Towards integrated water quality monitoring: Assessment of ecosystem health

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Abstract

National water quality monitoring in South Africa has in the past mainly focused on measuring physical and chemical variables. However, it is increasingly realised that measuring physical and chemical variables on their own cannot provide an accurate account of the general "health" of an aquatic ecosystem. Biological communities, on the other hand, are accurate indicators of overall environmental conditions. This paper examines the potential and feasibility of incorporating biological monitoring in a programme designed to assess ecosystem health. The current status of biomonitoring within the RSA Department of Water Affairs and Forestry is outlined and challenges for the future are discussed. It is concluded that biomonitoring should form an essential part of ecosystem health assessment, and research and development in this field is encouraged. The developmental process should be a collaborative partnership between resource managers and researchers.

Introduction

For almost 30 years after the enactment of the Water Act in 1956 (Act 54 of 1956), water pollution in South Africa was controlled primarily by applying a uniform effluent standard, i.e. an emission-based approach. Recognition of the need to account for the effects of effluents on receiving water led to the introduction of the special effluent standard, which imposed stricter limits on the quality of discharged effluents, and was applied in certain specified catchments. All effluents subject to regulation were required to meet either the general effluent standard or the special effluent standard (Van der Merwe and Grobler, 1990).

In a review of water quality management policies and strategies, the Department of Water Affairs and Forestry (DWAF, 1991) presented a revision of its policy, adopting a receiving-water-quality-based approach for non-hazardous substances and a pollution prevention approach for hazardous substances. The focus of the Department's water quality management has therefore changed in recent years, from controlling pollution at source to a user-based philosophy. This shift in policy towards a more integrated resource-based approach represents an important advance which essentially enables the establishment of a limit on levels of pollutants according to the water quality requirements of each user in a particular water system.

One of the users that must be considered in terms of water quality requirements is the aquatic environment. Unfortunately the status of our aquatic environments is currently not well documented, making it difficult to reliably assess the extent of alteration and the rate at which changes in water quality are occurring. Also, information for evaluating the effectiveness of water quality management plans, for identifying emerging problems and for anticipating future conditions under different management options is fundamental to the continuing process of developing and implementing policies and programmes to protect legitimate uses of water resources. Clearly, therefore, comprehensive monitoring and assessment programmes are needed to establish regional and national baselines of the chemical, physical and biological resource characteristics. Only then can the status of the changes in quality be assessed, and the overall effectiveness of the Department's water quality management policies be measured with confidence.

This paper addresses various aspects of biological monitoring and examines their potential and the feasibility of supplementing chemical and physical monitoring of water quality in South Africa.

Ecosystem health assessment

It is generally agreed that measuring only the physical and chemical attributes of water cannot provide the sole assessment of the health of an aquatic system (Gaufin, 1973; Lawrence and Williams, 1991 and Ten Brink and Woudstra, 1991). A major reason for this is our limited knowledge of the effects of toxic variables on biota. A further limitation of chemical monitoring is that it does not account for many man-induced perturbations, such as flow alterations and habitat degradation, which impair biological health. Physical and chemical information is, furthermore, biased towards the momentary conditions that exist at the time the sample is collected, often missing short-term events which may be critical to ecosystem health. Biological communities, on the other hand, are accurate indicators of overall environmental conditions, since they are subject to the totality of chemical and physical influences and integrate their effect over time.

Although up to now researchers have found it difficult to define ecosystem "health" (Chapman, 1992), the concept has often been considered as analogous to the human condition (Calow, 1992). As with the human condition, the absence of ecosystem health is often easily recognised or detected (Cairns and Pratt, 1992). Effects of contaminants on an ecosystem, that may lead to a decrease in the health of that system, can be scaled at different levels: organism, population, community and ecosystem level (Akkerman et al., 1991). In order to quantify the condition of an ecosystem, indicators of ecosystem health/disfunction should be consistent with the common symptoms of ecosystem health/degradation. Such symptoms may include: changes in the biotic size spectrum to favour smaller life forms, increased circulation of contaminants, reduced species diversity, increased dominance by exotic species, shortened food-chain length, increased disease prevalence, and reduced population stability (Rapport, 1992). In South Africa different geographic regions have different "natural" water quality, with the result that "natural" diversity (in structural terms), both with respect to quality and quantity of taxa, also varies. To use ecosystem dynamics effectively for baseline representation of ecosystem

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Received 26 February; accepted in revised form 1 July 1993.

health, therefore, would require rigorous definition of the relationship between such dynamics and environmental factors (Calow, 1992).

Biological monitoring

The assumption that measurement of the condition or health of biota can be used to assess the health of an ecosystem led to the introduction of biological monitoring or biomonitoring (Herricks and Cairns, 1982). Biological responses or indicators are used to determine the effect of changing environmental conditions. These changes may be due to natural causes, point sources or diffuse sources of pollution.

According to Anderson (1988), since water quality managers should rely on comparative data on both chemical composition and biological effects, biomonitoring techniques should be incorporated into management policies in order to adequately protect aquatic resources (Metcalfe-Smith, 1991). It appears that throughout the developed world biomonitoring is becoming a primary tool in assessing environmental condition and verifying compliance with effluent limitations (Herricks and Schaeffer, 1985).

Aquatic biomonitoring has taken on a variety of meanings, with different types of tests and different procedures being used for different investigations or surveys. Aspects regarding biomonitoring can broadly be classified under the following categories: bioassessments, toxicity bioassays, behavioural bioassays, measurement of bioaccumulation and fish health studies. A short discussion of each of these categories follows.

Bioassessments

Bioassessment refers to field-oriented biomonitoring protocols, and is usually based on ecological surveys of the functional and/or structural aspects of biological communities. Since biological communities are generally sensitive to low-level disturbances of a wide array of environmental factors, they can be regarded as good indicators of water quality and of general ecosystem health. Many groups of organisms have been proposed as indicators of ecosystem quality. These include diatoms (Dixit et al., 1992), algae (Patrick, 1973; Ten Cate et al., 1991 and Whitton et al., 1991), benthic invertebrates (Gaufin, 1973 and Metcalfe-Smith, 1991) and fish (Berkman et al., 1986 and Karr, 1981). Although no single group is favoured by the majority of biologists (Karr, 1981), it appears as if fish and benthic macroinvertebrates have received most attention.

Some of the advantages of using bioassessment in water quality planning and management are that:

- The overall ecosystem integrity (i.e. chemical, physical and biological) is reflected by biological communities.
- The effects of different contaminants are integrated by biological communities and a holistic measure of their total impact is therefore provided, allowing monitoring of the impacts of diffuse sources and effectiveness of management practices.
- Routine monitoring of biological communities can be relatively inexpensive, particularly when compared to the cost of comprehensive chemical assessment of microcontaminants (This does not mean that chemical and biological monitoring are mutually exclusive, since each has a specific and often complementary role).
- Chemical pollutant loadings are often not easily understood by the public, while the status of biological communities, portrayed as water quality information, is of direct interest to the public.
- Biological communities may be the only practical means of evaluating certain impacts for which criteria do not exist (e.g. diffuse source impacts or impacts responsible for habitat degradation) (Plafkin et al., 1989).

Toxicity bioassays

Bioassay (toxicity testing) is the term generally used for laboratory-based biomonitoring. Aquatic ecotoxicology is an interdisciplinary science, integrating toxicology with environmental chemistry and ecology, which investigates the effects of toxic substances already present in the environment and aims at predicting the effects of newly introduced compounds (Van der Gaag, 1991). Since environmental damage should be avoided, rather than having to rely on rehabilitation techniques after it has occurred, the predictive value of such tests is crucial (Cairns and Pratt, 1989).

Various test organisms have been used in acute (short-term) and chronic (full- life-cycle or long-term) toxicity bioassays, both to quantify the toxic effects of single (Sheedy et al., 1991) or multiple substances (Enserink et al., 1991), and to serve as biological indicators of effluent and receiving water quality (Birge et al., 1989). Particularly relevant ecologically are the effects on growth and reproduction, since even small changes in the levels of some variables can impair these processes quite drastically (Schober and Lambert, 1977). Survival and population growth of aquatic organisms, such as *Daphnia* (Kühn et al., 1989), exposed over relatively long (7 to 28 d) time intervals, are usually affected at concentrations much lower than the levels of specific chemicals that cause acute (24 to 48 h) effects (Savino and Tanabe, 1989). Although acute tests are valuable for quickly supplying an estimate of toxicity, and provide an indispensable "first-look" method, their results are not suitable indicators of safe or harmful concentrations in aquatic ecosystems (*Standard Methods*, 1989).

Behavioural bioassays

The use of behavioural bioassays is another way of exploring sublethal effects by monitoring the behaviour of fish or other animals when exposed to contaminated water. Some of the observable behavioural responses are: avoidance and changes in swimming behaviour or other locomotory activity, respiratory or heartbeat rates, valve movement and feeding activity (Kingsbury and Rees, 1978 and Lawrence and Williams, 1991).

Most of the behavioural assays have been developed for on-site monitoring. The main advantage of these early warning systems is that they are capable of detecting pollution almost immediately, and on a continuous basis. Automated continuous bioresponse systems usually make use of sophisticated computer and electronic technologies and they are expensive to implement. Sometimes it is also difficult to differentiate between the effect being monitored and background noise. It has been documented that, while using fish respiratory rhythms to detect appearances of deleterious materials in an effluent pipe, the entire group of fish produced an alert signal, without any changes in the chemical or physical attributes of the stream being measured. Fortunately, the recording of a minor earth tremor at the identical time that the fish produced an abnormal alteration in respiratory rhythm confirmed that this positive reaction was not related to water quality (Cairns, 1991).

Measurement of bioaccumulation

Bioaccumulation measurement refers to studies or methods monitoring the uptake and retention of chemicals in the body of an organism. The occurrence of potential toxicants (such as trace metals and pesticides) can be determined using tissue analyses. Field experiments are perhaps more realistic in simulating ambient conditions, whereas laboratory experiments permit isolation and more controlled study of individual transfer processes. Most laboratory experiments fall into 2 groups, namely those involving exposure of organisms to contaminated water and clean food (bioconcentration experiments) and those involving exposure of organisms to contaminated food and clean water (biomagnification experiments) (Mackay and Clark, 1991).

Whereas in toxicology acute bioassays describe effects of contaminants in the short term, and chronic bioassays provide some indication of the long-term effects, bioaccumulation testing provides information on potentially toxic effects on organisms feeding higher up the food chain. To show cause-and-effect relationships there should, therefore, be close coordination between bioassays and bioaccumulation testing (Anderson, 1988).

Fish health studies

Health studies or pathology (usually on fish) deal with the causes, processes and effects of disease. Pathological studies may include procedures such as necropsies (post-mortems), histological examinations, parasitological examinations and liver enzyme assays (Albert and Washuta, 1992). The general health of the biotic community is used as an indicator of the health of the associated environment.

Fish health studies have generally not been incorporated as part of routine water quality monitoring programmes. However, it seems that such studies, when performed as an adjunct to other water quality studies, can help to provide a more complete picture of the overall environmental condition (Albert and Washuta, 1992).

Habitat assessment

Unless biological samples (e.g. a bioassessment exercise) are collected at comparable physical habitats, it is difficult to distinguish biological community differences attributable to degraded habitat from those resulting from a degradation in water quality. Habitat, as affected by instream and surrounding topographical features, is a major determinant of aquatic community potential. Both the quality and quantity of available habitat affect the structure and composition of resident biological communities. Therefore, when sampling sites are not physically comparable, habitat characterisation is particularly important for proper interpretation of biosurvey results (Plafkin et al., 1989).

Populations living in higher quality habitats are relatively more secure and able to survive locally over longer periods. Maintaining water quality in the physical/chemical sense will not overcome deficiencies in the suitability or availability of habitat, though. Areas with better quality habitats will, furthermore, have a beneficial effect on water quality (Karr and Dudley, 1981).

Habitat, as the principal determinant of attainable biological potential, should set the context for interpreting the results of a bioassessment and can be used as a general predictor of biological condition. Chemistry can further help to explain and characterise certain impacts.

Holistic ecosystem assessment

Internationally many attempts have been made to design monitoring programmes to deal with the issue of toxic substances and ecosystem health. In general it appears that monitoring of toxicants tends to be fragmented, with different programmes for different substances, and also for different compartments (water, sediment, biota) of the aquatic environment.

There can be little doubt about the mutual dependence of physical quality (including habitat), biological health and chemical characteristics in the aquatic environment. Ten Brink and Woudstra (1991) defined an aquatic system as a coherent entity of shore, water, biota and bottom sediment, including the physical, chemical and biological components. Ecological integrity is attainable only when chemical, physical and biological integrity occur simultaneously (EPA, 1990). Chemical monitoring in the 3 major aquatic compartments (water, sediment, biota) and biological monitoring should be complementary to allow a proper assessment of environmental quality/health (Akkerman et al., 1991). Chemicals in the environment are subject to processes of transport and transformation, which means that measuring in the wrong compartments or in only one environmental compartment may produce misleading information. We must be aware of the effects of the environment on chemicals in order to effectively assess the effects of chemicals on the environment. It appears that when dealing with a specialist environmental surveillance programme, an integrated approach has to be followed.

A programme assessing ecosystem health may from sheer necessity consist of many interacting components (Fig. 1). Whether studies on all of these components can eventually be implemented will depend on the feasibility with regard to available manpower and funds, as well as the technological limitations and developments.

The purpose of the background study indicated in Fig. 1 will be to render the most effective and economic means by which such an ecosystem health assessment can be conducted. Contamination by many microcontaminants tends to be highly localised and associated with specific industries or activities where these substances are used on a large scale. Background information can thus assist in the selection of sampling sites and variables for a specific system. The background investigation will also provide information to aid the interpretation of the results obtained.

The physico-chemical component (Fig. 1) facilitates the monitoring of relevant trace metals and organic compounds in the water, sediment and biota. Some macroconstituents (nutrients, dissolved salts etc.) and dissolved oxygen, temperature and pH should also be monitored in the water.

Current situation and potential developments

The Department of Water Affairs and Forestry has been collecting data on the chemical quality and physical characteristics of the country's water resources since the early 1970s and an extensive physico-chemical data base is being maintained (Swart et al., 1991). However, there is a general lack of biological data in the current water quality information system. Some of the reasons that, throughout the world and locally, monitoring programmes have in the past usually excluded the collection of biological data, are:

- physical and chemical determinations can be expressed in simple numerical terms, whereas that is seldom possible with biological assessment;
- pollution control personnel (and water quality managers) are often engineers or chemists with little or no biological background;
- the collection of extensive biological data has, prior to the introduction of rapid bioassessment protocols, been extremely

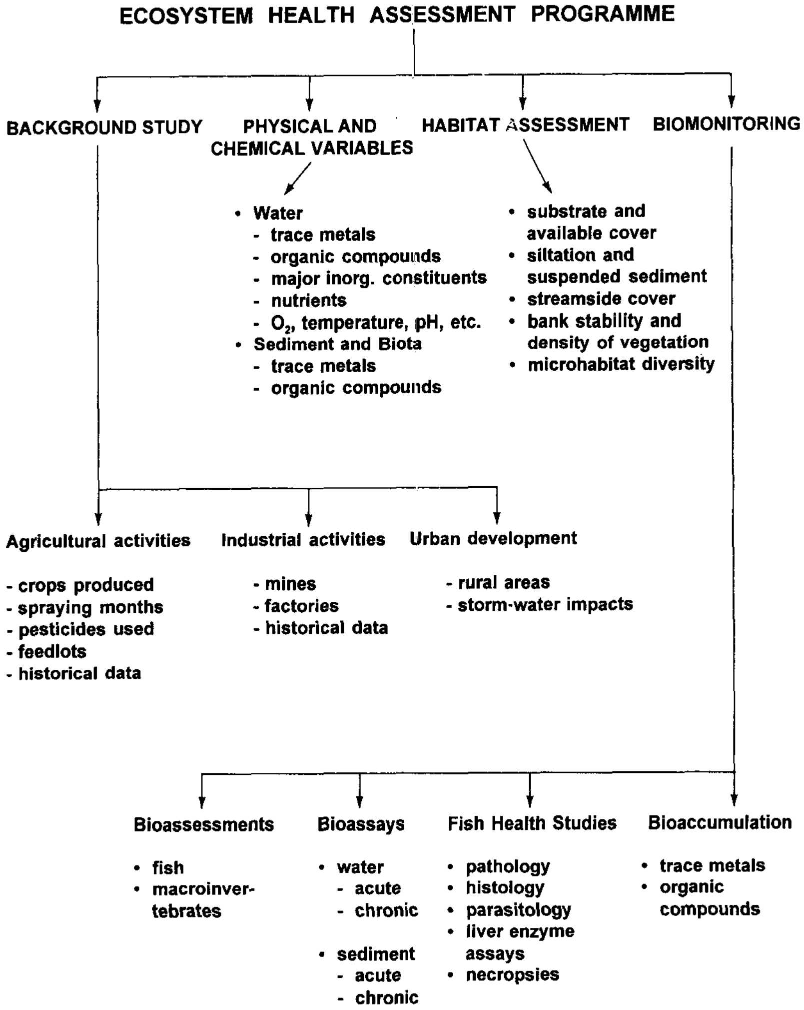

Figure 1
Conceptual framework of a monitoring programme to assess aquatic ecosystem health/integrity

time consuming and expensive; and

- biologists have been reluctant to simplify biological data to a point where it would be intelligible to those who must meet standards derived from a biological assessment (Cairns et al., 1973).

Recent developments in the field of rapid bioassessment protocols have changed this picture, however, and today we know that some methods of biological assessment can be as easy as and much cheaper than chemical and physical assessment. Biological data can also be summarised numerically and biological assessment, when properly applied, can furnish information that cannot be provided by other systems in that it gives a time-integrated picture of the health of an ecosystem and incorporates effects such as synergism, addition and antagonism. The collection and evaluation of biological data are, after training, within the abilities of field personnel without specialist training in taxonomy or ecology.

In recent years, and in most of the developed world, biological assessment approaches, chronic toxicity testing, sediment toxicity testing, and the chemical analyses of fish tissues and sediment for organic and inorganic compounds have become relatively routine water pollution control activities. In South Africa the last few years have been characterised by a renewed interest in incorporating biomonitoring practices into water quality monitoring approaches. The development of various biological indices, which focus on macroinvertebrates (Chutter, 1992) or fish (Engelbrecht, 1992) is receiving attention. The CSIR, some water boards, and departments of various Universities involved in aquatic sciences as well as the Department of Water Affairs and Forestry, have incorporated toxicity bioassays as part of their equipment for water quality assessment. Bioaccumulation testing, focusing on selected trace metals, has received attention (Du Preez and Steyn, 1992), and a project on artificial streams to monitor cause-and-effect relationships, using riverine invertebrate species or communities, is under way (Palmer and O'Keeffe, 1992).

Few local water quality studies have incorporated the evaluation of physical habitats. Various habitat assessment indices have been developed (Berkman et al., 1986, Plafkin et al., 1989), but need to be tested locally (and modified if necessary) for use in biosurveys.

Although chemical analyses of sediment provide indications of the relative degrees of contamination in sampling areas, they have thus far provided neither a measure of adverse biological effects nor an estimate of the potential for effects. Literature indicates that adverse effects to organisms associated with sediments cannot be correlated with concentrations of toxicants obtained from total (bulk) sediment chemical analyses (Long, 1992). Acute and chronic sediment toxicity assays may help to bridge this gap. These types of assays have until now received very little attention locally.

Challenges

It is, furthermore, important to realise that data in the form of numbers, activity of or effect on organisms, and values of physical and chemical variables only provide the opportunity for generating information. The content and quality of the eventual information are dependent on the methods of data acquisition, analysis and interpretation and also on how effectively the information is used in decision-making. Certainly there is a need for a programme specifically designed to relate the quality of the nation's surface water to the health and viability of the biotic communities dependent on those water resources. It is, however, of extreme importance that the procedures for a surveillance programme be tested in practice for their feasibility and potential before final decisions are made concerning the design and implementation of such a programme as part of national and regional monitoring and assessment.

The true worth of biological monitoring will be determined by the way in which biological information is presented. Biological information should be manager - and even public - friendly, and a format will have to be developed which best compromises between managerial information richness and ecological information richness. Furthermore, to view biological data in context, reference or baseline conditions will be needed to provide a tool for judging water quality in a biological context and the efficiency of management actions (Smol, 1992). The establishment of reference conditions is also viewed as a key step in developing values for supporting biological criteria or biocriteria (EPA, 1990).

The variability among natural surface waters across the country, resulting from climatic, landform, land cover (vegetation), soil type and other geographic differences favours the use of regional reference conditions rather than national reference conditions. Such regional reference conditions describe, within the relevant region, the characteristics of water-body segments least impaired by human activities, and can be used to define attainable biological or habitat conditions. Currently the USA makes use of 2 principal approaches, namely:

- site-specific reference sites for each impact evaluation or survey; and
- ecologically similar regional reference sites (e.g. ecoregions), based on the assumption that surface waters integrate the character of the land they drain, that allow comparison with impacted sites within the same region (EPA, 1990).

A further challenge will lie in distinguishing between natural and unnatural ranges of variation in biological data. Management action will depend on the knowledge that a certain impact causes an ecosystem or community to respond in some way that is outside its natural range of variation. The purpose and value of biological surveillance of aquatic systems lies in the timely detection of ecosystem change beyond the normal range of variability, so that remedial actions may be taken before such change becomes permanent (Chutter et al., 1986). Smol (1992) referred to a study which found that frequency of reporting events outside the natural range of variation actually decreased in studies that were conducted for over 6 years duration ("long-term" studies). Dependable information on natural ranges of variation thus require long-term data. The extent of a data set will, however, most often have to be balanced with resource availability in order to get a "best" answer.

The issue that will determine whether biomonitoring will be implemented as part of a holistic ecosystem assessment approach, however, is feasibility in terms of practicality and the availability of trained manpower (biologists) and funds. This implies that the biological techniques must be simple enough (not highly sophisticated) and, if to be implemented nationally, not require a high sampling frequency. Because aquatic organisms are exposed to all the variations in water quality, and hence reflect a time-integrated measure of water quality, biological sampling can be conducted less frequently than chemical sampling.

It must be kept in mind that when monitoring organisms in the aquatic environment, one is dealing with complex biological systems with thousands of different species that can interact, in one or more environmental compartments at a time, producing a number of different responses to a single toxicant. Due to this complexity, it is often difficult or even impossible to provide definite answers using only biological monitoring. The answer might lie in the following quote of Herricks and Schaeffer (1985): "The challenge of biomonitoring in complex systems is to provide the strongest scientific support in the absence of a full understanding of properties and interactions of the systems being assessed."

Conclusions

Environmental monitoring has advanced rapidly in the last decade or two. With regard to the evaluation and management of water quality, biological monitoring is inevitably part of the package of possible monitoring approaches. Biosurveys can provide a particularly useful approach where variable pollutant inputs occur, for monitoring diffuse source impacts, and for monitoring the effectiveness of management practices. It is clear that biomonitoring protocols need to be incorporated into monitoring actions in order to allow effective protection of aquatic resources. Biological data, however, have to be integrated with chemical and physical data in order to provide meaningful environmental information.

The Department of Water Affairs and Forestry is currently in the process of developing the necessary infrastructure to conduct biological monitoring (including aspects such as bioassessment protocols, acute and chronic bioassays, fish pathology and tissue residues assessment). Evaluation of various approaches and techniques is necessary to establish the feasibility, in terms of available resources, for conducting national and regional biosurveys. If the Department follows the world-wide trend, it will eventually move towards integrated monitoring and assessment of aquatic ecosystem health. The information generated from a broad spectrum of biomonitoring options will certainly allow an increase in ecologically focused management of water resources.

Information requirements are critical success factors which pose a challenge that can only be met through a long-term commitment to integrated water quality monitoring at regional and national levels. In addition, to address this challenge efficiently, it is essential to draw on the experience and expertise of researchers in these and associated fields, as well as organisations responsible for the monitoring and maintenance of a sustainable aquatic environment. The development process in the field of biomonitoring can only gain from a collaborative partnership between resource managers and researchers.

Acknowledgements

Drs Phillip Kempster, Eduard Sandmann and Lucy Randall, all colleagues at the Hydrological Research Institute, read and commented on the manuscript. Dr Jenny Day (Department of Zoology, University of Cape Town) provided most helpful technical and editorial advice. This paper is published with the permission of the Department of Water Affairs and Forestry.

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