B. Monitoring and Adaptive Management

1. Introduction

2. System status
   2.1. System status indicators

3. Information needs
   3.1 Information objectives and priorities

4. Monitoring plan

5. Adaptive monitoring
   5.1 Risk assessments for monitoring
   5.2 Use of models

6. Network design
   6.1 Quality control
   6.2 Water-quantity monitoring
   6.3 Water-quality monitoring
   6.4 Ecological monitoring
   6.5 Early-warning stations
   6.6 Effluent monitoring

7. Data sampling, collection, and storage
   7.1 Remote sensing

8. Data analyses

9. Reporting results
   9.1 Trend plots
   9.2 Comparison plots
   9.3 Map plots

10. Information use: Adaptive management

11. Summary

12. References

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 identifying performance indicators and how frequently and accurately they will be measured over time and space. The major challenge in monitoring is making the information obtained fit the information needed and then acting on that information, if, 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 as well as monitoring policies based on what they learn about the system they are managing. Just how much and how well they learn will be
largely based 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 resource 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 pre-arranged 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. Active adaptive management can be risky. It is possible such management experiments could degrade the system, e.g., kill some of the species in an ecosystem being 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 based on what is learned as it is learned, but without taking possibly risky experiments.

The questions to be addressed in establishing a monitoring program 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 program is sufficient to act upon, as well as what such acts should be. Often the impacts, 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 program's life cycle, as shown in Figure B.1. The process of monitoring and adaptive management is more than just measuring system attributes, collecting, storing, and analyzing 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.

Modeling can aid in identifying just what data are needed for the decisions being considered, and how accurate those data need be. (Some modeling examples in Chapter VIII illustrate this.) A dilemma of course is that if data obtained from a current monitoring program are intended to be of value to future managers, it is difficult to know today just what data, and their precision, those future managers may want.

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

The design of a monitoring system starts with defining the information needed for decision making. The information needed determines the attributes to be measured, i.e., the types of data to be collected and the kinds of analyses to be applied to the data. The monitoring plan identifies 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, respectively, and just how important it is to capture this temporal or spatial variability.

Once the network design has been defined, data collection, storage and analyses, and reporting and dissemination procedures need to be specified. 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 based on 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 are based 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 and costs and benefits of additional data.

Figure B.2 Water management activities to identify information needs.
The need for information 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 multi-purpose system management (see Table B.1).

Table B.1.  System functions and uses.

Additional surveys and monitoring are needed if sufficient data are not available to determine 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.

Water-quality surveys can give additional insight into the functioning of the aquatic ecosystem and the occurrence 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 provide 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 analyzed. Employing 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 are preferably 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. As an example for eutrophication, total phosphorus can be a good indicator of the status of the river. Salmon is an indicator for the ecological state of rivers such as the Columbia and Rhine Rivers. Such indicators should include what the public cares 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 without having 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 programs 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 program is the clear definition and specification of information needs. Information needs need to 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 "Twenty percent 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 representing the efforts to restore the ecology of the Rhine River this past half decade. 'Getting the salmon back into the river Rhine in the year 2000' is a statement 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. Effectiveness of a monitoring network can only be tested when the information needs based on one or more management objectives are defined.

Five different approaches for defining information needs can be distinguished:

1) the effect-approach: there can be an adverse effect of some kind that should be reduced within a certain period. The element of relativity can be used here.

2) the source-approach: there are sources that cause adverse effects. These sources have to reduce their effect, e.g. by reducing their loads on the environment. This is closely related to the effect-approach.

3) the achievement-approach: there is a goal to be achieved within a given time period. This approach gives an impression of how far the intended actions will be after some time. '…salmon back in the river Rhine' is an example of this approach.

4) 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.

5) the function-approach: the water system has to fulfill a specific function, e.g. be fit for salmon and / or swimming.

The different approaches listed above are often interrelated. Nevertheless, using each of these approaches can help facilitate the identification and specification of information needs. Information needs should be identified and described in sufficient detail to insure the design of a monitoring and assessment system that will meet these needs. Examples of such specified information needs include:
The identification of appropriate parameters and/or indicators.

• The definition of criteria for assessment, e.g. considerations for the setting of standards or criteria for the choice of alarm or trigger conditions for early warning, such as 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 within weeks or even months after sampling;

• Reliability requirements. To what extent is false information allowed? One hundred percent reliability is often impossible or prohibitively expensive. Depending on the consequences, information should be more or less reliable, however. 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 programs.

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 along with institutions responsible for the management and use of water resources should be involved in the process of specifying information needs. Both information users and information producers should be identified and both should closely interact.

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 consequently 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 as 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, etc.). This continuity is needed to detect significant and reliable trends in system performance characteristics.

4. Monitoring plan

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:

1. The information needs that will be covered by the monitoring program and, equally important, the information needs that will not be covered by the monitoring strategy.
2. 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).
3. The calculation methods, and the graphical, statistical, and other tools (such as indices) to be used.
4. The preconditions, suppositions, assumptions, and descriptions of the area, relevant industries, major demands, etc.
5. The organizational responsibilities for the monitoring program
6. A plan for the design and implementation of the monitoring network
7. An analysis of the risks and the possible problems that can lead to the failure of the monitoring program.

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 (for uses/functioning, issues and impacts), their occurrence and their hazardous character. 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 its cost. Since the benefits will not likely be expressed in monetary terms, this usually has to be a qualitative comparison, using judgment.

Integrated water management involves the consideration of all aspects of a water resource 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 departs from a focus on 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 affect the ways in which human beings use and impact the system. These factors should be assessed because of their ultimate effect on the integrity of the system. For example, one cannot ignore the addition of some 20 million people who now make their home, at least part of the year, in the Everglades region of South Florida in the US while trying to restore the hydrology and ecosystem to what it was like a half century ago before most of those 20 million arrived. The needs for reliable water supplies and flood control did not exist some 50 years ago. Nor did the pollutants discharged from municipalities, agriculture and industry. These 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 water quantities and qualities and ecological indicators, but also 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 labor-intensive to technology-intensive methods might be appropriate. In many cases, the lack of consistent and reliable data and the non-existence 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 will unlikely pose a risk to human health. On the contrary, if there are refuse dumps or industrial plants in that catchment, a high risk to human health and/or aquatic ecosystems is possible. 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 (because of a lack of monitoring) is available? What is the loss 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, based on their physicochemical properties and toxicity. Risk assessment, both regarding 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 assist 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 to humans and ecosystems. Computer models linked with geo-referenced databases can be used to analyze the impact of proposed measures, e.g. by simulating the flow and water level variations in a river and on flood plains 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). Models can be used in addition to monitoring to help understand what, where, and how often and how accurate to monitor.

Successful mathematical modeling for planning monitoring programs is possible only if the modeling 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. The monitoring of the quality and biology of the aquatic environment should be coupled with the appropriate hydrologic quantity monitoring. Finally, arrangements should be made to insure 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.

Table B.2. Network design aspects for various monitoring objectives.
It may often be necessary to carry out a preliminary sampling and analysis program 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 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.
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.

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 stream flow and quality gages a, b, and c. What ever number of stream gauges are going 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 influences 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 (e.g., continuous sampling, grab sampling, composite
sampling) will be dictated by both the temporal variability as well as 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.

6.4 Water-quantity monitoring

The main hydrological and hydrometeorological 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 possible parameters that can be measured. The use of these 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 hydrometeorological parameters. Major locations of 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 that are located at 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 level is 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:

1) The stability of the stage-discharge relationship;
2) Seasonal discharge characteristics and variability;
3) 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 flood and under ice conditions can be difficult but 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 challenge, if indeed it can be met.

6.5 Water-quality monitoring

When measuring water quality data (e.g. in case of computation of loads), the location of hydrological water-quality sampling devices should be at the same sites if possible.

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 their representativeness. 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 preferably should 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 kilometers long, depending on the width-depth ratio and 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 sampling 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 necessity to obtain information, which 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, e.g. 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 biotic group requires specific sampling and measurement methods, e.g. fine mesh nets collect phytoplankton and zooplankton, and waterfowl is measured through field observations. Some indicative parameters like dissolved oxygen, pH, water temperature, redox potential, etc. are best measured in situ, using sensor-based instruments. Such instruments require frequent calibrations.

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 on a species scale. A habitat is the place where an organism or a community of organisms lives, including all living and nonliving 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) can be used to assess habitat types. This scale has been adapted from the Joint Nature Conservancy Council (UK). The DAFOR scale 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-oriented or effect-oriented. Chemical analysis screening methods can detect increases in concentrations of specific substances. However, only a fraction of the large number of chemical substances that occur can actually be measured on-line. Biological early-warning systems can detect deterioration in water-quality through the biological effects on fish, daphnia, algae, bacteria, etc.

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 substances. If the detection of specific micropollutants (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, capability of identification 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 time interval between the moment of sampling until 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 of effluent discharges should be based on the amount and variability of the effluent discharged. Surveys of restricted duration using continuous or high-frequency sampling can be performed to gain the required insight into 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

Sampling is the start of the actual collection of information. Ways of sampling include spot sampling, periodic sampling, continuous sampling and large volume sampling. The most appropriate type of sampling 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. The conditions at the site, the distribution of what is being measured, and the access to the sampling site with the needed equipment can influence the choice of the site. Secondly, 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 of the sampling location. Thirdly, there is the choice of the sampling method. Some methods, even if recommended in the network design plan, may be unusable in specific situations, e.g. if the water depth 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 examine the effectiveness of the entire sampling program, including those aspects relating to the transportation, stabilization and storage of samples prior to analyses. Finally, safety precautions have to be met.
To make monitored data rapidly and conveniently available to users, they are almost always stored in computerized data files. These data include the measurement data and associated meta data. Meta data identify what the measured data are, when and where they were measured, what methods of measurement or laboratory analyses were used and by who, etc.

Often the weakest link within the monitoring program chain is the proper storage of data. If data are not accessible and complete with respect to the conditions and qualifiers pertaining to their collection and analysis or properly validated, the data will not likely 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, the computer software should perform internal checks on the measured data, e.g. correlation analysis and application of limit pairs. Examples of software control functions are $0 < \text{pH} < 14.0$, orthophosphate-P $\leq$ total-P, dissolved heavy metals $\leq$ 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, and
- data at or below the limit of detection.

### 7.1 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.

7.1.1 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, airplane 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 parts of it 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 color of the water. The substances present in the water often have unique characteristics with respect to the absorption and scattering of light. Thus the color of water varies with the concentration of different substances in the water.

Deep ocean water has a distinct blue color 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 color. Dissolved organic substances (such as humic acids) tend to give water a yellow color, and suspended sediment rich in organic matter (e.g. dead cells) tend to give water a brownish color.
The amount of reflection of the different colors can be used to identify which substances are present in water, and, along with advanced analysis techniques, to determine the concentrations of different substances in water. The substances that can be quantified based on optical measurements of reflected light include algae (chlorophyll), dissolved organic carbon (humic acids) and suspended sediment.

Optical remote sensing can be applied for the 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 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 that processes such as atmospheric scattering of light can have an important influence on the measurements. It is therefore important to remove the atmospheric influence using ‘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 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.
7.1.2 Applications in The Netherlands
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 been traditionally determined by collecting and analyzing water samples from fixed monitoring platforms or from ships. Analyses of the samples are made in the field or at a laboratory. This conventional method has a number of disadvantages. The spatial coverage of the Sea is limited due to high costs of collecting and analyzing the many samples required from each sampling site. Furthermore, the conditions at a sampling site can be changing during the time that it takes to collect the required number of samples from that site.
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 information that can be used. Routine data analysis is commonly directed toward obtaining information on average conditions, trends or changing conditions or testing 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:
1. A statement of the information to be produced. This is directly related to the specified information need.
2. Procedures for preparing a raw data record for graphical and statistical analysis including how data limitations like missing values, outliers, etc. are to be addressed before data analysis proceeds.
3. Means to visually summarize the behavior of the monitored data. Graphical presentations of the data are often useful to gain a better understanding of data value variability over time and space and to interpret statistical results.
4. Recommended statistical methods that yield the desired information. The selection of methods should match the statistical characteristics of the data being analyzed as well as the information need.

Data analysis protocols should be established before any data are collected and analyzed. Otherwise arguments can develop over data analysis methods. Statisticians can and do disagree over what statistical procedures are most appropriate. Whatever methods are used, one should understand the important assumptions of the methods, whether those assumptions are reasonable in the particular application, and the consequences of violations of these 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 using
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, comparable 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. Reproducing any previously performed analysis should lead to the same result.

A geographical information system (GIS) is a useful tool for the interpretation of spatial data such as 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 a geographical information system 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 depend 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 view in which, for instance, trends can be recognized at a glance. By showing standards or other references in the graph, the system status is put in perspective. The amoeba-type presentation is an example of this. Graphs can be line graphs, histograms, pie charts, etc.;
- 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, using indices, for example. Quality indices are often used for biological quality assessments.

9.1 Trend plots

A common way to show trends are 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 fifteen percent of the values should exceed the high value and fifteen percent 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 analyzed further for trend analysis.
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.

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 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.

In Figure B.6, stream health is shown 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) may have 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 in percent of these normal values. Sometimes log scales are convenient.
Figure B.6. Amoeba diagram showing status of system with respect to the target or normal state of, in this example, eight specified parameters (bug species).

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

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 percent of all site averages fell (i.e., 25 percent were higher and 25 percent 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.
Figure B.7. Comparison plots showing how selected parameter values at one site compare with the values at other sites in the area. The gray bands identify the middle 50% ranges. The small red squares are the specific site values.

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.

Table B.3. Ways of displaying information pertaining to whether or not sample data met the standards for the selected parameters.
Scorecards can also be used to compare data. Consider a biotic integrity index composed of 10 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 to indicate moderate degradation, and a score of 1 to indicate severe degradation. The 10 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.

Table B.4. Scorecard for indices of biotic integrity.
Data can be interpreted by risk assessments as well. This refers to the comparison of measured or modeled or predicted values with target values. Target (desired) values of various parameters will be based on specific functions of waters, e.g. use for drinking water or recreational use. The measured or predicted data are referred to as Predicted Values (PV), 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 Permissible Concentration (MPC) or function-related directives are also used. The risk quotient is the ratio of predicted (PV) over target (TV) value. 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.

![Map display showing lake shore areas, in red, that are at risk of bank failure.](image)
Figure B.9. Map displays showing distribution of habitat suitability index (SI) values for four ecosystem indicators applicable to southern Florida in the US. Separate colors represent ranges of SI values. The average index value is shown for each indicator. (based on Tarboton, SFWMD, 2001)

10. Information use: Adaptive management

Management decisions will always be made based on 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 program 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.

Models of the hydrologic 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, modeling, 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 provide 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 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 having the authority to commit 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 hydrologic 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 just periodically, say every 5 years, and carry out more routine low intensity monitoring during the intervening years.
11. Summary

The degree of success of any monitoring and adaptive management program 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 as low as possible financial and personnel costs. They address the two fundamental questions:

- are the data being collecting the right data; and
- 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 desired (e.g. biological monitoring in addition to chemical; and ambient water and sediment monitoring in addition to effluents) and no more money is available, then certain aspects of the existing program 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, variables, or 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, e.g. 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 program has to be based on the information requirements, which are in turn related to the needs of water managers. Monitoring programs should be iterative in character. The design of the future monitoring system should be based on information collected by the existing monitoring program. Monitoring programs must be continually 'designed', specified, detailed, described, or documented and updated to be sure that the monitoring system continually produces the information desired.

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