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99: Water Quality Monitoring

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Water quality monitoring is the process of gathering data that describes the physical, chemical, and biological condition of a water body. This chapter presents an overview of the processes involved in water quality monitoring and illustrates some of the approaches used with examples of existing monitoring programs. Over the last century, improved understanding of water quality, combined with advances in measurement and monitoring technology have increased the possibility of measuring hundreds of different variables in surface and groundwaters. However, efficient use of resources for monitoring depends on careful selection of objectives for the water quality monitoring program and on targeting variables and monitoring methods that address those objectives. Recent appreciation of the close link between the physical and chemical condition of a water body and its biological component has led to the incorporation of biological approaches in many large-scale programs to assess surface water quality. Today, monitoring programs take many forms, from measurement of a few specific variables to establish trends or effectiveness of remediation measures, to sophisticated evaluation of toxic impacts of wastewaters, to relatively simple determination of the state of the aquatic environment using citizen participation. Confidence in all data gathered and its resultant usefulness for management and policy development is essential; this can only be achieved by a careful program of quality assurance that extends from sample collection in the field, to analysis in the laboratory, to data handling and manipulation.

INTRODUCTION

Effective management of rivers, lakes, and groundwaters must be based on an understanding of their physical, chemical, and biological characteristics, that is, the water quality. This understanding can only be achieved through the collection and interpretation of appropriate information. The raw data that provides this information is obtained through the process of monitoring or data gathering. Monitoring is an activity that can take many forms, as illustrated in this chapter, but essentially it consists of the systematic collection of data over temporal or spatial scales. Human impacts on water quality and quantity hsa194 (*see*• and also **Chapter 205, Land Use Impacts On Water Resources – Science, Social and Political Factors, Volume 1**–**Chapter 207, Agriculture, Irrigation and Water Resources, Volume 1** for examples of specific impacts) have resulted in more complex management problems and an associated demand for relevant information that will help support management decisions. In addition, policy makers increasingly have to consider regional and even global scales in policy design. This expansion in the need for information is posing challenges for those responsible for monitoring, both in terms of meeting diverse needs within a limited resource base and in designing cost-effective methods and approaches that provide data that will be useful and meaningful.

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The term "monitoring" is used loosely to include all activities that involve the gathering of data by making measurements, whether in the field situation or during a process such as water treatment. In practice, many monitoring programs are set up to fulfill a particular goal aimed either at determining whether water is fit for a specific use or whether water quality has deteriorated because of human activities. Examples of more precise monitoring goals are:

Encyclopedia of Hydrological Sciences. Edited by M. Anderson.

- Operational monitoring (also known as *surveillance*) – checking compliance with set criteria such as maximum allowable concentrations, water quality standards or discharge consents
- Surveys – limited duration data gathering exercises to determine the status of the water body at that given time (for example, in response to an accidental pollution incident)
- Background monitoring – collection of baseline data to indicate reference, background or unperturbed conditions for comparison with other sites, or for comparison with the same sites when studying trends or recovery/remediation effects (often used to determine impacts of future or remote activities)
- Trend monitoring – long-term data gathering specifically aimed at showing environmental change over time
- Flux monitoring – gathering of data at defined boundaries to determine the flux of specific materials from one environment, or water body, to another

The diversity of reasons for monitoring and of methods used is too great to discuss in detail in this chapter – thus it presents a guide to the principal activities involved, together with an overview of the approaches taken to monitoring water quality in different geographical regions and with different objectives. Some selected examples of water quality monitoring programs from around the world are also included. Examples have been chosen to illustrate some practical approaches that are in more widespread use and from well-established programs that have been in operation for at least a number of years.

To ensure that monitoring activities result in useful and credible information, it is necessary to choose appropriate methods at all stages of the monitoring process – from field to laboratory, and even to data interpretation, storage, and handling – and to apply rigorous quality checks to all these stages. Reliable and accurate water quality data are the foundation of the information that is needed for aquatic resource management in conjunction with the appropriate hydrological information. The raw data, in themselves, may be of little value unless some process of interpretation and presentation is applied to make them accessible and understandable to the users, namely, water resource managers, policy makers, and the public. This interpretation can take the form of a simple graph showing fluctuations over time to a complete assessment of the environmental situation. Thus, water quality monitoring should not be seen as an activity on its own, but as part of the overall water quality assessment process. This process begins with the setting of objectives, continues through the data gathering exercise and concludes with interpretation and assessment.

HISTORICAL DEVELOPMENT OF WATER QUALITY MONITORING

The concept and understanding of water quality has been developing gradually over more than one hundred years and is likely to continue to evolve because of (i) increasing demand for water qualified by the type of use, (ii) increasing human demands on continental water resources, (iii) improving knowledge and perceptions about the aquatic environment, and (iv) developing technology, from field measurements and sampling, and laboratory analyses to data management, analysis, and communications.

In the 1850s, the first water quality analyses (e.g. Seine and Thames rivers) were based on a few physical and chemical variables, such as T°, pH, DO, K_{SC}, Cl, NH_4^+, and NO_3^-. The longest record of water quality for these variables exceeds 100 years for the Rhine River. Just before World War I, the first systematic geochemical studies of rivers were conducted on United States' and Canadian rivers, and routinely included the concentrations of major ions: Ca^{2+}, Mg^{2+}, Na^+, K^+, (usually measured as Na^+ plus K^+), Cl^-, SO_4^{2-}, NO_3^-, H_4SiO_4, and HCO_3^-, and sometimes other variables including NH_4^+, PO_4^{3-}, iron (as Fe_2O_3), aluminum (as Al_2O_3), and salinity. Although some sewage contamination studies were conducted as early as 1900, the first routine surveys of microbiological contamination indicators, including total fecal coliform counts, were conducted during the 1930s at public water supply intakes of major cities. Around the same time, the first routine measurements of riverine suspended particulate matter (SPM) were conducted to determine baseline fluxes prior to damming (e.g. USA, former USSR, China).

During the 1950s and 1960s, atmospheric nuclear bomb testing created a need for artificial radionuclide and plutonium surveys. These surveys generally were independent of other types of water quality monitoring and typically were not accessible to scientists or to the general public. Meanwhile, eutrophication issues and the development of automated nutrient analyses accelerated the measurements of N species and other nutrients including PO_4^{3-}, total P, and H_4SiO_4. Since the middle of the 1970s, organic carbon analyzers have enabled the analyses of total, dissolved, and particulate organic carbon concentrations (•TOC, •DOC, and Q4 Q5
•POC, respectively), which have been gradually replacing Q6
biochemical oxygen demand (BOD) and chemical oxygen demand (COD) measurements. Investigations of chemical components of water quality also have benefited greatly, since the 1970s, from technological advances in instrumentation and analytical techniques such as atomic absorption, ion chromatography, inductively coupled plasma spectrometry, gas chromatography, and mass spectrometry. Analytical improvements have been mostly driven by the growing demand for analyses of a growing list of contaminants such as polychlorinated biphenyls (PCBs), industrial products similar to the DDT insecticide, polyaromatic hydrocarbons

(PAHs), phthalate plasticizers and other persistent organic pollutants (POPs). POPs are highly toxic and accumulate in soils, sediments, and biological tissues because they have a high affinity for particulate matter, are highly soluble in fat tissues, and have a low solubility in water. Most of these compounds are not natural and typically occur at very low concentrations in the environment. The first routine surveys of sediment quality were also conducted in the 1970s. The combination of chemical (e.g. C, N, P, metals, POPs) and biological analyses (e.g. pigments, diatom assemblages) of sediment cores permitted the reconstruction of past water quality issues (e.g. salinization, eutrophication, oxygenation, acidification) over decades and more, opening another rapidly growing-scientific field in water quality, namely, the study of sediment archives.

Since the 1960s, water quality monitoring has also included biota, especially benthic species, photosynthetic pigment concentrations (as an indicator of primary productivity or algal biomass), algal species counts, and chemical analyses of contaminants in biota (e.g. freshwater mussels) or in specific tissues of the biota (e.g. fish muscle) (see following text).

The total number of variables that should be considered in a comprehensive water quality monitoring program, if all regulations and water quality approaches were strictly followed, would now exceed 500. Because of financial constraints, and because human activities which affect water quality vary spatially and temporally, most monitoring programs rarely include more than 100 variables for individual samples, even at the most well-equipped monitoring laboratories. In less developed countries, where water quality monitoring exists, the number of variables rarely exceeds 20, including major ions, some nutrients, total suspended solids (TSS), pH, T°, and conductivity. The choice of variables, and the laboratory-based analytical methods associated with those variables, is often governed by the resources (financial, technical, and human) available for the monitoring program. Where resources are not limited, the analytical techniques should be selected for which standardized methods and appropriate quality assurance programs (see following text) exist, bearing in mind any specified or anticipated detection limits. Electronic information sources, such as the National Environmental Methods Index (NEMI) (NWQMC, 2004a), can assist with such selection.

Efforts to obtain useful information with limited expenditure and/or resources have driven the development of water quality indicators (physical, chemical, and biological – see following text). An indicator is a measured variable, or combination of variables, that can be related to particular environmental conditions and is representative of those specific conditions, for example, the Secchi depth (see following text) as an indicator of eutrophication. It can also be a specific aquatic organism that is associated with a defined range of water quality variables (see following text).

MONITORING PROGRAM DESIGN

The setting of objectives should be the first activity in the steps required to design and implement a water quality monitoring program (Figure 1). Water quality monitoring can be very demanding on the resources of any organization, sometimes requiring considerable personnel, and/or advanced technical facilities. Expenditure on such resources must be justifiable by the ultimate provision of useful information for management or policy needs. In order to ensure that resources are not wasted, it is important to define clearly the objectives of any monitoring program in terms of its expected outputs. The objectives should take into consideration the technical capability of the monitoring organization and should be achievable within the resources available to the operators of the program. The more focused and well-defined the objectives, the more likely it is that resources will not be wasted and that expectations will be met (e.g. NWQMC, 2004b).

Water quality objectives, the related monitoring variables, and the type of water quality surveys and studies can vary markedly for the same water body among hydrological disciplines depending on the purpose of the scientific investigation (e.g. process studies made by geochemists, biogeochemists, and some hydrologists) or requirement for compliance with water quality criteria as might be evaluated by sanitary engineers or water managers (Table 1).

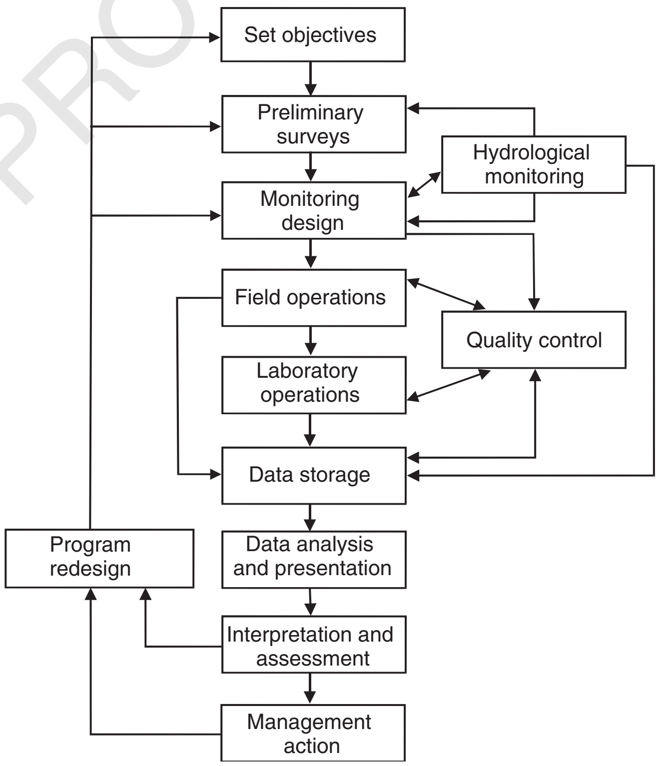

Figure 1 Stages of the water quality monitoring process

Table 1 Typical monitoring objectives and associated activities undertaken by different hydrological science disciplines

Disciplines	Objectives	Variables	Type of study, survey, or monitoring program
Environmental chemists	Detect and quantify trace amounts of any contaminants including degradation products	Trace elements, synthetic organic compounds, new compound on the market (e.g. pesticides) and/or synthesized by chemical and pharmaceutical industries	In-depth inventories; surveys of ambient backgrounds; sediment archives
Geochemists	Chemical composition with regards to natural drivers (lithology, climate...); inputs to oceans	Ca^{++}, Mg^{++}, Na^{+}, K^{+}; Cl^{-}, SO_4^{2-}, HCO_3^{-}; dissolved/colloidal/particulate trace elements; chemical speciations	Process studies (stream scale); fluxes (basin scale)
Biogeochemists	Cycles and transformations of nutrients (dissolved and particulate organic/inorganic)	Carbon, nitrogen, phosphorus, and silica species; micronutrients	Links with algal production and bacterial activities
Ecologists	Physicochemical quality; Q2 occurrence and levels of contaminants; pigment levels	•PH; T° TSS; color; dissolved oxygen; total dissolved solids; nutrients; ammonia contaminants; endocrine disruptors; chlorophyll A	Overall quality; general mapping; seasonal regime extreme events; bioaccumulations; biomagnifications
Limnologists	Ecological functioning; conservation; potential for lake uses; paleo-records of water quality	Dissolved O_2; nutrients; pH; conductivity; pigments; contaminants	Process studies (fine time, space, and scales); vertical profiles; seasonal variations; sediment mapping; sediment archives
Hydrologists	River fluxes of dissolved and particulate matter; tracers of water pathways	Major ions; SPM; natural isotopic tracers (e.g. $^{13}HCO_3^{-}$, $^{14}HCO_3^{-}$, $^{2}H_2O$, $^{3}H_2O$, $^{34}SO_4^{2-}$ ...); artificial radionuclides	Flood cycles; seasonal regimes; yearly fluxes; trends; stream order; structure of water quality
Sanitary engineers	Water-borne and water-related diseases; indicators of pollution	biochemical oxygen demand and chemical oxygen demand; microbial contamination indicators (fecal and total coli, streptococci); nitrate; endocrine disruptors; radionuclides	Water quality at intakes; continuous surveillance; detection of threshold quality (accidents)
Water manager	Comparison with water use criteria; pollution sources inventories	Most of above variables with growing focus on microcontaminants such as pesticides and endocrine disruptors	Contaminant mapping and budgets; longitudinal profiles; long-term surveillance; emergency survey
Community/citizen volunteer monitor	Trends in water quality in relation to water use/human impact; protection of biodiversity	Simple field measurements of physical/chemical variables; identification and enumeration of organisms	Trends; spatial surveys; species inventories

Well-defined objectives aid the efficient design of all stages of the monitoring program (Table 2), from the selection of measurement variables to site selection, to choice of field and laboratory methods, to data interpretation and presentation techniques (Spooner and Mallard, 2003). The simplest monitoring programs may have only one objective; an example would be to check that water abstracted from a well is fit for human consumption according to the World Health Organization (WHO) guidelines for drinking water quality (WHO, 2004). In this case there is a specific monitoring site (the point of abstraction from the well) and the variables to be measured, together with their recommended frequency, are defined by the need to check whether guidelines concentrations are met for specific variables. The output of the program is an assessment of whether, on each sampling occasion, the water in the well meets the concentrations defined in the guidelines and is considered fit to drink.

Table 2 Principal activities associated with each stage of a monitoring program

Stage of monitoring program	Principal activities
Setting objectives	Consider water uses, legislation, guidelines, standards, and so on
	Consider economic and technological constraints
	Define expected outcomes of monitoring program
	Establish data quality objectives
Preliminary survey	Survey literature and databases for existing physical, chemical, biological, or hydrological data, information on methods, and so on.
	Test field and laboratory methods if necessary
	Carry out special survey to evaluate potential sites and/or methods for long-term use
	Establish measurement quality objectives
	Evaluate technical and financial resources required
Program design	Decide spatial and temporal sampling regime
	Select monitoring media (water, sediments, biota), variables (physical, chemical, biological), field sites, sampling frequency, specific methods, and equipment
	Produce final program design, including guidelines for technical personnel, standard operating procedures, field record sheets, laboratory record sheets
Implementation	Field operations: Collect biota, sediments, and water samples for laboratory analysis, take *in situ* physicochemical measurements and carry out on-site biological and chemical analyses, record field data
	Hydrological measurements: collect information on flow, velocity, water level, and so on.
	Laboratory operations: Preparation of sample bottles and addition of pretreatment chemicals, analysis of samples, recording of results
Quality control	Checking accuracy of field and laboratory methods, for example, with sample blanks and duplicate samples
	Checking in-house analytical techniques with sample blanks and spiked samples
	Participation in interlaboratory quality assurance exercises
	Regular checking for suspect data in databases
Data manipulation	Data storage: Transferring results from field and laboratory operations into database
	Analysis of data: Application of statistical methods, for example, correlations, trend analysis
	Assimilation and presentation of data: Tables of results, data summaries, graphs

Source: Adapted from Chapman (1996).

The increasing need over the last few decades to manage and protect all aspects of water resources has led to a greater understanding of the functioning of water bodies and of their interactions with other components of the hydrological cycle. The demand for management of freshwater resources in an integrated way, such as that required under the European Union Water Framework Directive (EU, 2000) can lead to the need for monitoring programs with multiple objectives. It is particularly important that monitoring programs with multiple objectives are reviewed periodically to evaluate whether all the objectives are still valid and necessary and whether the program is achieving the objectives. There should be regular feedback from the users of the outputs of the monitoring program to the designers and operators in order to ensure that the program remains appropriate and cost-effective (see Figure 1).

Just as monitoring programs should be designed to meet specific objectives, they should also be designed specifically to suit the type of water body. This means that at least a fundamental understanding of the hydrology of the specific water body is necessary. Where this information does not already exist, it may have to be obtained through a preliminary survey. Typical hydrological information required before designing a monitoring program is summarized for the three main types of water body in Table 3. Knowledge of hydrological features is essential for selecting the appropriate sites for sampling. For example, it is important to know the direction and velocity of groundwater flow when selecting sites for boreholes with the aim of studying pollutant dispersion. In river waters, variations in contaminant concentrations are closely related to discharge and depend on whether the contaminant is in the dissolved state or is associated with particulate matter (*see* **Chapter 98, Water Quality, Volume 1**). Discharge in rivers is highly variable depending on rainfall, the size, and other physical and geological characteristics of the catchment and the resultant runoff, varying over minutes to hours to days to months to seasons, and for some climate impacts, to years or decades. Flux calculations (*see* **Chapter 93, Measuring Sediment Loads, Yields, and Source Tracing, Volume 1** and **Chapter 98, Water Quality, Volume 1**) depend on the river discharge at the time of sampling. Thus, wherever possible, it is recommended that measurements are made at frequent intervals or even continuously. In lakes and reservoirs, short residence times might influence the frequency of monitoring, whereas turbulence and mixing

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Table 3 Hydrological information and key measurements required for increasing complexity of water quality monitoring programs

Level of complexity of monitoring program	Rivers	Lakes/reservoirs	Groundwaters
All programs	Map of catchment plus:	Depth at samples site(s); water residence time; thermal regime plus	Type of aquifer; direction of groundwater flow plus:
Low ▼ ▼	Water level at time of sampling	Lake level at time of sampling, depth of thermocline if present	Piezometric level
▼ ▼ ▼	Discharge at time of sampling	As above plus vertical profiles of temp. and O_2 at time of sampling	Piezometric level between sampling, aquifer map
High	Continuous measurement of discharge	As above plus rate of water inflow and patterns of water movement within lake	Full knowledge of groundwater hydrodynamics

Modified from Meybeck *et al.* (1996).

might influence the sampling station locations and depths from which the samples are collected. For an explanation hsa114 of the hydrology of lakes and reservoirs, *see* **Chapter 118, Lake Ecosystems (Stratification and Seasonal Mixing Processes, Pelagic and Benthic Coupling), Volume 1** hsa115 and **Chapter 119, Reservoir, Volume 1**.

The necessity for preliminary information on chemical and ecological interactions depends on the nature of the intended water quality monitoring program. If a biological monitoring approach based on the presence or absence of certain species is to be used (see following text), it may be necessary to determine first of all whether the water body has any natural chemical characteristics that might affect the presence or absence of species to be included in the monitoring program. Similarly, a preliminary survey of the sources and nature of chemical discharges into a water body can assist in the targeted selection of chemical compounds to include in a biological or ecotoxicological monitoring program.

Many of the detailed aspects of program design, such as frequency of sample collection, number of samples, number of replicate samples, and so on, are important to the successful application of certain data analysis methods and statistical techniques. Thus it is important to consider, and even to select, the type of data analysis methods that will be applied to the results obtained before proceeding any further with the monitoring program design (Dixon and Chiswell, 1996). Finally, using all available information on the water body, including that from published sources, previous programs, or specific preliminary surveys, the monitoring program can be designed in detail. The design should consider and specify all the following activities:

- sites to be sampled, that is, location specified by grid reference,
- sample details, for example, precise depth at which each sample is to be taken,
- frequency of sampling,
- variables to be measured in the field, including hydrological variables,
- variables to be measured in samples returned to the laboratory,
- requirements for replicate sampling,
- methods for field analysis,
- methods and equipment for field sample collection and storage,
- methods for laboratory analysis of samples, including any instructions for storage of samples,
- recording procedures and storage methods for results,
- quality control procedures related to both field, laboratory, and data handling operations.

Time taken in specifying and documenting the precise details of each step of the monitoring program can be justified by the resultant confidence in the reliability of the data generated. Over the last decade, much progress has also been made in testing and standardizing aquatic monitoring methods, particularly through the International Organization for Standardization (ISO) (ISO, 2004a).

MONITORING IN THE FIELD

There are four important aspects to the field-based activities within a monitoring program:

- selection of sites at which samples should be taken,
- frequency with which samples should be taken,
- the type of samples to take,
- the methods to be used for sampling.

Selection of sampling locations depends on an understanding of the water body and the objective of the program.

It may also have to take into consideration the practicality of the method, the accessibility of the sites and intended use of the data obtained (e.g. statistical techniques, association with other grid-referenced data, anticipated links with other monitoring activities, etc.).

Programs with the objective of determining baseline or background water quality must be based on sample sites that are distanced from any human influence or, at the very least, be unaffected by the emissions for which they form the baseline or background measurements. Programs monitoring for impacts of particular emissions should include sites close to the emission and, if possible, distributed spatially over the anticipated range of effect. Sampling sites for operational monitoring programs are sometimes defined by the national or international water quality standards or guidelines against which the water quality is being monitored, or by the operational license controlling the activity. Typically, such sites are at the point of water abstraction or discharge. Water quality status monitoring requires sites to be geographically dispersed to cover the area of interest and to include all relevant water bodies, for example, nationally, regionally, or globally. For practical reasons it may be necessary to select one site to be reasonably representative of a large water body, although this assumption should be tested first with a set of synoptic samples collected over a wider area within the water body. Careful choice of such monitoring sites to avoid unusual influences, such as wastewater discharges and outfalls, is essential.

Sampling frequency must be chosen to give adequate data for interpretation of the expected changes in water quality without imposing too great a demand on resources. Long-term trends can be studied by means of infrequent sampling at regular intervals, such as once a year, provided the samples are always taken at the same time of the year to eliminate changes due to seasonal variations in water quality. Sampling to determine fluxes and loads may require high frequency sampling, continuous monitoring techniques or targeted sampling in relation to periods of high flow (see Robertson and Roerish, 1999 for a discussion of the applicability of different water quality sampling strategies). The degree of variability in physical, chemical, and biological aspects of water quality may have to be determined by a preliminary study before deciding on the most appropriate sampling frequency. Groundwaters usually show little variability over time, unless very shallow or influenced by tidal fluctuations, whereas most rivers are highly variable, depending on rainfall and runoff, which in turn is related to climate and season.

The *sampling methods* used depend on the medium to be sampled (water, sediment or biota) and the variables to be measured in the sample (e.g. USGS, 2004a). Chemical and microbiological analyses require samples to be collected without the risk of contamination by any substance or organism that will subsequently be measured in the sample. This can involve special cleaning or sterilization procedures for sampling equipment and sample storage bottles, as well as care in the way the samples are taken. For example, water samples for subsequent analysis of dissolved or particulate metal concentrations should not come into contact with metals, that is, sampling apparatus and sample bottles should be constructed of polyethylene plastic, Teflon, or glass with no metal parts.

Discrete samples of water, sediment, or biota are only representative of the point of sampling at the time that the sample was collected. Hydrological influences, such as flow in rivers and groundwaters or stratification in lakes, may require that either a number of samples are taken at different locations at the same time or that a time- or depth-integrated sample be obtained. Integrated samples can be taken either by mixing a series of discrete samples or by the use of a special sampling technique, for example, a hosepipe sampler, pumping mechanism, or isokinetic sampler (Figure 2). Time-integrated samples are produced by combining discrete water samples from the same site at regular time intervals or by continuously withdrawing water into a large container over a fixed time. This approach is only suitable where the variable being studied does not change biologically or chemically during the time interval between the first and the last sample being taken and mixed together. The precise choice of method should, where possible, be governed by the monitoring objectives and the associated measurement quality objectives.

SAMPLING DIFFERENT MONITORING MEDIA

Depending on the objectives of the monitoring program, it may be appropriate to take water samples, living organisms, sediments, or a combination of these media (see above). For certain types of biological or sediment samples, the same or similar collection methods may be used as for water samples. Specialized approaches may require their own methods and specific precautions to ensure that samples are not contaminated. Some of the more common methods are described here (Table 4, Figure 2).

Water Samples

Discrete water samples, sometimes known as *grab samples*, such as those commonly used for chemical, nutrient, and microbiological analysis, are taken by a field operator and transported to the laboratory. There are several methods available for collecting discrete samples, and the choice depends on the subsequent sample handling or on the need for depth (vertically from top to bottom of a site on the water body) and width (horizontally across the water body) integrated samples (e.g. USGS, 2004a). The simplest method involves submerging a jug or bucket –

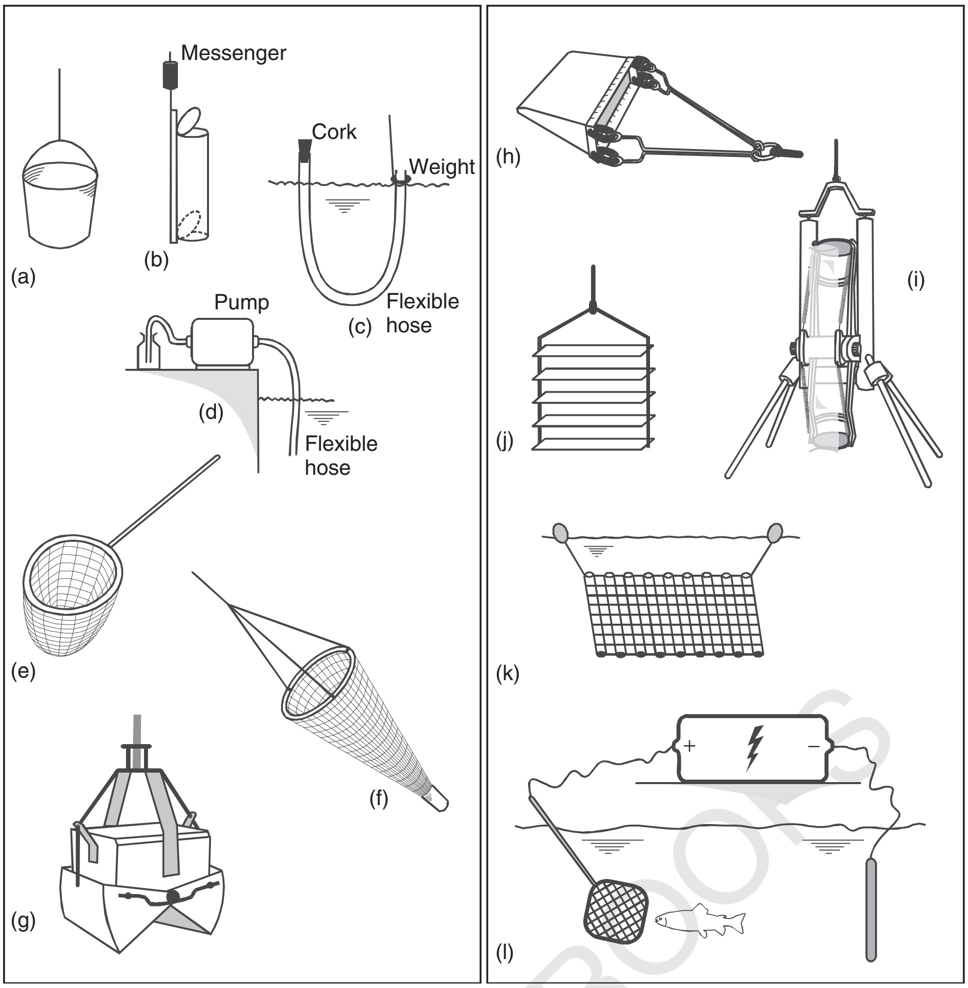

Figure 2 A selection of methods and equipment for collecting discrete or depth- and width-integrated water, sediment, and biota samples. (a) Simple bucket or beaker on a length of rope for collecting surface samples; (b) surface operated bottle sampler for grab samples at depth; (c) flexible pipe for integrating a depth sample in still waters; (d) mechanical or electrical pump for lifting volumes of water from specific depths; (e) fine mesh net on a rigid pole for collecting nonmotile organisms in shallow waters, for example, benthic invertebrates; (f) fine mesh net on a calibrated rope for collecting open water samples of organisms, for example, plankton; (g) mechanically operated grab for collected samples of deposited sediment and associated organisms in deep waters; (h) dredge-type sampler for collecting surface living organisms from shallow or deep waters; (i) remotely operated corer for collecting deposited sediments with minimal disturbance; (j) artificial substrate (e.g. flat plates suspended on a rope) for collecting attached organisms in all types of water body; (k) net or trap for collection of organisms such as fish; (l) electro-fishing equipment for near-quantitative sampling of fish

open face downwards – to the required depth and then slowly turning it upright so that it fills at the sampling depth (Figure 3). More complex methods involve remotely triggered devices, such as the Friedinger and Ruttner samplers (see Table 4, Figure 2), that open at depth to contain a vertical column of water of known volume. For certain advanced analytical measurements, or for variables occurring at very low concentrations, discrete samples are essential, combined with special pretreatment or storage conditions (e.g. addition of fixative chemicals, storage in the cold and dark). Depending on the subsequent analyses to be performed on the sample obtained (e.g. trace metals, microbiological), it may be necessary to take special precautions to avoid contamination of the water sample or the collection of an unrepresentative sample. Such precautions include facing the opening of the collection vessel into the water current, wearing sterile gloves, rinsing the sample bottle several times in the water body to be sampled and discarding the water (away from the collection point) prior to filling, avoiding sampling close to stream or lake beds so as not to disturb fine sediments, and careful cleaning of samplers between sampling trips.

Some water quality variables can be measured *in situ* with portable or fixed submersible probes on site or by

Table 4 Comparison of methods and equipment for sampling water, suspended particles, and aquatic organisms (see Figure 2)

Sampler/sampling mechanism	Figure No.	Type of sample	Most suitable habitats	Advantages	Disadvantages
Jug, bucket, beaker, or bottle	2a	Water, suspended sediment/particles inc. plankton and microorganisms	Lakes and rivers	Cheap, simple, quantitative.	Surface or subsurface samples only.
Bottle samplers (e.g. Friedinger, Van Dorn, Ruttner)	2b	Water, suspended sediment/particles inc. plankton and microorganisms	Still or slow flowing waters, groundwaters	Quantitative. Enables samples to be collected from discrete depths.	Expensive unless manufactured ''in-house''.
Hosepipe sampler	2c	Water, suspended sediment/particles inc. plankton and microorganisms	Still waters	Integrates sample from surface to depth. Quantitative. Cheap and simple to use.	Small volume of sample.
Water pump	2d	Water, suspended sediment/particles inc. plankton and microorganisms	Lakes and rivers, groundwaters	Quantitative if calibrated. Rapid collection of large volume samples. Integrated depth sampling possible.	Expensive. Requires power supply.
Isokinetic sampler		Water and suspended sediment	Flowing waters	Enables flow-related depth-integrated samples	Expensive
Collection by hand		Macrophytes, attached or clinging organisms	River and lake margins, shallow waters, stony substrates	Cheap – no equipment necessary.	Qualitative only. Specific organisms only collected.
Hand net on pole (c. 500 μm mesh)	2e	Benthic invertebrates	Shallow river beds, lake shores	Cheap, simple.	Semiquantitative. Mobile organisms may avoid net.
Plankton net	2f	Phytoplankton and/or zooplankton depending on mesh size	Open waters, mainly lakes	Cheap and simple. Large volume or integrated samples possible.	Qualitative only (unless calibrated with a flowmeter). Selective according to mesh size. Possible damage to organisms.

(*continued overleaf*)

Table 4 (*continued*)

Sampler/sampling mechanism	Figure No.	Type of sample	Most suitable habitats	Advantages	Disadvantages
Grab (e.g. Ekman, Peterson, Van Veen)	2g	Sediments, benthic invertebrates living in or on the sediment. Macrophytes and attached organisms	Sandy or silty sediments, weed zones	Quantitative sample. Minimum disturbance to sample.	Expensive. Requires winch for lowering and raising.
Dredge type (e.g. Surber sampler)	2h	Mainly surface living benthic invertebrates	Bottom sediments of lakes and rivers	Semiquantitative or qualitative analysis depending on sampler	Expensive. Mobile organisms avoid sampler. Natural spatial orientation of organisms disturbed.
Corer (e.g. Jenkins)	2j	Sediments, microorganisms and benthic invertebrates living in sediment	Fine sediments, usually in lakes	Discrete, quantitative samples	Expensive. Small quantity of sample.
Artificial substrates (e.g. glass slides plastic baskets)	2k	Epiphytic algae, attached invertebrate species, benthic invertebrates	Open waters of rivers and lakes, weed zones, bottom substrates	Semiquantitative. Cheap	May not be truly representative of natural communities. Positioning in water body important for successful use.
Poisons (e.g. rotenone)		Fish	Small ponds or river stretches	Total collection of fish species in area sampled	Destructive technique
Fish net/trap	2l	Fish	Open waters, river stretches, lakes	Cheap. Nondestructive.	Selective. Qualitative unless mark recapture techniques used.
Electro-fishing	2m	Fish	Rivers and lake shores	Semiquantitative. Nondestructive.	Selective according to current used and fish size. Expensive. Potential safety risk.

Modified from Friedrich *et al.* (1996).

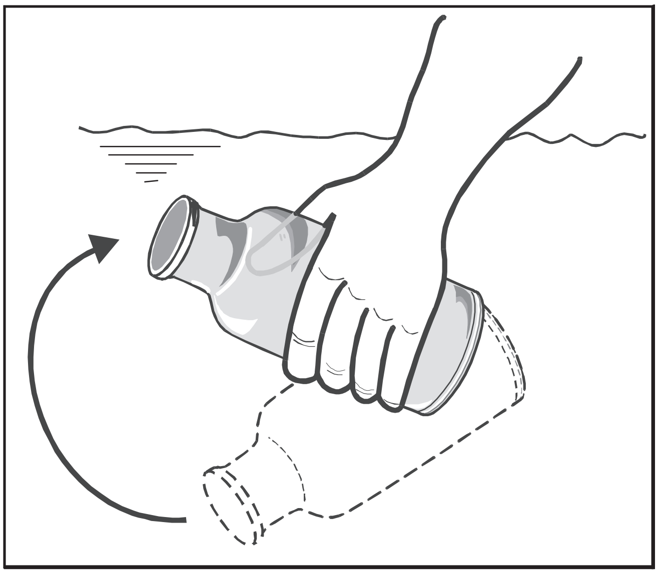

Figure 3 Taking a surface water sample by hand – the bottle is submerged with the opening facing downwards and then tilted up to allow it to fill at the required depth. The bottle should be rinsed several times in the water body before taking the sample and, if used in a river, the opening should be faced upstream. Care should be taken to avoid disturbance of sediment

diverting a flow of water through a monitoring instrument situated very close to the water body. Fixed monitoring instruments provide real-time data on changes occurring within the water body. The outputs can be either stored onto a data logging system and periodically downloaded or transmitted telemetrically to a central data gathering facility. Such systems are currently well developed for measurement of parameters such as velocity, temperature, oxygen, conductivity, pH, total organic carbon, turbidity, and fluorescence (Glasgow *et al.*, 2004). These types of measurements provide an essential early warning mechanism of changes in water quality at sites of water abstraction for municipal or industrial use. Permanent hydrometric stations provide real-time information of discharge that is essential for flood control planning and efficient operation of hydropower generation facilities in small catchments (e.g. NRC, 2004; USGS, 2004b).

Automated sample collection systems are available that divert water from the water body to a unit which fills sample bottles at preset time intervals or when remotely triggered to do so. Such sample collection mechanisms are particularly useful in remote locations where much time and effort may be spent traveling to and from the sampling site, especially if the required sampling frequency is high such as when estimates are being made of rainfall runoff or when loads are being calculated. The range of variables that can be determined in such samples is sometimes limited to those that will not be affected by the time delay between automatic collection and subsequent analysis in the laboratory, although some sampling systems enable the addition of chemical fixatives *in situ* and can refrigerate the samples until collection and analysis. Some automated sample collection systems can also be coupled to automatic analyzers capable of making a limited range of measurements within defined limits of accuracy (Glasgow *et al.*, 2004). All such remote and automated equipments do, nevertheless, require occasional maintenance and could also be subject to undesirable human interference.

Sediment

Sediments and particulate matter can be responsible for transporting and storing contaminants and nutrients in rivers and lakes. Monitoring programs involving sediment samples may be designed to determine, for example, the transport of contaminants in suspended sediment, storage of nutrients in surficial deposited sediment or the historical record of accumulation of contaminants over time. These three objectives require different approaches to the collection of the samples for analysis. The concentration of suspended sediments in rivers is closely related to discharge because of turbulent resuspension, especially during floods; thus it is essential that the discharge is known or measured at the time of sampling. Suspended sediment samples are usually collected in rivers by taking water samples using one of the methods mentioned above. The water samples can then be filtered or centrifuged to concentrate the sediment from the known volume of water sampled. In lakes, suspended sediment concentrations are determined from known volume water samples or using sediment traps. A simple sediment trap consists of a tube with a conical base ending in a collection vessel; the trap is usually suspended in the water column for a period of time ranging from hours to weeks. The tube collects all suspended material that is settling in the water column and can provide an estimate of sedimentation rates over time.

Sampling methods can affect data interpretation; for example, SPM is sampled by horizontal isokinetic samplers (to sample in such a way that the water-sediment mixture moves with no change in velocity as it leaves the ambient flow and enters the sampler intake) at several verticals in a cross-section of a river. SPM differs from TSS in a river sample because TSS samples are collected at one point on the river surface. Although, TSS may be very different from SPM for the same site at the same time, TSS are routinely used as a substitute for SPM to determine particulates fluxes because they are easier and much cheaper to obtain.

Samples of surficial deposited sediments in lakes or rivers can be collected by grabbing a volume of sediment with a scoop by hand (where the water is sufficiently shallow) or, in deeper waters, by using a remotely triggered grab sampler (Figure 2). Undisturbed samples that can be used to study the profile of grain size or chemical content with depth in the sediment (e.g. for historical studies) can be obtained using a coring device (Elliott and Tullett, 1978) (Figure 2). A full discussion of the use of particulate Q7 material in monitoring programs is available in •Thomas and Meybeck (1986).

Biological Samples

There are many ways in which biological samples are incorporated in water quality monitoring programs (Table 5) and the choice of sampling method is dictated by the biological approach being used. Most methods are either (i) passive, in which organisms are collected from their own environment for enumeration or analysis or (ii) active, in which organisms are deliberately placed into a particular environment and then removed for analysis at later intervals. Examples of some biological sampling methods are given in Table 4. Microbiological monitoring to determine whether water is of adequate quality for human consumption is the most widely performed water quality monitoring activity; it is carried out on surface and groundwaters, as well as treated water, prior to distribution to domestic users. Microbiological monitoring may also be included in monitoring programs designed to detect the impact of wastewater discharges, runoff from agricultural activity or the quality status of water resources. Samples must be collected, handled, and processed with special care to prevent contamination (see, for example, Myers and Wilde, 2003 for a detailed description of methods). Another common biological monitoring approach involves identifying and counting the invertebrates present at specific sites in a river and calculating a water quality index or pollution score (see Section on "Examples of monitoring programs"). This approach is based on the principle that certain organisms have particular environmental preferences or tolerances and can act as indicators of defined quality ranges (sometimes broadly correlated with physical and chemical quality indicators) (see following text). The index or score system usually prescribes the sampling and analysis method – the most common method of collecting samples is with a net, which provides a semiquantitative sample. Some of the more widely accepted methods have now been standardized by the ISO and by relevant national authorities. Planktonic organisms, suspended in the water column, can also be sampled by filtration, centrifugation, or sedimentation of a known volume of water sample collected by one of the water sampling methods described above and in Table 4. Particular groups of organisms can be collected by encouraging them to adhere to, or live on or in artificial substrates, such as glass or plastic plates with flat surfaces or baskets of stones (see Figure 2) (Chapman and Jackson, 1996).

Some groups of relatively immobile aquatic organisms provide useful media for studying the long-term pollution or recovery of water bodies with contaminants such as heavy metals or organic chemicals. These substances can be difficult to measure at low concentrations in the water, but are accumulated within the tissues of the organisms at concentrations higher than that found in the water itself. The higher concentrations can often be analyzed with less sophisticated equipment and thus enable detection in situations that might otherwise have been limited by available analytical equipment. Some organisms, such as those that feed on fine organic particles, can assimilate both dissolved and particulate contaminants, while others may specifically reflect the presence of substances dissolved in the water, or of accumulation in the aquatic food chain. When designing a monitoring program aimed at studying concentrations of contaminants in organisms it is important that the natural or background concentrations of the contaminant of interest, *in the specific tissues of the monitored organism*, should be known or determined in advance of the sampling program. An alternative approach is to use active monitoring, where organisms from a single batch or reference site, and with known background concentrations of the contaminant of interest, are placed in the water body to be monitored. Subsamples are then taken at time intervals for analysis.

EXAMPLES OF MONITORING PROGRAMS

The complexity of a monitoring program can range from regular measurements of one or two variables at a single site over a long time period to many physical, chemical, and biological variables at numerous sites and at varying time intervals, depending on the objectives. Every monitoring program should be designed to answer specific questions, that is, to generate data that can be used for research, management, or policy development. For this reason, there are many examples of different types of monitoring programs (Table 1) at local, national, regional, and even global scales (see Dixon and Chiswell, 1996 for a review of monitoring program design). Table 6 presents a selection of current examples of monitoring programs from around the world. More common approaches to water quality monitoring are highlighted in this section by reference to some specific examples.

Programs Based on Physical and Chemical Measurements

Some physical measurements can be very simple and inexpensive to perform, requiring relatively little training or expertise, and for these reasons they are incorporated in most monitoring programs (irrespective of whether they will yield useful information or not!). Methods range from the simple turbidity or transparency tube (e.g. Kent State University, 2004a) and Secchi disc (see following text) to handheld digital meters and *in situ* continuous monitoring

Table 5 Uses of biological methods for different types of water quality monitoring programs and their relative advantages and disadvantages

	Ecological methods						
	Indicator species[a]	Community studies[b]	Microbiological methods	Physiological and biochemical methods	Bioassays and toxicity tests	Chemical analysis of biota	Histological and morphological methods
Principal organisms used	Invertebrates, plants, and algae	Invertebrates	Bacteria and viruses	Invertebrates, algae, fish	Invertebrates, fish	Fish, shellfish, plants	Fish, invertebrates
Types of monitoring	Water quality status, impact surveys, trend monitoring	Impact surveys, trend monitoring	Operational surveillance, impact surveys	Early warning monitoring, impact surveys	Operational surveillance, early warning monitoring, impact surveys	Impact surveys, trend monitoring	Impact surveys, early warning monitoring
Types of pollution or other human impacts detected	Organic matter pollution, nutrient enrichment, acidification	Organic matter pollution, toxic wastes, nutrient enrichment	Human and animal fecal waste, organic matter pollution	Organic matter pollution, nutrient enrichment, toxic wastes	Toxic wastes, pesticide pollution, organic matter pollution	Toxic wastes, pesticide pollution, human health risks (toxic contaminants)	Toxic wastes, organic matter pollution, pesticide pollution
Advantages	Simple to perform. Relatively cheap. No special equipment needed. Trained biolo-gist/ecologist may be necessary	Simple to perform. Relatively cheap. No special equipment needed. Minimal biological expertise required	Can indicate risk to human health. Simple to perform. Relatively cheap. Very little special equipment required	Usually very sensitive. Commercial kits available for some methods. Cheap and expensive options. Some methods allow continuous monitoring	Usually simple to perform. Minimal equipment requirements. Fast results. Relatively cheap. Some continuous monitoring possible	Can indicate risk to human health. Requires less advanced equipment than for the chemical analysis of water samples	Some methods very sensitive. Simple and complex methods available. Cheap or expensive options
Disadvantages	Some methods only applicable within limited geographical area. Knowledge of taxonomy required. Results can be influenced by natural changes in aquatic environment	Relevance to aquatic systems not always tested. Results can be influenced by natural changes in aquatic environment	Organisms can be easily transported in water and thus it may be difficult to relate positive results to a specific pollution source	Specialized knowledge and techniques required for some methods	Laboratory-based tests not always indicative of field conditions	Analytical equipment and well trained personnel necessary. Generally expensive	Specialized knowledge required. Some special equipment needed for certain methods

[a]For example, biotic indices.
[b]For example, diversity or similarity indices. Modified from Friedrich *et al.* (1996).

Table 6 Examples of different types of water quality monitoring programs

Program type or name	Organizing agencies	Main aims or objectives	Key approaches	Further information
National water quality assessment program	Water Science Agencies (e.g. US Geological Survey), Environmental Protection Agencies, National Water Authorities	National water quality status and trends for rivers	Annual survey using water quality index based on benthic invertebrates	e.g. **http://water.usgs.gov/nawqa/** **http://www.epa.ie/Water/**
Great North American Secchi Dip-In	US EPA/North American Lake Management Society/Kent State University	National trends in eutrophication status of lakes and reservoirs	Citizen involvement; Annual measurement of transparency using a Secchi disc	**http://dipin.kent.edu**
Volunteer Lake Monitoring/Volunteer Stream Monitoring	US EPA Office of Water	National water quality status of lakes and of streams and rivers	Citizen involvement. Physicochemical and biological measurements at regular (e.g. monthly) intervals	**http://www.epa.gov/volunteer/** **http://www.ccmn.ca/english/**
GEMS/Water	United Nations Environment Programme (UNEP) and others	Assessment of global water quality and trends for rivers and lakes	Physical and chemical measurements at regular intervals. Results submitted to central database.	**http://www.gemswater.org/**
Lake recovery following controls on nutrient inputs	Lake Commissions and Environment Agencies	Trends in nutrients and trophic status	Nutrient concentrations and chlorophyll a	Commission internationale pour la protection des eaux du Léman, Lausanne
Suitability for withdrawal and treatment for public supply	All public water supply authorities in European Union (EU) countries	Compliance with quality criteria for water abstraction for public supply	Physical and chemical measurements as directed by EU Directives	**http://europa.eu.int/eur-lex/en/index.html**
Suitability for use in industrial or food processing	Individual process plants	Assessment of compliance with quality criteria of industrial process	Continuous online measurement of TOC, NH_4, pH	Numerous commercial examples
Early warning of contaminant upstream of water abstraction point	e.g. International Commission for the Protection of the Rhine	Warning of the presence of toxic chemicals or substances	Continuous bioassay using fish and *Daphnia* sp	**http://www.iksr.org/**

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instruments measuring, for example, temperature, oxygen, conductivity (as an indicator of total dissolved solids) or pH.

An indication of the trophic state of lakes, reservoirs, and ponds can be obtained from the measurement of transparency. Transparency is the ability of light to pass through the water column and is affected by particulate and dissolved material present in the water. It can be measured optically with a light meter or approximated by using a Secchi Disc (a flat round disc painted in black and white quarter segments). The depth at which the quartered disc disappears and reappears from sight when lowered and then raised in its horizontal position, is known as the *Secchi depth*. In eutrophic lakes, phytoplankton densities in the upper water layers can be very high, leading to reduced Secchi depth. Thus, measurements of Secchi depth provide a simple, inexpensive indicator of spatial or temporal variations in phytoplankton population density (and other suspended material) in lakes when biological expertise to identify characteristic species associated with nutrient enrichment is lacking. This simple technique is being used for a long-term monitoring program aimed at examining spatial differences and trends in the transparency of lakes throughout North America. Monitoring is performed on a designated day each year by volunteers and the results are submitted to a central database via the Internet. The program known as the *Great North American Secchi Dip-In* is coordinated by Kent State University, with the sponsorship of the United States Environmental Protection Agency (US EPA) and the North American Lake Management Society and commenced in 1994. Data are now available on more than 5900 water bodies (Kent State University, 2004b)

Carefully selected chemical measurements can often be used to indicate the impact of certain human activities on water quality. Typical examples are phosphorus, which is usually associated with sewage and domestic wastewater discharges, and nitrates, which are frequently associated with agricultural activities such as the use of inorganic fertilizers. Regular measurements of total phosphorus in Lake Geneva from the 1950s to the present time indicate the improvement in water quality resulting from efforts to control phosphorus in wastewater discharges (Figure 4). Monitoring water quality to determine the presence of, and/or recovery from, wastewater discharges can be based either on one or more selected chemicals that are known to occur in the effluent, such as a specific organic compound, or a general indicator measurement such as total organic carbon that can be automated and monitored continuously. For most regular monitoring activities, water samples are taken to the laboratory for analysis, but portable instruments exist for selected chemical measurements, such as nitrates. Although these instruments often have a narrow range of measurement and limited precision, they can be useful for emergency water quality monitoring, for obtaining a rough indication of a likely problem requiring more detailed investigation or for occasions where large distances need to be covered between sites without recourse to an analytical laboratory.

In some countries where technical resources are limited, water quality monitoring in river stretches affected by numerous industrial effluents or multiple sources of pollution is based on easily performed physical and chemical, and sometimes simple biological, measurements. The results from each site are compiled into a water quality index (usually based on a numerical score, e.g. 1–100) that provides a simple indication to policy makers of whether conditions are improving or getting worse. The Oregon Water Quality Index is just one of many examples – it is based on eight water quality variables (temperature, dissolved oxygen, BOD, pH, ammonia + nitrate nitrogen,

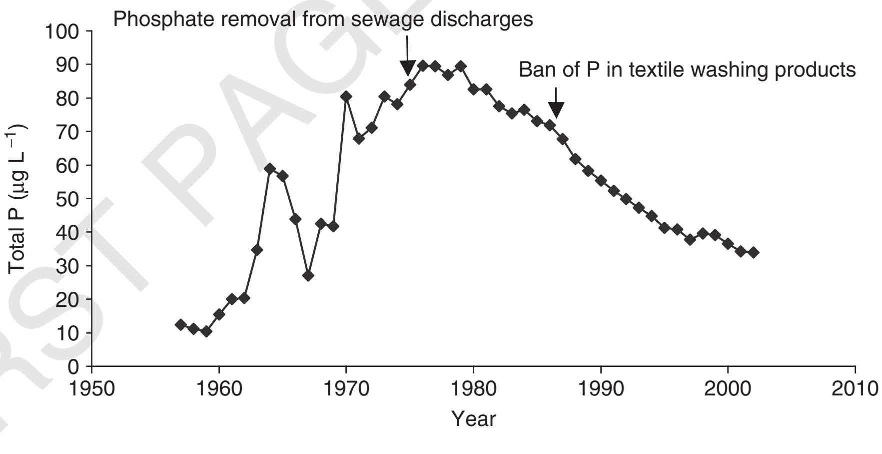

Figure 4 Decreasing concentrations of mean total phosphorus in Lake Geneva, reflecting improvements in water quality because of controls applied to wastewater discharges between 1973 and 2000 (Data from Commission Internationale pour la Protection des Eaux du Léman contre la pollution (CIPEL)). A color version of this image is available at http://www.mrw.interscience.wiley.com/ehs

total phosphorus, total solids, and fecal coliforms) and has been in use since the 1970s, although it has been updated recently to reflect recent understanding of water quality (Cude, 2001).

Biological Monitoring of Water Quality

Any change in water quality (whether natural or human-induced) usually affects, to some degree, the aquatic biota associated with the water body. Such effects, ranging from the death of sensitive species, to changes in the aquatic community structure, to metabolic changes or reproductive disorders and the accumulation of toxic substances in cells and tissues, have been exploited in many ways as a means of monitoring water quality or the "health" of a water body. Biological monitoring and assessment is now widely accepted as an effective means of determining the response of an aquatic system to human interference and different methods and approaches are being routinely included in many state, national, and regional assessments of water quality. In addition to water quality criteria based on physical and chemical measurements, biological quality criteria are now being built into regulatory standards to monitor point and nonpoint sources of pollutants into surface waters (Davis and Simon, 1995).

Even a quick visual or qualitative assessment of the biota present in a water body can give a rough evaluation of water quality or trophic status, especially if carried out by an experienced aquatic biologist. Such approaches range from simply identifying the common macrophytes present (if any), to lifting stones and examining them for specific invertebrate species, to taking semiquantitative benthic invertebrate samples with a net on a long pole. Such basic monitoring approaches can be developed into numerical indices that rank water quality, such as the many diversity, biotic, or similarity indices that are based on mathematical theory (Washington, 1984). One such example is the use of indicator species of macrophytes to assess the trophic status of rivers in the United Kingdom that are subject to wastewater discharges from sewage treatment works
Q8 (•Dawson *et al.*, 2000).

Benthic invertebrates are particularly suitable for monitoring water quality impaired by the presence of biodegradable organic matter because many species are sensitive to depletion of dissolved oxygen and they are relatively immobile. There are numerous examples of monitoring programs based on the presence or absence of sensitive benthic species, known as *indicator species*, and each has been (or should be) tailored to meet national or regional objectives. In general, the method is applicable to a wider geographical area when the score is based on the family level of identification as in the Biological Monitoring Working Party Score (BMWP) (ISO-BMWP, 1979).

Indictor species can even be used for rapid, on-site bioassessment of the effects of biodegradable organic wastes in rivers. Typically, benthic invertebrates are collected in shallow stretches of the rivers by kicking up the substrate and collecting dislodged invertebrates in a net on a long pole (Figure 2). The relative abundance of easily identifiable indicator species is noted whilst still in the field. The presence or absence of certain species, together with their relative abundance, enables the sample to be assigned an index. In Ireland, the sample is assigned a Q value ranging from Q1 to Q5 – the higher the Q value, the better the species community diversity and the better the water quality. Where additional observations are made, such as dissolved oxygen measurements, the presence of silt, and so on, the Q value can be assigned more accurately to correspond with four major water quality classes (McGarrigle *et al.*, 2002):

Class A Unpolluted (Q5, Q4–5, Q4); Class B Slightly polluted (Q3–4); Class C Moderately polluted (Q3, Q2–3); Class D Seriously polluted (Q2, Q1–2, Q1). This approach forms the basis of the Irish national river water quality monitoring program where designated sites are sampled at the same time of the summer each year. The results provide the data for the annual reports of water quality that identify trends in impacts from agriculture and other sources of biodegradable organic waste, such as sewage discharges, and the food processing and dairy industries (McGarrigle *et al.*, 2002; Clabby *et al.*, 2003; EPA, 2004). The simple classification enables policy makers and the public to see whether river water quality is improving or not (Figure 5). The cost-effectiveness of such approaches makes them particularly attractive for use in developing countries, but it is essential that the method is validated in the region of interest before being put into widespread use (e.g. Henne *et al.*, 2002).

Recent developments in the use of biological monitoring include the setting of biological criteria for water bodies (equivalent to water quality criteria based on physical and chemical standards) based on a variety of numerical indices (e.g. diversity indices (Washington, 1984)), indicator species, fish stock assessments, and so on. An example of the development of such indices has been presented by •Yoder and Rankin (1995). The approach has been Q9
endorsed by the USEPA (US EPA, 1999a; Hall *et al.*, 2000) as a means of describing reference conditions of aquatic communities inhabiting water bodies that have been designated for specific uses. Their use can aid the detection of impacts on water bodies, indicate whether a water body is meeting the quality criteria for its designated uses and indicate whether additional monitoring is necessary (Simon, 2000). The success of these criteria is based on the widely accepted premise that biological data are a better predictor of environmental impacts than chemical or toxicological data, especially when other information on the nature of the impact is lacking (Simon, 2000).

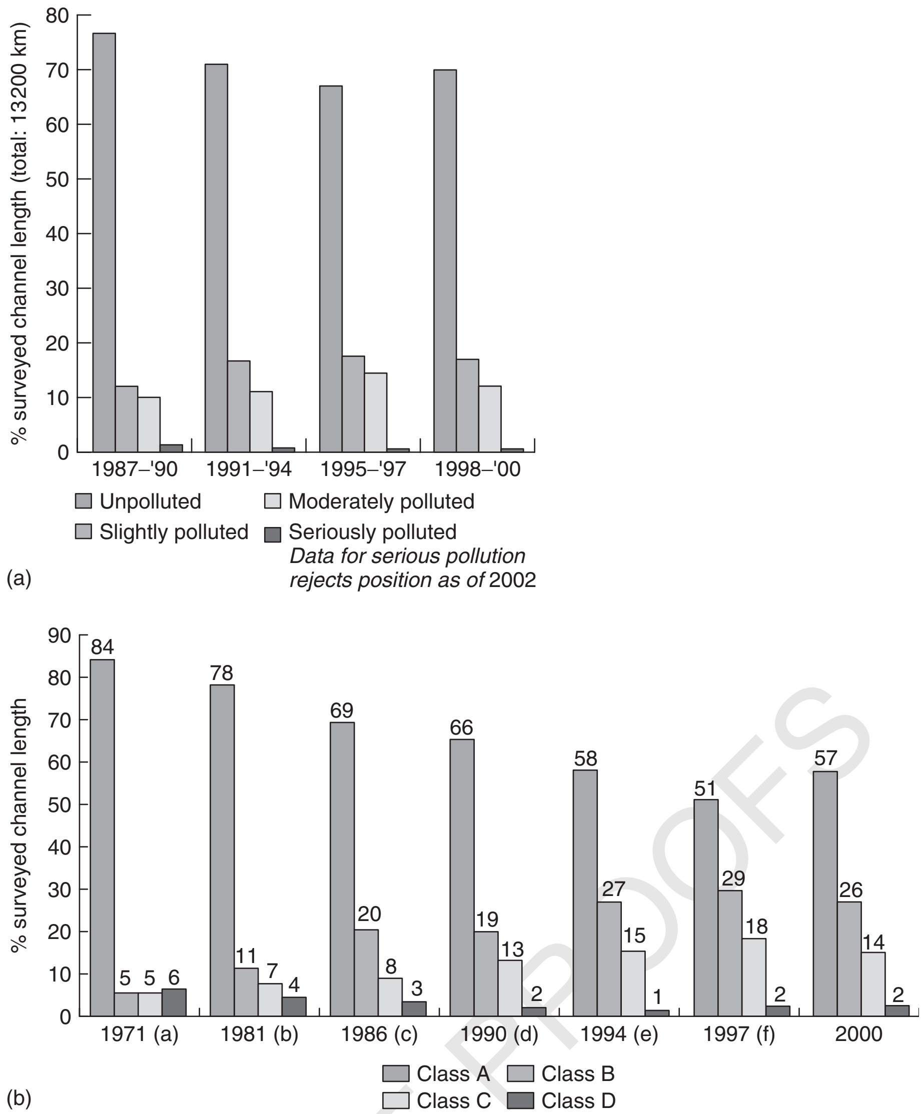

Figure 5 Changes in river water quality in Ireland as indicated by a biological assessment procedure. From McGarrigle *et al.*, 2002 (with permission from the Environmental Protection Agency) (**`http://www.epa.ie/NewsCentre/ReportsPublications/IrelandsEnvironment2004/`**). A color version of this image is available at http://www.mrw.interscience.wiley.com/ehs

Monitoring Toxic Pollution

Deliberate or accidental discharges of toxic compounds into water bodies upset the natural water quality, present a risk to the aquatic ecosystem, and may pose a threat to human health if the water is to be extracted for municipal use. Monitoring designed to establish the spatial and temporal extent of the discharge may take the form of a limited duration survey if the discharge is short-lived, but could also involve routine evaluation of the water quality if the discharge is continuous or long-term (as in some industrial discharges). Measuring chemical compounds can be expensive and require technically advanced equipment. Thus, when the discharge has known toxic potential, or when a combination of compounds could lead to toxic impacts, it can be simpler (and sometimes cheaper) to use a routine bioassay technique. Many toxicity and bioassay methods have been standardized (see ISO, 2004a) and some, such as the *Salmonella* mutagenicity assay (Ames test), have been incorporated into local or regional water quality monitoring programs, for example, São Paulo State, Brazil (Umbuzeiro *et al.*, 2001). Changes in the activity of fish in response to adverse environmental conditions, that is, a change in water quality, have been incorporated into biological early warning systems that monitor water quality upstream of water intake points on highly industrialized rivers. The river water is diverted

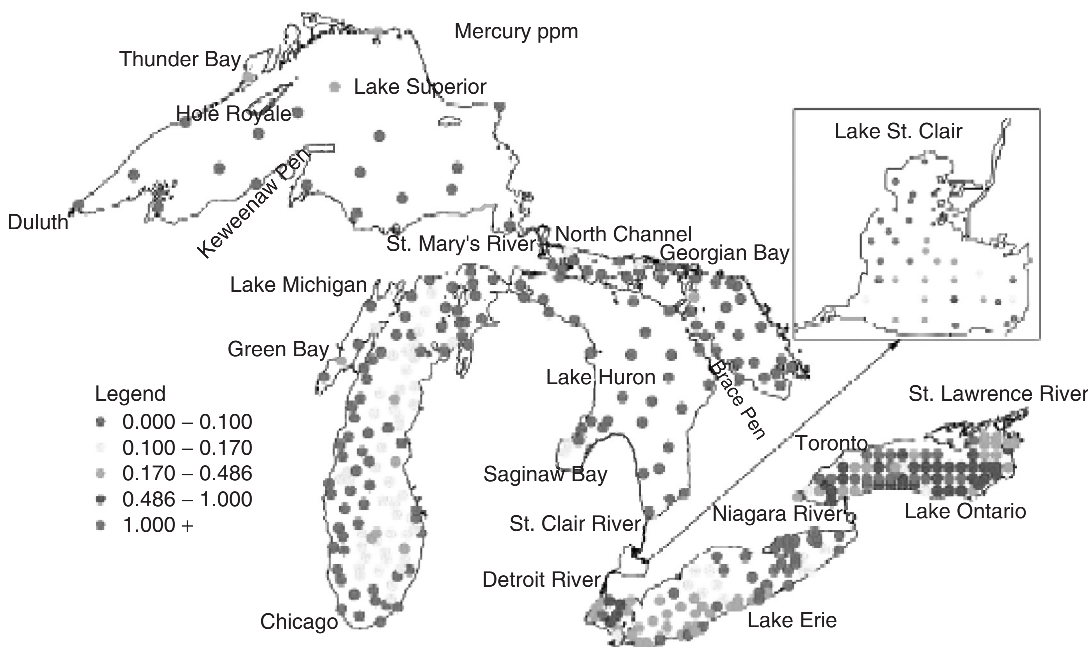

Figure 6 Total mercury concentrations in surficial sediments of the Great lakes (1997–2000). Spatial and temporal trends in surface water and sediment contamination in the Laurentian Great Lakes. *Environmental Pollution*, **129**, 131–144. (Reprinted from Marvin *et al.*, 2004. © 2004, with permission from Elsevier). A color version of this image is available at http://www.mrw.interscience.wiley.com/ehs

through tanks containing live fish and detectors register the levels of their activity.

Potentially toxic contaminants released to the environment from various human activities are transported with atmospheric deposition, runoff or direct discharge to surface water bodies. Persistent substances can accumulate in sediments to concentrations above those in the water itself and which can be more easily detected. Deposited sediments can also be used to illustrate historical changes in the concentration of persistent compounds or metals in the environment (e.g. Van Metre *et al.*, 1998). Sediments have been used in the long-term and spatial monitoring of contaminants such as mercury in the Great lakes of North America and Canada (Figure 6) (Marvin *et al.*, 2004)

Community and Citizen Monitoring Programs

The growing demand for information about water quality from policy makers and the public is stretching the resources of many government agencies and local authorities, and they can no longer keep up with the demand for monitoring data. One approach to meeting the demand for information while minimizing costs, is to involve local people or other interested citizens in monitoring activities. Such volunteer programs, that range from simple activities such as the Great North American Secchi Dip-In (see above) to detailed lake and stream monitoring (e.g. US EPA Office of Water; Canadian Community Monitoring Network) are proving to be extremely valuable for generating water quality information and even for getting local people involved in the management of their water resources. Training programs and instruction manuals for citizens are available from many State agencies (e.g. US EPA, 1997, 2004; •CCMP, 2004). Q10

DATA HANDLING AND REPORTING

Data handling and reporting are the final steps of the water quality assessment process (see Figure 1). In the past, there was a tendency to archive data sets generated from monitoring activities with very little scrutiny or interpretation of the data. As a result, the data generated were not transformed into useful information and rarely served the purpose of management or policy generation or refinement (Ward *et al.*, 1986). Data collection is the principal objective of all monitoring activity and in order to make the monitoring effort worthwhile, the data generated must be assessed or synthesized to provide meaningful information for management, policy guidance, or public use. Advances in computer-based data storage and handling facilities have not only made it easier to share data and to analyze it and present it in many different ways, but they have also created a stronger need to ensure the quality, compatibility, and comparability of data made freely available, especially through the Internet. Developments in online accessibility to databases, combined with a need for public accountability, has led to many international, national, or state agencies providing access to raw and/or synthesized data through the Internet (e.g. EEA, 2004; USGS 2004e). All data made available for public use must be reliable (see above regarding quality of data).

Modern monitoring techniques often result in data that is stored directly onto the electronic media from field or analytical equipment, using personal digital assistants (PDAs), field computers, data loggers, telemetric transfer mechanisms or cabled links. In addition, the widespread availability of inexpensive, handheld Global Positioning System (GPS) units has led to greater use of Geographic Information Systems (GIS) in data storage and presentation. Nevertheless, some information such as that recorded in the field by a field operator may have to be entered into a database manually and it is therefore essential that quality assurance procedures are applied as rigorously to data storage and handling activities as to any other step in the complete monitoring process (see following text). Links should be maintained between all relevant data that could have a bearing on the interpretation of any particular data set so that misinterpretation is avoided. For example, it is important that discharge data are available in association with water quality data for rivers; this might necessitate combining data from a hydrometric database with that from a different water quality database.

QUALITY ASSURANCE AND CONTROL

The data generated from a monitoring program must be of high quality, reliable, credible and, as far as possible, compatible with data generated from similar monitoring programs. This should be achieved through a rigorous process of quality assurance applied at all stages of the monitoring process, from sample collection in the field to data storage. It has been suggested by Meybeck *et al.* (1996) that approximately 10–20% of the total financial, technical, and personnel resources available in any monitoring program should be devoted to quality assurance procedures. For data compatibility with other monitoring programs, it is useful to adopt standardized methods, such as those published by the International Organization for Standardization (ISO) (ISO, 2004a), the German Industrial Standards (DIN – Deutsche Industrie-Normen), US EPA or other national standards where available. If accreditation and validation by a third party is not appropriate (perhaps because of the expense involved) quality assurance can be implemented by reference to international standards such as ISO 9000 or ISO 14000 (ISO, 2004b).

Whereas quality control may be very familiar to those working in an analytical laboratory, it is much less so to workers engaged in field work or nonchemical monitoring methods. Quality control for field sampling and measurements can be achieved by thorough training and the provision of detailed written operation procedures or manuals. Such procedures should also specify the appropriate storage and handling for the analysis that is to follow, ensuring that no deterioration or changes in composition can take place that might influence the eventual analytical results. Field note books or record sheets should always be used to record all necessary information in the field, such as the time, date, and location of sample collection, depth, method used, measurements taken, deviations from standard procedures, and so on. These notebooks can help variations from expected analytical results to be checked for possible explanations, such as unforeseen environmental influences, deviation from standard methodology or sampling site, and so on. From the point of sampling, all samples should be logged with a unique identification code that accompanies the sample through its handling and analysis in the laboratory to the final output and storage of results. In this way it is possible to trace the history of each sample including, for example, whether the sample was split for different analyses, diluted, concentrated, and so on. All equipment, whether field or laboratory, should be properly maintained and periodically calibrated (where appropriate) in accordance with the manufacturers' recommendations. Records of these activities should also be kept.

Analytical Quality Control

Analytical quality control is well established in many laboratories involved in water quality monitoring programs and demonstrates that the laboratory is producing data of adequate precision, accuracy, and sensitivity. It is based on a system of traceability and feedback; for this purpose a laboratory logbook should be maintained for all analytical procedures to which samples are submitted. There are two main aspects to analytical quality control: internal quality control and external quality control. The former involves the choice of method appropriate to the objectives of the monitoring program, and the validation of the method. Validation includes determining (i) the linearity of the calibration, (ii) the limit of detection, (iii) within-day or day to day precision, and (iv) the accuracy of the method. Typical methods for checking validity include:

- the inclusion of a blank sample, for example, distilled water, in a batch of analyses,
- duplicate analyses carried out on the same sample, and
- the use of certified reference materials.

The use of reference materials in routine analysis and the production of Shewhart charts enable a continuous check to be kept on the precision and accuracy of the technique (Briggs, 1996). Where problems are encountered, they should be addressed.

External quality control is particularly important where different laboratories contribute results to a single monitoring program and for which comparability between the data generated by the participating laboratories is important (e.g. USGS, 2004c). External quality control also provides a method by which a laboratory can have its own accuracy checked independently (e.g. USGS, 2004d). Samples with known and unknown concentrations of the relevant variables are distributed to participating laboratories from a single reference laboratory. Each laboratory analyses the samples and reports its results to the reference laboratory. The deviation of each laboratory from the target value of each individual analysis is reported to the participating laboratory together with comments on whether the accuracy of the results submitted is satisfactory or not (Briggs, 1996; USGS, 2003). If the results show poor accuracy, measures should be taken by the laboratory to improve performance and the level of confidence associated with the results from that laboratory should be associated with any data made available for comparison with results from other laboratories. Laboratories providing data to national or regional databases may be required to take part in national accreditation programs (e.g. NWQMC, 2004b). As a general rule about 10% of all analyses should include external quality assurance samples.

Data Checking and Validation

The full process of quality control in a monitoring program should extend to the handling and storage of the data. Results should be scrutinized as soon as they are generated and before they are stored in a database or entered into reports. Inexplicable results should either be omitted from reports or flagged and, where possible, a degree of confidence assigned. The sudden or unexpected occurrence of unusually high or low values should automatically initiate checks on all stages of the sample handling and processing from collection in the field to final analysis in the laboratory. Events that could have resulted in unusual results, such as flood conditions in a river, change in the method of sampling, different analytical procedure, and so on, should have been recorded in field and laboratory notebooks. Where no explanation can be found, equipment and reagents should be checked and instruments should be recalibrated. Errors can be introduced in the manual copying of instrumental outputs or readings and their transcription from one notebook to another or onto a computer through keyboard entry. Many modern instruments will connect directly to the computer and transfer data electronically, thus reducing the risk of transcription errors. Databases for storing monitoring data can be arranged to highlight results that do not fall within expected ranges and this acts as another check on their validity.

CONCLUSIONS

Monitoring programs to define water quality occur at local, national, regional, and even global scales. These programs take many forms depending on the specific program objectives, varying from highly specific measurements associated with regulatory compliance to broad, multidisciplinary programs aimed at defining environmental quality status. The methods and approaches that are currently in widespread use vary from simple physical measurements to determination of trace concentrations of complex organic chemicals, from identifying the presence or absence of key indicator organisms to measuring physiological and biochemical processes in organisms, and from annual sampling events to determine long-term trends to intensive or continuous discharge-linked measurements to determine fluxes. Modern requirements to make monitoring data and their interpretation available to diverse users, including policy makers, other monitoring programs and often the general public, has placed an even greater emphasis on the need for quality assurance of monitoring data. Quality assurance techniques need to be applied to all of the steps involved in the gathering of monitoring data – from field sample collection, to laboratory analysis, to data handling and storage. This overview has highlighted some of the diverse approaches currently taken to monitoring water quality and the key steps involved in the monitoring processes.

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Keywords: water quality monitoring; surveys; field measurements; monitoring program design; quality assurance

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