re-established in the autumn.

**Figure 4.6** Isotherms (°C) in Esthwaite Water, English Lake District, showing summer stratification and autumn overturn. Data and image © Deborah Chapman

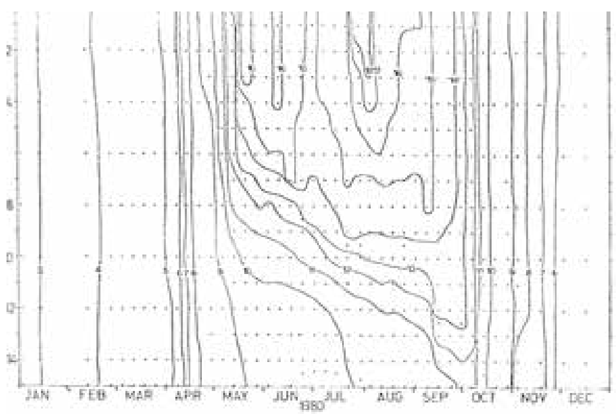
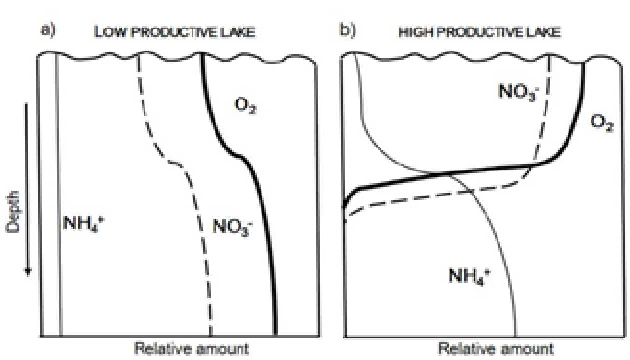



**Figure 4.7** Vertical distribution of oxygen ($O_2$), nitrate ($NO_3^-$), and ammonia ($NH_4^+$) in stratified lakes. Nitrate and oxygen concentrations follow similar patterns with depth in lakes with low productivity (a), whereas the relative amount of ammonia increases at low oxygen concentrations in highly productive lakes (b) (after Brönmark and Hansson 2017)




Lakes in which total mixing occurs and where water circulates to the lake bottom are known as holomictic. Meromictic lakes have layers of water that do not mix. These lakes have a permanent, stabilised water layer at the bottom. Thermal variations may still occur in the upper layer of meromictic lakes at different times of the year. Examples of meromictic lakes include the deep lakes, such as Lake Tanganyika and Lake Malawi. Due to the absence of mixing between the water layers, the bottom layer contains no dissolved oxygen and is therefore largely devoid of life.

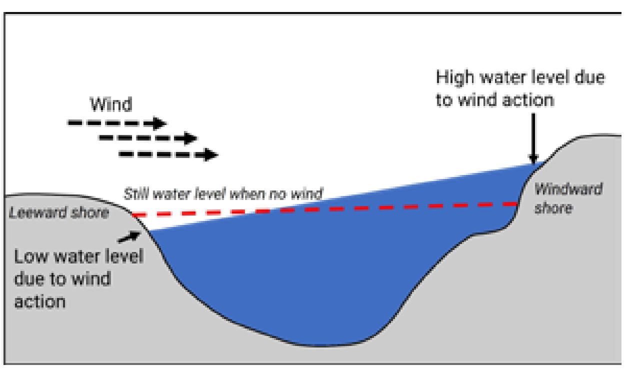
Stratification within a lake or reservoir has implications for water quality. Water trapped in the hypolimnion does not have an opportunity to exchange gases at the water surface. In addition, the biological material that sinks down from the epilimnion is decomposed as it passes through the hypolimnion, and this degradation process uses up oxygen. As a result, the hypolimnion may suffer from deoxygenation and may even become anaerobic close to the sediment. The deoxygenation may be more severe when there are high densities of phytoplankton in the epilimnion. Anoxic conditions influence other chemical processes, such as oxidation and reduction within a lake or reservoir. Ammonium, for example, is not stable in high oxygen conditions and is readily oxidised to nitrite and nitrate (**Fig. 4.7a**). By contrast, highly productive (eutrophic), stratified lakes that are anoxic below the thermocline may have high ammonium levels at depth (**Fig. 4.7b**). Understanding the thermal behaviour, depth of the thermocline, and associated implications for water quality, are particularly important for reservoirs where water can be abstracted from different depths.

## 4.4 Wind and water movements

The forces responsible for the movement of water in lakes are: wind, changes in atmospheric pressure, horizontal density gradients, and the influx of water into the lake. Understanding water movements is important for selecting appropriate sampling locations and for interpreting the resultant chemical and biological data. The movement of water, apart from a steady flow in a definite direction from inflow to outflow (when present), is mostly turbulent, i.e., variable velocities in any direction may be observed. The effect of the wind on the lake surface is to move water downwind and to the right in the Northern Hemisphere and to the left in the Southern Hemisphere. The first effect is due to the stress of the wind on the water and the second effect is due to the rotation of the earth or to geostrophic forces.

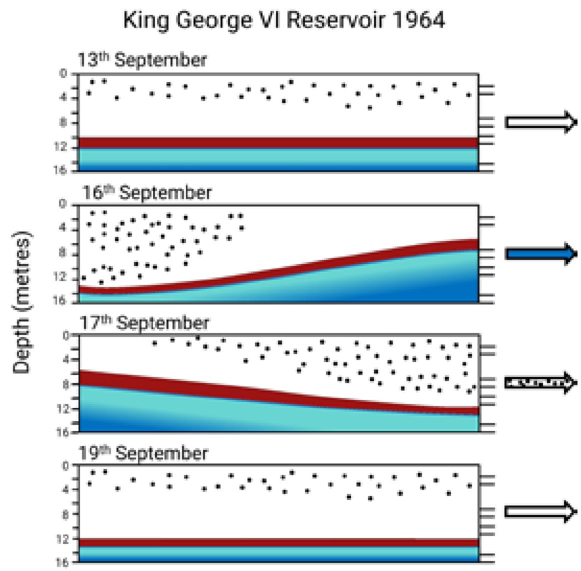
Strong winds (or a difference in barometric pressure at one end of a large lake) can increase the water level significantly at the windward shore of large lakes, and decrease it at the leeward shore (**Fig. 4.8**). When the wind stress is removed, the water level tilts back, creating a standing wave that moves back and forth. This is known as an external, or surface seiche. These are generally quite small (e.g., 1–2 mm in Lake Mendota), but can be larger, e.g., Lake Geneva (1.9 m) and Lake Michigan (3 m). The rhythmic changes in direction of seiches are an important type of deep water movement in lakes and are responsible for the vertical and horizontal transport of heat and dissolved substances. Surface or external seiches can lead to noticeable differences in water quality at the windward and leeward ends of lakes and reservoirs.

**Figure 4.8** Wind action can cause differences in water level at the leeward and windward ends of a lake or reservoir




Internal seiches occur when lakes are stratified. These internal standing waves form at the thermocline or metalimnion (see section 4.4). Their periodicity and amplitude is usually much larger than for surface seiches, i.e., about 10 times larger. The waves of internal seiches can also lead to considerable mixing of water of different qualities between the epilimnion and hypolimnion. Wind can pile epilimnion water at

**Figure 4.9** The impact of wind on a stratified drinking water supply reservoir in the UK. The quality of the water at the four extraction points on the south side of the reservoir varies during the two days of the wind event. Data from Metropolitan Water Board, London and image © J.E. Ridley and J.A. Steel




the leeward end of a lake and then, when the wind strength decreases, some mixing of the epilimnion and hypolimnion occurs. When the wind drops altogether, the epilimnion water flows back and piles up at the former windward end. Hypolimnion water moves in compensation to the leeward end, and an oscillation (rocking motion) between the two layers (a seiche) begins and continues with progressively decreasing amplitude. For more information see Moss (2009) and Moss (2018). Under these circumstances, the water quality at the same sample point can vary considerably with the motion of the seiche. Where a reservoir has several water abstraction depths, the quality of the water taken from the same abstraction level, can be potentially quite different before, during, and after a wind event due to the presence of seiches. In **Fig. 4.9** the water abstracted on 13 September was from the epilimnion with low levels of phytoplankton. On 16 September, due to wind action, the water abstracted at the same depth comprised deoxygenated water from the hypolimnion. On 17

September the surface phytoplankton were mixed deeper into the epilimnion and the abstracted water was high in suspended particles. Two days later when the wind ceased, the thermocline stabilised and the abstracted water was clear again.

The waves generated by internal seiches propagate and break internally in a similar manner to surface waves. The breaking of the waves internally leads to pockets of water in the surface epilimnion layer that have arisen from the metalimnion. This can result in temporary patches of differing water quality and plankton populations within the epilimnion. These patches eventually mix with the main body of the water.

Large lakes, like the oceans, can have major water movements within them called gyres, which are large, turbulent, rotating bodies of water. In Lake Geneva, for example, gyres have been discovered to be in the order of 10 km in size (Evangelista 2018). These water movements could result in changing patterns of water quality, which are currently poorly understood in many large lakes.

## 4.5 Light and primary productivity

Radiation in the form of visible light is important for primary production in lakes. The physical, chemical and biological nature of the water column of lakes and reservoirs affects the quality of light and its penetration to depth within the lake. The penetration of light can, as a result, be a useful indicator of the quality of lake water. Solar radiation in the range 400 to 700 nm (i.e., visible light) is used in photosynthesis and is known as "photosynthetically active radiation" (PAR). When radiation reaches the surface of a lake or reservoir, some is reflected back at the surface and some (about 50%) is scattered back from beneath the surface by suspended particles, or converted to heat within the first metre. The light that penetrates below the surface is absorbed by the water, by the dissolved organic substances, and by the suspended material in the water. Overall, there is a downward flux of light that decreases as light is attenuated (attenuation = absorption + scattering).

The penetration of light (especially the PAR) is an important factor in controlling the growth of photosynthetic plants (algae and macrophytes) in lakes. Shading by buildings and vegetation on the banks of the lake and by macrophytes with floating leaves can reduce the growth of phytoplankton in the water column (see section 5.2). Light penetration into the lake water can be measured with a light meter (photometer). Transparency is also a measure of how far light is penetrating into the water column; it can be estimated approximately with a Secchi disc (see **Fig. 6.16**). Lakes with high phytoplankton densities have low Secchi depths because the phytoplankton are absorbing the light and the light does not penetrate far into the water column.

# CHAPTER 5

# CHEMICAL AND BIOLOGICAL CHARACTERISTICS OF LAKES AND RESERVOIRS

As for rivers, the chemical characteristics of a lake are affected by its watershed, the atmosphere, land uses and the lake bottom. The processes that drive residence time, mixing in the water column, and nutrient cycling, all affect the chemical nature of a lake.  Many of the human activities that influence water quality in rivers also affect lakes, either directly or indirectly when rivers flow into lakes.

## 5.1 Natural chemical and physico-chemical characteristics

As with rivers, natural sources of elements and chemical compounds originate from the watershed. A natural source of salts in lakes is igneous and sedimentary rock. The salt composition of the water that drains through the rocks reflects the relative contribution of the soluble ions that make up the rocks. Generally, $Mg^{2+}$ > $Ca^{2+}$ > $Na^{+}$ > $K^{+}$, but this can vary depending on the rock type and climate. The ability of water to dissolve these ions from rocks increases with temperature, acidity, water flow and levels of dissolved oxygen.

Dissolved organic carbon (DOC) is organic material derived from the breakdown of plant and animal material, such as leaves and woody debris. The amounts of these humic substances in a lake affect its apparent and true colour, which in turn affects the level of light penetration which is essential for photosynthesis. High levels of DOC give lake water a yellow/brown colour. Dissolved organic matter (DOM), especially humic substances, play a major role in the complexation, absorption and immobilization of many organic contaminants and heavy metals. The absorption process can increase the bioavailability of these contaminants leading to possible bioaccumulation in organisms (Fig. 1.2) (see guidebook on *"Freshwater Quality Monitoring with Biota")*.

The concentration of dissolved oxygen in lakes influences the type of organisms that can live there and is a good indicator of the overall health of a lake. Oxygen diffuses from the atmosphere into the lake at the surface and is also released into the water by aquatic plants and algae. It may also be transported into the lake with lake inflows. Oxygen concentrations can be reduced by the respiration of plants, animals and bacteria and by chemical reactions in water and sediments. In stratified lakes, the vertical transport of water that has been oxygenated at the surface can be suppressed at the thermocline. This can lead to an oxygen gradient through the water column, where the epilimnion may be close to saturation or supersaturation, and the hypolimnion may have very little dissolved oxygen or even become anoxic. The four main types of vertical profile of dissolved oxygen found in lakes are described in **Box 5.1**. In polymictic lakes where there is constant mixing, dissolved oxygen is generally distributed homogeneously throughout the vertical profile, whereas in meromictic lakes where the water layers never mix, there is permanent anoxia in the hypolimnion. Occasionally, the maximum oxygen concentration is found in the hypolimnion. This is usually caused by transport mechanisms and horizontal circulation caused by the inflow of denser and cooler waters into the hypolimnion, for example from an inflowing river.

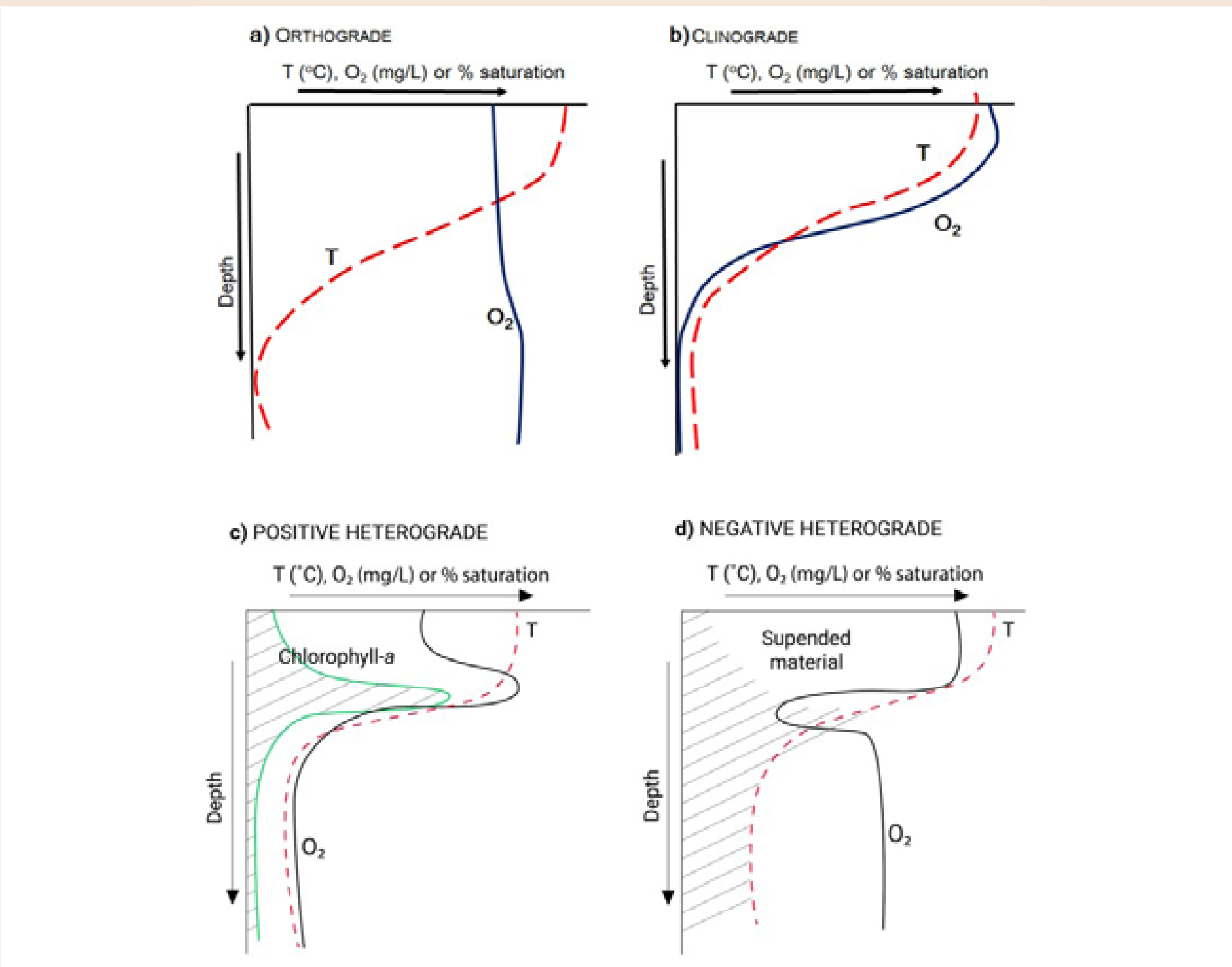
## BOX 5.1 VERTICAL PROFILES OF OXYGEN IN LAKES

*a) Orthograde* Complete circulation and uniform vertical distribution of dissolved oxygen in an unproductive (oligotrophic) lake results in an orthograde profile. The oxygen content of the hypolimnion can actually be slightly higher than that of the epilimnion because there is limited oxygen consumption in the saturated, colder water.

*b) Clinograde* This profile is typical of a stratified, eutrophic lake in summer. The loading of organic matter to the hypolimnion increases the consumption of dissolved oxygen. During the summer, the oxygen levels can be close to saturation or supersaturation in the epilimnion, with an anoxic hypolimnion.

*c) Positive heterograde* In some stratified lakes, there can be an increase in dissolved oxygen above the thermocline because of the accumulation of phytoplankton in the upper metalimnion, particularly cyanobacteria. This creates a positive heterograde oxygen profile.

*d) Negative heterograde* High consumption of oxygen in the lower part of the metalimnion by decomposing organic material, or by aquatic organisms, can produce a negative heterograde profile. The occurrence of low oxygen in the metalimnion is common in monomictic and meromictic lakes.




*Adapted from Tundisi and Tundisi (2012)*

When anoxic conditions develop, a number of processes can occur, such as the denitrification and reduction of nitrite to ammonia (see **Fig. 4.7**), and the reintroduction of large amounts of iron and manganese back into the water column from the sediments. Phosphorus is readily adsorbed onto the insoluble Fe II hydroxides and oxides, and other fine particles in the water column that may settle to the lake bed. The reduction of $Fe^{3+}$ to soluble $Fe^{2+}$ results in the release of phosphorus which may be mixed throughout the water column during overturn and is then available as a nutrient for algal growth. The release of phosphorus from sediments can make a major contribution to the total phosphorus load in lakes. Hydrogen sulphide can also develop during anoxic conditions, which makes water uninhabitable for fish, and methane gas may be produced by methane-producing microorganisms (Borrel *et al.* 2011).

Prolonged hypolimnetic deoxygenation is more common in tropical and sub-tropical lakes. The ambient temperature of these lakes is relatively warm with a smaller range in temperature changes. This facilitates higher rates of decomposition, which uses up the available oxygen in the hypolimnion. Immediately after and for a few years following inundation of a new reservoir behind a dam, deoxygenation can be a major problem especially in tropical reservoirs. The decaying, submerged carbonaceous material can have an oxygen demand higher than the oxygen supply available in the reservoir, particularly when the flooded valley includes submerged forests (**Fig. 5.1**).

**Figure 5.1** Decaying tree stumps exposed during low water level in a reservoir created by damming and flooding a wooded river valley © Deborah Chapman

Biological activity can lead to fluctuations in dissolved oxygen over short time periods, such as between daylight and darkness as a result of photosynthesis and respiration. Photosynthesis is restricted to the depths to which adequate light can penetrate, and occurs only during daylight hours. The vertical distribution of phytoplankton in the water column can also influence the vertical concentrations of dissolved oxygen. High levels of chlorophyll, resulting from high phytoplankton densities, can sometimes be associated with supersaturation of dissolved oxygen (more than 100% oxygen saturation) in the epilimnion when solar radiation is high.

The pH of lake water is related to its chemical properties, the geochemistry of the water basin, and the effects of biological processes such as photosynthesis, respiration and decomposition. The pH of most lakes is between 6.0 and 9.0, although lakes with high concentrations of acids have a pH between 1.0 and 2.0. In extremely nutrient-rich lakes with high phytoplankton densities and extreme $CO_2$ depletion, or in lakes with high levels of carbonates (i.e., soda lakes), the pH can be greater than 10. During photosynthesis, $CO_2$ and $HCO_3^-$ are removed by primary producers and this increases the pH (the water becomes more basic as carbonic acid is removed). The diffusion of atmospheric $CO_2$ at the air-water interface is not adequate to halt this pH increase. Continuous reduction in the $CO_2$ level can eventually limit photosynthesis.

Nitrogen and phosphorus are the most common nutrients in a lake, but some phytoplankton such as diatoms also require silica. The nutrients are used by plants and algae until one of the nutrients is exhausted and cells can no longer grow and multiply. Whichever nutrient becomes exhausted is considered to be the limiting nutrient. Phosphorus is used by algae as soluble-P (orthophosphate), and this is usually the limiting nutrient in freshwater bodies. Natural sources of nutrients into lakes include direct run-off from soils, turbid in-flowing fluvial waters from watersheds with high erosion rates, excretion from animals in and around a lake, and precipitation. Where inputs of phosphorus to a lake are limited, phosphorus may become almost completely depleted in the water column, leading to the collapse of phytoplankton populations, or the selective survival of those that can exploit nutrients at depth. Decomposition of plankton and the associated release of nutrients back to the water is also an important source of nutrients in a lake.

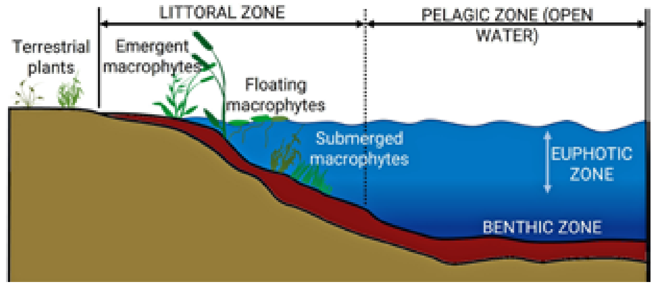
## 5.2 Biological characteristics

The flora and fauna in lakes are an integral part of the lake ecosystem, and the presence, behaviour and growth rates of different species can affect and be influenced by water quality. Some lake species are an essential resource for human communities, such as fish for food, whereas others can cause potential problems for use of the water for drinking or recreation, e.g., the presence of toxic cyanobacteria. Hence, understanding the biology of lakes is important for both interpretation of water quality data and the management of water quality in lakes.

The lake environment can be divided into three zones: the open water or pelagic zone (also known as limnetic zone), the edges or the littoral zone, and the bottom of the lake which is known as the benthic zone (**Fig. 5.2**). This chapter concentrates on the pelagic and littoral zones because the organisms of these zones can have the greatest influence on water quality, and understanding the characteristics of these zones can assist with interpreting water quality data. For further information on using biota for monitoring water quality, see the accompanying guidebook on *"Freshwater Quality Monitoring with Biota"*.

The productivity of a lake (sometimes considered equivalent to its fertility) is the ability of the lake to produce new biomass. The primary producers in lakes are the photosynthetic plants and algae that depend on light and essential nutrients to generate new biomass. They form the base of the food chain on which other groups of organisms depend. There are also decomposer organisms, such as bacteria and fungi, that contribute to the food web. In lakes of low productivity, due to low levels of nutrients (N and P), periphyton (algae living attached to the sediment) are often the dominant primary producers,

**Figure 5.2** The three main zones of a lake or reservoir




but as lake productivity increases phytoplankton and submerged macrophytes become more important. In highly productive lakes, phytoplankton and emergent macrophytes in the shallow littoral zones are the dominant primary producers.

The littoral zone can occupy a large portion of the total lake area, especially in small lakes and is typically the most productive area of a lake. Human uses of a lake, other than for abstraction of water, are often focussed on the littoral zone. These uses include swimming, boating and fishing, for which water quality may be important to protect human health and preserve the lake ecosystem. The organisms present must be able to tolerate the physical conditions of the littoral zone, including the effects of high radiation (ultraviolet radiation exposure from sunlight), water-level fluctuations (e.g., desiccation), and wave action (e.g., shear stress).

Littoral zones can benefit water quality in a lake by trapping sediments with their associated nutrients and contaminants, and by providing important habitats that support a stable ecosystem. Hence the loss, or damage, of littoral zones can contribute to a deterioration in water quality. They are vulnerable to alteration by human activities, such as water level fluctuations for hydropower and flood control, and macrophyte control to provide access to open water for boats. The physical and biological responses to alterations in the littoral zone can cause a loss of fine sediment, which reduces nutrient availability over time; desiccation and nutrient pulses when the littoral zone is re-flooded; and a reduction in the taxonomic richness of macrophytes and invertebrates (Carmignani and Roy 2017).

The open water of lakes is mostly dominated by phytoplankton but, in sheltered areas where wind action is minimal, free floating macrophytes, i.e., without root attachment to the substrate, can also be a major contributor to primary production. However, dense growths of free floating macrophytes, such as Water Hyacinth (*Eichhornia crassipes*), can create problems for navigation by boats, access by fisherman and block light to the deeper layers of the pelagic zone (Dersseh *et al.* 2019).

### 5.2.1 Phytoplankton

Phytoplankton are mostly single-celled, microscopic organisms (**Fig. 5.3**) that need light for photosynthesis. Their growth in the water column is influenced by a combination of physical, chemical and biological factors:

- *Physical*: Temperature, residence time, mixing and stratification, and light
- *Chemical*: Nutrients
- *Biological*: Predation and competition

In temperate zones, phytoplankton populations typically fluctuate in response to periods of warmer water and increased sunlight in the summer and colder water with less light in the winter months. Phytoplankton reproduce mostly by cell division, with generation times of hours or days. In order to develop populations within a lake, their growth rate must be faster than the rate at which cells are flushed out. Therefore, populations are more likely to increase to high densities (sometimes referred to as bloom conditions) in lakes with long residence times (weeks/years) and a constant supply of nutrients. Cyanobacteria (blue-green algae) are mostly slow growing and are often associated with lakes and reservoirs with high residence times and stratification. In addition, they appear to be less susceptible to grazing by zooplankton. Cyanobacteria are able to store phosphorus and some species can fix atmospheric nitrogen, enabling them to overcome any potential nutrient limitation that may affect other algal species in the same water body.  Therefore, cyanobacteria are well equipped to out-compete many other phytoplankton groups. This causes problems for many lakes and reservoirs because some cyanobacteria release toxins when the cells decompose. The toxins can present a serious health risk to people drinking the water or using it for recreational purposes (Chorus and Welker 2021).

**Figure 5.3** Phytoplankton seen with a microscope. Credit: Thctamm, via Wikimedia Commons Licenced by CC BY-SA 3.0

The downward flux of light in a lake decreases exponentially as light is attenuated in the water column. The layer in the water column in which there is sufficient light to support cell growth is known as the euphotic zone. The limit of the euphotic zone (known as the euphotic depth) is usually where less than 1% of the surface light remains. A rough approximation of the depth of the euphotic layer can be determined with the use of a Secchi disc (see **Fig. 6.16**). The Secchi depth ($Z_s$) is a measure of the transparency of the water and, therefore, also of the amount of suspended material, including phytoplankton.

During stratification, water movements are restricted to the epilimnion. Live algal cells may be maintained in the surface layers by water movements, or they may actively maintain themselves where more light is available by vertical migrations in the water column. However, during periods when a lake is mixed, turbulent movements within the water column may carry algae to depths below the euphotic zone where there is insufficient light for photosynthesis. As a result the algae may die and the population declines. The decomposing cells eventually sink, contributing to deoxygenation in the deeper water.

The nutrient status of lakes has become the basis of a commonly-used classification. The gradual change from nutrient poor water to nutrient rich water is a natural process that would be very slow without human interference. This gradual enrichment is known as eutrophication. Lakes are frequently classified as oligotrophic, mesotrophic, eutrophic or hypereutrophic. As lakes become progressively more eutrophic, they become less suitable for some uses. If intended for potable water supplies they may require substantial treatment to remove the phytoplankton and suspended material. Over time, eutrophic lakes may support less commercially-viable fisheries and present potential health risks for recreational use due to the presence of cyanobacteria. Eutrophication is a global water quality issue highlighting how human activities have caused the deterioration of many lakes to the extent that restoration is now very difficult (e.g. Meli *et al.* 2014; Grizzetti *et al.* 2019).

Particular water quality characteristics can assist in identifying the trophic status of lakes, namely phosphorus, chlorophyll (the green pigment in plants and algae that serves as a surrogate measure of phytoplankton biomass) and water transparency as shown in **Table 5.1**. Many countries have adapted this classification to their own designations of lake trophic status and include these parameters in their routine monitoring of water quality in lakes (see section 7.4).

### 5.2.2 Periphyton and macrophytes

Periphyton are microscopic plants attached to other plants and to the substrate (**Fig. 3.5**), or embedded in a matrix of organic detritus. They are autotrophic and can include important primary producers in a lake, such as cyanobacteria. Macrophytes may be emergent, floating and submerged (**Fig. 5.2**) depending on the availability of light, the substrate, and water movement. They grow most successfully where water movement is restricted and the substrate comprises mixed sand and mud, where their roots can take hold. Therefore, they are more common in sheltered bays and on lee shores, where sediment accumulates (**Fig. 5.4**). However, if there is an excessive input of sediment, macrophyte growth declines due to burial or light limitation (possibly from turbidity caused by high rates of sediment loading). The presence of macrophytes with floating leaves can reduce light penetration to the water column below, and this can then reduce the ability of submerged macrophytes and phytoplankton populations to grow. Macrophytes are both a source and sink for nutrients in the littoral zone, hence they are very important for nutrient cycling. Bottom dwelling invertebrates are at their most abundant and diverse in the littoral zone of lakes where they provide an important food source for predatory fish.

**Table 5.1 Lake trophic status and the associated typical values for total phosphorus, chlorophyll, Secchi depth and oxygen saturation**

| Trophic category | Mean Total P (mg m$^{-3}$) | Mean annual chlorophyll (mg m$^{-3}$) | Chlorophyll maximum (mg m$^{-3}$) | Mean annual Secchi disc transparency (m) | Secchi disc transparency minimum (m) | Oxygen (% saturation) |
|---|---|---|---|---|---|---|
| Ultra-oligotrophic | 4.0 | 1.0 | 2.5 | 12.0 | 6.0 | <90 |
| Oligotrophic | 10.0 | 2.5 | 8.0 | 6.0 | 3.0 | <80 |
| Mesotrophic | 10–35 | 2.5–8 | 8–25 | 6–3 | 3–1.5 | 40–89 |
| Eutrophic | 35–100 | 8–25 | 25–75 | 3–1.5 | 1.5–0.7 | 40–0 |
| Hypereutrophic | 100.0 | 25.0 | 75.0 | 1.5 | 0.7 | 10–0 |

*Source: Based on Organisation for Economic Cooperation and Development [OECD] (1982)*

**Figure 5.4** Macrophytes with emergent and floating leaves rooted in the fine sediment at the sheltered shore of Lough Allua, Ireland © Deborah Chapman

## 5.2.3 Zooplankton and fish

Zooplankton populations are governed by the interaction of several factors, principally food supply, predation, and habitat availability. Protozoa, rotifers and crustaceans are the major groups of zooplankton in freshwaters (Fernando 2002; Kobayashi *et al.* 2009). In nutrient rich lakes with high phytoplankton populations, zooplankton may gather at specific depths where the phytoplankton on which they feed are most abundant. Excretion by zooplankton returns ammonia and phosphates to the water, and these can be important sources of nutrients for phytoplankton when their growth is otherwise nutrient-limited. Fish are sensitive to oxygen concentrations, although certain groups of fish are tolerant of low oxygen concentrations, such as cyprinids (e.g., carp). Eutrophic waters are more likely to suffer from periods of low oxygen saturation, especially at night when photosynthesis is not possible and phytoplankton densities are high. The drop in oxygen concentrations can cause stress, and even mortality, amongst fish populations.

The success of the fish community in any lake or reservoir depends on an adequate food supply during their growth from newly hatched fry to adults. Many fish species vary their diet as they grow, with zooplankton often being an important food source for juvenile fish. Fish generally feed on larger more visible zooplankton, leaving the small cladocera, rotifers and copepods. These smaller zooplankton species are less efficient algal grazers, allowing phytoplankton populations to increase. Hence, the species and population densities of fish can indirectly affect water quality by influencing phytoplankton populations, and hence chlorophyll $a$ and nutrient levels.

# CHAPTER 6

# BASIC PRINCIPLES FOR MONITORING IN RIVERS, LAKES AND RESERVOIRS

All monitoring and assessment activities should be designed and planned to address specified objectives, or key questions (see the accompanying guidebook on *"Introduction to Freshwater Quality Monitoring and Assessment")*. The elements of the process covered in this chapter are network design and field operations (**Fig. 1.1**). Laboratory operations are covered in the guidebook on *"Quality Assurance for Freshwater Quality Monitoring Programmes"*.

The design of any freshwater monitoring programme must consider and select the appropriate monitoring media (typically water, sediment, suspended particles, fish, invertebrates, macrophytes or phytoplankton), the sampling locations, sampling frequency, and the individual physical, chemical and biological parameters for measurement. These must be chosen so that they provide the necessary information to address the objectives of the monitoring programme. Understanding the basic principles of the hydrology and ecology of rivers, lakes or reservoirs, assists in making the appropriate choices and subsequently in interpreting the monitoring data obtained.

Water and biota are the most common media for monitoring programmes in rivers, lakes and reservoirs, but sediments can also be very useful, as discussed in the accompanying guidebook on *"Freshwater Quality Monitoring using Particulate Matter"*. Biological approaches to monitoring are covered in detail in the guidebook on *"Freshwater Quality Monitoring with Biota"* and are only discussed here with respect to sample collection. The most comprehensive monitoring programmes use water, biota and particulate matter, although the different media may be sampled at different frequencies, with water typically sampled most frequently. The chemical parameters analysed depend on the objectives of the monitoring programme and financial constraints. Chemical parameters are commonly measured by taking water samples back to the laboratory. However, some chemical parameters, and most of the common physico-chemical parameters, can be measured ***in situ*** using sensors.

## 6.1 Sampling protocols and quality assurance

Before commencing any water quality field sampling, it is imperative to design a sampling protocol, taking into account the health and safety of field personnel, specific equipment required, and appropriate quality assurance measures (see guidebook on *"Quality Assurance for Freshwater Quality Monitoring Programmes"* for further details). Some factors to be considered before commencing field water quality sampling are:

- Is all the necessary personal protective equipment (PPE) available, e.g., waders, life-jackets, disposable gloves?
- Are sample sites safe for access by both male and female technicians?
- Are all the appropriate quality assurance and quality control protocols being adhered to? This may include ensuring field blanks and replicate samples are collected.

Once at the sample site, the location should be checked with a map and/or GPS (global positioning system) to ensure the location is correct.

An adequate number of appropriate sample bottles is essential. Ideally, new bottles should be used but when reusing bottles they should be rigorously cleaned between uses (i.e., washed with detergent, rinsed twice with tap water, and twice with deionised water) and stored in a clean, dust-free environment. Any necessary preservatives should be added in advance of the sample collection and the bottle should be labelled specifying the preservative added and an expiry date. However, preservatives should not be added in advance to the bottles if the samples are to be collected directly into the bottle from the water body (see section 6.2.1). It is important that the correct type of bottle (e.g., plastic or glass) is used so that there is no risk of samples being compromised for the subsequent analytical procedures. Some analyses require specific preparation of the bottles, such as acid washing for heavy metals samples. Details of recommended sample bottle types, nominal sample volumes, storage times and preservatives for a range of water quality parameters are given in International Organization for Standardization [ISO] (2018) and Rice, Baird and Eaton (2017).

It is important to avoid sample contamination when sampling for water quality analysis. Possible sources and ways to avoid contamination during sampling, together with the best way to transport samples are suggested in **Box 6.2**. Lids must be tightly secured onto containers and they should be maintained in an upright position. All samples should be transported as quickly as practical to the analytical laboratory. The transportation vehicle should be clean and have adequate storage facilities for empty and filled sample containers. If the vehicle is not equipped to keep samples cool, samples must be transported in coolboxes (**Fig. 6.1**). The vehicle should not be used for any other purpose that might cause contamination of samples, and its interior and coolboxes or refrigerators should be regularly cleaned

## BOX 6.2 SOURCES OF SAMPLE CONTAMINATION AND WAYS TO AVOID THEM

*Sources of sample contamination*

- Residue from earlier samples remaining on the surfaces of sampling containers, and other equipment, such as funnels, filters, etc.
- Contamination from the sampling site during sampling (e.g., due to sediment disturbance).
- Residual water adhering to ropes, chains, handles.
- Contamination from hands, fingers, gloves and general handling.
- Contamination of bottle caps or tops by dust, soil, sediment or water.
- Degraded reagents.

*Ways to avoid contamination*

- Avoid disturbing the sides or bottom of the water body when sampling.
- If it is necessary to wade into the water, take the sample as far away from the standing position as possible.
- Thoroughly rinse, inside and out, all equipment that comes into contact with the samples between each use.
- Store bottle caps and tops securely, away from sources of dust, soil and sediment.
- Wipe and dry ropes, chains and handles between sampling and prior to storage.
- Avoid touching the sample with fingers, hands or gloves, especially during microbiology sampling where no contact should be made with the interior or rim of the sample bottle or its cap.

**Figure 6.1** Example of a coolbox for transporting samples back to the laboratory © Patrick Cross

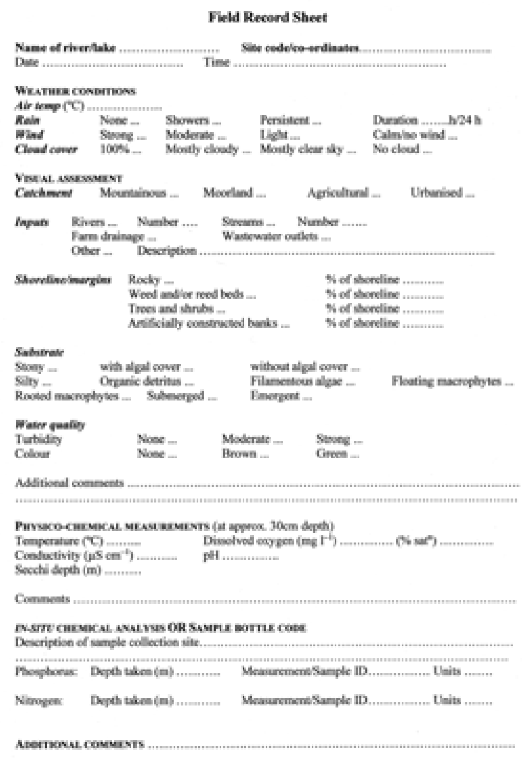
and maintained. If samples cannot be delivered to the laboratory in time for the analyses to be conducted within the recommended timeframe according to internationally accepted standards, samples should be appropriately preserved, e.g., frozen, and the preservation information should be recorded.

Field record sheets (paper or electronic) should be completed for each sampling location. The necessary details can vary depending on the specific sampling design but some key details are given in **Box 6.3** and an example of a field record sheet is given in **Fig. 6.2**.

## 6.2 Water sampling

Sampling is the first operational stage in a water quality monitoring programme, and the approach used must ensure that the monitoring results are representative of the water body being sampled. Sampling methods range from the very simple to much more complex, and this complexity is often related to the degree of homogeneity of the water quality in the waterbody. There are many different types of sampling instruments, ranging from a simple bottle or bucket to more complex pumps and automatic sampling devices. The sampling method used must not cause any significant changes in composition in the water sample before the analyses are carried out.

**Figure 6.2** Example of a field record sheet © Deborah Chapman



**Field Record Sheet**

**Name of river/lake** ........................ **Site code/co-ordinates**................................
Date .................................... Time ......................................................

**WEATHER CONDITIONS**
***Air temp*** (°C) ...................
***Rain*** None ... Showers ... Persistent ... Duration .......h/24 h
***Wind*** Strong ... Moderate ... Light ... Calm/no wind ...
***Cloud cover*** 100% ... Mostly cloudy ... Mostly clear sky ... No cloud ...

**VISUAL ASSESSMENT**
***Catchment*** Mountainous ... Moorland ... Agricultural ... Urbanised ...

***Inputs*** Rivers ... Number .... Streams ... Number ......
Farm drainage ... Wastewater outlets ...
Other ... Description ..........................................................................

***Shoreline/margins*** Rocky ... % of shoreline ..........
Weed and/or reed beds ... % of shoreline ..........
Trees and shrubs ... % of shoreline ..........
Artificially constructed banks ... % of shoreline ..........

***Substrate***
Stony ... with algal cover ... without algal cover ...
Silty ... Organic detritus ... Filamentous algae ... Floating macrophytes ...
Rooted macrophytes ... Submerged ... Emergent ...

***Water quality***
Turbidity None ... Moderate ... Strong ...
Colour None ... Brown ... Green ...

Additional comments ..........................................................................
..........................................................................................

**PHYSICO-CHEMICAL MEASUREMENTS** (at approx. 30cm depth)
Temperature (°C) ......... Dissolved oxygen (mg $l^{-1}$) ............. (% sat$^{n}$) .............
Conductivity (µS $cm^{-1}$) .......... pH ..............
Secchi depth (m) ..........

Comments ..........................................................................................

***IN-SITU* CHEMICAL ANALYSIS OR SAMPLE BOTTLE CODE**
Description of sample collection site...........................................................
..........................................................................................
Phosphorus: Depth taken (m) ........... Measurement/Sample ID................ Units .......

Nitrogen: Depth taken (m) ........... Measurement/Sample ID................ Units .......

**ADDITIONAL COMMENTS** ..............................................................................
..........................................................................................

### 6.2.1 Grab samples

Grab, or dip, samples are single samples that give a snapshot of the quality of the water at the exact time and place the sample was taken. This type of sampling is best applied when the water quality is reasonably uniform spatially and temporally. Grab samples are also used when the objective of the sampling programme is to test compliance of the water with prescribed quality criteria, such as limits specified for a licenced discharge facility. Discrete samples are grab samples taken at precise locations, depths and times.

A composite sample can be compiled from a mixture of grab samples taken at different times or locations and mixed to provide a single sample. Composite samples can also be collected automatically by a specially-designed sampling device that mixes them, or they can be collected automatically and mixed manually. The advantage of composite sampling

## BOX 6.3 KEY DETAILS FOR INCLUSION IN A FIELD RECORD SHEET

Sampling location (name and/or code)

GPS location (especially if it is a new sampling location)

Sampling date and time

Name and signature of sample collector

Values for any *in situ* field measurements, e.g., temp, dissolved oxygen (DO), pH

Unique sample number for each sample taken

Purpose of samples taken (e.g., microbiology, metals, Volatile Organic Carbons (VOCs))

Whether each sample is a grab or composite sample (for composite samples indicate the time over which the sample was taken)

Details of any preservative used or filtration carried out

Any notable observations from a visual inspection of the site, e.g., weather, water colouration, obvious sources of contamination

Any deviations from the Standard Operating Procedures (SOPs) for the sampling

is that it gives a measure of the average quality of the water over the specified time (samples taken at different times and mixed together), or space (samples taken at different locations within the water body and mixed together). Composite sampling over time can be useful when trying to capture short-term water quality changes, such as those arising from storm events. Integrated samples represent defined spatial areas and may be collected with suitable equipment that integrates the sample as it is collected, or by combining samples taken from several different spatial (horizontal or vertical) stations. Integrated samples are useful in rivers or streams in which water quality varies across width and depth, and in stratified lakes to characterise the different thermal layers.

A bucket or similar container can be used to collect a grab sample. The water column must be well mixed to ensure the grab sample is representative of the location. A bridge is usually the ideal location to use a bucket to collect water from a river, or a pontoon or similar walkway on a lake. Buckets are particularly useful when the water depth is too great for wading and it is not possible to use a sampling pole or deploy a boat, or when access is not possible due to excessive vegetation or steep embankments. The bucket is lowered by rope over the side of the bridge, pontoon or embankment by hand or by using a small winch. When the bucket has filled, the contents can be poured into an appropriate set of sample bottles for future analysis. Health and safety protocols, such as wearing a lifejacket, should always be exercised when working from such locations, to avoid potential traffic hazards or falling from a height. A plastic bucket can also be used to collect samples for measurements with sensors, such as pH, temperature and conductivity, when the water is too deep to make the measurements directly in the waterbody. The sensors can be held in the bucket until a stable reading is obtained.

Dip sampling (**Fig. 6.3**) is the direct collection of water into the sample container or bottle. This can only be done if the water source is accessible by wading or

**Figure 6.3** Taking a dip sample directly from the water body using the sample bottle © Patrick Cross

**Figure 6.4** A scoop on an extendable pole used for taking surface samples © Deborah Chapman

other means. The sampler should collect the sample as far away from themselves as possible without disturbing the sediments. In a river, the sample must be taken facing upstream. If sediment or benthic biota samples are also going to be collected, the water sample should always be taken first. The bottle should be pre-rinsed three times with water at the sample location and emptied away from where the sample will be taken. This cleans the collection bottle of any trace elements. The bottle is then lowered beneath the surface with the open mouth facing downwards, and slowly faced upright so that the bottle fills with water from below the surface. The bottle should then be capped immediately. Any preservative, if required, must be added after the sample bottle has been filled.

Scoops are useful for reaching out into a waterbody to collect a surface water sample when the water is too deep to wade (**Fig. 6.4**). Most scoops have a limited reach of about 2–3 metres, depending on the length of the pole, and are usually made of stainless steel or plastic. If this does not reach the desired sampling location, a boat or other means of access may be required. As with dip sampling, the scoop is rinsed three times with water to be sampled before taking the sample, which is then transferred to a pre-rinsed labelled sample bottle. The scoop can also be used to collect water to rinse the sample bottle.

Weighted bottles, either plastic or stainless steel, can also be used when the water is too deep for wading. An uncapped bottle is inserted into a weighted holder that is attached to a rope for lowering into the water. This can be done from a bridge or pontoon, as for sampling with a bucket.

There are several types of commercial samplers used to collect instantaneous discrete grab samples from a desired depth. They are based on the principle of a cylinder with stoppers or flaps. The ends of the sampler are held open while the cylinder is lowered in a vertical or horizontal position. This allows the free passage of water through the cylinder until it reaches the desired depth, at which a weighted messenger is sent down the rope or cable attached to the sampler. The messenger releases the stoppers or flaps allowing them to close and enclose the water sample. The flaps remain closed while the cylinder is raised. This technique of sample collection may not work well where there is a strong water flow. The sampler should be lowered to the desired depth three times prior to sampling in order to rinse it. When taking multiple depth samples, care should be taken to ensure the sediment is not disturbed. The water sample is removed from the sampler through a valve which is used to fill respective sample containers (**Fig. 6.5**). When the samples are to be analysed for metals or organic compounds, the sampler should be made from an inert material, such as teflon or acrylic, so that is does not contaminate the samples and care must be taken to avoid aeration when filling sample bottles.

**Figure 6.5** Emptying a depth sample from a Ruttner sampler into sample bottles © Deborah Chapman

**Figure 6.6** Teflon® bailer used for water sample collection (Kaur *et al*. 2018). Licensed under CC BY 4.0

Bailers are a type of grab sampler (**Fig. 6.6**) most suitable for still waters. They are usually made of fluorocarbon polymer (Teflon®) and are used for surface water sampling where the monitoring objectives do not require a sample from a discrete interval in the water column. A closed-top bailer with a bottom check-valve is adequate for many sampling programmes. The bailer fills as it is lowered through the water column. Water is continually displaced through the bailer until it is full. The valve then closes and the bailer can be retrieved. The sample is emptied from a tube at the bottom into the sample containers. One of the advantages of bailers is that they are usually easy to clean (e.g., Teflon®) but some are disposable, which may be important if the sampling site has very high concentrations of contaminants.

In deep lakes, an integrated sample can be collected by using a series of bottles that are all pre-rinsed and placed along a string at desired depth intervals. The bottles fill simultaneously when triggered and the resultant samples are mixed.

Simple depth integrated samples of the surface few metres of a lake can be collected using thick tubing or a length of thick hosepipe. If sampling from a boat, the tubing should be rinsed on one side and sampling should be done on the other side of the boat. The tubing is slowly lowered vertically down through the water until the top is approximately 15 cm above the surface. A stopper is then placed into the top end of the tubing and the tubing lifted out of the water. Before taking the tubing fully out of the water, the bottom stopper is secured in place, in order to avoid any loss of sample. If the tubing is flexible, the bottom needs to be weighted so that the tube stays vertical as it is lowered into the water. After placing the stopper in the top of the tube, the bottom end is raised by pulling up the cord attached to the bottom. The sample should be well mixed when it is emptied into the sample containers for different analyses.

More advanced approaches to integrated sampling in rivers use discharge-weighted methods, such as equal-width (EWI) or equal-discharge (EDI) increment procedures (USGS 2006).

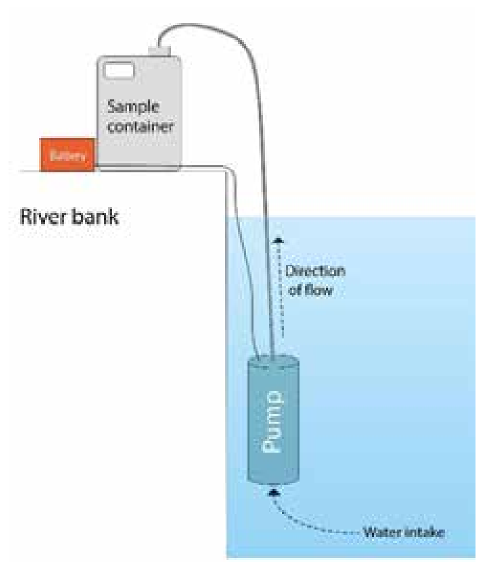
### 6.2.2 Sampling with pumps

Peristaltic pumps (**Fig. 6.7**) can be used to collect water samples from any depth. The pump is positioned at or near the surface water level, e.g., on the river bank, and the tubing or pipe intake is positioned in the water column at the desired depth for a discrete water sample. A vertical integrated sample can be collected by moving the intake tube vertically through the water column at a constant rate. If a sample for a specific time period is required, the intake tubing can be moved up and down the water column for the desired period of time.

Submersible pumps can be put into the water column and used to collect water samples directly into a sample container (**Fig. 6.8**). The intended analytes should be considered when choosing the type of submersible pump and tubing, so that there is no risk of the pump contaminating the samples. If inert material is needed to avoid contamination, stainless steel or Teflon® is preferable. The pump should be flushed and rinsed between sample locations and the tubing should also be changed. If contamination is not an issue, the pump and tubing can be rinsed with deionised water and then several volumes of the water from which the sample will be collected passed through it and discarded before collecting

**Figure 6.7** A portable peristaltic pump that can be used to take samples from depth in still waters by lowering the tubing to the desired depth © Patrick Cross

**Figure 6.8** Taking a water sample with a submersible pump that is lowered to the required depth. The sample is collected into a sample bottle at the surface




the sample in a sample bottle. A grab sample can be collected by holding the pump submerged in position until the sample bottle is filled. An integrated sample can be collected by raising and lowering the pump through the water column and collecting the water into a mixing vessel prior to dispensing into sample containers. Depending on the intended parameters for analysis, the mixing vessel may also need to be made of inert materials and decontaminated between sampling locations.

### 6.2.3 Automatic samplers

Automatic samplers reduce the frequency with which technical personnel need to go out into the field. An automatic sampler can collect grab samples based on time, flow or water-level. The samplers contain sample bottles that are filled by a water pump. Bottles can either be filled once at a specified time to represent individual grab samples or they can be partially filled several times, at set time intervals, to obtain a composite sample for the set time period, e.g., hourly samples over 24 hours. Automated sampling systems can also be triggered to begin sampling at certain water levels (e.g., during a flood) or activated remotely if a high discharge event is anticipated.

Automated systems must be placed adjacent to the sample site and calibrated prior to use to ensure the appropriate volume of sample is collected. Small portable models can run using battery power but more permanent monitoring stations may require a full power supply. Long-term monitoring programmes would ideally have permanent automatic samplers with large numbers of sample bottles, alongside continuous monitoring of discharge.

## 6.3 Monitoring with biota and sediments

The basic principles of monitoring with biota are described in the guidebook on *"Freshwater Quality Monitoring with Biota"*, and sediments are discussed in the guidebook on *"Freshwater Quality Monitoring using Particulate Matter"*. This section highlights some important considerations when using these approaches in river, lake and reservoir water quality monitoring programmes.

### 6.3.1 Biota

The most common approach to monitoring water quality with biota in rivers is based on the presence and abundance of macroinvertebrates whereas, for lakes, phytoplankton are often used. Macroinvertebrates are relatively immobile and therefore reflect the water quality of the location in which they occur. They also have life cycles of months to years and can integrate the overall influences on water quality over long time periods (i.e., years compared with the minutes represented by a single grab sample). Macroinvertebrates can be used for water quality monitoring by focussing on a few indicator species that are easily identified, such as in the citizen science method MiniSASS (Water Research Commission 2022), or to a detailed level of family or species identification as in the BMWP score (Hawkes 1998) and Irish Q-score (Toner *et al.* 2005). Phytoplankton have very short generation times (hours to days) and reflect changes in water quality, such as nutrients and temperature, over periods of days to weeks. The identification and enumeration of phytoplankton is time consuming, requiring specialist training. Hence measurement of the green photosynthetic pigment, chlorophyll *a*, is commonly used as an indication of the biomass or density of the total phytoplankton population.

#### *Collection and preservation of macroinvertebrates*

Depending on the method used for monitoring with macroinvertebrates, it may be necessary to take a quantitative or semi-quantitative sample. These are usually collected by disturbing the sediment by kicking for a fixed amount of time and allowing the dislodged organisms to be carried by the water current into the open mouth of a D-net (**Fig. 6.9)** or by sweeping the net through marginal vegetation. Samples are washed into white plastic trays to facilitate the separation of organisms from stones and organic debris (**Fig. 6.9**). Organisms can be identified and recorded on-site, or preserved in 70 per cent alcohol for later identification in the laboratory. Benthos samples, particularly in lakes, can be collected using a sediment grab sampler (e.g., **Fig. 6.10**). These penetrate to a certain depth in the substrate, often 10–15 cm, and the jaws close around the sample. The contents of the grab are then sieved through a 0.4 mm mesh and the organisms are collected and preserved. Undisturbed cores of soft sediment can be collected with corers (**Fig. 6.11**), enabling interstitial organisms to be sampled quantitatively at different depth profiles by sectioning

**Figure 6.9** A D-net used for collecting a macroinvertebrate sample that has been emptied into a white tray for sorting and identification © Deborah Chapman

**Figure 6.10** A Van Veen grab for collecting sediment samples © Patrick Cross

**Figure 6.11** Removing an intact sediment core from Lake Nganoke, New Zealand. By Susie Wood Lakes380, Licenced by CC BY-SA 4.0, via Wikimedia Commons

the core and sieving each section through a fine sieve to collect the organisms.

### *Plankton sampling*

There are two main approaches to sampling plankton: quantitative or qualitative. Quantitative estimates of plankton species abundance and total biomass (as wet or dry weight) are obtained by collecting discrete samples of known water volume using the same sampling equipment as for water quality samples (section 6.2), and counting or weighing the total individuals present per unit volume. For later identification, a fixative or preservative is usually added to the sample so that it can be stored without the plankton decomposing. Phytoplankton samples are best identified fresh as soon as possible after collection but, if necessary, they can be preserved. Advice on preservation of plankton samples is available in ISO (2018) and ASTM (2019).

To concentrate the plankton in the water sample, the sample may be filtered through a net with a mesh size chosen to retain the plankton groups required by the monitoring programme, e.g., phytoplankton or zooplankton. Delicate organisms can be allowed to settle to the bottom of the sample vessel and carefully decanted into counting chambers. In many lakes, and especially during cold seasons, plankton numbers may be very low and large volumes of water may need to be collected for each sample. Another sampling method, particularly suited to zooplankton samples, is a box-shaped device known as a Schindler-Patalas trap (Department of Environment and Science [DES] 2018 (**Fig. 6.12**). It can be lowered to a specific depth and triggered to close. This traps the plankton present at that depth in a known volume of water. The sample is filtered to retain the desired size of plankton through tubing at the bottom.

Qualitative or semi-quantitative plankton samples can be collected using plankton nets of different mesh sizes and diameters. Spatial coverage of plankton in a waterbody can be obtained by placing a plankton net at the desired sampling depth and towing it slowly from a moving boat around the desired area. As the net is dragged through the water column, phytoplankton and/or zooplankton are retained in the net. This plankton is then preserved and stored for later analysis. The volume of water sampled is estimated as the length of the tow, multiplied by the area of the mouth of the conical net. Plankton density in the waterbody is calculated from the counts of individuals, or their total weight, divided by the volume

**Figure 6.12** Collecting a plankton sample with a Schindler-Patalas trap (DES 2018) By State of Queensland, Licenced under CC BY 3.0 AU

**Figure 6.13** Sampling the water column for plankton by taking a vertical haul with a plankton net © Patrick Cross

of water filtered, and expressed as numbers per litre or mg per litre. A plankton net can also be used to determine the density of plankton in a specific location in the water column by lowering the net to a known depth and slowly hauling it to the surface (**Fig. 6.13**). The volume of water column sampled in this case is represented by the depth to which the mouth of the net was lowered multiplied by the area of the net mouth.

### *Sampling and analysis for chlorophyll a*

Water samples for chlorophyll *a* analysis can be collected by any of the methods mentioned in section 6.1. The recommended sampling frequency for chlorophyll *a* is at least monthly when phytoplankton populations are growing (which can be all year round). If the sample is to be filtered in the laboratory, it must be placed in a dark bottle or wrapped, to block light and stop photo decomposition. It should be stored in a coolbox during transport. A known volume of the sample is filtered *in situ,* or in the laboratory, taking all the same precautions in both situations. The water is filtered through a fine glass-fibre filter that retains particulate material greater than 1µm in size on the filter paper. The chlorophyll is extracted from the phytoplankton trapped on the filter with a solvent, such as acetone, and analysed with a spectrophotometer or fluorometer. A standard procedure for chlorophyll *a* analysis is available in ISO (1992) and Rice, Baird and Eaton (2017).

### *Particulate matter and sediment*

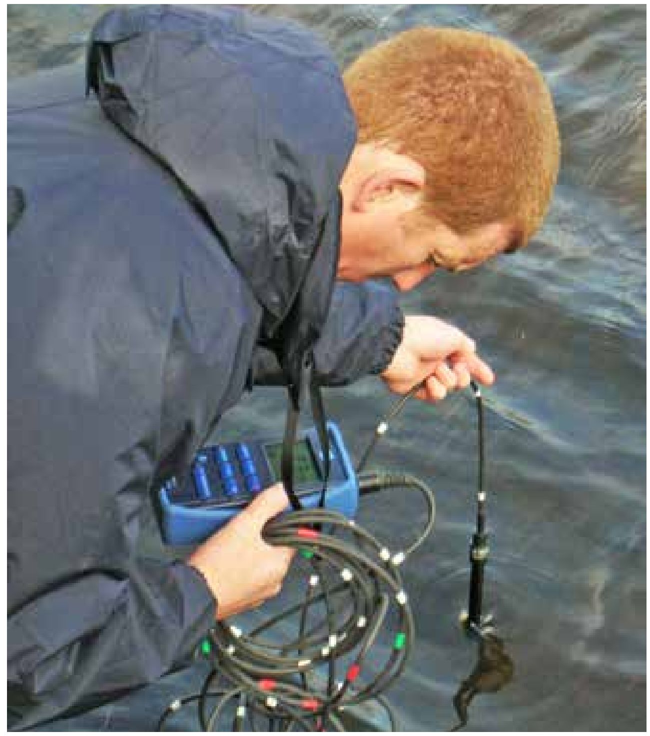
Use of particulate matter and sediment in water quality monitoring programmes is discussed in more detail in the guidebook on *"Freshwater Quality Monitoring using Particulate Matter"*. Particulate matter comprises mineral and organic particles, including microscopic biota. It may be in suspension but, when turbulence is reduced, it is deposited on the bottom of the waterbody as sediment. Particles in suspension can be collected using any of the water sampling techniques described in section 6.2 and then filtered for specific analyses according to the information required, e.g., total suspended solids (TSS). Time-integrated samples of suspended matter being deposited to the bed of a river, lake or reservoir can be collected using sediment traps (Boyce *et al.* 1990). The simplest form of sediment trap comprises a wide tube tapering to a conical end, attached to a cable or rope and held at a known depth with a floating buoy and an anchor. The sediment from above the column settles into the trap and can be subsequently removed. Sediment traps may need to be left *in situ* for weeks or months depending on the amount of suspended particulate matter collected and the rate at which it may decompose within the trap.

Bottom sediment samples can be collected from discrete depths within the sediment depending on the information required. If a sampling programme is designed for determining historical pollution in sediments, an intact core is probably required (e.g., Fig. 6.11), which can then be sectioned into specific depth intervals. The type of corer used will depend on the turbulence and depth of the water, the volume of sediment required for each sample and ease of access (see guidebook on *"Freshwater Quality Monitoring with Particulate Matter"*. Routine sampling for current status may only require the top few centimetres of sediment, which can be obtained using a grab sampler (e.g., Fig. 6.10).

## 6.4 *In situ* and continuous measurements

*In situ* field measurements should represent, as closely as possible, the ambient physical and chemical properties of the water at the time of sampling. Such measurements typically include pH, conductivity, dissolved oxygen (DO) and temperature, although the range of measurements that are possible with sensors is constantly increasing. Dissolved oxygen and temperature should be measured by placing the sensor directly into the waterbody at the required depth, because changes may occur in these parameters if samples are brought to the bank, shore or boat. When measuring directly in the water (**Fig. 6.14**), the sensor reading should be allowed to stabilise before recording the value. Some measurements, such as pH and conductivity, may be taken from a grab sample, but this should be done immediately after the sample is collected. Conductivity should be measured before placing a pH sensor in the same water sample.

**Figure 6.14** Waiting for the sensor reading to stabilise while taking a reading directly in the water body © Deborah Chapman



Continuous water quality measurements can be carried out with sensors left *in situ* that either store data for manual downloading or send the data continuously telemetrically or via the internet. Most sensors are quite delicate instruments and need to be protected. Therefore, they are usually attached to an anchored floating buoy or suspended in a flow of water from the water body that is pumped through a bypass system housed adjacent to the sampling location. Buoy-based monitoring systems often carry sensors at multiple depths in the deepest part of the water body (**Fig. 6.15**), with the data collected being sent to a computer, where immediate access is possible. Solar panels can be used on the platforms to provide power for the sensors and their telecommunication system as in **Fig. 6.15**. Sensors left *in situ* for long periods of time are usually subject to biofouling by attached growths of aquatic organisms, such as microalgae. Therefore, the sensors need to be cleaned regularly and the data obtained must be checked and validated.

**Figure 6.15** An anchored buoy with continuous monitoring sensors suspended at depth underneath. Solar panels provide power for the sensors and telemetry system. © Timothy Sullivan


### *Secchi disk*

The Secchi disk is used *in situ* to indicate water transparency in lakes. It is a flat disc that is usually painted in black and white quarter segments and attached to a weighted and graduated rope or wire (**Fig. 6.16**). Water transparency is a measure of the depth of light penetration into the water column, and is considered an important aesthetic characteristic in lakes, which may determine their suitability for recreational use, such as game fishing and swimming. Water transparency is reduced by the presence of suspended material, such as the planktonic organisms, and the Secchi depth is often used as an indicator of the amount of phytoplankton in the water column and hence the nutrient status (see section 5.2.1). To take a Secchi depth measurement, the disc is lowered into the water until it is no longer visible and then slowly raised. When the disc becomes visible again, the depth of the disc from the surface is recorded from the graduated rope.

## 6.5 Sample site selection

The choice of sampling locations depends on the objectives of the monitoring programme, the practicality of locations for regular access (e.g., distance from laboratory, ease of equipment and sample transport) and their safety for field sampling personnel. Examples of monitoring programme design, including sampling locations, in relation to specific assessment objectives are given in chapter 7. Inevitably, compromises are necessary between ideal sampling locations, the logistics of access, and financial constraints. The greater the variability in the water quality, the greater the number of samples required (spatially and temporally) to obtain a statistically-sound estimate of water quality (Strobl and Robillard *et al.* 2008).

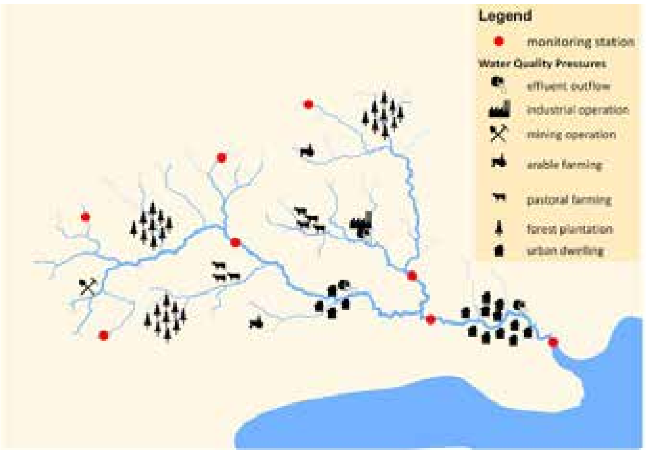
### 6.5.1 Rivers

Wherever possible, water quality sampling locations should be at, or close to, discharge measurement stations, i.e., gauging stations. Alternatively, whenever water quality samples are taken, flow should be

**Figure 6.16** A secchi disc for measuring the transparency of the water (DES 2018) By State of Queensland, Licenced under CC BY 3.0 AU

measured in a defined position for which the cross-sectional area has been previously determined at the sampling location. This enables discharge to be calculated for the time of sampling (see section 2.1).

**Figure 6.17** Examples of potential sampling locations (red dots) in a small river catchment with multiple activities within the catchment




Ideally, for a full assessment of a major river system, there should be at least one sampling site at the headwaters to assess the baseline, or least impacted, water quality. Further sites should be located at intervals downstream, in order to detect changes in water quality associated with activities within the catchment. Sampling sites should also be situated immediately upstream and downstream of major tributary confluences and stretches of the river with potential influences from land-based activities, such as urban and agricultural areas, impoundments, and industrial sites (**Fig. 6.17**). Where rivers cross national or State boundaries, sampling sites should also be located at the point at which the river enters the State, and where it leaves the State. These sampling sites give information regarding the river water quality and quantity coming into and leaving a region.

For calculation of the flux of elements, compounds and suspended materials from a river catchment to a receiving water body, e.g., the coastal zone, one water quality sampling station at the mouth of the river may be adequate. Flux stations must be located sufficiently upstream from the junction with the receiving water body to avoid changes in water level or water quality caused by the receiving water body, especially if the river flows into the tidal zone of a saline water body. The choice of location for a flux station must also ensure that there is no major pollution source nearby that could influence the water quality at the monitoring station.

The downstream reaches of rivers can be very wide, up to several kilometres in some cases. Sampling at these sites should be done at a number of vertical profiles across the river, which can then be mixed to give depth-integrated measurements. For small and medium rivers, only one sampling point may be adequate at each location provided the river is well mixed and the water quality is homogeneous and representative of the water quality of that section of the river. For most rivers this would need to be confirmed with some preliminary sampling, unless the river is very small. This is usually done using a cross-section of the river downstream from a physical structure that induces mixing, such as rapids, a waterfall or a river bend. At least three points within the cross-section, and three depths at these points, should be sampled for analysis. Typically, these sampling points would be close to the left and right banks, and in the centre of the river. The depth samples should be taken just below the surface, at mid-column and just above the river bed. If all these samples give very similar water quality results, then a single sampling station can be selected anywhere in the river cross-section because any point is effectively representative of the river water quality.

As discussed in chapter 2, laminar flow can cause an effluent from a point source discharge to be forced to flow along the side of the river on which the discharge point is located, and it may continue to flow along the side of the river for many kilometres downstream before mixing finally occurs. If sampling is being carried out with the objective of determining the immediate effect of the effluent on the receiving river, sampling stations along the appropriate side of the river need to be included. However, if the objective is to determine the general water quality in that river, including the inputs from the point discharge, the sampling station must be further downstream, where full mixing has occurred.

### 6.5.2 Lakes and reservoirs

Selecting sampling locations in lakes must take into consideration the objectives of the monitoring programme, the morphology of the lake, and whether it stratifies. It has been suggested by Makela and Meybeck (1996) that, as a general guide, the number of sampling stations should be $\log_{10}$ of the area of the

**Figure 6.18** Example of a bathymetric map showing a lake with three sub-basins and the potential locations of three sampling stations


lake in km$^2$ (to the nearest whole number), e.g., a lake of 10 km$^2$ would need one sampling station, a 100 km$^2$ lake would need two stations, etc. The morphology of lakes plays a significant role in how the water behaves and on the water quality in different areas of the water body (see chapter 4). It is unlikely that a lake will have homogeneous water quality unless it is very small, shallow and well-mixed. In that case, one sample station at the centre, or at the deepest part of the lake may be sufficient for monitoring long-term trends. For lakes with several sub-basins, individual monitoring stations in each sub-basin may be required (**Fig. 6.18**). For a more comprehensive determination of water quality, samples should be taken from:

- each section of a lake that can be regarded as a homogeneous water mass,
- in areas of the lake that are likely to be influenced by inputs from rivers or other discharges, and
- in areas where the influence of the inputs might occur as a result of dispersion and mixing.

Lake Erie in North America, for example, has three distinct basins that are monitored and assessed independently because they have different physical and chemical characteristics (Hutter *et al.* 2011).

Lakes with an irregular shoreline require a preliminary survey prior to the design of a sampling programme to determine whether there are variations in water quality in different areas of the lake that need to be taken into consideration before finally selecting sampling stations. A sampling station should not be located near structures in the lake, such as harbours, boat ramps, piers, fuel docks and houseboats (which can be point sources of contamination) unless these structures are relevant to the objectives of the monitoring programme.

Vertical variations in water quality can be ascertained by taking multiple samples throughout the water column. If the water column is fully mixed, a single sample can be taken below the surface, taking care not to include any surface debris or floating algae. Ideally, an integrated sample should be collected down through the water column, especially in the epilimnion when the lake is stratified (see section 6.2.1). An integrated sample covers any slight variations in water quality with depth that may be due to lateral water movements, light penetration and phytoplankton migrations, etc.

Samples for water quality analysis in a stratified lake should be taken in relation to the position of the thermocline, which could change from one sampling occasion to the next due to internal seiches (see section 4.4). When it is important to know water quality variability with depth, at least four depth samples should be taken: 1 metre below the surface, just above the thermocline, just below the thermocline, and 1 metre above the bottom of the lake. Samples from within the thermocline are necessary if the metalimnion is several metres deep. To detect stratification at a sampling station, a temperature reading can be taken at 1 metre below the surface and another 1 metre up from the bottom of the lake. If there is a notable difference in temperature (e.g., more than 3 ˚C) it is likely a thermocline may be present. This implies that there will be significant differences in water quality between the epilimnion and the hypolimnion, e.g., dissolved oxygen and pH. The position of the thermocline should be determined in lakes of 10 metres depth or more. This can be carried out by taking temperature readings at regular intervals down through the water column (e.g., 10 cm, 50 cm, or 1 m intervals depending on total depth). The water column may be well-mixed at overturn (de-stratification) and in this case fewer depth samples, a composite sample from two or more depths, or an integrated depth sample may be sufficient to represent the water quality of the lake.

**Table 6.1** Advantages and disadvantages of probability and judgemental sampling designs

| Probability | Judgemental |
|---|---|
| *Advantages* | |
| Provides ability to calculate uncertainty associated with estimates<br>Provides reproducible results within uncertainty limits<br>Provides ability to make statistical inferences<br>Can handle decision error criteria | Can be less expensive than probabilistic designs<br>Can be very efficient with knowledge of the site<br>Easy to implement |
| *Disadvantages* | |
| Random locations may be difficult to locate<br>An optimal design depends on an accurate conceptual model | Depends upon expert knowledge<br>Cannot reliably evaluate precision of estimates<br>Depends on personal judgement to interpret data relative to study objectives |

*Source: After United States Environmental Protection Agency [USEPA] (2002)*

### 6.5.3 Judgemental versus probability approaches to sampling site selection

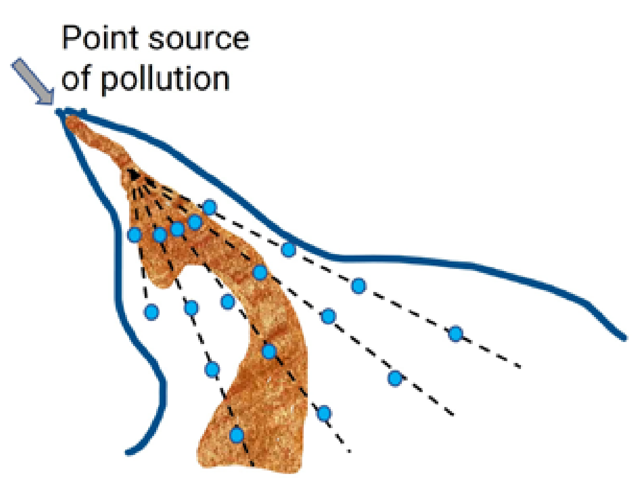
The examples of site selection described so far represent judgemental sampling approaches. Sampling locations can also be selected using probability-based or random sampling approaches (**Table 6.1**) and refined using modelling or statistical analyses (e.g., Kovács *et al.* 2015; Lee *et al.* 2014a; Lee *et al.* 2014b; Tanos *et al.* 2015; O'Hare *et al.* 2020). Probability-based or random sampling approaches are based on a given sampling design, which would usually be one of the following:

- *Completely random* Each sample has an equal probability of being chosen. A sample chosen randomly is meant to be an unbiased representation of the situation.
- *Stratified random* The study area is divided into separate and relatively homogeneous sections. Sampling points are located at random within each section.
- *Systematic* Sample points are selected according to a predetermined methodical pattern, which guarantees that each point is equally representative. For example, running transects from a baseline at regular 10 m intervals represents a systematic sampling design.
- *Random-systematic* Similar to the systematic sampling design, but transects are run from a baseline at random intervals.

The results from these sampling techniques can then be statistically analysed to find variations in quality over time.

Grid sampling is particularly useful when high density spatial coverage is required to distribute sampling effort evenly across the study area (Edsall *et al.*

**Figure 6.19** Sampling to establish the dispersion and dilution of a point source of pollution. Samples are taken at points along an array of transects



2005). Transect sampling can be used to determine horizontal variability in water quality between two points, such as across a river, or with distance from a discharge point (**Fig. 6.19**).

## 6.6 Sampling frequency

Once the sampling locations have been established and verified as providing a good representation of the water quality, sampling frequency can be decided. The required frequency depends on the objectives of the monitoring programme, the variability in the water quality and the financial resources of the monitoring programme. The frequency should be adequate to ensure that the samples are also representative through time. As a general rule, samples should be taken in each season to allow for seasonal variations caused by climatic factors or human influences. For long-term trends, samples can be taken once a year, at the same time every year.

In many monitoring programmes, sampling frequency is based on the capacity of the analytical laboratory, but this frequency may not provide adequate information for an accurate assessment of water quality. Increased sample frequency increases costs and when financial resources are limited, choices may need to be made and the frequency of sampling for selected parameters reduced.

### 6.6.1 Rivers

River water quality and the fluxes of transported materials are highly changeable in time at a given sampling location due to variations in run-off and discharge (see section 2.1.1). Ideally, sampling for physical and chemical water quality in rivers receiving multiple point source and diffuse inputs from human activities should be carried out at frequent intervals, such as weekly. Frequent sampling for multiple parameters places a huge burden on financial and human resources, so less frequent intervals, such as monthly, are often used. A combination of frequent or continuous monitoring for basic parameters or those with direct risk to human health, together with less frequent intervals for contaminants, is a good compromise. Additional sampling can be carried out during special events, such as floods or accidental spilling of contaminants in the catchment. Automatic samplers that can be triggered remotely to capture these events are particularly useful, especially if the sample location is remote from the laboratory. Sampling for biota to determine river water quality status over long time periods is usually carried out annually, or even every two or three years, depending on available resources.

### 6.6.2 Lakes

Depending on geographical location, water quality in lakes may change seasonally due to temperature, sunlight and changes in land-use practices. In lakes that stratify, especially temperate lakes, samples should be taken before spring stratification, late in the summer stratification, and after the autumn overturn. For long-term trend monitoring in lakes, one sampling occasion a year, always at the same time of year, is usually adequate.

If a lake is used for drinking water or contact recreation, frequent sampling will be needed to ensure protection of human health. For drinking water abstraction, at least weekly water sampling may be necessary with real-time continuous monitoring near the abstraction point. Lakes used for contact recreation, such as swimming and boating may require weekly microbiological analyses during the period of most intense use.

Monitoring of phytoplankton and zooplankton may be more frequent in the season during which they are most active, and at a lower frequency in winter. Sampling frequency depends on the objectives of the monitoring programme. For example, if information on the seasonal dynamics of plankton in association with nutrient inputs is required, at least monthly samples will be necessary. However, if determination of long-term trends is the main objective then twice yearly, or quarterly, sampling will be adequate.

Modern developments in lake monitoring using *in situ* sensors (see section 6.4) and remote sensing, enable data to be collected for certain parameters continuously, such as chlorophyll *a*. Discrete sampling campaigns may only be required for calibration or validation purposes. Satellite and optical monitoring are opening up new, cost-effective opportunities for monitoring lakes and reservoirs (e.g., Seegers *et al.* 2021) A recent review of the use of remote sensing for continuous monitoring of water quality is available in Yang *et al.* (2022).

# CHAPTER 7

# MONITORING FOR WATER QUALITY ASSESSMENTS

Monitoring is the process of collecting water quality data. It generally requires considerable human, technical and financial resources and, therefore, it is important that the data collected are used to the maximum extent possible for water quality assessments. Water quality assessment is the process of evaluating the monitoring data and turning it into useful information that supports management and policy. The assessment examines the monitoring data, together with other information that could influence the data obtained, or in relation to expected or prescribed water quality values or indicators. Some of the most common reasons for carrying out water quality assessments are:

- To observe status and trends in water quality at national scale to inform water policy and management.
- To determine the suitability of waterbodies for specific uses, such as recreation, fisheries and drinking water abstraction.
- To inform the design and to determine the effectiveness of conservation, protection and restoration measures.
- To identify waterbodies or areas of a waterbody that require additional management action.
- To determine the extent and effects in a waterbody of long-term, new or accidental sources of contaminants.

Monitoring and assessment should continue during and after management measures are implemented, in order to determine the effectiveness of any actions.

Water quality assessments must be developed with clear and precise objectives. The objectives inform the design of the monitoring programme, such as sampling locations, sampling frequency, physical, chemical and biological measurements, and data analysis approaches. Sometimes multiple assessments with different objectives may need to use the same data, resulting in multi-purpose monitoring programmes that need to compromise on sample locations and frequency to achieve the varying objectives. This should be taken into consideration in the final assessments. For example, the density of multi-purpose monitoring stations and the frequency with which they are sampled for status and trends objectives may not be adequate for an impact assessment following an accidental pollutant discharge, which usually requires an intensive sampling campaign.

It can be quite common for several monitoring programmes to be carried out on the same waterbody by different groups with different interests in water quality management, such as wildlife and conservation bodies, State environment agencies, local water agencies, etc. All of these may measure different parameters at different locations and frequencies. Wherever possible, such activities should be co-ordinated to prevent unnecessary duplication of effort. Different agencies may gather information that could be of potential interest to another agency undertaking a water quality assessment. Therefore, all information from all monitoring agencies should be freely available (e.g., see Bowes *et al.* 2018), inter-comparable and of known quality (see accompanying guidebook on *"Quality Assurance for Freshwater Quality Monitoring"*).

## 7.1 Baseline water quality assessment

When monitoring commences for the first time in a waterbody, it can be difficult to know whether the measured concentrations of some elements or chemical compounds represent the natural condition, or whether they are affected by an unknown wastewater discharge or land run-off within the catchment. It is often necessary, therefore, to characterize the waterbody by carrying out some monitoring that provides the baseline values as a starting point for assessment of water quality changes in the future. The number of sampling sites and the range of parameters included for a baseline water quality assessment are often greater than those used in future assessments. In addition, information relating to natural causes of variation in water quality, together with potential pollution sources, needs to be gathered as part of the baseline assessment. This information can help identify river stretches and tributaries, or areas in a lake or reservoir, that demonstrate unimpacted ("natural") and impacted water quality.

Background monitoring in rivers is usually carried out in headwaters or upstream unpolluted tributaries or river stretches where human influence is minimal. Station density and sampling frequency can be low because there would normally be little variation in water quality. If resources permit, it is useful to collect background data on water, sediments and biota. However, for any assessment that compares background information with data from lower stretches of a river catchment, it must be taken into consideration that there is a natural change in water quality, sediment composition and biota as the river passes from headwaters to middle and lowland reaches (see Chapter 3).

A basic lake survey is needed before any new monitoring programme is initiated in a lake or reservoir, including any baseline monitoring. The basic survey determines the bathymetry and the temperature-depth profile (see Chapter 4). Temperature-depth profiles need to be carried out several times during the year to assess the depth and duration of any stratification. A bathymetric survey may only need to be conducted once, unless the lake or reservoir is subject to siltation and erosion. When the bathymetric map has been produced, any sub-basins that may have distinct water quality can be identified and sediment, water and biota sampling can then be planned. The temperature-depth profile is also essential for determining any potential influences on chemical and biological quality and to inform any future monitoring activities.

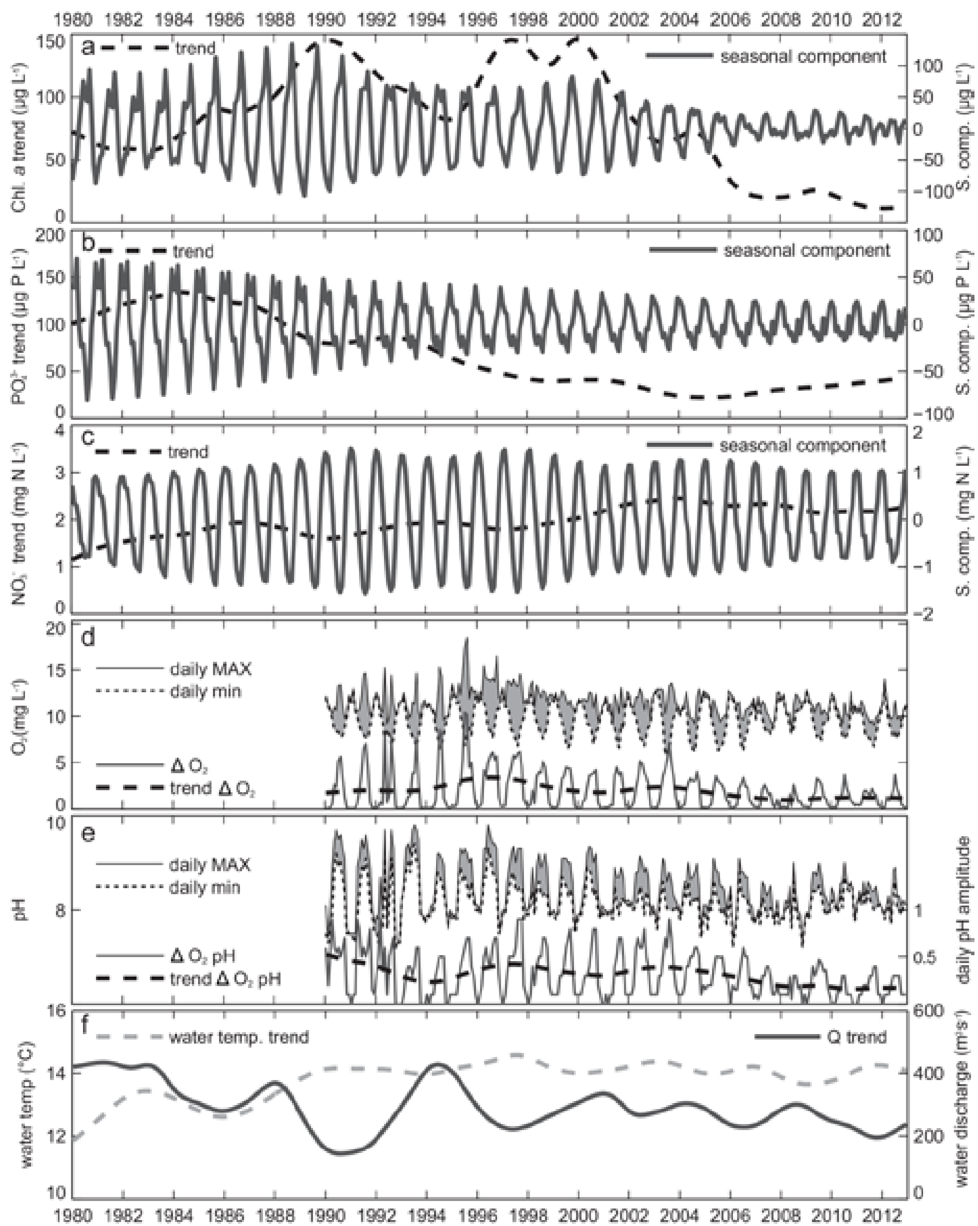
## 7.2 Status and trends

The status of a waterbody is the physical, chemical and biological condition representative of a particular time that may be instantaneous or averaged over a longer period. A combination of many different water quality measurements is often used to describe the status (Uddin, Nash and Olbert 2021). A water quality index compiled from specific measurements enables water quality to be assigned to a range of classes, such as from bad to excellent. The classes can be colour coded and presented on a coloured map, making the assessment easily understood by non-specialists. Such indices may comprise physical and chemical variables, a biological index, or a combination of both. Many national water and environment agencies now make their assessments available on-line, presented in this way (see for example EPA maps in Ireland at: https://gis.epa.ie/EPAMaps/default) The information can be used to plan management strategies by targeting waterbodies with poor water quality.

Trends in water quality are one of the most common assessments carried out with water quality monitoring data. A trend requires either monitoring at equally spaced time intervals or high frequency monitoring data that are averaged over fixed time intervals using the same monitoring stations under similar environmental conditions. For example, in eutrophic lakes that stratify, it is important that measurements are taken each year during the same phase of stratification (i.e., usually fully stratified) because that is when the impacts of eutrophication are at their greatest. In polluted rivers with point source discharges, periods of low flow when dilution is at a minimum are most appropriate, and measurements during periods of high flow may be needed to capture pollutants associated with additional suspended materials. It can take many years to establish trends, but they are essential to assess accurately the efficiency of a restoration programme or for deciding the best means of combating pollution.

Different water quality parameters have different patterns and ranges of natural variability, and this must be taken into consideration when deciding on the frequency of sampling for trends. Incorrect sampling frequencies can lead to wide variations in annual average concentration that could mask any trends. An example of an in-depth analysis of trends in the River Loire in France is given by Minaudo *et al.* (2015). This analysis showed an apparent decline in river eutrophication associated with control of direct inputs of phosphorus but also highlighted the impacts of seasonal variability (see **Fig. 7.1**).

**Figure 7.1** Trends and seasonal fluctuations in chlorophyll a (a), phosphate (b) and nitrate (c) upstream of several major tributaries (station 18) on the River Loire, France. Corresponding fluctuations in $O_2$ (d), pH (e) and temperature in the lower Loire (station 19) (f) and discharge at station 15 in the Middle Loire. Source: Minaudo *et al.* (2015) Licensed under CC BY 3.0



## 7.3 Water use and compliance

Water quality assessment in relation to a specific water use and for *in situ* activities such as water contact recreation (swimming, boating), aquaculture, or commercial or recreational fisheries, focusses on checking whether the water quality is safe to use. It typically involves monitoring at specific locations, such as water abstraction points, at a frequency that is prescribed by the most sensitive water use. However, the potential natural variability must also be taken into account when selecting the frequency of sampling. Drinking water abstraction, for example, requires very frequent or continuous monitoring because of the need to protect human health from pathogens and toxic substances, whereas lower risk activities such as boating may only require weekly sampling. The assessment is made by comparing the water quality data with target values or standards for the specified water use. Continuous monitoring of selected parameters at the point of water intake is also common in the food and drinks industries.

Monitoring and assessment for water use may involve early warning surveillance for potentially harmful water quality at critical locations, e.g., drinking water intakes and aquaculture facilities. This approach uses continuous monitoring for indicators of water quality change, such as total organic carbon, ammonia and turbidity, at very limited sampling sites, upstream or close to the facility, in order to provide warning that contaminants may be on their way towards the intake. The information is provided instantaneously by comparing the sensor results continuously against threshold values or ranges. The monitoring system may be linked to intake pumps, which can be automatically shut down if critical threshold values are exceed. Early warning surveillance can also use biological monitoring approaches by continuously exposing sensitive organisms to water diverted from the waterbody through a tank (see Shedd *et al.* (1996) and Mikol *et al.* (2007) for examples).

Assessment of water quality in a reservoir needs to provide information that will support the best management plan for the whole reservoir in order to reduce phytoplankton growth (see section 5.2.1), and possibly to determine the depth that will provide the best quality water for abstraction. Such monitoring needs to be carried out very frequently, or preferably continuously, using *in situ* sensors close to the point of abstraction or at the intake tower (**Fig 7.2)**.

Assessment for compliance with regulations or licences requires monitoring of prescribed parameters at locations and intervals specified in the licence. For example, for an effluent discharge licence, a high number of sampling stations in a small area close to the discharge may be necessary, depending on the distribution and mixing of the effluent in the waterbody (e.g., **Fig. 6.19**). For rivers, discharge values at the time of sampling are important because the river discharge influences the dilution of the effluent. Assessment of compliance is usually made by comparing water quality measurements with limits or threshold values, effluent discharge objectives, environmental quality objectives, or other conditions stipulated in the licence. Quality assurance of the sampling and analysis for the water quality parameters stipulated in the licence is particularly important if the assessment is to be used for legal proceedings for non-compliance (see guidebook on *"Quality Assurance for Freshwater Quality Monitoring")*.

**Figure 7.2** Continuous monitoring of water quality at a drinking water treatment plant intake tower. Water from the intake gate is diverted through a tank in which the sensors are placed. The outputs from the sensors are relayed to a control room, where the information is used to decide on depth of abstraction and level of treatment required
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## 7.4 Ecosystem health and eutrophication

Degradation of aquatic ecosystems in rivers and lakes is often caused by excess nutrients leading to eutrophication, toxic contaminants, or physical disturbance leading to habitat loss, erosion and sedimentation, and increased turbidity. A full assessment of the state of river or lake ecosystems should therefore include:

- Measurements of physical and chemical parameters that influence the biota, such as oxygen, temperature and nutrients.
- Representative groups of organisms, such as macroinvertebrates, fish and algae.
- River discharge or lake level and stratification.
- Sediments (suspended and deposited).

Pollution indicators, such as biochemical oxygen demand, salts, and toxic metals may also be needed.

A baseline assessment should be carried out covering all seasons with a high density of monitoring stations (see section 7.1). For long-term trends in ecosystem health, the most stable time of year should be chosen to enable comparison from year to year, i.e., sampling should not occur during the storm or hurricane season. Standardised sampling and analysis protocols should be implemented to enable comparison of results between seasons and years. For many long-term river ecosystem assessments at national or international scale, selected stations are only sampled every few years.

Lake ecosystems are typically assessed against trophic status indicators (see **Table 5.1**), such as nutrients (N, P and Si), chlorophyll *a* and transparency. The number and location of sampling stations depends on the size and morphology of the lake (see section 6.4.2). Eutrophication can cause rapid changes in lake water quality, especially in warmer seasons, and to monitor these changes the sampling frequency should be high – ideally once a week but no less than monthly (Thomas *et al.* 1996). Samples should be taken at multiple depths depending on the overall depth of the lake and the degree of stratification. An integrated sample can be used for the epilimnion to monitor phytoplankton and the associated chemical variables (e.g., chlorophyll *a*, N and P). An example of a long-term monitoring of lake ecosystems is available at the International Institute for Sustainable Development [IISD] (2019). If the quality of the water is important for drinking water supplies, collection, identification and enumeration of phytoplankton species may be important, especially if toxic cyanobacteria are a potential concern (Chorus and Welker 2021).

## 7.5 Contaminant monitoring and assessment

Monitoring toxic substances (e.g., heavy metals such as lead and mercury, persistent organic pollutants such as pesticides and PCBs, and pharmaceutical compounds) is an important aspect of many water quality assessments that examine the impact of human activities. Determining their sources and behaviour in the waterbody may require sampling and analysis of water, biota and sediments for the toxic substance and its various chemical forms (e.g., mercury and methylmercury). The final selection of sampling media, sampling stations and frequency of sampling can be determined from a preliminary intensive survey taking into consideration existing knowledge of the potential or actual sources. A comprehensive assessment for contaminants should provide information on:

- their likely sources and pathways,
- how they react with particulate matter and/or sediments,
- whether they undergo chemical changes in the sediments,
- whether they are absorbed, metabolized, and possibly transformed by the aquatic biota, and
- whether they are transported and deposited elsewhere in the waterbody.

**Box 7.1** illustrates how different approaches are being used in the Great Lakes of North America.

## 7.6 Assessment of fluxes from rivers

Assessment of fluxes, provides information for management of the transport of sediment, nutrients and contaminants from land to sea via rivers, from one river system to another river, from a river to a lake, or across boundaries in transboundary rivers. Flux ($\theta$, mass per unit time, usually t $a^{-1}$) is dependent on river discharge, which varies with rainfall and run-off (see section 2.1), therefore water quality sampling for flux monitoring often focuses on maximum water discharge periods when the maximum transport of any dissolved or particulate substances occurs. Water quality data must be collected simultaneously with discharge data at the flux monitoring station. To obtain the flux, continuous monitoring data of discharge ($Q$ $m^3 s^{-1}$) is multiplied by continuous monitoring data of concentrations (C mass per volume, usually mg $l^{-1}$) over a specific time period (between $t_1$ and $t_2$):

$$\theta = \int_{t_1}^{t_2} C(t)Q(t)\delta t$$

Continuous monitoring of many water quality parameters is not practically possible and therefore it is necessary to extrapolate concentrations between two sampling events. If composite samples are collected, they must be weighted according to the water discharge at the time of collection of each of the samples. An assessment of nutrient fluxes to the coastal water of China from the major rivers over a six-year period is described by Tong *et al.* (2015).

## 7.7 Accidents and early-warning

Following a catastrophic event, such as an industrial accident that discharges large quantities of toxic chemicals into a waterbody, or the failure of a mine tailing dam, it is necessary to implement an emergency monitoring and assessment programme. Sampling generally commences close to the point of discharge and at intervals downstream or with increasing distance from the source. Analysis of water, sediment and biota samples usually focuses on the known compounds that were released but, to enable a full assessment of the impacts on the

### BOX 7.1 MONITORING CONTAMINANTS IN THE GREAT LAKES OF AMERICA

Intensive sediment surveys in the Great Lakes in the 1970s and 1980s discovered high levels of mercury, PCBs and organochlorine pesticides in all of the Great Lakes. Spatial surveys have continued since then to monitor the recovery of the sediments following the ban on use of these persistent toxic compounds. A distinct decrease was evident in surface sediment contamination with compounds such as dieldrin, hexachlorobenzene, octachlorostyrene and mirex, decreasing by 50 per cent in surface sediments over the period 1986-1997 (Marvin *et al.* 2004).

**Figure 7A** Zebra mussel used for monitoring contaminants in the Great Lakes of America. By NOAA Great Lakes Environmental Research Laboratory. Licenced under CC BY-SA 2.0

The National Oceanic and Atmospheric Administration (NOAA) have had a Mussel Watch Program in the Great Lakes since 1992 where mussels are collected and analysed for contaminants in their tissues. This programme is now focusing on emerging contaminants (National Oceanic and Atmospheric Administration [NOAA] 2022a). They also have a Lake Sturgeon Health Assessment that uses the eggs of sturgeon, a fish present in the Great Lakes, to assess PCB and dioxin contamination that will cause health impacts for the fish (NOAA 2022b). This assessment will ultimately help develop remediation strategies.

ecosystem, biological and toxicological testing using biota may also be included (see guidebook on *"Freshwater Quality Monitoring with Biota"*). Monitoring should be continuous for selected parameters, or at least at regular intervals, until no impact on water quality or the ecosystem can be detected. In the case of persistent pollutants that are transported with particles and sediments, or accumulated by aquatic biota, this may be months or years (see **Box 7.2**).

Although accidents cannot be predicted, users of the water downstream of major industrial sites, may need to be warned of imminent changes to water quality arising from a chemical spill or other accidental discharge in order to have time to close any abstraction points. The approach used for early warning monitoring needs to be related to the anticipated risk. In the case of the mining facilities with tailing dams, early warning monitoring should include methods of detecting changes in turbidity, suspended solids and possibly colour. If toxic compounds are anticipated, a biomonitoring system may also be necessary where water is diverted through a chamber in which sensitive organisms are held (see examples in the guidebook on *"Freshwater Quality Monitoring with Biota")*. The behaviour of the organisms is monitored electronically and any sudden changes are immediately communicated by an alarm system. Continuous and semi-continuous monitoring methods (chemical screening and biological monitoring) are used to detect unreported spills on the River Rhine in Europe to protect drinking water abstraction points. The Rhine is highly urbanised, with many industrial sites along its path. It also functions as an important shipping route and has suffered major spills in the past (Diehl *et al.* 2005).

Early warning monitoring may also be used to protect water users from naturally occurring hazards, such as cyanobacteria. For example, measurement of phycocyanin fluorescence can provide an effective early warning system for cyanobacteria in reservoir intakes. Threshold values can be established for the intake that are triggered from an Algae Online Analyser (AOA), which is a fluorometer that can differentiate between different types of phytoplankton. An example of this approach for the Sulejow Reservoir in Poland is described by Izydorczyk *et al.* (2009).

## 7.8 Transboundary monitoring and assessment

Many rivers cross national or State boundaries, and many lakes have more than one riparian country or State around their margins. Typically, each jurisdiction monitors water quality immediately after a river enters the State and again just before it leaves, and will have at least one monitoring location in the territorial region of any lakes. The range of parameters monitored depends on the need to determine background water quality entering the jurisdiction or the quality of water passing to downstream jurisdictions including, for example, nutrients, suspended solids and selected contaminants. If the waterbody is part of an international agreement or a water basin organisation, the monitoring scheme may be agreed and implemented by members so that a catchment-wide approach can be taken to managing water quality. These organisations promote data sharing from individual members' monitoring networks or agree on a harmonised monitoring scheme in which all members participate. The River Danube in Europe (**Fig. 7.3**) is an example of basin-wide monitoring and management through international and transboundary cooperation (International Commission for the

**Figure 7.3** The River Danube in Europe. The river basin includes territory from 19 different countries, 14 of which co-operate for monitoring, assessment and management. By Shannon. Licenced by GFDL

## BOX 7.2 THE IMPORTANCE OF MONITORING AND ASSESSMENT FOLLOWING ACCIDENTAL POLLUTION

*Samarco tailings dam disaster, Brazil*

The Fundão dam in Brazil, which held mining waste (iron ore tailings), collapsed killing 19 people and displacing hundreds on 5 November 2015. It destroyed aquatic life and polluted 668 km of watercourses from the Doce River to the Atlantic Ocean, leaving hundreds of thousands of people (including indigenous people) without access to clean water. It is the highest volume release of mine tailings ever recorded, making it the world's largest mining environmental disaster. The impact monitoring carried out by the mining company after the event was inadequate and provided very little data, with several physical and chemical parameters not reported. The lack of appropriate data resulted in only a very small fraction of the released tailings being cleaned up even 12 months after the dam collapse (Fig. 7B) (Carmo *et al*. 2017).

**Figure 7B** River Gualaxo do Norte in 2017 – two years after the accidental release of mine tailings upstream. By Agência Brasil Fotografias. Licenced under CC BY 2.0

*Aznalcóllar tailings dam breach, Spain*

A smaller tailings dam breach in Spain in April 1998 led to a relatively efficient and comprehensive clean-up operation immediately after the accident. Acidic water and heavy metal-bearing tailings flooded land along the Ríos Agrio and Guadiamar rivers. Most of the accidentally discharged tailings and contaminated soils were removed, mechanically and manually, to an open pit within nine months of the discharge event. Geomorphological and geochemical surveys of the river channel, floodplain and valley floor, together with sediment and water sampling after the clean-up, were carried out in January and May 1999. This assessment of clean-up works showed that a sufficient quantity of the accident-related sediment had been removed and that surface sediments had recovered to pre-spill metal concentrations (Ag, As, Cd, Cu, Pb, Sb, Tl, Zn). Using the information obtained from the monitoring, a long-term fate analysis of the contaminants from the spill could be undertaken to predict contaminant storage and remobilisation back to the water column. This information could then be used to feed into long-term impact models, from which remediation strategies could be implemented (Hudson-Edwards *et al.* 2003).

Protection of the Danube River [ICPDR] 2021). Fourteen countries co-operate in the monitoring and protection of the River Danube through the International Commission for the Protection of the Danube River (ICPDR). They have collectively agreed to implement the EU Water Framework Directive (WFD) 2000/60/EC, (European Commission 2000), and other related Directives that apply to water policy and have implications for catchment management. Through the TransNational Monitoring Network (TNMN) these countries monitor long-term trends in water quality and pollution loads in the Danube River and its major tributaries. They share their data, which is published in annual yearbooks (ICPDR undated-a). The Joint Danube Survey (JDS) monitoring programme takes place every six years using a harmonised monitoring programme in which all countries participate using agreed methods and sample locations (ICPDR undated-b). This generates information that can be used to manage the whole river basin by identifying hotspots of river pollution. Long-term datasets like these can be used to enhance future monitoring programme design and to respond to fresh challenges from emerging contaminants and future climate pressures within transnational river basins (Chapman *et al.* 2016).

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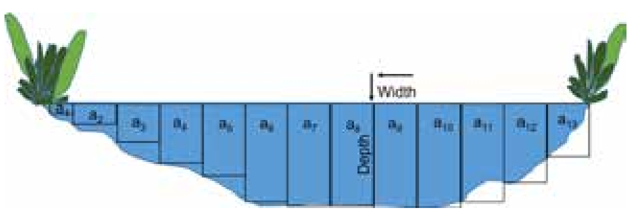
# Appendix A

# SIMPLE METHODS FOR MEASURING RIVER DISCHARGE

### *Step 1 Measure the cross-sectional area*

The cross-sectional area can be calculated from the total width and average depth across the channel, or from summing the areas of all of the vertical columns across the channel width as shown in Fig. A.1.

**Figure A.1** Dividing a cross section of a river into equal width vertical columns in order to calculate cross-sectional area




To obtain the average channel depth, a number of measurements need to be taken across the width of the channel. The river width should be divided into equal segments and the depth of each segment should be measured using a measuring stick or lead and line. The International Organization for Standardization method, ISO 748:2021(ISO 2021), details the Mean Section Method which recommends that river channels of different widths should be divided into a certain number of subsections (n), as shown in Table A.1. For example, a channel of between half and one metre should be divided into 6 or 7 sections.

**Table A.1** Recommended number of intervals (n) across a river channel at which depth should be measured according to standard method ISO 748:2021 (ISO 2021)

| Channel Widths (m) | n = |
|---|---|
| <0.5 | 5-6 |
| >0.5-1 | 6-7 |
| >1-3 | 7-12 |
| >3-5 | 13-16 |
| >5 | >/=22 |

### *Step 2 Measure velocity*

Velocity is the speed at which the water in the river flows in a certain amount of time and is measured in metres per second ($m\ s^{-1}$). Within a river channel, the water in contact with the bed and the banks is slowed by friction. Thus, the water in the centre moves the fastest. To get representative measurements, velocity is taken at multiple points where depth has been measured, or within each river section used to calculate the cross-sectional area.

The velocity can be measured directly using a calibrated flowmeter. Where total depth is less than 1 metre, the total depth at the point of measurement should be multiplied by 0.6 to determine the depth from the bottom at which the flowmeter should be placed (Fig. A.2). This is considered the point of average discharge in that location. If the depth is more than 1 metre, then velocity measurements must be taken at two different depths, 0.2 and 0.8 times the total depth.

**Figure A.2** Velocity should be measured with a flowmeter placed at 0.6 of the depth at each vertical interval across the width of the river

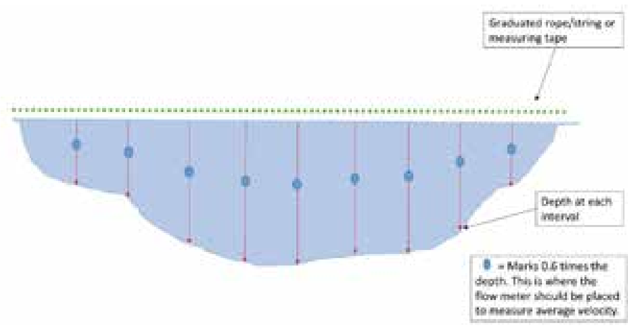
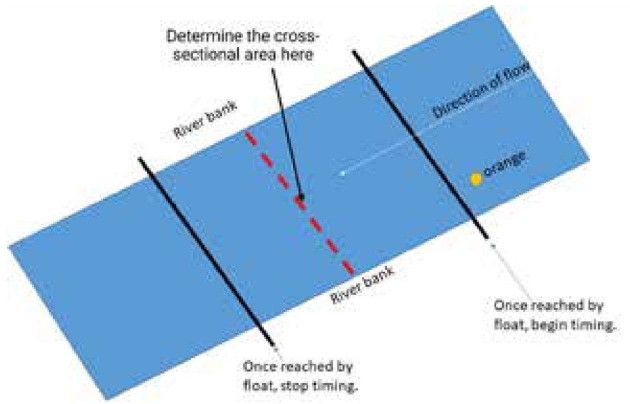



**Figure A.3** Procedures for measuring flow in a shallow river using the float method




## Measuring discharge from a bridge

For rivers that are not suitable or safe to wade into, measurements can be taken from a bridge. Firstly, measure the span of the bridge from shore to shore to get the width of the river, then divide this width into equal segments. At each segment, a weighted, calibrated line should be lowered to the water surface and the distance recorded. The line should then be lowered to the river bed and the distance recorded again. The stream depth for each segment can then be calculated by subtracting the distance to the water surface from the distance to the river bed.

The next step, like before, is to multiply the river depth by 0.6 or by 0.2 and 0.8, giving the depth(s) from the river bed where the flow meter will be lowered to record the velocity measurement.

## Alternative method for measuring velocity

If a flowmeter is not available, velocity can also be measured using a floating object, e.g., an orange or slightly filled plastic bottle (Fig. A.3). Firstly, a fixed distance along the river should be measured, e.g., 10 metres, and the start and end points marked clearly. The float is then placed in the water before the upstream marker so that it reaches a constant velocity travelling downstream. Using a watch or stopwatch, the timer is started as soon as the float passes the upstream marker, and then stopped timing when it reaches the downstream endpoint marker. Passes should be discarded if the float gets held up in the stream by any obstacle (e.g., cobbles, roots, debris). Once this process has been repeated at least three times at different distances from the bank, an average of the times can then be calculated. The velocity can then be estimated using the following equation:

Velocity = Distance (m) ÷ Time (s)

This velocity measurement can be used, together with the cross-sectional area of the river (which should be taken at the mid-point of the stretch of river used for timing the float), to calculate the river discharge.

## *Step 3 Calculating discharge*

## Example 1

Table A.2 gives a simple example of a stream discharge calculation using a flowmeter. The total stream width is 6.2 m, and is divided into five sampling segments, which gave an average depth of 0.33 m, and an average velocity of 0.17 m $s^{-1}$. Firstly, the cross-sectional area is calculated by multiplying the total stream width (6.2 m) by the average depth (0.33 m), which equals 2.05 $m^2$. The river discharge equation ($Q = v \times a$) can then be used to calculate the stream discharge [$0.17 \times 2.05 = 0.35$ $m^3$ $s^{-1}$].

**Step by step methodology of measuring discharge in a shallow river**

Choose a site that is safe and accessible and at a place in the river where the water is free flowing without obstructions such as vegetation.

Before entering the water ensure all necessary personal protective equipment is in place, e.g., wear a life-jacket.

Secure a measuring tape where the water meets the bank and stretch it across the width of the river to the opposite bank, and record the total width.

Divide the total width by a relevant number of intervals at which depth and flow will be recorded. Either leave the tape in place or mark the intervals on a string or rope and place this string across the channel, bank to bank. If the same monitoring station will be used again in the future, the makers can be left at each side of the bank to ensure discharge is always recorded at the same location with the same piece of marked string.

Record depth at each of the marked intervals and average to give the average depth.

Flow is measured using a calibrated flowmeter at each interval at which depth was measured.

Place the flowmeter propellor at 0.6 of the depth at that point of measurement, facing upstream into the flow. Stand downstream and avoid causing any disturbance of the flow to the meter. Allow the reading given by the flowmeter to settle for at least 30 seconds before recording velocity in the notebook or field record sheet.

Move on to the next measuring point and repeat the process. It will probably be necessary to adjust the depth of the propellor at each measuring point.

**Table A.2** Depth and velocity at river segments across width. Note: ideally the river should be divided into at least 20 segments because it is greater than 5 m in width (see Table A.1), but for ease of illustration, only five segments have been shown.

| Segment | 1 | 2 | 3 | 4 | 5 | Average |
|---|---|---|---|---|---|---|
| Depth (m) | 0.31 | 0.31 | 0.36 | 0.35 | 0.32 | 0.33 |
| Velocity with flowmeter ($m\ s^{-1}$) | 0.15 | 0.16 | 0.19 | 0.2 | 0.15 | 0.17 |

## Example 2

In this example the stream discharge is calculated using the float method to measure stream velocity (Table A.3). The distance measured for the velocity was a 4 m stretch. The total stream width was measured at 7.3 m, with an average depth of 0.45 metres, giving a cross-sectional area of 3.29 $m^2$ [7.3 m multiplied by 0.45 m].

**Table A.3** Time taken for a float to reach a designated point downstream. The times were recorded and then averaged. The distance the float travelled each time was then used along with the average time taken to calculate the velocity.

| Segment | 1st float recording | 2nd float recording | 3rd float recording | Average |
|---|---|---|---|---|
| 1 | 36 | 38 | 36 | 36.6 |
| 2 | 34 | 35 | 32 | 33.6 |
| 3 | 38 | 37 | 36 | 37 |
| Average | | | | 35.7 i.e., 36 seconds |
| Velocity | | | | 4 m per 36 s = 0.1 m $s^{-1}$ |

The stream was divided into three segments, with each segment repeated three times to measure the average velocity. The average time, over all three segments, for the float to travel the 4 m stretch was 36 seconds. The velocity can then be determined by using the simple equation:

Velocity = Distance (m) ÷ Time (s)

For this example, the velocity is therefore calculated as 4 metres divided by 36 seconds, which gives a velocity of 0.1 m $s^{-1}$.

The stream discharge ($Q = v \times a$) can then be calculated using the velocity value:
$0.1 \times 3.29 = 0.33$ $m^3$ $s^{-1}$.

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