Chapter 3 - DESIGNING A MONITORING PROGRAMME

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The design of a monitoring programme should be based on clear and well thought out aims and objectives and should ensure, as far as possible, that the planned monitoring activities are practicable and that the objectives of the programme will be met.

It is useful to prepare a programme document or study plan, which should begin with a clear statement of the objectives of the programme and a complete description of the area in which the monitoring is to take place. The geographical limits of the area, the present and planned water uses and the present and expected pollution sources should be identified. Background information of this type is of great help in preparing a precise description of the programme objectives and in deciding on some of the elements of the study plan. Subsequent sections of the study plan should cover the locations and frequency of sampling and the variables for analysis. The plan should also specify whether the analyses will be done in the field or in the laboratory. This decision must take into consideration the resources available for all the necessary field and laboratory work, data handling, analysis and interpretation, and the preparation and distribution of reports.

The principal elements of a study plan are:

• a clear statement of aims and objectives,

• information expectations and intended uses,

• a description of the study area concerned,

• a description of the sampling sites,

• a listing of the water quality variables that will be measured,

• proposed frequency and timing of sampling,

• an estimate of the resources required to implement the design, and a plan for quality control and quality assurance.

3.1 Purpose of monitoring

The principal reason for monitoring water quality has been, traditionally, the need to verify whether the observed water quality is suitable for intended uses. However, monitoring has also evolved to determine trends in the quality of the aquatic environment and how the environment is affected by the release of contaminants, by other human activities, and/or by

waste treatment operations. This type of monitoring is often known as impact monitoring. More recently, monitoring has been carried out to estimate nutrient or pollutant fluxes discharged by rivers or groundwaters to lakes and oceans, or across international boundaries. Monitoring for background quality of the aquatic environment is also widely carried out, as it provides a means of comparing and assessing the results of impact monitoring.

No monitoring programme should be started without critically scrutinising the real needs for water quality information. Since water resources are usually put to several competing beneficial uses, monitoring should reflect the data needs of the various water users involved.

The implementation of a monitoring and assessment programme may focus on the spatial distribution of quality, on trends, or on aquatic life. Full coverage of all three elements is virtually impossible, or very costly. Consequently, preliminary surveys are necessary in order to determine the focus of the operational programme.

The monitoring and assessment of water quality is based, ultimately, upon the fundamental physical, chemical and biological properties of water. However, water quality monitoring and assessment is a process of analysis, interpretation and communication of those properties within the wider context of human activity and use, and the conservation of the natural environment. It is not a fixed process, therefore, but is adapted in the light of local, national or international needs. The final aim is to provide information useful for management. Styles and strategies of management vary greatly, depending on institutions, resources and priorities.

Water quality monitoring and assessment can be conducted from a number of different perspectives which may combine the following goals in different ways:

• Uses of water. Does water meet user requirements for quantity and quality? (For example, with respect to meeting use-defined standards. In this context conservation of biodiversity may be considered a water use.)

• Influences on water quality from direct use or from other human activities or natural processes. What are these influences?

• Impacts on water quality (e.g. water as a medium for pollutant transport and exposure).

• Control and regulation of water quality. What is the capacity of water to assimilate pollutants? Are standards met? Are control strategies and management action appropriate and effective?

• How does water quality differ geographically in relation to uses and quality influences?

• How have past trends in water quality, influences and policies led to the present status?

• What factors in present water quality and in the past, present and planned activities, give an insight into future trends? What will these be?

• How does water quality influence other parts of the environment, such as marine coastal waters, soils, biota, wetlands?

These are examples of the types of goals, answers or information that are sought in undertaking water quality monitoring. They approach water quality from different

perspectives in terms of basic variables and present status, time trends and spatial differences, uses, pollution impacts and management needs for information for decisions and action. These differences will result in different approaches to the design and implementation of monitoring programmes, to the selection of variables to be measured, to the frequency and location of measurements, to the additional information needed for interpretation and to the way in which information is generated and presented to meet particular information requirements.

3.2 The need for information for management

When a water quality monitoring programme is being planned, water-use managers or similar authorities can reasonably expect that the programme will yield data and information that will be of value for management decision-making. The following are examples of the type of information that may be generated by a monitoring programme:

• How the quality and quantity of water in a water body relate to the requirements of users.

• How the quality and quantity of water in a water body relate to established water quality standards.

• How the quality of water in a water body is affected by natural processes in the catchment.

• The capacity of the water body to assimilate an increase in waste discharges without causing unacceptable levels of pollution.

• Whether or not existing waste discharges conform to existing standards and regulations.

• The appropriateness and effectiveness of control strategies and management actions for pollution control.

• The trends of changes in water quality with respect to time as a result of changing human activities in the catchment area. Quality could be declining as a result of waste discharges or improving as a result of pollution control measures.

• Control measures that should be implemented to improve or prevent further deterioration of water quality.

• The chemical or biological variables in the water that render it unsuitable for beneficial uses.

• The hazards to human health that result, or may result, from poor water quality in the water body.

• How developments in the catchment area have affected or will affect water quality.

• The effects that deteriorating water quality have on plant and animal life in, or near, the water body.

The list above is not exhaustive, it merely provides examples. The information required from a monitoring programme does, however, provide an indication of the type of programme that should be implemented. Some monitoring programmes will be long-term and intended to

provide a cumulative body of information; others will have a single objective and will usually be of short duration.

3.3 Objectives of water quality monitoring

It is particularly important that the objectives of a water quality monitoring programme be clearly stated and recorded. The very act of writing them down generally results in careful consideration being given to the possible options. Written objectives help to avoid misunderstandings by project participants, are an effective way of communicating with sponsors, and provide assurance that the monitoring programme has been systematically planned. They are also important when the programme is evaluated to determine whether or not the objectives are being met.

The objectives may be very general, such as when monitoring is for several purposes or when it would be premature to prepare highly detailed objectives, whereas statistical descriptions of objectives are usually reserved for the more advanced types of monitoring programme. To help with the establishment of objectives, the following questions might be addressed:

• Why is monitoring going to be conducted? Is it for basic information, planning and policy information, management and operational information, regulation and compliance, resource assessment, or other purposes?

• What information is required on water quality for various uses? Which variables should be measured, at what frequency and in response to which natural or man-made events?

• What is practical in terms of the human and financial resources available for monitoring? There is little point in setting unrealistic objectives.

• Who is responsible for the different elements of monitoring?

• Who is going to use the monitoring data and what are they intending to do with the information? Will it support management decisions, ensure compliance with standards, identify priorities for action, provide early warning of future problems or detect gaps in current knowledge?

The following is a list of typical monitoring objectives that might be used as the basis for design of sampling networks. The list is not intended to be exhaustive, merely to provide some examples.
• Identification of baseline conditions in the water-course system.

• Detection of any signs of deterioration in water quality.

• Identification of any water bodies in the water-course system that do not meet the desired water quality standards.

• Identification of any contaminated areas.

• Determination of the extent and effects of specific waste discharges.

• Estimation of the pollution load carried by a water-course system or subsystem.

- Evaluation of the effectiveness of a water quality management intervention.

- Development of water quality guidelines and/or standards for specific water uses.

- Development of regulations covering the quantity and quality of waste discharges.

- Development of a water pollution control programme.

There are two different types of monitoring programmes: those with a single objective which are set up to address one problem only, and multi- objective programmes which may cover various water uses, such as drinking water supply, industrial manufacturing, fisheries, irrigation or aquatic life. It is rare that a monitoring programme has a single objective. In practice, programmes and projects generally combine multiple objectives and data are used for multiple purposes. Monitoring with several objectives is commonly the first major, national programme to be established in a country. The design of such programmes requires preliminary survey work, so that the selection of sampling sites takes into account such considerations as actual and potential water uses, actual and potential sources of pollution, pollution control operations, local geochemical conditions and type(s) of water body.

Data may also be shared between agencies with similar or distinct objectives. In the case of the river Rhine, early warning monitoring for contamination is carried out in the upstream part of the river by the authorities in Switzerland. The information is passed on to downstream countries (Germany and France), who contribute to the cost of the exercise.

3.4 Preliminary surveys

When a new programme is being started, or a lapsed programme is being reinstated, it is useful to begin with a small-scale pilot project. This provides an opportunity for newly trained staff to gain hands-on experience and to confirm whether components of the programme can be implemented as planned. It may also provide an opportunity to assess the sampling network and provide indications of whether more (or possibly fewer) samples are needed in order to gain knowledge of the water quality at various points throughout a water body.

During the pilot project or preliminary survey it is important to test assumptions about the mixing of lakes, reservoirs and rivers at the selected sampling sites and times. It might be appropriate, therefore, to consider variations in water quality through the width and depth of a river at selected sampling sites throughout an annual cycle in order to confirm the number of samples required to produce representative data (see section 3.7.1).

In a lake or reservoir, it may be necessary to sample at different points to determine whether water quality can be estimated at a single point or whether the lake or reservoir behaves as a number of separate water bodies with different water quality characteristics. It is also essential to investigate variation in water quality with depth and especially during stratification. Lakes and reservoirs are generally well-mixed at overturn (i.e. when stratification breaks down) and sampling from a single depth or the preparation of a composite sample from two depths may adequately represent the overall water quality (see section 3.7.2).

For groundwaters, it is important during preliminary surveys to confirm whether or not the well casing is perforated, allowing access to more than one aquifer. If this is the case then an alternative site should be sought or measures taken to sample from a single aquifer only. The latter is generally problematic.

Preliminary surveys also help to refine the logistical aspects of monitoring. For example, access to sampling stations is tested and can indicate whether refinements are necessary to the site selection. Sampling sites could also be found to be impractical for a variety of reasons, such as transport difficulties. Similarly, operational approaches may be tested during the pilot project and aspects such as the means of transport, on-site testing techniques or sample preservation and transport methods, can be evaluated. Sample volume requirements and preservation methods can then also be refined.

Preliminary surveys also provide opportunities for training staff and for ensuring that staff are involved in the planning process. Such involvement, together with the undertaking of preliminary surveys, may often avoid major problems and inefficiencies which might otherwise arise.

3.5 Description of the monitoring area

The description of a monitoring area should consider as a minimum:

• definition of the extent of the area,

• a summary of the environmental conditions and processes (including human activities) that may affect water quality,

• meteorological and hydrological information,

• a description of the water bodies, and

• a summary of actual and potential uses of water.

A monitoring programme commonly covers the water-course system of a catchment area (i.e. a main river and all its tributaries, streams, brooks, ditches, canals, etc., as well as any lakes or ponds that discharge into the river or tributaries). The catchment area is defined as the area from which all water flows to the water-course. The land surface that slopes in such a way that precipitation falling on it flows towards the water-course is called the topographic catchment area. In some cases groundwater enters the water-course system from a groundwater catchment area, all or part of which may lie outside the topographic catchment. Topographic and groundwater catchment areas are rarely coincident.

Since a water-course system may be very large, it is often convenient to divide the catchment into several small sub-catchments. A catchment area, and its associated water-course, is hydrologically and ecologically discrete and, therefore, constitutes a logical unit for the planning and management of water use and for the monitoring of water quality. The dynamics of upstream water quality and sources of pollution can be related to downstream effects. A description of the catchment area includes its size (in km^2), its geographical location and the identification of each water body in the water-course system.

3.5.1 Conditions and processes

Environmental conditions in the catchment area should be described as fully as possible, because these have an effect on water quality and it may be useful to refer to this material when data are being evaluated. The natural processes that affect water quality have been described in Chapter 2. Reference should be made to these processes when the description of environmental conditions is prepared. In particular, rock composition, vegetation (both terrestrial and aquatic), wildlife, land form, climate, distance from salt-water bodies, and

human activities in the catchment area should be reported. Human activities should be described mainly in terms of population and land use. The presence of cities and towns and the use of land for industry, agriculture, forestry or recreation are of interest.

3.5.2 Meteorological and hydrological information

Rainfall and ensuing run-off are of vital importance, especially when the programme includes the monitoring of fluxes or suspended loads of eroded materials. Some data interpretation techniques also require reliable hydrological information. If there is a gauging station or hydroelectric power plant near a sampling location, reliable data on river flow should be available. If they are not, estimates of flow can be based on data from the closest stream gauging station. As a last resort, it may be possible to estimate run-off from a calculation involving precipitation on the catchment area, the surface area of the catchment, a run-off factor and a time-of-flow factor. Measured values, however, are always much better than estimates. Where estimates have to be made, it is appropriate to request the assistance of experts in the hydrological services. Further information on hydrological measurements and calculation of flux is available in Chapter 12.

3.5.3 Water bodies

Reservoirs and lakes in the catchment should be described by their area, depth and, if possible, volume (calculated from bathymetric maps). The theoretical retention or residence time of a lake (see section 2.1.1) can vary from months for some shallow lakes to several decades (or more) for the largest lakes. In some cases rivers discharge into continental water bodies without outlets, such as the Dead Sea and the Aral Sea. These water bodies act as terminal recipients for surface waters. The characteristics of lakes frequently result in incomplete mixing (see section 2.1.2) and actual residence times vary widely because lake waters are, as a consequence, rarely homogeneous.

Figure 3.1 Schematic representation of the water balance of a lake
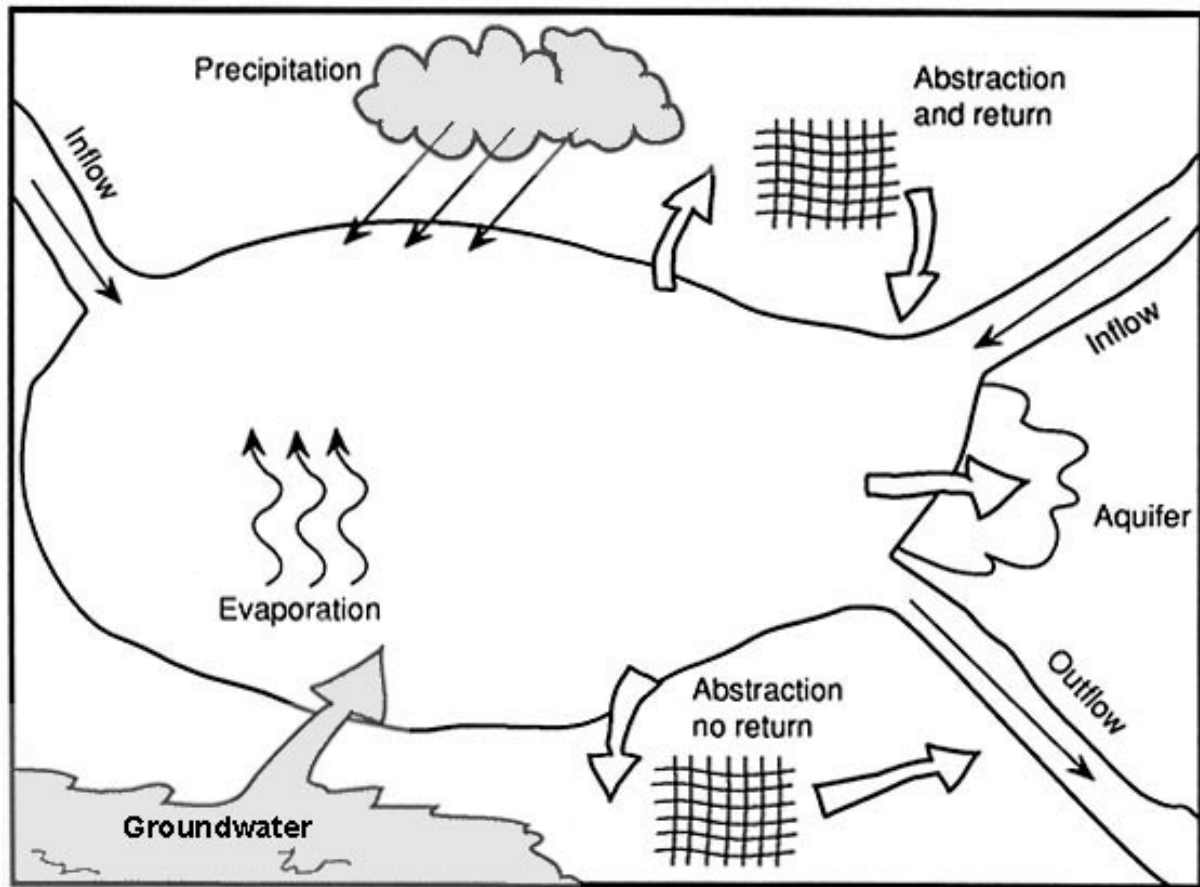
Impounded rivers and lakes are subject to a wide range of influences. The composition of the water in a lake or reservoir is influenced by the water budget, i.e. by the balances between inputs and outputs, by interchanges between the water column and sediments, and by the build-up of organic matter as a result of biological activity. However, the major inputs are usually from tributary rivers and streams that may carry a range of materials of both natural and artificial origin. There may also be point discharges directly into the lake, e.g. sewage and industrial wastes, and diffuse discharges from agricultural drainage, underground sources and rainfall. The major outputs from lakes are rivers and direct abstraction for public, agricultural and industrial use. Other outputs include evaporation and loss to groundwater. The water balance of a lake is shown schematically in Figure 3.1.

Rivers and streams should be described by their dimensions and their flows. A hydrograph, if available, provides particularly useful information. A map showing the catchment area of the river and the course that it follows is also useful. Features such as waterfalls, rapids, narrow and broad sections should be shown on the map and any unusual features described in the report. The location of man-made structures, e.g. bridges, dams, wharves, levees, gauging stations and roads leading to the river, should be shown on the map and described in the text of the report. The location of roads and trails through the monitoring area should also be shown, together with information on whether they are usable in all seasons of the year.

Figure 3.2 Interactions between surface water and groundwater (After Foster and Hirata, 1988)
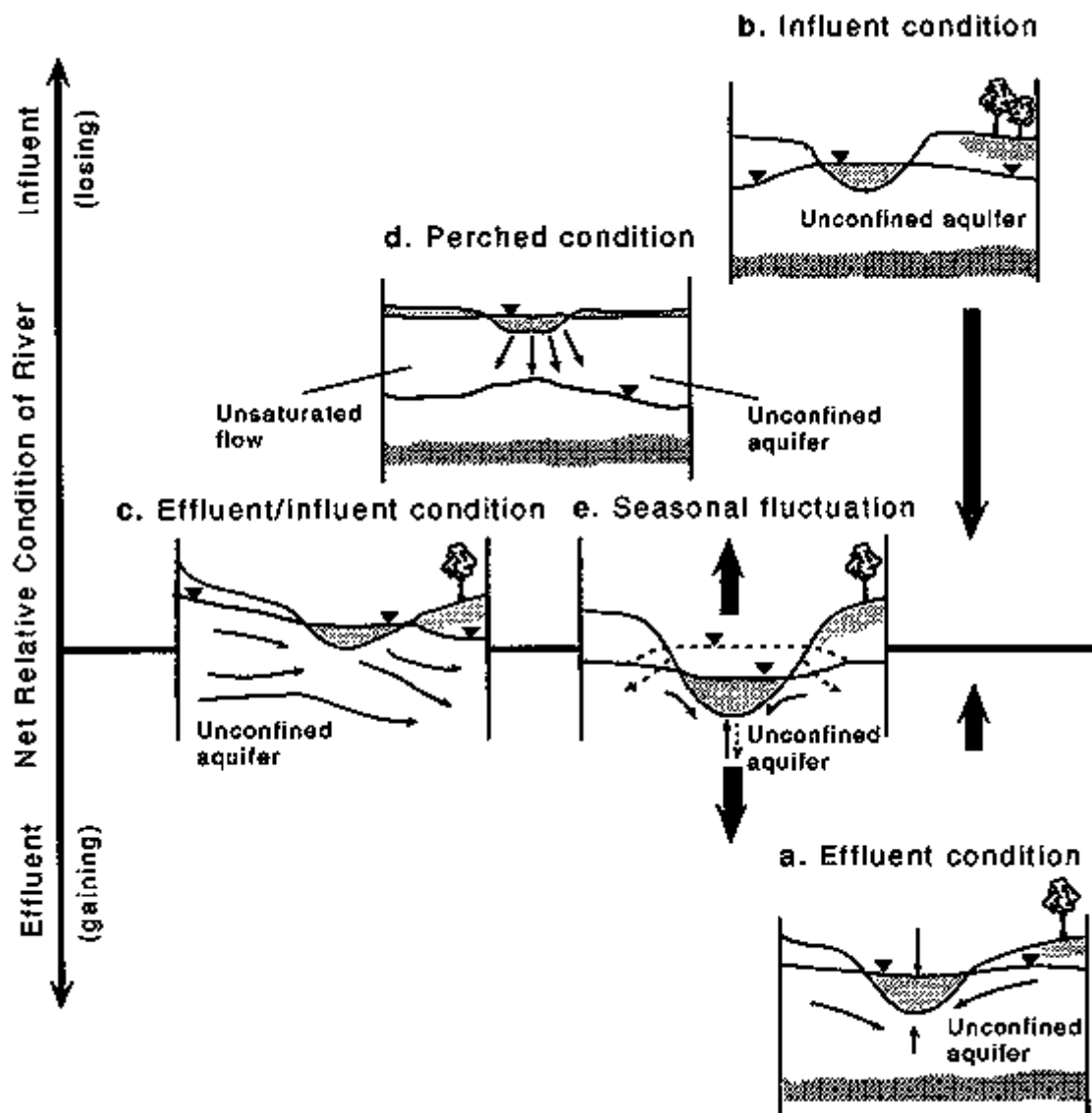
The description of aquifers will include extent, rock types, whether confined or unconfined, charts of water levels or piezometric head, main recharge and discharge areas and surface water-courses in hydraulic continuity with the aquifer (Figure 3.2).

3.5.4 Water uses

Present uses of water should also be identified in the description of the monitoring area and the quantities withdrawn should be determined and listed. Many users contaminate the water during its use and return it to the stream or lake in a worse condition than when it was withdrawn. A possible exception to this is hydroelectric power generation where some aspects of water quality may be completely changed, for example by reduction of suspended solids and the increase of dissolved oxygen. Some of the common uses of water were listed in Table 2.3, together with their classification as consuming and/or contaminating. Any water uses that are planned but not implemented should also be included in the report, and the list may be supplemented by an identification of point and non-point sources of pollution.

Table 3.1 Links between types of monitoring site and programme objectives

| Type of site	Location	Objectives
Baseline site	Headwater lakes or undisturbed upstream river stretches	To establish natural water quality conditions To provide a basis for comparison with stations having significant direct human impact (as represented by trend and global flux stations) To test for the influence of long-range transport of contaminants and the effects of climatic change
Trend site	Major river basins, large lakes or major aquifers	To test for long-term changes in water quality To provide a basis for statistical identification of the possible causes of measured conditions or identified trends
Global river flux site	Mouth of a major river	To determine fluxes of critical pollutants from river basin to ocean or regional sea Some trend stations on rivers also serve as global flux stations

Source: Based on the GEMS/WATER monitoring programme

3.6 Selecting sampling sites

Processes affecting water quality and their influence should be taken into account when sampling sites are selected. A sampling site is the general area of a water body from which samples are to be taken and is sometimes called a "macrolocation". The exact place at which the sample is taken is commonly referred to as a sampling station or, sometimes, a "microlocation". Selection of sampling sites requires consideration of the monitoring objectives and some knowledge of the geography of the water-course system, as well as of the uses of the water and of any discharges of wastes into it (Table 3.1). Sampling sites can be marked on a map or an aerial photograph, but a final decision on the precise location of a sampling station can be made only after a field investigation.

The following examples illustrate how sampling sites may be chosen. The choices are made with respect to the hypothetical catchment area in Figure 3.3 and are based on some of the monitoring objectives listed in section 3.3.

Figure 3.3 Typical sampling sites for multi-purpose monitoring. The numbers are the sampling sites quoted in Examples 1 - 6 (see section 3.6)
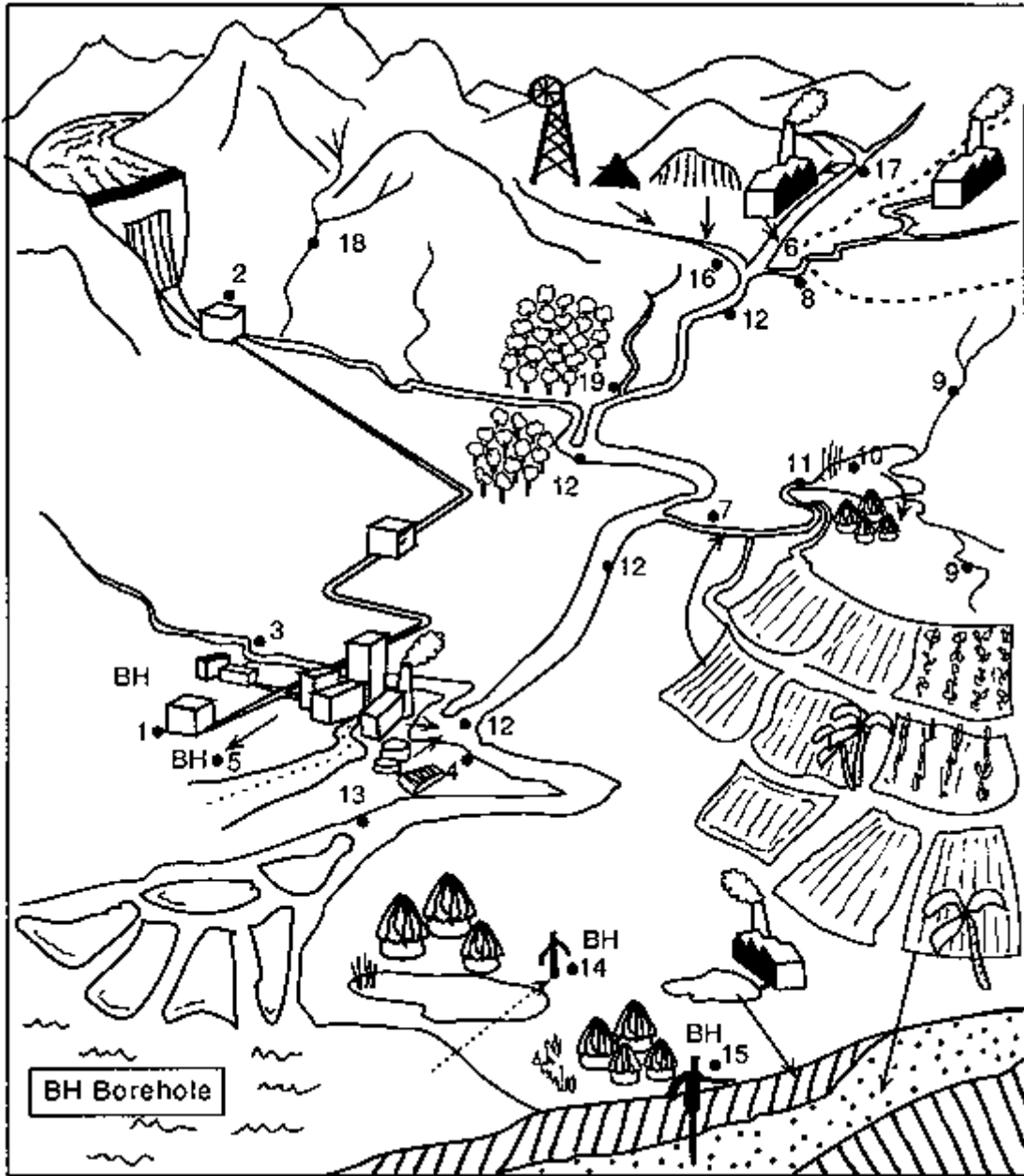
Example 1

Objective	Identification of baseline conditions in the water-course system.
Key question	What are the background levels of variables in the water?
Monitoring	Analyze for dissolved oxygen, major ions and nutrients. Characterize seasonal or annual concentration patterns. Determine annual mean values of water quality variables.
Information expectations	A description of the quality of water in the water-course system before it is affected by human activities.
Sampling network required	Fixed.
Sampling sites	1, 9, 10, 11, 17, 18.

Example 2

Objective	Detection of any signs of deterioration in water quality.
Key question	Are any new water quality problems arising?
Monitoring	Detect any short-term trends. Detect any long-term trends.
Information expectations	Description and interpretation of water quality changes with respect to time.
Sampling network required	Fixed.
Sampling sites	7, 12, 13, 14, 15, 19.

Example 3

Objective	Identification of any water bodies in the water-course system that do not meet the desired water quality standards.
Key questions	What are the designated uses? What are the water quality standards for the designated uses?
Monitoring	Survey for presence of contaminants. Determine extreme values of contaminating variable(s).
Information expectations	Description of the contaminating variable(s), the extreme values measured, when and where they occur and how they conflict with the standards. Evaluation of the hazards to human health, damage to the environment and any other adverse effects. Interpretation of the general state of the water bodies relative to the established standards.
Sampling network required	Fixed.
Sampling sites	4, 5, 6, 7, 8, 15, 16, 19.

Example 4

Objectives	Identification of any contaminated areas.
Key questions	What are the indicators of contamination? What are the contaminating substances? Where are the possible sources?
Monitoring	Detect contamination. Determine the concentration of the variables that indicate

contamination. Determine the areas affected by the contaminants and whether these areas are increasing. Detect the main pollution source(s).

Information expectations	Maps or charts showing the distribution of contaminants. Classification charts, maps and/or lists showing the contaminated areas in order of severity in relation to the source(s) of pollution. Classification is usually made in three or five classes.
Sampling network required	Recurrent (short-term).
Sampling sites	4, 5, 6, 7, 8, 16, 19.

Example 5

Objective	Determination of the extent and effects of specific waste discharges.
Key questions	How far away from the point of discharge does the effluent affect the receiving water? What changes are being made to the ambient water quality? How does the effluent affect the aquatic ecosystem?
Monitoring	Determine the spatial distribution of pollutants. Measure the effects of pollutants on aquatic life and various water uses.
Information expectations	The extent to which water quality has changed compared with baseline conditions. Cause-and-effect relationships at different levels of the water ecosystem, e.g. basic nutritional requirements of fishes and fish population. Maps showing the distribution of pollution. Comparison with water quality guidelines.
Sampling network required	Recurrent (short-term).
Sampling sites	4, 6, 8, 12, plus others as necessary.

Example 6

Objective	Evaluation of the effectiveness of a water quality management intervention.
Key question	What are the positive and negative results of a particular water quality management intervention in terms of its effects on the concentration of polluting substances in the water?
Monitoring	Determine whether the particular water quality management intervention has resulted in significant changes in water quality. Compare mean values of contaminant concentration before and after the intervention. Detect short- and long-term trends.
Information expectations	Evidence that mean concentration of contaminants was higher before the management intervention. Contaminant concentrations are decreasing with time.
Sampling network required	Fixed and recurrent (short-term).
Sampling sites	4, 5, 6, 7, 14, 15, 16, 19 (for example).

3.7 Selecting sampling stations

3.7.1 Rivers

Sampling stations on rivers should, as a general rule, be established at places where the water is sufficiently well mixed for only a single sample to be required. The lateral and vertical mixing of a wastewater effluent or a tributary stream with the main river can be rather slow, particularly if the flow in the river is laminar and the waters are at different temperatures. Complete mixing of tributary and main stream waters may not take place for a considerable distance, sometimes many kilometers, downstream of the confluence. The

zone of complete mixing may be estimated from the values in Table 3.2. However, if there is any doubt, the extent of mixing should be checked by measurements of temperature or some other characteristic variable at several points across the width of the river. If there are rapids or waterfalls in the river, the mixing will be speeded up and representative samples may be obtained downstream. Sampling for the determination of dissolved oxygen, however, should take place upstream of the rapids or waterfall because the turbulence will cause the water to be saturated with oxygen. In such a case, several samples should be taken across the width of the river to allow for the possibility of incomplete mixing.

A bridge is an excellent place at which to establish a sampling station (provided that it is located at a sampling site on the river). It is easily accessible and clearly identifiable, and the station can be precisely described. Furthermore, a bridge is often a hydrological gauging station and, if so, one of the bridge piers will have a depth gauge marked on it, thus allowing the collection of stream flow information at the time of sampling (see Chapter 12). Usually, a sample taken from a bridge at mid-stream or in mid-channel, in a well mixed river, will adequately represent all of the water in the river.

Table 3.2 Estimated distance for complete mixing in streams and rivers

Average width (m)	Mean depth (m)	Estimated distance for complete mixing (km)
5	1	0.08-0.7
	2	0.05-0.3
	3	0.03-0.2
10	1	0.3-2.7
	2	0.2-1.4
	3	0.1-0.9
	4	0.08-0.7
	5	0.07-0.5
20	1	1.3-11.0
	3	0.4-4.0
	5	0.3-2.0
	7	0.2-1.5
50	1	8.0-70.0
	3	3.0-20.0
	5	2.0-14.0
	10	0.8-7.0
	20	0.4-3.0

To verify that there is complete mixing at a sampling station it is necessary to take several samples at points across the width and depth of the river and to analyse them. If the results do not vary significantly one from the other, a station can be established at mid-stream or some other convenient point. If the results are significantly different it will be necessary to obtain a composite sample by combining samples taken at several points in the cross-section of the stream. Generally, the more points that are sampled, the more representative the composite sample will be. Sampling at three to five points is usually sufficient and fewer points are needed for narrow and shallow streams. Suggestions are provided in Table 3.3 for the number of points from which samples should be obtained in streams or rivers of different sizes and with different flow rates.

3.7.2 Lakes and reservoirs

Lakes and reservoirs can be subject to several influences that cause water quality to vary from place to place and from time to time. It is, therefore, prudent to conduct preliminary investigations to ensure that sampling stations are truly representative of the water body. Where feeder streams or effluents enter lakes or reservoirs there may be local areas where the incoming water is concentrated, because it has not yet mixed with the main water body. Isolated bays and narrow inlets of lakes are frequently poorly mixed and may contain water of a different quality from that of the rest of the lake. Wind action and the shape of a lake may lead to a lack of homogeneity; for example when wind along a long, narrow lake causes a concentration of algae at one end.

Table 3.3 Suggested sampling regimes for composite samples in flowing waters

Average discharge (m³ s⁻¹)	Type of stream or river	Number of sampling points	Number of sampling depths
< 5	Small stream	2	1
5-140	Stream	4	2
150-1,000	River	6	3
≥ 1,000	Large river	≥ 6	4

If there is good horizontal mixing, a single station near the centre or at the deepest part of the lake will normally be sufficient for the monitoring of long-term trends. However, if the lake is large, has many narrow bays or contains several deep basins, more than one station will be needed. To allow for the size of a lake, it is suggested that the number of sampling stations should be the nearest whole number to the $\log_{10}$ of the area of the lake in km². Thus a lake of 10 km² requires one sampling station, 100 km² requires two stations, and so on. For lakes with irregular boundaries, it is advisable to conduct preliminary investigations to determine whether and where differences in water quality occur before deciding on the number of stations to establish.

Access to lake and reservoir sampling stations is usually by boat and returning to precisely the same locations for subsequent samples can be extremely difficult. The task is made simpler when the locations can be described in relation to local, easily identified landmarks. This, as well as the representativeness of samples taken at those locations, should be borne in mind when sampling stations are chosen.

The most important feature of water in lakes and reservoirs, especially in temperate zones, is vertical stratification (the special features of tropical lakes are described in Chapter 2), which results in differences in water quality at different depths. Stratification at a sampling station can be detected by taking a temperature reading at 1 m below the surface and another at 1 m above the bottom. If there is a significant difference (for example, more than 3 °C) between the surface and the bottom readings, there is a "thermocline" (a layer where the temperature changes rapidly with depth) and the lake or reservoir is stratified and it is likely that there will be important differences in some water quality variables above and below the thermocline. Consequently, in stratified lakes more than one sample is necessary to describe water quality.

For lakes or reservoirs of 10 m depth or more it is essential, therefore, that the position of the thermocline is first investigated by means of regularly-spaced temperature readings through the water column (e.g. metre intervals). Samples for water quality analysis should then be taken according to the position and extent (in depth) of the thermocline. As a general guide, the minimum samples should consist of:

- 1 m below the water surface,

- just above the determined depth of the thermocline,

- just below the determined depth of the thermocline, and

- 1 m above the bottom sediment (or closer if this can be achieved without disturbing the sediment).

If the thermocline extends through several metres depth, additional samples are necessary from within the thermocline in order to characterise fully the water quality variations with depth. Whilst the position of the thermocline is stable, the water quality for a given station may be monitored by fewer samples but, in practice, the position of a thermocline can vary in the short- (hours) or long-term (days) due to internal seiches (periodic oscillations of water mass) and mixing effects.

Even in warm climates, and in relatively shallow lakes and reservoirs, the possibility of a thermocline should be investigated by taking temperature profiles from the surface to the bottom. The Smir reservoir in northern Morocco, for example, although only 8 m deep had a temperature difference of 4 °C between the surface and the bottom in August 1991. A thermocline was detected between 5 m and 7 m below the surface and significant differences were reported for measured values of both pH and dissolved oxygen above and below the thermocline. In general, therefore, in tropical climates where the water depth at the sampling site is less than 10 m, the minimum sampling programme should consist of a sample taken 1 m below the water surface and another sample taken at 1 m above the bottom sediment.

3.7.3 Groundwater

Sampling points for groundwater monitoring are confined to places where there is access to an aquifer, and in most cases this means that samples will be obtained from existing wells. To describe such a sampling station adequately, it is essential to have certain information about the well, including depth, depth to the well screen, length of the screen and the amount by which the static water level is lowered when the well is pumped. One sample is usually sufficient to describe the water quality of the aquifer. If the water in the well is corrosive and is in contact with steel pipe or casing, the water samples may contain dissolved iron. Wells with broken or damaged casings should be avoided because surface water may leak into them and affect the water quality.

Springs can also be useful groundwater sampling points, provided that they are adequately protected against the ingress of contamination with surface water. Springs are often fed from shallow aquifers and may be subject to quality changes after heavy rainfall.

Other possible sampling stations are boreholes drilled especially to investigate the features of an aquifer, although these are expensive and would be justified only in particular circumstances.

3.8 Monitoring media and variables

There are three principal media which can be used for aquatic monitoring: water, particulate matter and living organisms. The quality of water and particulate matter is determined by physical and chemical analysis whereas living organisms can be used in a number of different ways (see Chapter 11). Whole communities of organisms, or the individuals that normally belong to that community, can be studied as indicators of water quality.

Alternatively, the physiology, morphology or behaviour of specific organisms can be used to assess the toxicity or stress caused by adverse water quality conditions, or organisms and their tissues can be used as a medium for chemical monitoring of contaminants in the aquatic environment.

The most common biological measurement of surface water samples is the determination of phytoplankton chlorophyll pigments, which give an indication of algal biomass. Chlorophyll measurements are useful for assessing eutrophication in lakes, reservoirs and large rivers, or as an indication of productivity in most surface waters.

Each aquatic medium has its own set of characteristics for monitoring purposes, such as:

• applicability to water bodies,

• inter-comparability,

• specificity to given pollutants,

• possibility of quantification (e.g. fluxes and rates),

• sensitivity to pollution with the possibility of amplifying the pollution signal by several orders of magnitude,

• sensitivity to sample contamination,

• time-integration of the information received from instantaneous (for point sampling of the water) to integrated (for biotic indices),

• required level of field personnel, storage facility of samples, and

• length of the water quality determination process from field operation to result.

The most significant characteristics of each medium are given tentatively in Table 3.4. Water, itself, is by far the most common monitoring medium used to date, and the only one directly relevant to groundwaters. Particulate matter is widely used in lake studies, in trend monitoring and in river flux studies, whereas biological indices based on ecological methods are used more and more for long-term river and lake assessments.

Water quality can be described by a single variable or by any combination of more than 100 variables. For most purposes, however, water quality can be adequately described by fewer than 20 physical, chemical and biological characteristics. The variables chosen in a monitoring programme will depend on the programme objectives and on both existing and anticipated uses of the water. Drinking and domestic consumption, agricultural irrigation, livestock watering, industrial uses and recreational use all require water of a specific quality. Selecting the variables to include in a monitoring programme will often require a compromise between "like to know" and "need to know". However, some variables must be measured if the basic programme objectives are to be achieved. Further information on the sources, range of concentrations, behaviour and transformations of water quality variables is available in the companion guidebook *Water Quality Assessments*.

Table 3.4 - Principal characteristics of media used for water quality assessments

Characteristics	Water	Particulate matter		Living organisms			
		Suspended	Deposited	Tissue analyses	Biotests	Ecological surveys[1]	Physiol. determin.[2]
Type of analysis or observation	←physical→						
	←chemical→[3]						
				←biological→			
Applicability to water bodies	rivers, lakes groundwaters	mostly rivers	lakes, rivers	rivers, lakes	rivers, lakes	rivers, lakes	rivers, lakes
Intercomparability[4]	←global→			depends on species occurrence	global	←local to regional→	
Specificity to given pollutant	←specific→				←integrative→		
Quantification	←complete→ quantification of concs & loads		concentrations only	quantitative	semi-quantitative	←Relative→	
Sensitivity to low levels of pollution	low	←high→			variable	medium	variable
Sample contamination risk	high[5]	medium	←low→		medium	←low→	
Temporal span of information obtained	instant	short	long to very long (continuous record)	medium (1 month) to long (> 1 year)	instant to continuous[6]	←medium to long→	
Levels of field operators	untrained to highly trained	trained	untrained to trained	trained	←medium→ to highly trained		
Permissible sample storage duration[7]	low	high	high	high	very low	high	na
Minimum duration of determination	instant. (*in situ* determ.) to days	days	days to weeks	days	days to months	weeks to months	days to weeks

na Not applicable

[1]   Including algal biomass estimates

[2]   Histologic, enzymatic, etc.

[3]   Including BOD determination

[4]   Most biological determinations depend on the natural occurrence of given species and are, therefore, specific tp a given geographic region

[5] For dissolved micropollutants
[6] e.g. organisms continuously exposed to water
[7] Depending on water quality descriptors

Source: *Meybeck et al.*, 1996

The simplest combination of variables is temperature, electrical conductivity, pH, dissolved oxygen (DO) and total suspended solids (TSS). These give the bare minimum of information on which a crude assessment of overall water quality can be based. More complex programmes may analyze up to 100 variables, including a range of metals and organic micro-pollutants. Moreover, analysis of biota (plankton, benthic animals, fishes and other organisms) and of particulate matter (suspended particulates and sediments) can add valuable information.

The water quality variables for baseline stations, trend stations and global river flux stations included in the basic monitoring component of the Global Environment Monitoring System's GEMS/WATER programme are listed in Table 3.5

In many monitoring programmes a known, or suspected, water pollution condition is the reason for deciding to analyze for specific water quality variables. Another possible reason is to determine whether a water is suitable for a planned use. Some variables may be part of a basic monitoring programme, while others will be specific to the pollution condition or planned use. Some pollution conditions and planned uses, together with the variable that should be measured, are as follows:

• *Organic wastes* are contained in municipal sewage and in the discharges from abattoirs, food-processing and similar agricultural industries. The variables that should be measured are biochemical oxygen demand (BOD), chemical oxygen demand (COD), total organic carbon (TOC), dissolved organic nitrogen, total phosphorus and faecal coliforms.

• *Eutrophication r*esults from nutrients entering surface water, either from a point discharge or in run-off from agricultural land. The variables that should be measured are nitrate, nitrite, ammonia, total phosphorus (filtered and unfiltered), reactive silica, transparency and chlorophyll *a*.

• *Agriculture and irrigation* can result in excessive concentrations of certain elements and compounds entering water bodies (particularly nitrates and phosphates from fertilisers, as well as pesticides and herbicides). In addition, high concentrations of some elements can cause problems for the use of water in agriculture (e.g. soil permeability may be altered, certain plants can be adversely affected and livestock can be poisoned). Agricultural practices can also influence erosion. The variables that should be measured for specific agricultural uses of water include total dissolved solids, total suspended solids, boron, selenium, sodium, calcium, magnesium and faecal coliforms (depending on the intended agricultural application). For irrigation water it is important to measure the sodium adsorption ratio (SAR) as follows:

$$SAR = \frac{Na^+}{\sqrt{(Ca^{2+} + Mg^{2+})/2}}$$

Pesticides and herbicides used in agriculture frequently lead to the contamination of both surface water and groundwater. Monitoring programmes should take into account available information concerning the types and quantities of agricultural chemicals used in the monitoring area, their characteristics and their application patterns. Some of the variables that might have to be measured are dieldrin, aldrin, sum of DDTs, atrazine, lindane (γ-hexachlorocyclohexane or HCH), aldicarb, organophosphorus pesticides and 2, 4-dichlorophenoxyacetic acid (2, 4-D).

• *Industrial effluents* may contain toxic chemicals, organic or inorganic or both, depending on the industrial process. Some knowledge of industrial processes is, therefore, necessary before a rational decision can be made on the variables for which analyses should be made. Examples of the water quality variables that should be measured in industrial waters are total solids, BOD, COD, trihalomethanes, polynuclear aromatic hydrocarbons, total hydrocarbons, phenols, polychlorinated biphenyls, benzene, cyanide, arsenic, cadmium, chromium, copper, lead, iron, manganese, mercury, nickel, selenium and zinc.

• *Effluents and leachates from mining operations* affect surface water and groundwater, often very severely. The minerals being mined provide an indication of the metals for which analyses should be made. Often there will be other minerals present in non-commercial concentrations and these may be present in the mine wastes. Analysis for both the dissolved and the particulate fractions of metals should be included in the monitoring programme.

• *Acidification* of lakes, rivers and groundwater results from the long-range transport of atmospheric pollutants. Drainage water from coal mines is strongly acidic and often leads to acidification of water bodies. Water that has become acidified should be analysed for the dissolved fraction of metals such as aluminium, cadmium, copper, iron, manganese and zinc, as well as for pH and alkalinity.

Table 3.5 Variables used in the GEMS/WATER programme for basic monitoring

Measured variable	Streams: baseline and trend	Headwater lakes: baseline and trend	Groundwaters: trend only	Global river flux stations
Water discharge or level	x	x	x	x
Total suspended solids	x	-	-	x
Transparency	-	x	-	-
Temperature	x	x	x	x
pH	x	x	x	x
Electrical conductivity	x	x	x	x
Dissolved oxygen	x	x	x	x
Calcium	x	x	x	x
Magnesium	x	x	x	x
Sodium	x	x	x	x
Potassium	x	x	x	x
Chloride	x	x	x	x
Sulphate	x	x	x	x
Alkalinity	x	x	x	x
Nitrate	x	x	x	x
Nitrite	x	x	x	x
Ammonia	x	x	x	x
Total phosphorus(unfiltered)	x	x	-	x
Phosphorus, dissolved	x	x	-	x
Silica, reactive	x	x	-	x
Chlorophyll *a*	x	x	-	x
Fluoride	-	-	x	-
Faecal coliforms (trend stations only)	x	x	x	-

Source: WHO, 1991

3.9 Frequency and timing of sampling

Sampling frequency at stations where water quality varies considerably should be higher than at stations where quality remains relatively constant. A new programme, however, with no advance information on quality variation, should be preceded by a preliminary survey (see section 3.4) and then begin with a fixed sampling schedule that can be revised when the need becomes apparent.

Table 3.6 Sampling frequency for GEMS/WATER stations

Water body		Sampling frequency
Baseline stations		
Streams	Minimum:	4 per year, including high- and low-water stages
	Optimum:	24 per year (every second week); weekly for total suspended solids
Headwater lakes	Minimum:	1 per year at turnover; sampling at lake outlet
	Optimum:	1 per year at turnover, plus 1 vertical profile at end of stratification season
Trend stations		
Rivers	Minimum:	12 per year for large drainage areas, approximately 100,000 km^2
	Maximum:	24 per year for small drainage areas, approximately 10,000 km^2
Lakes/reservoirs	For issues other than eutrophication:	
	Minimum:	1 per year at turnover
	Maximum:	2 per year at turnover, 1 at maximum thermal stratification
	For eutrophication:	
	12 per year, including twice monthly during the summer	
Groundwaters	Minimum:	1 per year for large, stable aquifers
	Maximum:	4 per year for small, alluvial aquifers
	Karst aquifers:	same as rivers

The time interval between the collection of samples depends on the water body and its specific characteristics. An interval of one month between the collection of individual samples at a station is generally acceptable for characterising water quality over a long time period (e.g. over a year in a river) (see Table 3.6), whereas for control purposes weekly sampling may be necessary. If significant differences are suspected or detected, samples may have to be collected daily or on a continuous basis. In extreme cases, time- integrated, composite samples may have to be made up by mixing equal portions of samples taken at regular intervals over a 24-hour period, but this should be done only if they conform with the requirements of the objectives and are not to be used for the determination of unstable variables, such as dissolved oxygen. Individual samples taken at a given station should be obtained at approximately the same time of day if possible, because water quality often varies over the course of the day. However, if detection of daily quality variations or of the peak concentration of a contaminant in an effluent is of interest, sampling at regular intervals (e.g. every two or three hours throughout the day) will be necessary. Exceptional conditions of stream flow are frequently of interest because it is at maximum and minimum flow rates that extreme values of water quality are reached. For example, when flowing at its peak rate, a river usually carries its greatest load of suspended material, while pollutants will be the least diluted when a river is at minimum flow. The violation of a waste discharge regulation and the seriousness of its environmental effects will often be easier to detect during periods of minimum flow. Sampling regimes may need to take such factors into consideration (see section 12.3).

It is usual to take samples of groundwater at only one depth. Frequency of sampling is low for large, deep, confined aquifers, which typically have long residence times, but higher (perhaps monthly) for shallow, unconfined aquifers with short residence times. Sampling should be supplemented by occasional mapping to describe the aquifer fully.

Sample collection should be frequent enough to enable an accurate calculation of the mean concentrations of the variables included in the monitoring programme. The frequency of sampling required to obtain a desired level of confidence in the mean values depends on statistical measures, i.e. standard deviation and confidence interval. Sampling frequencies for GEMS/WATER baseline and trend stations are shown in Table 3.6.

3.10 Source literature and further reading

Chapman, D. [Ed.] 1996 *Water Quality Assessments: A Guide to the Use of Biota, Sediments and Water in Environmental Monitoring*. 2nd edition, Chapman & Hall, London.

Désilets, L. 1988 *Criteria for Basin Selection and Sampling Station Macrolocation*. Inland Waters Directorate, Water Quality Branch, Scientific Series No. 164. Environment Canada, Ottawa.

Foster, S.S.D. and Hirata, R. 1988 *Groundwater Pollution Risk Assessment: A Method Using Available Data*. Pan-American Centre for Sanitary Engineering and Environmental Science (CEPIS), Lima.

Meybeck, M., Kimstach, V. and Helmer, R. 1996 Strategies for water quality assessment. In: D. Chapman [Ed.] *Water Quality Assessments: A Guide to the Use of Biota, Sediments and Water in Environmental Monitoring*. 2nd edition, Chapman & Hall, London, 23-57.

WHO 1991 *GEMS/WATER 1991 - 2000: The Challenge Ahead*. Unpublished document WHO/PEP/91.2, World Health Organization, Geneva.

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