Appendix B: Monitoring and Adaptive Management

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Monitoring the impacts or outcomes of any water management policy provides a way of assessing just how well the policy meets expectations. Developing a monitoring plan requires the identification of performance indicators and how frequently and accurately they will be measured over time and space. The major challenge in monitoring is to make the information obtained fit the information needed and then to act on it, as and when appropriate. This is called adaptive management: what most of us do throughout our lives. Over time managers should be able to improve their management and their monitoring policies on the basis of what they learn about the system they are managing. Just how much and how well they learn will largely depend on the effort given to developing and implementing an effective monitoring and adaptive management strategy.

1. Introduction

Monitoring is the process of observing what is happening. Managers of water resources systems need to know what is taking place in their systems, both over time and over space. This usually requires sampling one or more elements or features of the system according to prearranged schedules, using comparable methods for data measuring or sensing, recording, collection and analysis. Monitoring provides information on the state of the system. Adaptive management is the action taken in response to that information with the aim of improving how the system performs.

Adaptive management can be active or passive. Active adaptive management, defined by Holling (1978), involves managing the system in ways that maximize the understanding obtained from the monitored data. Active adaptive management involves experiments aimed at discovering the limits of system vulnerability and resilience. Such management can be risky. It is possible for management experiments to degrade the system, for example by killing some of the species in an ecosystem that is managed to protect them. For this reason managers are often reluctant to assume those risks just to learn more. Hence, if adaptive management is implemented, it is often passive adaptive management, sometimes called adaptive assessment or adaptive implementation. Passive adaptive management strategies strive to manage the system in the best way possible, correcting mistakes and implementing changes on the basis of what is learned as it is learned, but without making possibly damaging experiments.

The questions to be addressed in establishing a monitoring programme for adaptive management are what to measure, where and how often to measure or record each parameter, with what accuracy, and why. The challenge is to know when the information derived from a monitoring programme is sufficient to act upon, as well as what action to take. Often the results, especially the ecological impacts, of a change in a management policy will be observable only long after the change has been implemented.

These questions are addressed in the various stages of a monitoring programme's life cycle, as shown in Figure B.1. The process of monitoring and adaptive management is more than just measuring system

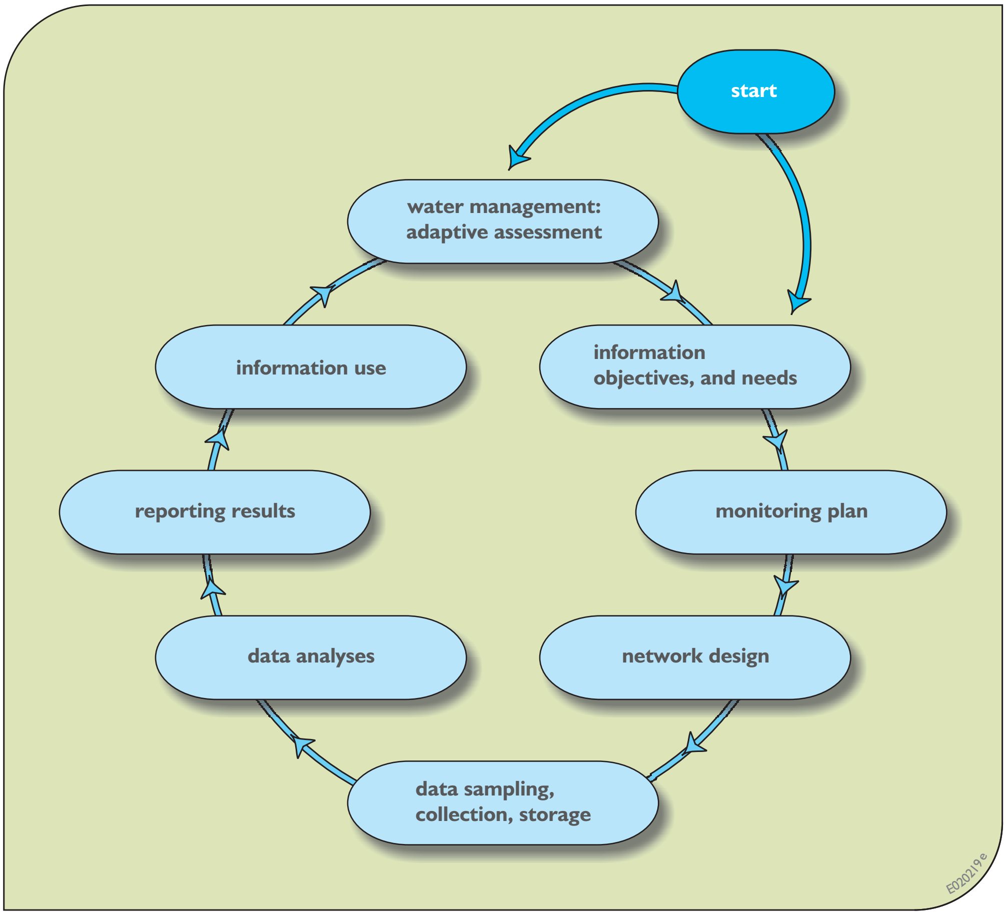

Figure B.1. Chain of activities in monitoring and assessment (Adriaanse and Lindgaard-Jorgensen, 1995).

attributes, collecting, storing, analysing and publishing the measured data, and then acting on the results. It is a sequence of related activities that starts with the identification of information needs, and ends with the use of the information. All too often time and money is invested to obtain data before sufficient thought has been given to how those data will or could be used and their value compared to their cost.

Modelling can help identify just what data are needed for the decisions being considered, and how accurate those data need be. (Some modelling examples in Chapters 4 and 7 illustrate this.) A dilemma, of course, is that if data obtained from a current monitoring programme are intended to be of value to future managers, it is difficult to know today just what data and what precision those future managers may want.

The design of a monitoring system starts with defining the information needed for decision-making. The information needed determines the attributes to be measured – the types of data to be collected and the kinds of analyses to be applied to them. The monitoring plan specifies these data, their required accuracy and their frequency of measurement. Frequency of measurement and the density of monitoring sites are in part dependent on the variability of an attribute's or parameter's value over time and/or space, and just how important it is to capture this temporal or spatial variability.

Once the network design has been defined, data collection, storage and analysis procedures need to be specified, along with plans for reporting and disseminating the results. This information should be included in the monitoring plan.

The last element in Figure B.1, 'information use', is input to the 'managers' of the system. Actions taken to manage the system more effectively on the basis of this new information may lead to changes in the information needs. As information needs change, this chain of activities will repeat itself. Each component of the monitoring cycle is subject to change and enhancement over time, reflecting changes in knowledge or goals, improvements in methods and instrumentation, and budgets.

2. System Status

Information needs depend on the issues and problems facing water managers. To identify management priorities several activities are needed. As suggested in Figure B.2, these include identifying the functions and the uses served by the system being managed. This in turn involves carrying out inventories and assessments of available and accessible information, making field surveys if information is lacking, identifying criteria and targets, and evaluating the use, costs and benefits of additional data.

Specifications of information needs should be based on the analysis of water management issues and opportunities. These in turn are determined from inventories, surveys, stakeholder concerns about what needs attention, and failures to meet standards, targets, or management criteria. Issues and targets can include existing or future problems or threats, e.g. flooding, toxic contamination, water supply shortage. They can include the full range of qualitative and quantitative aspects in multipurpose system management (see Table B.1).

functions & uses	flooding	scarcity	erosion/sedimentation	biodiversity	continuity	salinity	acidification	pollution	eutrophication
human health	●	●	●			●		●	●
ecosystem functioning	●	●	●	●	●	●	●	●	●
fisheries	●	●	●	●	●	●	●	●	●
recreation	●	●	●	●	●	●		●	●
drinking water	●	●	●			●	●	●	●
irrigation		●				●		●	●
industrial use		●	●			●		●	●
hydro power		●	●		●				
transport medium & navigation	●	●	●		●				

Table B.1. System functions and uses.

Additional surveys and monitoring are needed if sufficient data are not available to identify the causes of known problems. Surveys and monitoring generate new data that can relate to a broad range of subjects, such as the evaluation of site conditions (e.g. post-flood surveys), the variability of monitoring parameters in space and time, or the screening of the occurrence of pollutants or toxic effects in water and sediments.

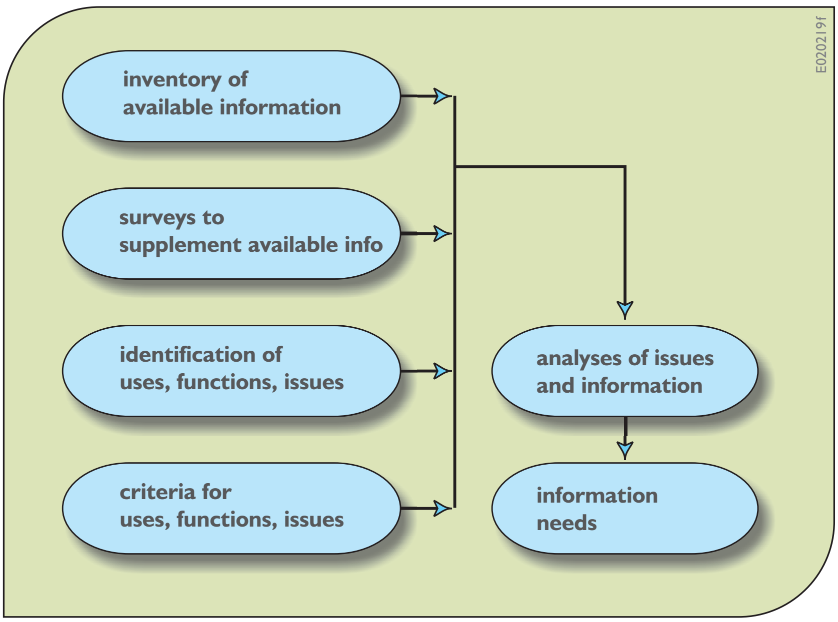

Figure B.2. Water management activities to identify information needs.

Water quality surveys can give additional insight into the functioning of the aquatic ecosystem and the incidence of pollution and toxic effects in the water. Investigating the structure of the macro-invertebrate community, the upstream and downstream differences in the river reach, and the changes that occur over time can provide an assessment of the biological quality of the aquatic zone of a river. Chemical screening of surface water, sediment and effluents at hot spots and key locations can allow an assessment of the chemical quality of the aquatic zone of a river. Additionally, specific target compounds, toxic effects in surface water, sediments and effluents that might be expected can be measured and analysed. By means of ecotoxicological tests, the concentrations of a broad range of chemicals and variation in sensitivity among species can be assessed.

2.1. System Status Indicators

System status or performance indicators should ideally be measurable parameters. Indicator parameters should sufficiently characterize or represent functions and uses of water bodies and/or be of value for testing the effectiveness of management decisions. For example, total phosphorus can be a good indicator of the eutrophication status of the river. The presence of salmon is an indicator for the ecological state of rivers such as the Columbia and Rhine Rivers. Such indicators should include those that the public care about and thus suitable for communicating with policy makers or the public. Important criteria for choosing an indicator are:

- *Communication*. The indicator should be appealing to those who will use it.
- *Simplification*. The indicator should provide insight into the situation, without having to go into great detail. The oxygen concentration in a river, for example, is a good indication of its quality for aquatic organisms; there is no need to identify the concentrations of all oxygen-demanding substances.
- *Data availability*. Sufficient data for the indicator should be available, otherwise its information content may be unreliable.

3. Information Needs

As many monitoring programmes are 'data rich, but information poor,' attention should be directed towards the end product of monitoring: information. The ultimate goal of monitoring is to provide information needed to answer specific management questions. Thus, a critical step in developing a successful, tailor-made and cost-effective monitoring programme is the clear definition and specification of information needs. These must be known before design criteria can be derived for the development or planning of a monitoring and assessment system.

Information needs come from management objectives. Management objectives might be stated in terms like '20% reduction of pollution in the next five years', or 'No more interruptions in the intake of drinking water within two years'. There should be an element of relativity ('percentage reduction of …') or quantity ('no more …' or 'less than …') in the specification. Next to that, an element of time ('… within two years') is imperative. Consider for example the 'Salmon 2000' slogan that summarized the efforts to restore the ecology of the River Rhine this past half decade. 'Getting the salmon back into the Rhine in the year 2000' is a goal that can be measured. There is an element of quantity (a more or less stable population of salmon) and an element of time (the year 2000). These elements can be converted into a monitoring strategy. The effectiveness of a monitoring network can only be tested when the information needs related to one or more management objectives are defined.

Five different approaches to defining information needs can be distinguished:

- *The effect approach*. There may be an adverse effect of some kind that should be reduced within a certain period. The element of relativity can be used here.
- *The source approach*. There are sources that cause adverse impacts. Their effects have to be reduced, for example by reducing their loads on the environment. This is closely related to the effect approach.
- *The achievement approach*. There is a goal to be achieved within a given time period. This approach gives an impression of the effects of the intended actions after a stated time. 'Salmon back in the River Rhine In the year 2000' is an example of this approach.

- *The background approach*. 'There may be no change in' a given parameter, or 'the river has to be back in its original state by' a given time. This is usually comparable to the ecological function of a water resource system.
- *The function approach*. The water system has to fulfil a specific function, such as being fit for salmon and/or swimming.

The different approaches listed above are often interrelated. Nevertheless, each of them can help facilitate the identification and specification of information needs. These needs should be identified and described in sufficient detail to ensure the design of a monitoring and assessment system that will meet them. Examples of such specified information needs include:

- The identification of appropriate parameters and/or indicators.
- The definition of criteria for assessment, such as considerations for the setting of standards or criteria for the choice of alarm or trigger conditions for early warning in the event of floods or accidental pollution.
- Requirements for reporting and presentation of the information, e.g. visualization, degree of aggregation, indices.
- Relevant error margins specified for each monitored indicator. What detail is relevant for decision making?
- Response times identifying when specified information is needed. In early-warning procedures, information is needed within hours, whereas for trend detection information is needed weeks or even months after sampling.
- Reliability requirements. To what extent is false information allowed? It is often impossible or prohibitively expensive to have 100% reliability. Depending on the consequences of error, more or less reliable information should be required. Together with the relevant margins of error, these reliability requirements may be a determining factor when selecting locations, frequencies and methodologies in the design of monitoring programmes.

Information needs should be comparable between places and situations, and should be linked to specific issues, which are in turn linked to specific management needs. Interested stakeholders should be involved in the process of specifying information needs alongside institutions responsible for the management and use of water resources. Both information users and information producers should be identified and should interact closely.

3.1. Information Objectives and Priorities

Information objectives indicate the intended use or purpose of the information and the management concern. The information may be needed for compliance with established standards or targets, for planning, for early warning of hazards, or for scientific understanding of natural processes or impacts.

As information needs are derived from issues, the prioritization of issues leads to a prioritization of information needs. Information is mostly needed on high-priority issues. If the same information need arises from various issues, this information need should be given increasing priority. By collecting this information once, a variety of issues may be addressed.

Information objectives evolve as water management develops, targets are met or policies change. Consequently, monitoring strategies often need to be adapted to changing information needs over time. Information needs require a regular rethinking (revision) of the information strategy in order to update the concept. When revising monitoring strategies for time-series measurements, one should not neglect the need for continuity (in parameters being measured, in locations where data have been collected, in the analytical methods used and so on). This continuity is needed to detect significant and reliable trends in system performance characteristics.

4. Monitoring Plans

A monitoring plan provides the basis or rationale for the design of monitoring networks. Monitoring plans should specify what has to be measured (also in terms of accuracy, type 1 and type 2 errors, etc.) and why. The network design specifies how and where it should be measured. The monitoring plan should also include the data analysis and reporting procedures that in turn can influence network design requirements.

Elements of a monitoring plan are:

- the information needs that will be covered by the monitoring programme and, equally important, the information needs that will not be covered by the monitoring strategy
- the type of monitoring (physical, chemical, biological, hydrological, early warning, effluent), the indicator variables to be measured and the preconditions for selecting locations (minimum/maximum distance from border, intake point, etc.) and sampling frequencies (in terms of reliability)
- the calculation methods, and the graphical, statistical and other tools (such as indices) to be used
- the preconditions, suppositions, assumptions, and descriptions of the area, relevant industries, major demands and so on
- the organizational responsibilities for the monitoring programme
- a plan for the design and implementation of the monitoring network
- an analysis of the risks and the possible problems that can lead to the failure of the monitoring programme

Monitoring plans are the bridges between information needs and monitoring networks.

The selection of the parameters to be monitored is usually based on their indicative character, their occurrence and the hazards they present. For reasons of efficiency, the number of monitored parameters should be restricted to those whose uses are explicitly identified. The benefits derived from measuring any additional parameter should be compared to the cost incurred. Since the benefits will probably not be expressed in monetary terms, this usually has to be a qualitative comparison, using judgement.

Integrated water management involves the consideration of all aspects of a water resources system. This includes its watersheds, its aquifers, rivers, lakes, reservoirs and wetlands, its estuaries and coastal waters, its natural ecosystems, its regulatory measures for environmental media, its management and monitoring strategies, and its relations to social and economic factors. An integrated approach eschews a focus on only localized separate components of the system in isolation. Monitoring plans should reflect these interdependencies and facilitate an integrated approach to water management.

An integrated management approach includes humans as a central element in the system. This implies recognition of social, economic, technical and political factors that influence the ways in which human beings use and affect the system. These factors should be assessed because of their ultimate effect on the system's integrity. For example, in trying to restore the hydrology and ecosystem of the Everglades region of South Florida to what it was like a half century ago, one cannot ignore the addition in recent decades of some 20 million people who now make their home there for at least part of the year. The needs for reliable water supplies and flood control were much less fifty years ago, as were the pollutants discharged from municipalities, agriculture and industry. These extra people, together with their pollutants, are not going away. To manage integrated systems, managers need to know their condition and how their condition reacts to people and their activities. This in turn requires monitoring not only of water quantities and qualities and ecological indicators, but also of their major drivers: humans and their activities.

5. Adaptive Monitoring

One approach to monitoring when the precise level of detail or precision is not known is an adaptive stepwise or phased plan, proceeding from coarse to fine assessments. At the conclusion of each step, an evaluation can be made of whether or not the information obtained is sufficient. Such stepwise testing strategies can result in a reduction in unnecessary data collection. In general, a phased approach to monitoring, going from broad to fine and from simple to advanced, may also be cost effective. Additionally, for developing countries or countries in transition, stepwise monitoring strategies going from labour-intensive to technology-intensive methods might be appropriate. In many cases, the lack of consistent and reliable data and the lack of a baseline against which progress can be measured are additional arguments for a phased approach.

5.1. Risk Assessments For Monitoring

Risk assessment can help considerably in prioritizing monitoring activities. For example, consider flood protection and water quality management.

- The central question in *flood prevention* is what protection is available at what price, and what remaining risk has to be accepted by society. Risk assessment (or, more comprehensively, flood risk management that includes risk assessment, mitigation planning and the implementation of measures) will show which hydrological, meteorological and other data should be monitored or observed.
- The *quality of water* in a small, sparsely populated catchment is unlikely to pose a risk to human health. Conversely, if there are refuse dumps or industrial plants in a catchment, there may be a high risk to human health and/or aquatic ecosystems. Thus, by using risk assessment one can decide which of all the monitoring activities have higher or lower priority. Identify priorities by asking what may go wrong when insufficient information is available (because of a lack of monitoring). What loss is likely when less than optimal decisions are made because of insufficient information or money? The same questions can be asked in the design or optimization of monitoring networks. What are the consequences for decision-making if there are no or only limited results from monitoring?

Risk assessment can also be used to prioritize specific pollutants, on the basis of their physico-chemical properties and toxicity. Risk assessment, regarding both biological agents and chemical substances, can also help in setting priorities for establishing health-related monitoring and/or early-warning systems in general, and in selecting appropriate parameters for monitoring in particular. Although still to be developed, good systems will include hazard identification, dose–effect relationships, exposure assessment and risk characterization (both qualitative and quantitative).

5.2. Use of Models

Models (numerical, analytical or statistical) can assist in developing a monitoring and assessment plan. They can help in screening (the preliminary evaluation of) alternative policies, in optimizing monitoring network design, in assessing the effectiveness of implemented measures, and in determining the physical and health impacts on humans and ecosystems. Computer models linked with geo-referenced databases can be used to analyse the impact of proposed measures, for example by simulating the flow and water level variations in a river and on floodplains during floods. Models can play an important role in early-warning systems (flood forecasting, travel time computations in emergency warning systems in the event of accidental pollution). They can be used in addition to monitoring to help understand what, where, and how often and how accurately to monitor.

Successful mathematical modelling for planning monitoring programmes is possible only if the modelling activities are integrated with data collection, data processing and other techniques and approaches for identifying system characteristics. One cannot calibrate and verify models without data, yet even uncalibrated models can often help identify just what data are needed and how accurate they need to be for the purposes of management and decision making.

6. Network Design

The design and operation of monitoring networks includes the selection of attributes or parameters to be measured, the locations where they are measured, and their sampling frequencies. The network design should meet the requirements specified in the monitoring plan. The type and nature of the system being monitored should be understood (most frequently through preliminary surveys), particularly its spatial and temporal variability. Monitoring of the quality and biology of the aquatic environment should be coupled with the appropriate hydrological quantity monitoring. Finally, arrangements should be made to ensure the quality of data. This requires the periodic checking and maintenance of the monitoring network as well as the computer data management and storage system.

The design of a monitoring network is influenced by its purpose or purposes. Table B.2 summarizes some of the design considerations that will vary for different purposes.

It will often be necessary to carry out a preliminary sampling and analysis programme to obtain a better understanding of the parameters to be monitored. The objective in the survey, a better understanding of the processes, is not directly related to the information need, but will give information for the monitoring network design. For instance, a survey to find out the distance it

Table B.2. Network design aspects for various monitoring objectives.

design aspects	trend detection	testing for compliance	early warning
	objectives		
variables	long term interest/ policy goals	included in the standard	depending on possible accident spills
locations	significant and independent locations	representative for the water system	hot spots for accidental spills and interests
reliability/ accuracy	no discontinuities in time-series	representative for the test period	reliability more important than accuracy
sampling frequency	relatively low, depending on dynamics of the aquatic system	relatively low, depending on dynamics of the aquatic system	high frequency, depending on dispersion of pulse inputs
response time	not important	less important	crucial

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takes for the water at the confluence of two rivers to mix completely will be useful when choosing water quality sampling locations.

6.1. Site Selection

The desired spatial coverage of a monitoring network depends on the spatial variability of the data being measured, and how important it is to capture or measure that variability. For monitoring meteorological parameters on watersheds, the shorter the distances between adjacent sampling sites, the greater probability of measuring any spatial variation that may exist. However, more monitoring equipment will be needed and hence costs will increase. There is a tradeoff between the accuracy of the estimates of spatially varying parameter values and cost. These relationships are shown in Figure B.3.

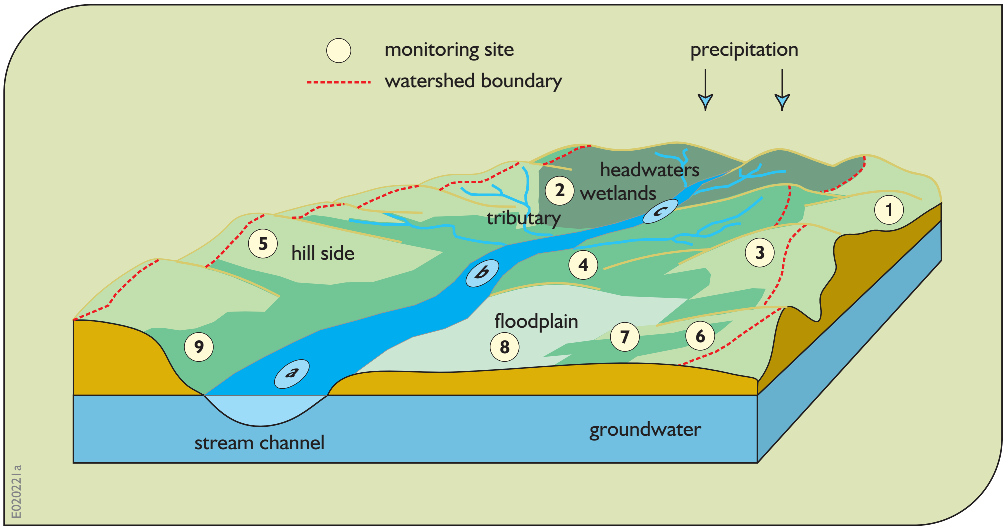
Referring to Figure B.3, if rainfall is being recorded at the monitoring sites 1 through 9 the estimate of the average rainfall over the entire watershed would be much more accurate than if only site 2 or 8 existed, or even if both existed and were used to make that estimate. Similarly for streamflow and quality gauges a, b, and c. Whatever the number of stream gauges to be used, they should be placed where one knows significant changes are likely to occur, such as just upstream and downstream of the confluence of tributaries.

6.2. Sampling/Measurement Frequencies

Water quantity and quality, sediment characteristics and biota vary over time as well as space. This variation over time affects decisions about the frequency of sampling. The objectives of monitoring strongly influence the time scale of interest, e.g. long-term variations for trend detection, short-term changes for flood forecasting and early warning. The required frequencies and methods of sampling (continuous sampling, grab sampling, composite sampling, etc.) will be dictated by both the temporal variability and the monitoring objectives. The cost–accuracy tradeoff relation shown in Figure B.3 applies to temporal sampling frequency as well as to spatial coverage.

6.3. Quality Control

Quality control should be performed to ensure the achievement of an acceptable standard of accuracy and precision.



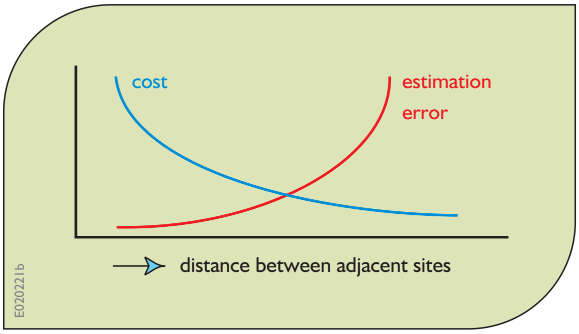


Figure B.3. Density of monitoring sites influences estimates of average conditions over a watershed or along a stream. The density of monitoring sites also affects the cost of monitoring.

6.4. Water Quantity Monitoring

The main hydrological and hydro-meteorological parameters – such as precipitation, snow cover, water level, river flow, suspended and bed load sediment discharges, evaporation and transpiration, soil moisture, and data on ice conditions – are measurable. The use of such data has increased during the past decades, due largely to developments in the use of models and forecasting systems that require these data.

Spatial representativeness is crucial in the selection of monitoring sites for hydro-meteorological parameters. The most common locations for gauging stations are the lower reaches of rivers, immediately upstream of the river mouth or where the rivers cross borders, near the confluence with tributaries and at major cities along the river. In general, a sufficient number of gauging stations should be located along the main river to permit interpolation of water level and discharge between the stations. Water balances require observation stations at small streams and tributaries as well. Gauges on lakes and reservoirs are normally located near their outlets, but sufficiently upstream to avoid the influence of drawdown.

Hydraulic conditions are an important factor in selecting sites on streams, particularly where water levels are used to compute discharge using stage-discharge rating curves. Unambiguous relationships are found at stations located on streams with natural regimes, not affected by variable backwater at the gauge caused by downstream tributaries or reservoir operations or by tidal effects.

The frequency of measurements, data transmission and forecasting depends on the variability of the hydrological characteristics and the response time requirements. Systematic water-level recordings, supplemented by more frequent readings during floods, are appropriate for most streams. The installation of water-level recorders will usually be required for streams whose levels are subject to abrupt fluctuations. For flood forecasting or flood management, telemetric systems may be used to transmit data whenever the water level changes by a predetermined amount. Continuous river flow records may be necessary in the design of water-supply systems, and in estimating the sediment or chemical loads of streams, including pollutants.

Factors to be considered in determining the number and distribution of discharge measurements within the year include:

- the stability of the stage-discharge relationship
- seasonal discharge characteristics and variability
- accessibility of the gauge in various seasons.

At new stations, many discharge measurements at different flow levels are needed to define stage-discharge relationships. At existing stations the frequency of measurements is dictated in part by the number needed to keep the stage-discharge relationship up to date. Adequate determination of discharge during floods and under ice conditions can be difficult, but is of prime importance where applicable. In situations where the channel shape can readily change during high-flow conditions, keeping an up-to-date stage-discharge relationship is a challenging (or perhaps indeed unattainable) goal.

6.5. Water Quality Monitoring

When water quality is monitored, water quantity (flow) should also be monitored at the same sites and times.

For specific human uses, standards may dictate the water quality parameters that need monitoring. Management issues may also dictate the parameters of interest. For ecological functioning, parameters are specified by the selected method of assessment (indices, habitat factors) and regional reference communities. The selection of hazardous pollutants as monitoring parameters will usually depend on the specific problem substances produced and/or discharged into the water and on their probability of occurrence. In practice, this should be based on results of site-specific preliminary surveys.

Nationally and internationally recognized lists of problem substances can often be used as the starting point for the selection of monitoring parameters. They are among or indicative of the pollutants that are of general concern. The availability of reliable and affordable analytical and measurement methods may also influence the selection of monitoring parameters.

In general, the selection of sampling sites is based on how representative they are. The distance between sampling locations can be critically evaluated from their degree of correlation by statistical analysis of time series of parameters. However, this is possible only if these time series are available. In transboundary rivers, sampling should preferably be performed at or near to border crossings. Sampling in the river and in the main tributaries upstream of the confluence can show the contribution (e.g. pollution load) of different tributaries. The selection of sampling sites downstream of a confluence should avoid the uncertainties related to incomplete mixing. Mixing zones can be several kilometres long, depending on the width–depth ratio and the turbulence of the main river.

Considerations of the local representativeness of the sampling point at the river site may be based on preliminary surveys, taking into account the hydrology and morphology of the river. In general, locations in the main flow of the river will be chosen for water and suspended solid sampling. Bottom sediment can best be sampled in regions where the suspended material settles. As a consequence, most sediment samples are taken near riverbanks and in the downstream sedimentation area.

The number of sampling points for sediment monitoring strongly depends on the objectives. For trend detection, a low number of sampling points or mixing samples into composite samples can sometimes yield enough information. If spatial information is to be estimated, the number of sites will increase and composite samples will normally not be used.

The selection of the sampling frequency for surface water quality parameters should be based on the variability in parameter values, and on the statistical significance and accuracy required for specific objectives. Examples of specific objectives include trend detection, load calculation and compliance testing.

Sampling frequencies for suspended solids are very similar to surface water sample frequencies. For load calculation, a higher sampling frequency is recommended during the start of flooding periods, when the main load of suspended solids is transported. The precision of the estimates obtained by sampling at regular intervals depends mainly upon the distribution of the total load over the year. The reliability of load estimates obtained with current monitoring equipment can be improved by increasing the sampling frequency.

The need to obtain information that is integrated or differentiated over time and space should determine the selection of methods for measurement and sampling of water and sediment quality and biota. There are various possible methods, including grab sampling, depth integrated sampling, time-proportional composite sampling and space composite sampling. Monitoring of the biological status implies measurement and sampling of biotic groups. Each group requires specific sampling and measurement methods; fine mesh nets collect phytoplankton and zooplankton, for example, and waterfowl can be measured through field observations. Some indicative parameters like dissolved oxygen, pH, water temperature and redox potential are best measured *in situ*, using sensor-based instruments. Such instruments require frequent calibration.

6.6. Ecological Monitoring

Monitoring of ecological parameters can be carried out on the level of species, communities or ecosystems. For many purposes, monitoring the habitat of communities or ecosystems is appropriate and much less demanding than doing so on a species scale. A habitat is the place where an organism or a community of organisms lives, and comprises all living and non-living factors or conditions of the surrounding environment. Habitat descriptions consider the physical environment together with the representative floral and faunal assemblages present. They are often suitable for environmental impact assessments.

Habitat and community descriptions can be based on two types of scales. The DAFOR scale (dominant, abundant, frequent, occasional, rare), adapted from the Joint Nature Conservancy Council (UK), can be used to assess habitat types. It is designed to allow consistent recording of habitat features within and between sites. This habitat detail can be used with species lists produced from site sampling. Only one feature may be recorded as dominant, while any number of features may be recorded as abundant, frequent, occasional or rare.

Species data recorded on site can be assessed using the SACFOR scale (superabundant, abundant, common, frequent, occasional, rare). Fauna and flora species can be identified and recorded where possible. When sampling is not applied, the most abundant species observed and any noteworthy or rare species at each site can be identified *in situ*, with a further list of species expected or typical of such habitats.

6.7. Early-Warning Stations

Measurement systems in an early-warning station are either substance- or effect-oriented. Chemical analysis screening methods can detect increases in concentrations of specific substances. Biological early-warning systems can detect deterioration in water quality through the biological effects on fish, daphnia, algae, bacteria and other species.

The pollutants that may occur in hazardous concentrations should be monitored for early warning. Automatic *in situ* sensors can measure simple indicative parameters such as dissolved oxygen, pH, or oil. If the detection of specific micro-pollutants (e.g. pesticides) is needed, advanced, but more expensive, analytical systems based on gas chromatography with mass spectrometry (GC-MS), high-performance liquid chromatography (HPLC) can be used. Toxicological effects in organisms on various trophic levels can be measured with automated biological early-warning systems.

Early-warning equipment puts high demands on operation characteristics such as speed of analysis, identification capacity and reliability of operation. Characteristics such as the precision and reproducibility of the analysis are less critical.

Early warnings should provide enough time for emergency measures to be taken. The relation between response time (the interval between the moment of sampling and the alarm) and the travel time of the pollution plume in the river, especially in high flows, from the warning station to the site where the water is used (e.g. water intake for drinking water) influences the location of an early-warning station.

The sampling sites should obviously be chosen in such a way that no pollutants are missed in the sampled water. The measurement frequency should be determined by the expected size of pollutant plumes (elapsed time for the plume to pass the station). Dispersion of the plume occurs between the discharge location and the sampling location due to the discharge characteristics of the river. Furthermore, the frequencies should provide sufficient time to take action in the event of an emergency. Additional (intensified) sampling is recommended after the first indication of accidental pollution.

6.8. Effluent Monitoring

The selection of effluent monitoring parameters and their priorities can be based on risk assessments. Existing national or international priority lists of chemical substances can also be helpful. In addition to specific pollutants, an emphasis should be placed on aggregate parameters and total effluent toxicity testing.

Sampling frequencies and sampling methods for effluent discharges should be based on the amount and variability of the effluent. Surveys of restricted duration using continuous or high-frequency sampling can be performed to gain the required insight into the discharge characteristics of batch and continuous effluent generation processes. The statistical significance and accuracy required for specific objectives (e.g. for compliance testing or load calculation) can be a basis for selecting the sampling frequencies and sampling methods.

7. Data Sampling, Collection and Storage

7.1. Overview

Sampling is the first stage in the actual collection of information. Methods of sampling include spot, periodic, continuous and large-volume sampling. Which method is most appropriate will depend on the variable of interest and on the characteristics of the watershed or water body. Sampling equipment should be designed to minimize the contact time between the sample and the sampler and the likelihood of sample contamination.

There are a number of sampling decisions that must be made. The first is the choice of the precise sampling site. This can be affected by the conditions at the site, the distribution of what is being measured, and the ease of access to the sampling site with the needed equipment. Second, the frequency and time of sampling must be determined. Different time-based effects can influence this decision. Natural cycles may occur, as well as production and discharge cycles of industries or other facilities just upstream. Third, there is the choice of the sampling method. Some methods, even if recommended in the network design plan, may not be usable in particular situations, for example where the water is too shallow. Fourth, decisions must be made regarding the transporting, stabilizing and storing the samples. Fifth, quality-control procedures must be implemented. All sampling methods should be periodically tested using field-based quality-control and audit procedures specifically designed to reveal the effectiveness of the entire sampling programme, including those aspects relating to the transportation, stabilization and storage of samples prior to analysis. Finally, safety requirements have to be met.

To make monitored data rapidly and conveniently available to users, they are almost always stored in computerized data files. They include the measurement data and associated meta data. The latter identify what the measured data are, when and where they were measured, what methods of measurement or laboratory analyses were used and by whom, and so on.

Often the weakest link within the monitoring programme chain is the proper storage of data. If these data are not accessible and complete with respect to the conditions and qualifiers pertaining to their collection and analysis, or are not properly validated, then the data are not likely to satisfy any information need.

Computer hardware and software used to store and manage data must be tested, maintained and upgraded regularly. The software has to insure against data loss. It must identify the correct secondary data. Furthermore, it should perform internal checks on the measured data, such as correlation analysis and application of limit pairs. Examples of software control functions are $0 < \text{pH} < 14.0$, orthophosphate-P (total-P), dissolved heavy metals (total heavy metals), and calculation of the 10% (lower) and 90% (upper) limit pairs. The software should give users a warning when data fall outside these ranges. All such calculations should be tested for accuracy before using a computer database management system.

Clear procedures should be agreed upon for the interpretation and validation of the measurement data. These will include how to deal with:

- data limitations such as missing values
- sampling frequencies that change over the period of record
- multiple observations within one sampling period
- uncertainty in the measurement procedures
- censoring the measurement signals
- small sample sizes
- outliers (values that do not conform with the general pattern of a data set)
- measurement data rounding
- data at or below the limit of detection.

7.2. Remote Sensing

A variety of remote sensing techniques using aerial photography or satellite images are available for monitoring some parameters. They may be used for the identification of different vegetation types, biotopes and landscape elements. Laser-altimetry provides a useful technique for monitoring forest and grassland structure and sediment bank development.

7.2.1. Optical Remote Sensing for Water Quality

A number of satellite-based optical sensors can be used for monitoring of water quality. The spatial resolution of these sensors renders this method of monitoring suitable for large inland water bodies or coastal waters. For remote monitoring of smaller water bodies where higher spatial resolution is needed, aircraft-based sensors can be used.

When natural sunlight, including the visible spectrum, hits the surface of a water body, some of it may be directly reflected at the surface, some may enter the water where it is absorbed and scattered by particles, and some may be transmitted through the water. The amount of absorption and scattering are the main factors influencing the reflection of light from the water, and thus the colour of the water. The substances present in the water often have unique characteristics with respect to the absorption and scattering of light. Thus the colour of water varies with the concentration of different substances in it.

Deep ocean water has a distinct blue colour because in clear water there is a lot of scattering of blue light (wavelength of blue) compared to the other wavelengths in the visible spectrum. Light absorption is relatively low. If a water body contains algae, then the light scattering by the algae cells dominates the light scattering by water. Also, there will be more light absorption at the wavelengths of blue and red light. As a result, there is a relatively high reflection of green light and the water looks green. Due to different pigments present in different algae types, algae-dominated water bodies can also take on a brown or reddish colour. Dissolved organic substances (such as humic acids) tend to give water a yellow colour, and suspended sediments rich in organic matter (e.g. dead cells) tend to give water a brownish colour.

The amount of reflection of the different colours can be used to identify which substances are present in water and, along with advanced analysis techniques, to determine the concentrations of different substances. The substances that can be quantified on the basis of optical measurements of reflected light include algae (chlorophyll), dissolved organic carbon (humic acids) and suspended sediment.

Optical remote sensing can be applied for assessment of water quality and classification of inland and coastal waters. Sediment plumes can easily be observed and can often give a good indication of the spreading of river water (typically with high sediment concentrations) in coastal seas. The extent of eutrophication can also be monitored. With several consecutive images, the changes in water quality over time can be followed. One disadvantage of remote sensing is that the frequency of available images is inflexible, and on cloudy days no images can be collected.

By using specialized software and computer models, the measured spectral reflection data can be reworked into water quality concentrations, as indicated in Figure B.4. An important aspect in this process is to correct for atmospheric influences on the measured reflection. The measured reflection values are often very low, so processes such as atmospheric scattering of light can have a considerable influence on the measurements. It is therefore important to remove the atmospheric influence by means of 'atmospheric correction' procedures.

Sensors can measure the surface temperature as well as reflected light. The method based on the reflection of natural sunlight is called 'passive' remote sensing, as opposed to 'active' remote sensing that measures the reflection of a beam sent out by the sensor itself (e.g. radar). It is possible to convert the measured spectral reflection data from an airplane or satellite sensor into

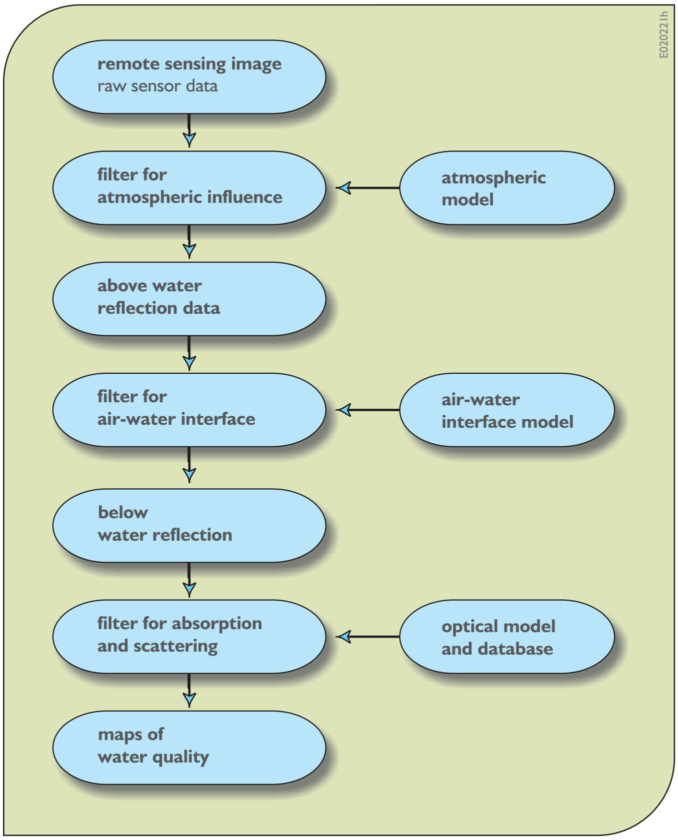


Figure B.4. Steps for obtaining water quality data from optical remote sensing.

an image or map of reflection values. For water quality information, the reflected light signal can be converted to concentrations of water quality parameters, such total suspended matter or chlorophyll. The steps involved in this are shown in Figure B.4.

7.2.2. Applications in the North Sea

The water quality of the North Sea and inland waters is based on concentrations of certain water quality parameters such as algae and suspended matter. These concentrations have traditionally been identified by collecting and analysing water samples from fixed monitoring platforms or from ships. Analyses of the samples are made in the field or at a laboratory. This method has a number of disadvantages. The spatial coverage of the sea is limited due to high costs of collecting and analysing the many samples required from each sampling site. Furthermore, the conditions at a sampling site may be changing during the time that it takes to collect the required number of samples.

Remote sensing is now being used as a relatively inexpensive monitoring method to supplement traditional water quality monitoring, by providing spatial coverage of the water body at different particular times.

8. Data Analyses

Data analysis converts raw data into usable information. Routine data analysis is commonly directed toward obtaining information on average conditions, trends or changing conditions, or to test for compliance with a standard. To compare and trace information obtained from the raw data, protocols for data analysis have to be developed. Using these protocols, many data analysis procedures can be automated.

Data analysis protocols should include:

- A statement of the information to be produced. This is directly related to the specified information need.
- Procedures for preparing a raw data record for graphical and statistical analysis, including how data limitations such as missing values or outliers are to be addressed before data analysis proceeds.
- Means to visually summarize the behaviour of the monitored data. Graphical presentations of the data often serve to give a better understanding of data value variability over time and space and help to interpret statistical results.
- Recommended statistical methods that yield the desired information. The selection of methods should match the statistical characteristics of the data being analysed as well as the information need.

Data analysis protocols should be established before any data are collected and analysed. Otherwise arguments can develop over the analysis methods. Statisticians can and do disagree over what statistical procedures are most appropriate. Whatever methods are used, one should understand the important assumptions that underlie them, whether these assumptions are reasonable in the particular application, and the consequences of violations of the assumptions. If a data analysis protocol is agreed upon, any subsequent discussion can focus on the resulting information.

Water quality and biological samples often require laboratory analyses. This is not the place to go into what is required for the analysis of different types of parameters, except to note that whatever analyses are performed they should be scientifically acceptable and validated. Laboratory equipment should be properly maintained and calibrated with the use of reference materials. The laboratory should undergo effective internal as well as independent quality-control audits and participate in inter-laboratory check sample schemes. Laboratory personnel should be properly trained. These and other basic elements of quality assurance should be followed and enforced to obtain reliable, verifiable results.

A major quality-control issue in data analysis is traceability. It must be possible to trace back to the raw data used in the analysis as well as to the exact analysis method. Reproduction of any previously performed analysis should lead to the same result.

Geographical information systems (GIS) are useful tools for the interpretation of spatial data such as those found on maps and satellite pictures. Integrating spatial data with time-series data, each possibly originating from different agencies/sources, into one system is not easy. Standardized interfaces should be used to interconnect databases and provide for integration with a GIS. Relational databases can be used together with GIS and data processing models. Data processing based on accepted, compatible standards will make assessment and reporting comparable, even when the software used is not the same.

9. Reporting Results

Selecting the method or methods of presenting the data is not a trivial issue. What methods are best depends to a large measure on the target audience. Possible presentation techniques, from a detailed presentation to an aggregated overview, include:

- Tables that list measurement data. No data are lost but the reader has to glean the needed or desired information from the data.
- Statistically-processed measurement data are transformations of the original data into values that make changes in time and/or space more visible.
- Graphs providing a medium in which, for instance, trends can be recognized at a glance. Showing standards or other references in the graph puts the system status in perspective. The amoeba-type presentation discussed in Section 9.2 is an example of this. Graphs may be line graphs, histograms, pie charts or various other forms.
- Geographically presented information shown on a map. Different data from multiple locations can be displayed as multiple layers of geographically referenced information. This often provides a better understanding of the spatial distribution of the parameters involved.
- Aggregated information for rapid interpretation of large amounts of data, for example using indices. Quality indices are often used for biological quality assessments.

9.1. Trend Plots

Trends are often displayed as time-series plots, examples of which are shown in Figure B.5. If a significant long-term trend exists, it may be apparent upon visual examination of a plot of the raw data. Many parameters exhibit strong seasonality and therefore a 'typical' range of values can also be shown. In Figure B.5, the 'typical' range was defined to encompass approximately 70% of the values for each month. In this case, 15% of the values should exceed the high value and 15% should be lower than low value. The shaded areas in Figure B.5 represent the 'typical' range across the middle of each plot. Comparing the data points to that shaded area makes any trend more apparent should it exist.

If seasonal variability is too great to use the time-series plots to identify long-term trends, a twelve-month moving mean can be calculated for each site. The moving mean smoothes out seasonality in many cases and makes long-term trends easier to see. If the moving mean plot suggests that a trend might exist, the raw data can then be analysed further for trends.

9.2. Comparison Plots

One way of comparing data is through the use of amoeba plots. An amoeba plot is a schematic representation of a given condition compared to the 'natural' average or

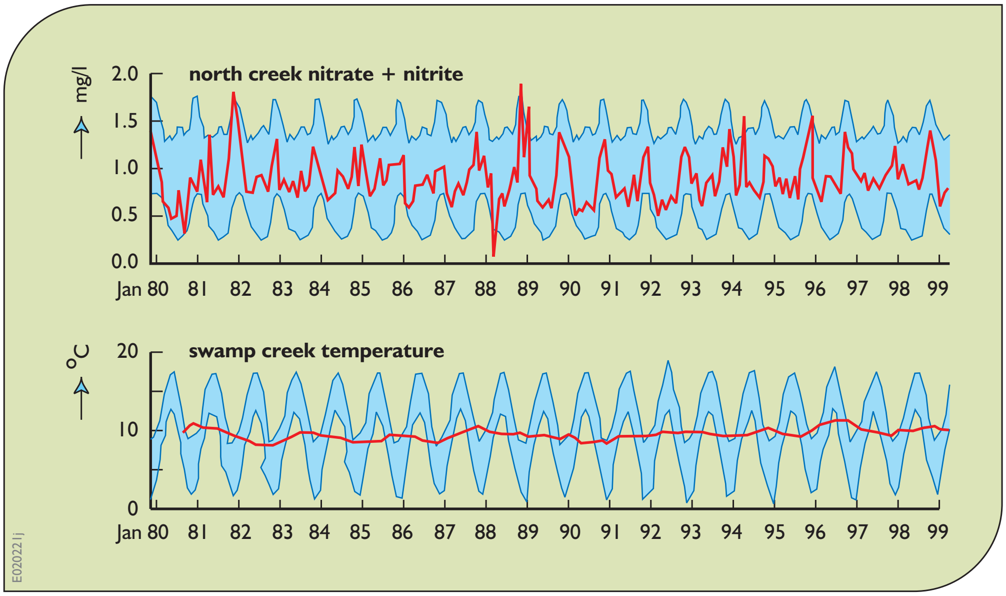


Figure B.5. Examples of trend plots. The shaded areas are the ranges of values in a specified percent of the data. A moving mean plot is shown in the lower graph for temperature data.

baseline condition. For the water body under study, a set of parameters considered to be representative of the water body's condition is chosen. The reference 'system' is represented by plotting the value of the parameters under 'natural' conditions on a circle. The present values of the selected parameters are plotted relative to the circle. This provides an amoeba-like figure, representing deviations from the reference or normal state, as illustrated in Figure B.6.

The figure shows stream health as indicated by eight measures of stream bugs (benthic macroinvertebrates). Stream bugs are excellent indicators of stream health. They are relatively easy and inexpensive to collect. They play a crucial role in the stream nutrient cycle, and their populations affect the whole ecosystem. The presence or absence of pollution-tolerant and intolerant bug types can indicate the condition of the stream. Population fluctuations might indicate that a change (positive or negative) has occurred in the stream. One can detect population fluctuations in a short period of time.

The circle in Figure B.6 represents the normal (healthy) value of each parameter. Deviations from that circle are expressed as percentages of these normal values. Log scales are sometimes convenient.

Amoeba plots can be used to compare data at a given site or compare the data at one site with those of other sites in a specified region.

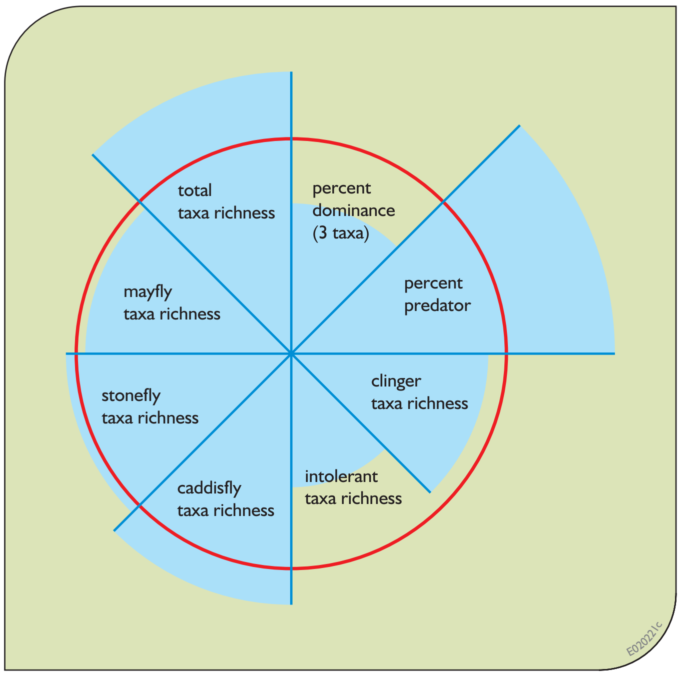


Figure B.6. Amoeba diagram showing status of a system with respect to the target or normal state of, in this example, eight specified parameters (bug species).

Figure B.7 illustrates another way to compare the baseline averages measured in one stream to the median levels for all tributaries measured in the region. The shaded area represents the range in which the middle 50% of all

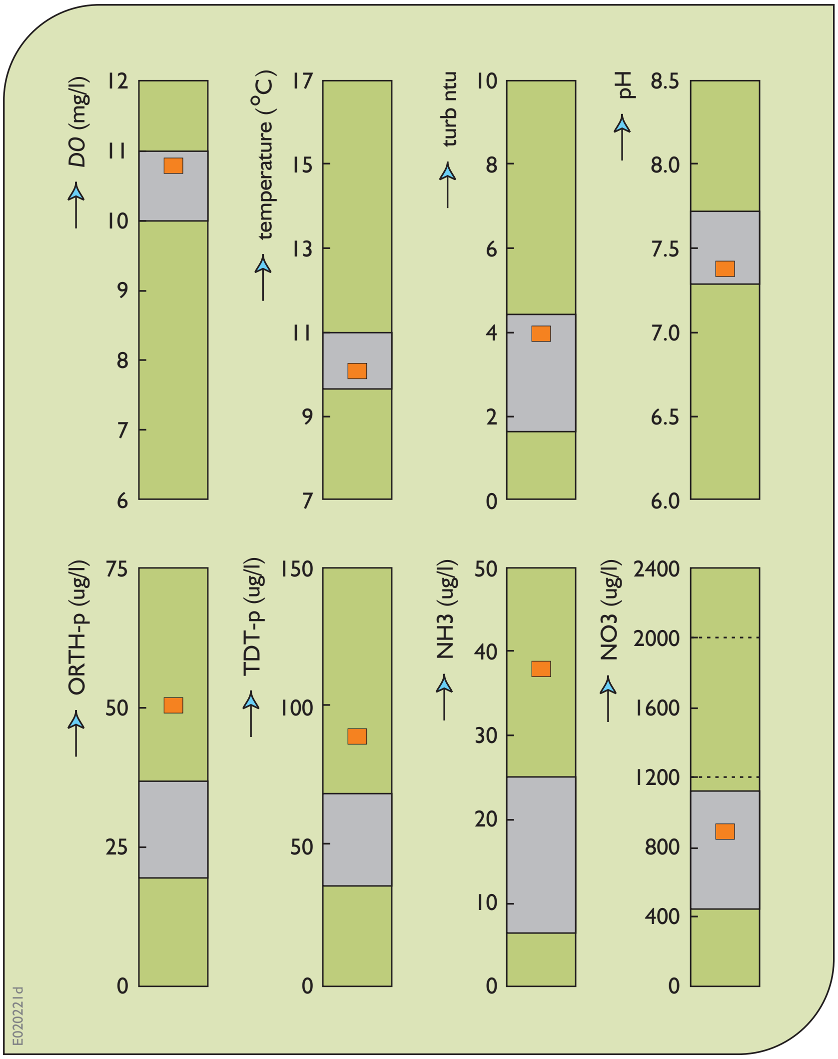


Figure B.7. Comparison plots showing how selected parameter values at one site compare with the values at other sites in the area. The grey bands identify the middle 50% ranges. The small red squares are the specific site values.

site averages fell, i.e. 25% were higher and 25% were lower than the shaded area. Along with these charts can be tables, not shown here, that list the average, minimum and maximum values for each parameter for each stream.

Other ways of displaying data are shown in Table B.3. In this case the data are being summarized with respect to the percentage of values that met specified standards.

Scorecards can also be used to compare data. Consider a biotic integrity index composed of ten different indicators of stream biology. Each indicator characterizes some aspect of the community that responds to degradation. The actual value of each indicator is calculated, and from that value, a score of 1, 3, or 5 is assigned to the indicator. A score of 5 indicates little or no degradation, a score of 3 moderate degradation, and a score of 1 severe degradation. The ten metric scores are then added to produce the overall score that ranges from 10 to 50. (If any indicator values are missing no score is given.) The resulting scorecard is shown in Table B.4.

Data can be interpreted by risk assessments as well. This refers to the comparison of measured, modelled or predicted values with target values. Target (desired) values of various parameters will be based on specific functions of waters, such as use for drinking water or recreation. The measured or predicted data are referred to as Predicted Values (PV), and the target or desired values are referred to as Target Values (TV). For the former, terms like Predicted Environmental Concentrations (PEC) of pollutants are sometimes used. For the latter, terms like Predicted No Effect Concentrations (PNEC) or Maximum

parameter collected	# of samples	# of samples not meeting criteria	% of samples not meeting criteria
D.O.	231	16	7.1
Temperature	245	17	6.9
Turbidity	234	15	6.4
pH	231	1	0.4
Enterococcus	127	64	50.4
Fecal Coliforms	235	172	73.2

Table B.3. Ways of displaying information pertaining to whether or not sample data met the standards for the selected parameters.

code	site name	1994	1995	1996	1997	1998	1999	2000
1	Nicki Creek	44	36	28	26		30	22
2	Bear Creek	36	34	<30	28		26	16
3	Eelco Creek	25	26				20	14
4	Simon Creek		<30		dry		dry	dry
5	Bug Creek	35	<30		30		22	28
6	Jos Creek						28	24
7	Sus Creek			26	26	18	24	26
8	Jen Creek	32	22			20	28	24
9	Beaver Creek		<30				dry	dry
10	Wolf Creek		<30		24		22	22
11	Erik Creek	18	26			32	34	28

Table B.4. Scorecard for indices of biotic integrity.

Permissible Concentration (MPC) or function-related directives are also used. The risk quotient is the ratio of predicted (PV) over target (TV). This ratio will indicate the relative priority of that parameter.

The outcome of a sediment quality assessment could be expressed as a PEC/PNEC ratio. If this ratio is <1, little priority is given to the potential risk derived. If this ratio is >1, a certain risk is indicated. Classifying the responses might help to visualise the estimated risks in time trends or spatial gradients. The more function-related the quality criteria used, the more specific the conclusions that can be drawn on which function might be impeded due to the pollution present.

9.3. Map Plots

Two examples of map plots are shown in Figures B.8 and B.9.

Figure B.8. Map display showing lake shore areas, in red, that are at risk of bank failure.

10. Information Use: Adaptive Management

Management decisions will always be made on the basis of uncertain information. These uncertainties in our ability to predict the impacts of our management decisions motivate the use of adaptive approaches to management. Adaptive management is the process by which management policies change in response to new knowledge gained from research and new information obtained from monitored data about the system being managed. Adaptive management requires a monitoring programme to detect changes in the system, the ability to evaluate trends in system performance and, finally, the authority and willingness to modify management decisions in response to those trends in an effort to improve system performance.

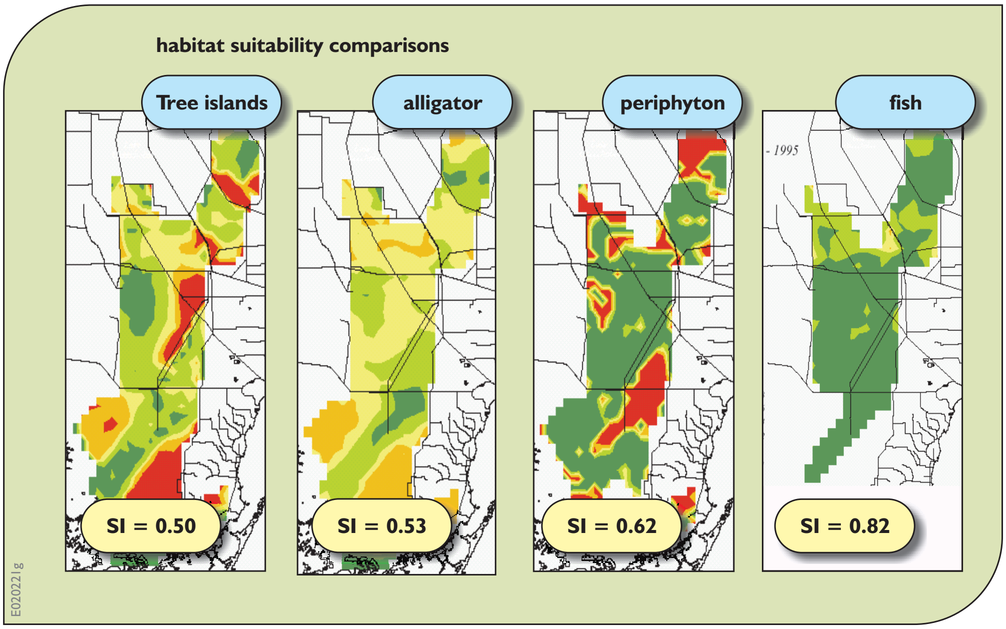


Figure B.9. Map displays showing distribution of habitat suitability index (SI) values for four ecosystem indicators applicable to southern Florida in the United States. Separate colors represent ranges of SI values. The average index value is shown for each indicator. (Based on Tarboton et al., 2004).

Models of the hydrological and ecological responses to management decisions, together with monitored observations, are essential components of any adaptive approach to management. An effective research strategy can lead to improved monitoring designs, improved interpretation of monitored parameter values, and improved predictive power of models and other assessment tools used in management. An integrated approach to monitoring, modelling, research and management can lead to an improved understanding of how the overall system functions and how best management practices can be implemented. Each component continually needs refining, as our understanding of the system being managed increases.

Adaptive management and decision-making is a challenging blend of scientific research, monitoring and practical management that provides opportunities to act, observe and learn, and then react. Both monitoring and management actions need to be adaptive, continually responding to an improved understanding that comes from the analysis of monitored data in comparison to model predictions and scientific research. It is a cycle, as illustrated in Figure B.10. Adaptive management requires explicit consideration of system structure and function, well-defined management goals and actions, and assessment of the anticipated system response to management decisions.

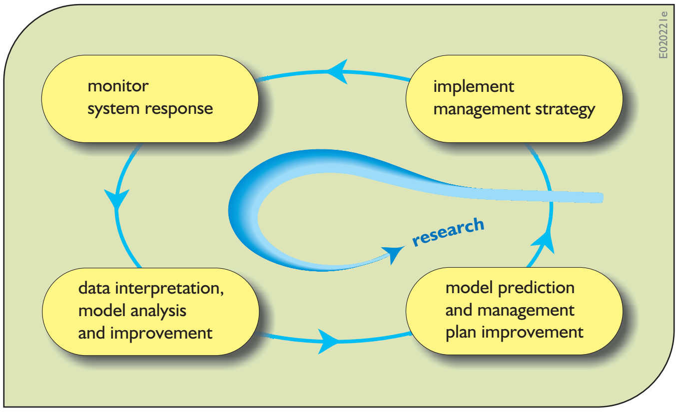


Figure B.10. The continually updating process of an adaptive approach to management.

The design of an adaptive management plan is best accomplished in cooperation with policy-level personnel who have the authority to commit the resources and technical personnel needed to identify scientific issues and evaluate monitoring data. Management that is to be adaptive has to rely on monitored data, and given the response times of many hydrological and ecosystem performance criteria used to judge success or failure, there must be a long-term commitment of resources to monitoring and all that it entails. But monitoring costs money and hence should be efficient. In the interest of cost savings, some water management agencies intensively monitor river basin processes and parameters only periodically, say every five years, and carry out more routine, low-intensity monitoring in the intervening period.

11. Summary

The degree of success of any monitoring and adaptive management programme can be expressed using the two terms 'effectiveness' and 'efficiency'. Effectiveness is the extent to which the information obtained from monitoring meets the information needs of management, and the extent to which management decisions reflect this increased information and understanding. Efficiency is concerned with obtaining the information at the least possible cost in funding and personnel. The two aspects address the two fundamental questions:

- Are the data being collecting the right data?
- Can the required information be obtained at a lower cost?

The answers to these questions are strongly related to the available budget for monitoring, and to the issue of whether more or other information is needed. If more information is required (e.g. biological monitoring in addition to chemical; or ambient water and sediment monitoring in addition to effluents) and no more money is available, then certain aspects of the existing programme must be reduced. For example, parameters reflecting the combined impacts from a number of separate parameters can be considered instead of single water quality variables. The number of stations or variables, or the frequency of sampling can be altered. If the need for other information means reductions in current data monitoring (e.g. measuring surface water quality data instead of effluent data, or using biological classification instead of chemical classification), then conflicts may arise with existing regulations and data users.

The total benefits and costs related to the monitoring information system are not only dependent on the number of sampling locations or the equipment and personnel required for laboratory analyses. Benefits also include any increased system performance due to the additional monitoring information. To quantify the benefits in financial terms, it is necessary to calculate the consequences of a shortfall in the monitoring design, for example the financial implications of incorrect decisions, or the cost related to the absence of specific information on a particular water system.

The design of a monitoring programme has to be based on the information requirements, which in turn are related to the needs of water managers. Monitoring programmes should be iterative in character. The design of the future monitoring system should be based on information collected by the existing monitoring programme. Monitoring programmes must be constantly 'designed', specified, detailed, described, or documented and updated to be sure that the system continually produces the information desired.

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