Introduction

Today, the problems posed by the shortage of water and continuing pollution demand more effective ways of monitoring and managing our lakes and rivers. In Europe, the statutory requirements of the Water Framework Directive (WFD) make further demands on our collective expertise and require a sound understanding of the processes that regulate the dynamics of aquatic systems. Freshwater ecosystems are highly dynamic and change on time-scales that range from a few hours to several months. The development of models that simulate these processes is often hampered by the lack of sufficient data to parameterize the processes and validate the models. In this article, I review some of the challenges posed by this lack of information and suggest ways in which they can be met by using automatic monitoring systems of the kind described by Rouen et al. (2005, this volume). The examples are drawn from recent modelling studies in semi-arid regions. One of these studies is the project tempQsim (EVK1-CT2002-00112) funded by the European Commission. In this project, detailed field and model analyses have been performed at eight catchment study sites in south and south-east Europe. A number of perceptual models for the study sites have been established, and results are being used to improve selected catchment models and provide a more adequate description of pollution dynamics (e.g. Tournoud et al. 2004, Tzoraki et al. 2004). Results from the extensive field studies and model tests are now being used to derive recommendations for more tailored monitoring concepts in highly dynamic, but ‘data scarce’ environments, such as are frequently found in Mediterranean river basins.

The objectives of monitoring

Despite all the effort devoted to monitoring lakes and rivers, the practical benefits gained are often few. Harmancioglu et al. (1999) identified a number of reasons for the failure of such programmes. They include a limited understanding of the key drivers, difficulties in selecting the most appropriate sampling frequency and a lack of integration between measurement and management. Aquatic monitoring programmes are typically
designed to meet two, often conflicting, objectives: (i) to gather information that improves our scientific understanding; (ii) to gather information that allows the quality of the water to be assessed and documented, and deviations from a ‘target’ status to be detected. Many existing programmes have developed in an \textit{ad hoc} way. Most scientific investigations are of short duration whilst the schemes developed by governmental institutions are usually designed to meet very basic statutory requirements.

Bartram \& Ballance (1996) suggested the following definition of such ‘sampling’ activities:

- \textit{Monitoring} is the long-term, standardised measurement and observation of the aquatic environment in order to define status and trends.
- \textit{Surveys} are finite duration, intensive programmes to measure and observe the quality of the aquatic environment for a specific purpose.
- \textit{Surveillance} is the continued measurement of specific properties for the purpose of water quality management and operational activities.

These distinctions are, however, rather arbitrary since most sampling programmes have to meet several practical as well as scientific objectives. If the different activities are carried out independently, it is also difficult to integrate the results efficiently. It is, therefore, important to identify key variables which can be investigated at all levels.

The methods used for monitoring

A number of factors influence the choice of the methods used for monitoring freshwater ecosystems. In some cases, technical problems are encountered that depend on the sensitivity and reliability of the measuring instruments. In others, the problems are logistical and are often related to the way in which the instruments are used, e.g. the spatial disposition of the sensors or the sampling frequency. A number of articles in this Special Issue have addressed the problems posed by rapid rates of change (May et al. 2005, Rouen et al. 2005). Reservoirs in semi-arid areas are particularly difficult to monitor since large variations in the inflow are usually associated with large variations in the quality of the water. Two different types of water quality variations can usually be distinguished:

- Systematic variations in the pollution load associated with moderate increases in the flow.
- Episodic variations in the pollution load associated with extreme increases in the flow.

In both cases, very high sampling frequencies are required to estimate the pollutant loads, and the timing of the measurements needs to be matched to the system dynamics.
The results from a sampling campaign in Sardinia (Diliberto & Botti 2004) provide a good example of the water quality variations associated with a moderate increase in the flow (Fig. 1a). The Mulargia catchment is less affected by erosion than many others in the Mediterranean (Botti, 2003). According to our current understanding, particulate nutrients accumulate on the land and on exposed river beds during the dry period, forming an easily removable fraction. During the moderate increase of runoff, the concentration of the particulate nutrients in the river water increases rapidly and reaches a maximum that coincides with the peak of the flood. On the falling limb of the hydrograph, the concentration of particulate nutrients decreases and approaches baseline levels in less than four hours. Most of the total phosphorus exported during the flood (ca. 84 % and 99 %) is in particulate form. The same is also true for the total nitrogen, where the particulate fraction accounts for ca. 59 % to 96 %. The results in Fig. 1b, are taken from the same study and show the effect that antecedent flow conditions have on the flux of particulate nutrients. Although the first flood only represented 10 % of the annual runoff, it exported 32 % of the annual load of particulate nutrients. In both these examples, the flux of particulate nutrients was estimated by collecting water samples with an automatic pump and relating these concentrations to the corresponding stage measurements. Although the variations in the flow were quite pronounced, there was still a reasonable match between the frequency and timing of sampling and the observed event.

The results in Fig. 2 show a different situation where the flows are episodic. The example is taken from the Medjerda river in Tunisia, which is the main tributary of the Sidi Salem reservoir, and illustrates the difficulties in monitoring larger catchments under highly dynamic conditions. The Medjerda catchment is monitored intensively in comparison with other river systems in semi-arid areas (Louati et al. 1998). The monitoring programme comprises more than 30 sampling points for the Medjerda river and its main tributaries, sampled manually. Samples at a number of locations have been taken at intervals of sometimes less than a week. Nevertheless, the data (provided by DGETH) for 1990/1991 show a mismatch between the timing of sampling and the peaks in the hydrographs. This situation of a sudden rise of the flood and highly varying water quality parameters is typical for the semi-arid basins in the Mediterranean and requires a further increase of samplings and installation of automatic stations.

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Linking monitoring and modelling

In situations where it is difficult to select the most appropriate sampling frequencies, model simulations can help quantify the variability of the key driving variables. The first step is to validate the chosen model with historical data and then use the simulations to test the effectiveness of different sampling strategies. Even in situations where validation is difficult due to the low density of data, mutual benefit may be derived from linking modelling and monitoring. Assuming a functional model, the process of calibration and validation can highlight limitations in data availability more precisely (in terms of given variables and sampling intervals). Conversely, where very detailed data sets have been collected, modelling studies can be useful in identifying whether sampling intervals could be extended or some variables omitted.

In many cases there are more data available on water quantity dynamics, than on water quality. Under such conditions, the ex ante simulation of flow variability with adequate hydrological models is recommended. Results will provide important information on the duration of flood periods and in particular on the duration of the rising limb of the hydrograph. Such information then allows the timing of water quality samples to be planned much better.

The main benefit of modelling water quality dynamics is that the integrity of data can be checked. Independent data can, in any case, be provided from water quality samples at different locations. Water quality models are generally helpful in calculating the range of pollution inputs and interactions amongst the individual state variables. Models also provide important means to check orders of magnitudes of the data collected.

The efficient monitoring of river systems is hampered by water quality variations in time at a given location, and also along the flow path. However, numerous water quality modelling tools have been successfully implemented to help resolve this. These modelling tools can provide good background information on pollution sources and pathways, and are helpful in relating the water quality data from monitoring stations to a more comprehensive understanding of massfluxes within a catchment. Moreover, modelling tools are also helpful in identifying hidden or unknown point-sources between given sampling points. The calculation of loadings to downstream water bodies or at catchment outlets is often an important target of monitoring programmes, in particular in the context of the EU-WFD. If the sampling frequency is rather low, modelling results can help to calculate loadings between the samplings. The higher the flow variability is, the more difficult it is to apply existing modelling tools. This is of special importance in Mediterranean catchments, where there is a dominance of temporary streams. Experiences from the modelling studies within the tempQsim project indicate that there is still a need to improve catchment modelling tools in order to describe the short-term changes in concentrations and loadings adequately. Major limitations for existing models are considered to be the impact of transmission losses, mass accumulation, and restricted capabilities to calculate run-off and water quality dynamics on a subdaily basis.

The link between models and monitoring is hampered further by the fact that most of the river water quality models are able to simulate chemical water quality status better than ecological status. In the context of implementing the EU-WFD, however, a number of new indicators for assessing the ecological status have been developed in projects such as AQEM\(^2\) and STAR\(^3\) (e.g. Hering et al. 2003). If a similarly close link between modelling variables and monitoring parameters must be achieved as when assessing chemical status, then a corresponding revision of modelling concepts is required.

Linking monitoring and management

The strategies used to monitor lakes and rivers are usually developed in an ad hoc way with very little attention being paid to the questions these programmes are supposed to answer. Very often, comparable systems have been sampled using different methods and some sites visited on several occasions to collect the same samples. In such cases the integration of the results from the various campaigns is very difficult. Many sampling programmes are also very inflexible and cannot be changed to include new variables. In these situations, the challenge is to strike the right balance between measuring a few variables at frequent intervals, an extended number of variables at less frequent intervals, or measuring a large number of variables in irregular individual sampling campaigns. An approach based on the ‘lowest common denominator’ invariably underestimates the information required to achieve even a basic understanding of the system dynamics. An approach based on the measurement of a ‘catch-all’ set of variables may identify the key drivers but fail to highlight the critical processes. The development of long-term monitoring programmes that meet the requirement of the managers as well as the scientists is particularly

\(^2\) AQEM – The development and testing of an integrated assessment system for the ecological quality of streams and rivers throughout Europe using benthic macroinvertebrates. A project under the Fifth Framework Programme of the European Union, Contract No. EVK1-CT-1999-00027.

\(^3\) STAR – Standardisation of river classifications: framework method for calibrating different biological survey results against ecological quality classifications to be developed for the Water Framework Directive. A project under the Fifth Framework Programme of the European Union, Contract No. EVK1-CT 2001-00089.
Table 1. Different activity levels in the framework of a hypothetical monitoring programme. Each level has a different degree of detail regarding indicators to be investigated and sampling frequency.

<table>
<thead>
<tr>
<th>Level</th>
<th>Aim</th>
<th>Expected deliverables</th>
<th>Activity (Example: reservoir monitoring)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Assessment</td>
<td>Knowledge of existing system properties and sensitivities</td>
<td>Monitoring of seasonal change in the phytoplankton community</td>
</tr>
<tr>
<td>B</td>
<td>Modelling</td>
<td>Knowledge of system dynamics and fluxes</td>
<td>Modelling the growth patterns of different functional groups of phytoplankton and the risk of toxic algal blooms</td>
</tr>
<tr>
<td>C</td>
<td>Management</td>
<td>Knowledge of parameters for controlling system operation</td>
<td>Investigation of key variables and formation of management recommendations e.g. on water transfers and artificial mixing</td>
</tr>
</tbody>
</table>

difficult. Very often, the established programmes are criticised for being:
- too expensive and time consuming
- designed for a very limited number of functions
- too inflexible to meet the needs of the modellers and systems analysts.

The first obstacle to overcome is the high cost of fieldwork. Since these costs are likely to rise, the only solution is to target sampling campaigns more effectively (e.g. by concentrating on a few critical events) and to make better use of automatic monitoring systems. The automatic monitoring stations described in this volume were designed to meet a number of pre-defined functions and be capable of modification to meet new demands. The second obstacle to overcome is the design of the sampling programme. Such programmes should always be designed to meet defined objectives whilst retaining some flexibility to respond to future changes in these objectives. Table 1 illustrates some of the objectives that might be set in the different stages of a lake sampling programme. The first ‘assessment’ stage is relatively straightforward, but more sophisticated methods would be required to support the critical ‘modelling’ stage.

This sequence of activities broadly matches those required to support the EU Water Framework Directive. The WFD includes two statutory requirements which will have a major effect on the development of sampling programmes:
- The requirement to establish an inventory of water bodies that includes the identification of deviations from good ecological status.
- The requirement to produce coherent reports that outline the measures needed to return the water bodies to good ecological status.

For most Member States, the first requirement will lead to a major expansion in the routine sampling programmes established on lakes and rivers. The second requirement is more demanding and may require the systematic expansion of catchment-based measurements and process-based modelling. Member States will be expected to establish a coherent and comprehensive overview of the anthropogenic impacts affecting water quality. Three types of monitoring are envisaged: surveillance, investigative and operational. Automatic monitoring systems of the kind described here (Rouen et al. 2005, this volume) could thus play an important part in reducing the costs of these activities and help concentrate the sampling effort at the more vulnerable or sensitive systems.

Concluding remarks
The future management of our water resources will require the integrated application of new monitoring and modelling techniques. The case studies presented in this volume (Allott et al. 2005, Cruz-Pizarro et al. 2005, Elliott et al. 2005, George et al. 2005, May et al. 2005, Reynolds et al. 2005, Rouen et al. 2005) demonstrate what can be achieved when models validated by high resolution measurements are used to address problems posed by water managers. The challenge now is to apply similar techniques to less ‘data-rich’ environments and simplify the automatic monitoring systems used so that they require less maintenance. New low maintenance lake monitoring stations are currently being developed for the EU project CLIME (Climate and lake impacts in Europe). The costs associated with the maintenance of these systems are, however, still high and require the long-term commitment of both staff and support facilities. The cost of maintaining these sampling programmes can be reduced by applying new technology but expert staff will still be required to analyse and interpret the results. The preamble of the WFD states that ‘Water is not a commercial product like any other but, rather a heritage which must be protected, defended and treated as such’. Improved monitoring and more efficient links between independent sampling campaigns should deliver a major break-through in our understanding of the value of water resources, but also allow a more targeted and economical planning of restoration measures.
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References


