ENVIRONMENTAL WATER QUALITY in Water Resources Management

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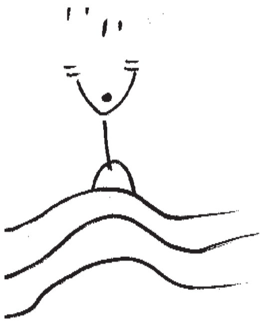


Contents

Who should read this book?

This book will help anyone working with water resources to make decisions about water quality, specifically environmental aspects of water quality.

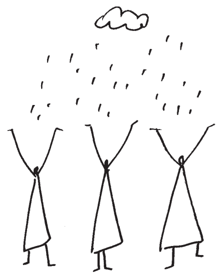
The book explores the balance between water resource protection and water resource use, with a particular focus on water quality. A balance is necessary because the National Water Act (NWA) requires that water resources be protected and managed to meet the water quality requirements of ecosystems. At the same time the Act also requires that water be used for social and economic benefit.

Environmental water quality (EWQ) is an approach which requires the combined use of water physico-chemistry, biomonitoring and ecotoxicity information to assess environmental water quality health and to make management decisions. Knowledge of the EWQ approach is useful to industrial and mining environmental managers, water resource managers working in water resource protection and water quality management and to anyone who has to deal with integrated water resource management, point and non-point source pollution, licensing waste disposal and setting Resource Quality Objectives.

The book provides simple, accessible information and can therefore be used by people from water boards, water utilities, catchment management agencies, water user associations, catchment forums, local government, agricultural associations, farmers unions, schools and universities.

The three chapters of the book provide information about the context and application of EWQ, followed by an illustrative case study. There are then three technical appendices that provide more detail about each EWQ component. Concepts and terms are introduced and amplified as they arise. A reference list and recommendations for further reading are provided.

As this is an introductory text, some readers may find some sections rather simple. Please bear in mind that the primary aim is to expose all readers to a wide range of concepts and to demonstrate the importance of integration and linkages.



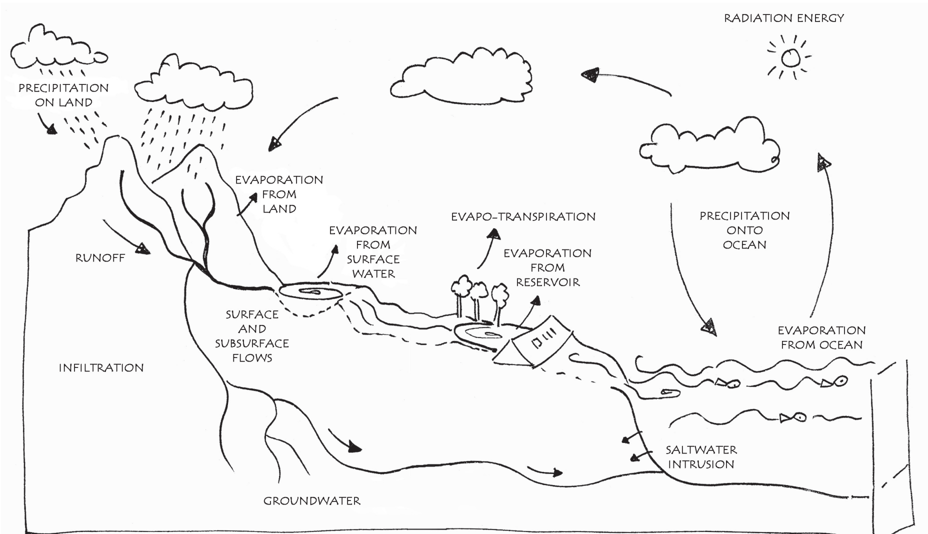
Introduction

"Water for people and people for water"
(Palmer CG et al. 2002).

We all depend on water for life, well-being and economic prosperity. In our homes water is used for drinking, cooking and washing. In our workplaces water is used for agriculture and industry. Water provides for recreation and our need for natural beauty, and it can be part of our spiritual awareness. Water is so important and is used in so many ways that if it is over-used, we risk damaging our very life source. This happens when we take too much water out of aquatic ecosystems, and put in too much waste.

The South African National Water Act (NWA) (No. 36 of 1998) recognises that water resources are part of the integrated water cycle made up of water ecosystems – rivers, wetlands, lakes, dams, estuaries and groundwater – and the processes of precipitation, transpiration, infiltration and evaporation. Closely connected to the water cycle is the use that people make of water resources. The NWA promotes protection of water resources so that people can use water both now and into the future. Water is at the heart of "a better life for all".

This book focuses on environmental water quality (EWQ), in particular the use of water resources for waste disposal, and the effect that waste disposal has on ecosystems. The term *water quality* is used to describe the microbial, physical, chemical and radiological properties of water. These properties affect both ecosystem health and the "fitness for use" of the water.



THE WATER CYCLE

Managing water quality requires attention to both water resource *protection* – and water resource *use*, and requires decisions about balancing the two. Both over-protection and under-protection are expensive. Over-protection is expensive for users, and under-protection is expensive for the environment (and thus ultimately also for the users). If we really want to move towards sustainability, and to take account of social, economic and environmental costs and benefits, it is essential that we answer two questions. How much should aquatic ecosystems be protected? & How much can aquatic ecosystems be used? Translated into the terms of EWQ, this means considering 1) the volumes, concentrations, and toxicity of waste water that ultimately enters aquatic ecosystems; and 2) instream objectives for pollutants that are appropriate for different levels of ecosystem health. Ecosystem health may be expressed as one of four classes – excellent, good, fair and poor.

Objectives for the various classes of ecosystem health are termed *ecospecs* (ecological specifications). Objectives set to meet the needs of different users are termed *userspecs*. When ecospecs and userspecs are integrated they are termed Resource Quality Objectives (RQOs).

The EWQ approach can provide quantified and descriptive ecospecs for single substance pollutants, as well as complex industrial effluents. In addition to setting objectives, EWQ can be used to derive appropriate licence conditions and criteria for waste water discharge.

Consideration of domestic water consumption raises questions about human health, which are sometimes confused with issues of ecosystem health. Criteria for human health and ecosystem health are not synonymous. Aquatic ecosystems are not necessarily more sensitive to changes in water quality than are domestic, agricultural and industrial users. For example, faecal pathogens in water may have little or no effect on the aquatic ecosystem health, yet have a major effect on the human use of water for drinking or recreational purposes. EWQ relates specifically to ecosystem health and function. Conditions protective of human health require additional, specific assessment.

EWQ is about contributing to healthy aquatic ecosystems so that they can offer people the most appropriate range of goods and services.

1. Water law, water ecosystems, and water resource protection

"Water for people and people for water"

People do need water – but water also needs people. People need encouragement and information in order to care for water. South African water law and policy was developed to meet the needs of both people and water resources. How and why this was done is addressed in the book *"Some, For All, Forever – aquatic ecosystems and people"* (Palmer CG et al. 2002), which is summarised in this chapter.

Some of the most advanced water law and policy in the world has come from South Africa. The originality of the South African approach lies in clearly setting two primary objectives – equity and sustainability. Equity involves fairness to people now, and sustainability involves fairness to future generations and to the environment.

What is "the environment" for water? The following section gives an answer.

Water ecosystems and water resources

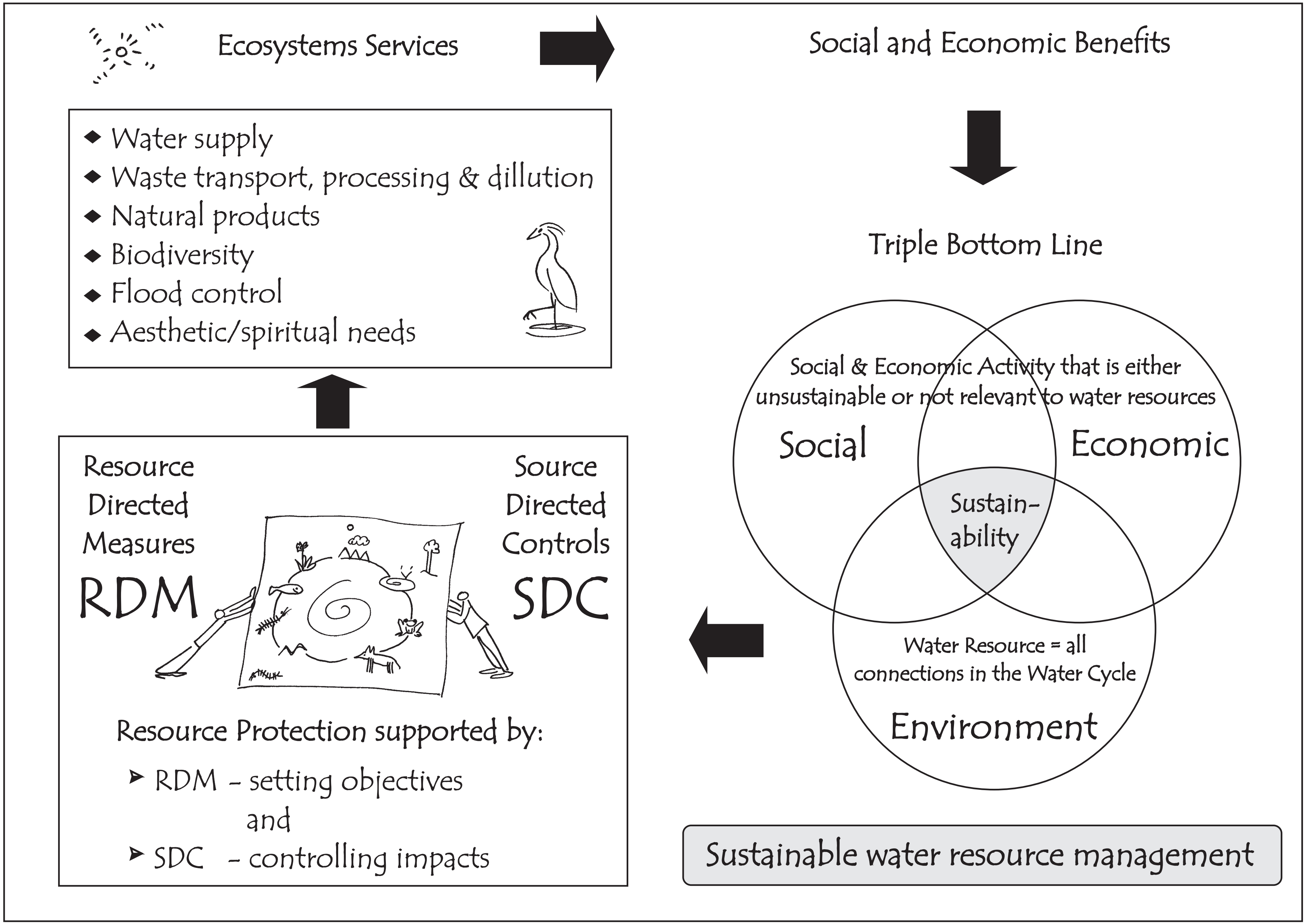
From the perspective of people's needs, water in the environment is collectively called the water resource. Water resources are sometimes seen simply as sources of water for human requirements such as domestic, agricultural, industrial and recreational uses. Water resources in the environment – better known by scientists as aquatic ecosystems – provide people with much more than

just the commodity water. They offer people a range of goods and services, including water supply, waste dilution, transport and processing, supply of natural products, nature conservation and biodiversity, flood control, recreation, beauty and places for spiritual activities.

Water is part of the complex natural world, where it is found most of the time in the aquatic ecosystems of rivers, wetlands, lakes, estuaries and groundwater. Dams also act as aquatic ecosystems and function in a similar way to lakes. Water cycles between the atmosphere and aquatic ecosystems through processes such as rainfall and other forms of precipitation, transpiration, infiltration and evaporation. This is the hydrological cycle or water cycle. Geographically, the water cycle and its aquatic ecosystems are located in catchments.

Ecosystems are complex. They comprise both biotic (living) and abiotic (non-living) components. The biotic components are the microbes and algae, floating, rooted and riparian plants, invertebrates such as crabs, snails and insects and vertebrates such as fish, amphibians, reptiles, birds and mammals. The abiotic factors can be grouped in three major categories, depending on whether they are related to flow, water quality and physical structure. All of these interact with one another and these interactions influence the goods and services that people find useful.

Ecosystem goods and services contribute to social and economic well-being. When social, economic and environmental benefits overlap, this creates a "zone" of sustainability. It is the aim of sustainable water resource management to remain in that zone. This is why it is so important to balance water resource use with water resource protection, and to undertake water resource protection both by setting goals and objectives for water resources in the environment (resource directed measures – RDM) and by controlling water resource use activities (source directed controls – SDC).


Ecosystems Services
Social and Economic Benefits
Water supply
Waste transport, processing & dillution
Natural products
Biodiversity
Flood control
Aesthetic/spiritual needs
Triple Bottom Line
Social & Economic Activity that is either unsustainable or not relevant to water resources
Social
Economic
Sustain-ability
Water Resource = all connections in the Water Cycle
Environment
Resource Directed Measures
RDM
Source Directed Controls
SDC
Resource Protection supported by:
RDM - setting objectives
and
SDC - controlling impacts
Sustainable water resource management

Changes in water quality can be natural, caused by geographical, geological or seasonal differences. But most water quality changes are human-generated. It is people who are responsible for the discharge of wastes into water resources, or the over-use of land resources that leads to erosion and sedimentation. The best approach to managing water resources therefore links the environmental aspects of water quality directly to social and economic factors (see van Wyk et al. 2003).

The National Water Act is based on an integrated approach to water policy, law and implementation. Applied to EWQ, integration means understanding how the chemical, microbiological, radiological and physical characteristics of water (the water quality) link to the responses of living organisms and ecosystem processes (the environment). It means understanding how the abiotic aquatic ecosystem components – water quality, flow, and physical structure – provide the conditions for the biotic processes. Integration also means understanding how these combined bio-physical processes link to social and economic processes through the human use of water resources.

Traditionally, the understanding of natural systems and their biophysical characteristics has been separated from social science approaches which address needs and aspirations of people and from economic approaches which address financial and governance issues. Sustainable resource management demands that these three areas be integrated. The key linking concept in this integration is that only functioning ecosystems can provide people with valuable goods and services.

Resource protection and use

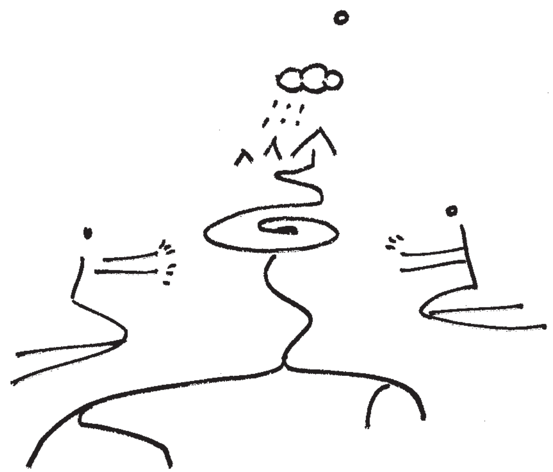
Integrated water resource management (IWRM) is a balance between water resource protection and water resource use. It is in the interests of everybody that water resources are protected and

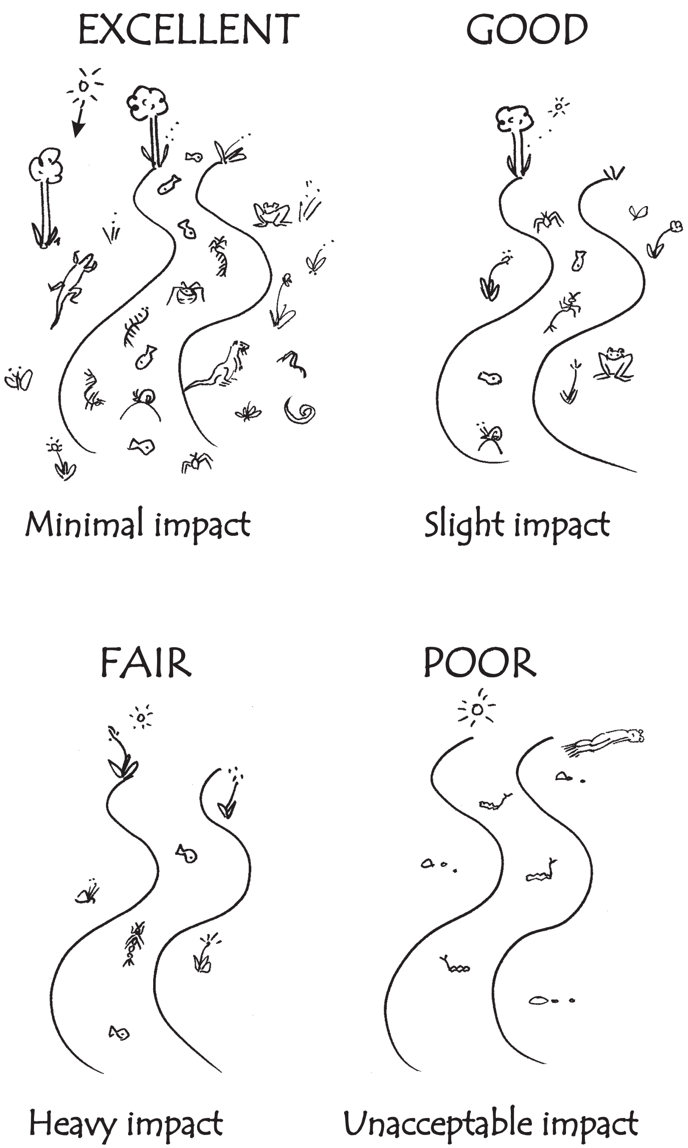
used efficiently. Both over-protection and under-protection are inefficient and expensive. This can be summarised as “know what to protect, and by how much”.

The NWA makes use of two different kinds of mechanisms to find the right level of protection – Resource Directed Measures (RDM) and Source Directed Controls (SDC). RDM provide descriptive and quantitative goals for the state of the resource, while SDC specify the criteria for controlling impacts such as waste discharge licences and abstraction licences.

RDM includes the development of quantifiable and descriptive goals for ecosystem conditions (ecospecs) and water user requirements (userspecs). Ecospecs and userspecs are combined to form resource quality objectives (RQOs). A RQO can be more protective than an ecospec if there is a particularly sensitive user need, but normally the ecospec defines the level of protection.

The EWQ approach allows water resource managers to select the most appropriate ecospecs, userspecs and RQOs. Managers can then define the appropriate licence criteria to control water use (SDC). EWQ also provides methods for monitoring progress towards the achievement of RQOs and for meeting licence criteria.





Water Resource Classification

Ecospecs ensure that the ecosystem remains at, or attains, a specified level of ecosystem health. Different levels of ecosystem health are described by a classification system ranging from Excellent (unimpacted), to Good (slightly to moderately impacted), to Fair (heavily impacted), to Poor (unacceptably heavily impacted). This classification is a key step in resource protection. It allows each resource class to have its specific ecospecs and therefore be protected and used to a different degree.

Ecosystems in each class offer different goods and services. Ecosystems in an Excellent class offer greater biodiversity, conservation, recreational, aesthetic and spiritual options, whereas ecosystems in a Fair class offer greater water abstraction and waste disposal options.

Classification allows for choice and provides for both resource protection and resource use. But the choice of ecosystem class is not easy. We cannot have full resource protection and full resource use at the same time – we have to choose. The 'hard' uses of the resource, such as abstraction and waste disposal, go hand in hand with economic growth but cause deterioration in ecosystem health. The 'soft' uses of the resource, such as recreation and nature conservation, bring social benefits although they may not generate much direct economic benefit. The connection between EWQ and classification, and the plan for implementation is described in part 3 (from page 39).

Sustainability and governance

It is difficult to evaluate the relative values of all the goods and services offered by aquatic ecosystems, even though environmental economists have attempted to quantify the value of natural systems and social impacts. However, the equity and sustainability aims of the NWA will only be met if social, economic and environmental outcomes are all taken into consideration in both the short term and the long term. Government and institutions need an integrated approach, so that their actions reflect real environmental and social values as well economic values. It is a huge challenge to actually achieve the lofty aims of protecting water resources for long-term benefits.

Nevertheless, South Africa has taken significant steps in this direction. The first step has been to recognise that a catchment or river basin is the natural unit for water resource management, and put into place the management structures for this. The NWA makes provision for catchment management agencies (CMAs) to manage groups of catchments in large water management areas (WMAs). It will be these CMAs' decisions that will affect the quality of life for both this generation and the generations to come.

Integrated thinking has also penetrated the business world. The King 2 Report (2002) requires that South African companies are audited, and therefore report, against a triple bottom line: economic, social and environmental. EWQ can assist in quantified environmental reporting and auditing.

Careful resource use : the speed limit analogy

The use of all natural resources, from rangelands to rivers, is governed by the same logic. If you're a farmer, you can crowd your land with stock, but they'll eat all the grass and bush. You might still make a lot of money for a short time, but very soon the vegetation will be overgrazed, the soil will become eroded, your animals will have nothing to eat, and you will make very little money. This is why farmers are careful about how many animals they put in a field.

Similarly for a river. Suppose everyone takes out as much water and puts in as much waste as they want. In a wet year everyone might be happy, although the water may become a bit polluted. But in a dry year, there won't be enough water for everyone. What there is will probably be poor quality water.

The river may stop flowing, people downstream will get nothing, and the river will be reduced to smelly polluted pools, breeding grounds for diseases such as malaria, bilharzia, and cholera. The fish, water plants, riverside plants and insects which help to clean up the water will almost disappear. The riverbanks will erode, the river bed will silt up, the river will no longer be a natural resource but become a health hazard.

Resource protection and classification provide the 'speed limits' for water resource use. They provide the rules to prevent over-use. Like any speed limit, resource protection is inconvenient for those who lack a long-term view, those who are selfish and incautious. Like a speed limit, resource protection is a societal decision intended to guard people from the selfish and risky actions of others, and to make sure that a common resource continues to provide safely for the needs of society over the long term. Any legal limitations on human behaviour, whether speed limits or resource protection, only work if people comply. They only work if people understand the reason for the limitations, agree with them, and stick to them. One of the aims of this book is to encourage water users to stick to the limits. Speed kills. And over-use kills ecosystems.

Ecosystem structure and function, and EWQ

One of the challenges of resource protection is the way different ecosystems and their components are inter-connected. Upper, middle and lower river reaches, estuaries, and the sea, are all one downstream continuum. Each downstream reach is dependent on, and affected by, upstream reaches. Dissolved and suspended particles, nutrients, organic material and sediments all move along a downstream gradient. Recent research shows how much estuaries and coastal marine environments are dependent on fresh water inputs, and conversely how estuaries also require marine water. Groundwater systems provide base-flows to rivers, and wetlands may be associated with aquifers, rivers, lakes or estuaries, and form a continuum with the terrestrial environment.

We sometimes forget that water is not the only component of aquatic ecosystems. The *bio-physical environment*, as it is known, includes all the *abiotic* (non-living) and *biotic* (living) components. The abiotic components are the water itself (e.g. flow), the chemicals in the form of organic or inorganic particles dissolved or suspended in the water, and the sediments – clay, mud, sand, gravel, cobbles, boulders and bedrock. All of these abiotic components are in continuous interaction, and provide the habitat for the biota – the microbes, invertebrates, fish, amphibians, birds, mammals, riparian vegetation and instream vegetation.

The three main abiotic factors that make up the habitats of plants and animals are

1) water quality 2) flow and 3) physical structure. This book mainly deals with water quality, so a brief description of the link between water quality, flow, and physical structure is now provided (further reading can be found in Gordon et al.1992).

Flow:

The patterns of flow in rivers are described by hydrological data. South Africa has a comprehensive monitoring network of rain gauges and flow gauging weirs, and a sophisticated ability to model and manage water quantity. Hydrologists can calculate the water storage in dams and the quantity of water available in different catchments.

The amount of water flowing in a river, together with the slope of the river bed, determines the water depth, width and velocity. The shape and size of the substrate affects turbulence. Taken together, all these factors make up the *hydraulic habitat* of riverine organisms. For example filter-feeding blackflies, mayflies or caddisfly larvae prefer to live in fast currents, on rock (cobble, boulder or bedrock). These small animals filter the water and remove tiny organic particles for their food. Each has a different feeding adaptation. Their filtering contributes to the capacity of river to clean itself and thus to process wastes.

Flow can have a great effect on water quality. Higher flows provide more dilution and therefore lower concentrations of chemicals. Conversely, low flows mean higher concentrations of chemicals. If human settlements discharge waste continually into a river reach, the concentrations in the river will be highest during the low flow (dry) season. But the dry season is the season when water is most needed by irrigation farmers. When the farmers abstract water for irrigation, this further decreases the flow and the dilution capacity of the river. Clearly it is necessary to integrate the management of water quantity (flow) with the management of water quality, although in practice this is only done occasionally, on a priority basis.

The relationship between flow and water quality varies with the particular circumstances. For example, storm water run-off in an urban area is more ‘flashy’ and more likely to carry suspended or dissolved pollutants. In a heavily populated rural area there may be a likelihood of pollutants seeping into the groundwater which feeds the dry season flow in rivers.

Physical structure:

The physical structure of a system is called its geomorphology – literally, the shape of the earth. Precipitation (mainly rainfall) and gravity together sculpt the earth. Water flows and seeps downwards, dissolving and carrying particles of different sizes. The interaction of water and the ground material of the earth affects the habitats available to aquatic organisms.

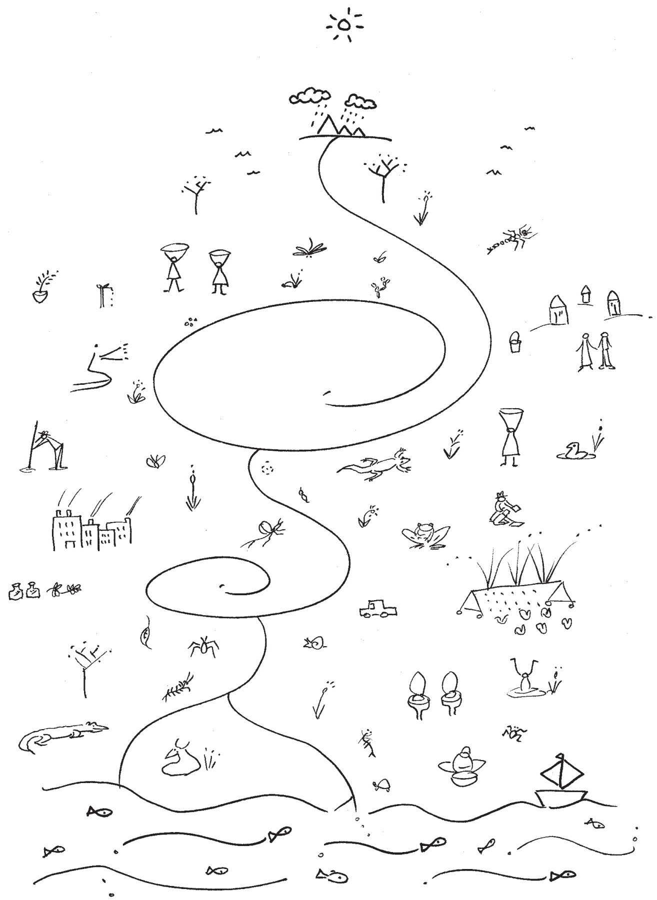
The basic water chemistry of an aquatic ecosystem is a reflection of the geology of its catchment. Dissolved particles become part of the water chemistry. Tiny suspended particles contribute to the turbidity of the water, described by the water quality variable TSS (total suspended solids).

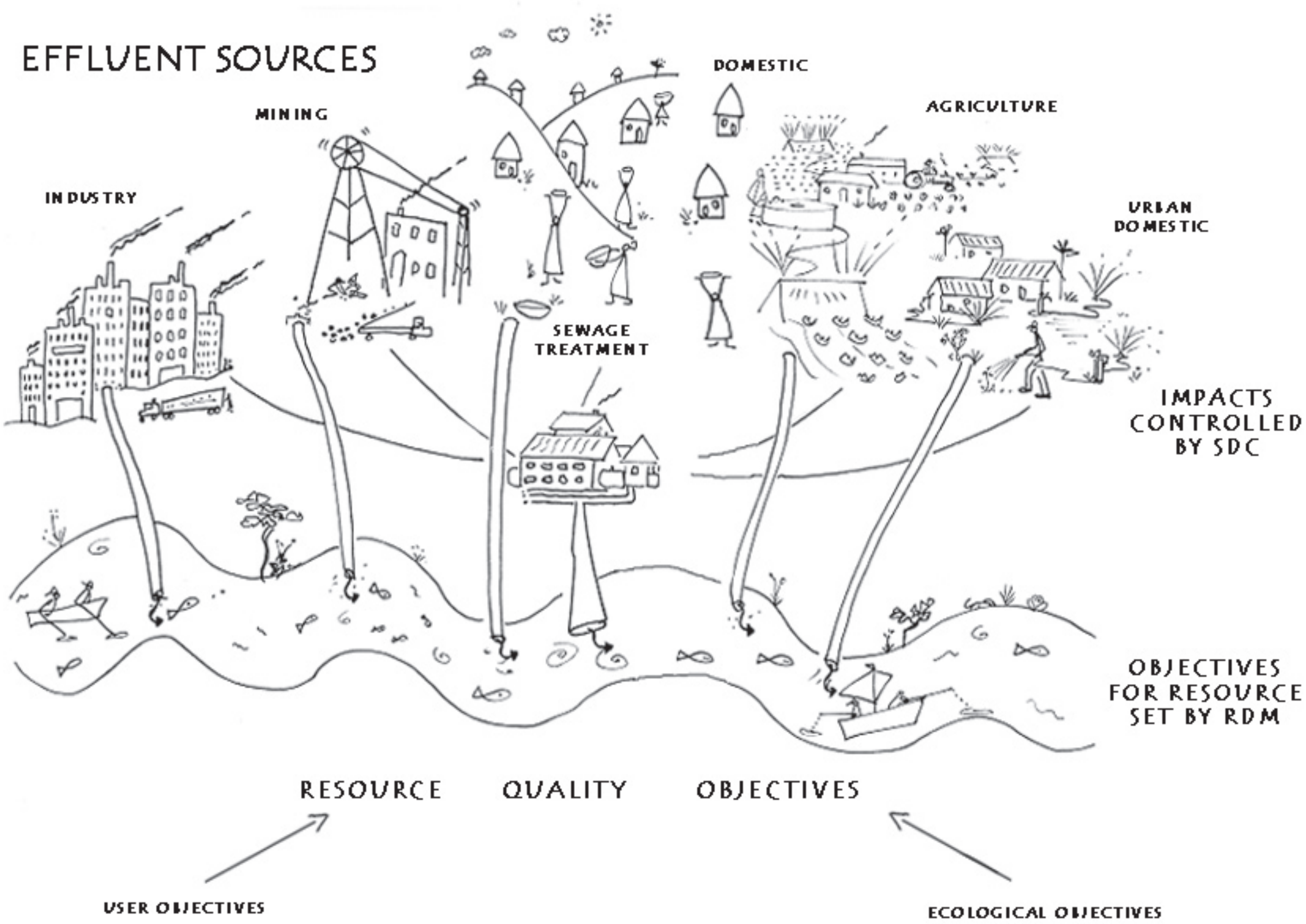
Larger particles, from silt, sand and gravel right up to cobbles and boulders, form the substrate. Different habitats are created by combinations of flow velocity, water depth and substrate particle size. Aquatic organisms are closely adapted to exploit these different hydraulic habitats.

An ecosystem service: waste water processing

Water resources offer people a wide range of goods and services. One of the most important of these is waste water processing – the dilution, break-down, transport and assimilation of waste water. The ability of aquatic ecosystems to process wastes is one of their main services to human society. But there are limits to how much waste they can process. Water managers and users have to decide how much waste and what sort of waste can be disposed into rivers and other aquatic ecosystems.

A common abuse of ecosystem waste disposal services is the practice of using wetlands to contain wastes of intractably poor water quality. Wetlands are frequently the “cinderellas” of aquatic ecosystems. (Breen et al. 1997; Palmer RW et al. 2002). Waste disposal to streams and rivers also happens via sewage treatment works (STW). The sewage discharge then has to meet instream objectives (RQOs) and the local authority has to decide on what the STW can accept.




EFFLUENT SOURCES
MINING
INDUSTRY
DOMESTIC
AGRICULTURE
URBAN DOMESTIC
SEWAGE TREATMENT
IMPACTS CONTROLLED BY SDC
OBJECTIVES FOR RESOURCE SET BY RDM
RESOURCE QUALITY OBJECTIVES
USER OBJECTIVES
ECOLOGICAL OBJECTIVES

Ecosystems assimilate, dilute and transport wastes, but these processes can be overloaded to the point where the ecosystem is damaged. The overload is generally called *pollution*. Use of water resources for waste dilution makes obvious the link between management of water quality and water quantity. When flow decreases, either because of natural seasonal cycles or because of increased abstraction, then wastes are less diluted, more concentrated and potentially more harmful to the ecosystem.

The way ecosystems deal with wastes is described by the terms *assimilation* and *assimilative capacity* (Roux et al. 1999). Assimilation refers loosely to the process by which an ecosystem takes in and deals with waste material. Assimilative capacity refers to how much waste can be taken in to the ecosystem up to a specified limit of damage.

Some wastes, such as domestic sewage, are fairly easily processed and assimilated into the ecosystem. Sewage is a nutrient for certain microbes and algae, which grow and become part of the ecosystem. However when too much sewage is discharged, problems of *eutrophication* arise.

Some wastes, such as salts, cannot be truly assimilated. They can only be diluted and transported. Other wastes become adsorbed onto natural particles in the water such as clays or carbon-based colloids. Adsorbed in this way, they are not *bio-available* and are therefore not harmful. But they are not truly assimilated either, and if circumstances change, for example a change in pH or salinity, the pollutant may be released again.

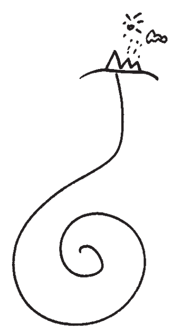
Some recommended reading

Some, For All Forever (Palmer CG et al. 2002) is a simple introduction to South Africa's water law and the interactions between aquatic ecosystems and people. It introduces the concept that aquatic ecosystems (rivers, wetlands, lakes, dams, estuaries, ground water and the sea) provide people with a range of goods and services. The book stresses that it is impossible for these goods and services all be supplied to the same degree, at the same time, in the same place. People have to choose which goods and services they want, in which area. The book describes the National Water Act's system of classifying aquatic ecosystem health so that people can make these informed choices.

Vanishing Waters (Davies and Day 1998) is a comprehensive accessible text on freshwater ecosystems and their use, with South African examples.

Stream Hydrology, an introduction for ecologists (Gordon et al. 1992) provides an excellent description and discussion of the relationship between flow, physical structure and biota.

Challenges for catchment management agencies: lessons from bureaucracies, business and resource management (Rogers et al. 2000) introduces the concept of strategic adaptive management as it applies to catchment management.

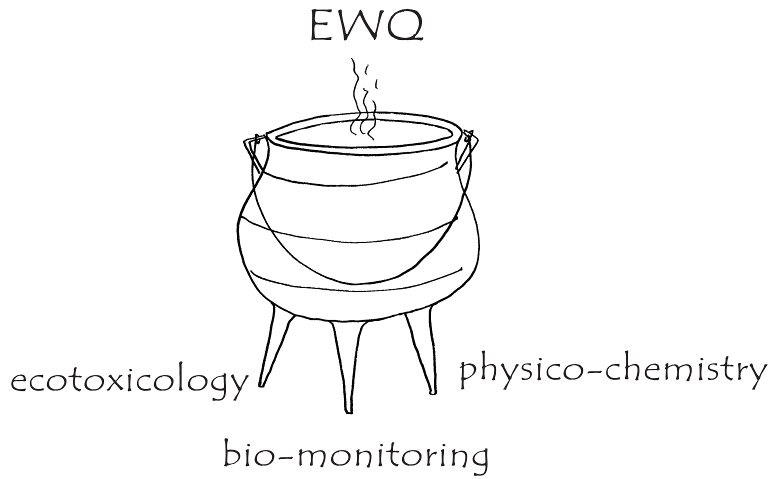


2. EWQ – an integrated approach

“Water for people and people for water”

More than one approach is needed to understand the complex interactions resulting from the pollution of aquatic ecosystems. There are three main EWQ “windows” or kinds of information that contribute to an integrated picture:

- information about the physico-chemistry of the water – gained through a *chemical and physical analysis* of the water
- information about the presence, absence and abundance of biota in the ecosystem – gained through *biomonitoring*
- information about the responses of specific biota to specific concentrations of chemicals or mixtures – gained through *ecotoxicology*



The elephant analogy

The environment is so complex that we only ever ‘see’ it in partial glimpses. But we can use different techniques to get a variety of perspectives of its complexity. However inadequate the picture from each technique, by putting all the information together we can begin to build a picture of the whole.

Suppose you are one of a group of five people who are led, blindfolded, into a large room. You are told there is an animal in the room, covered with a sheet. You are led up, and told to put your hand through a hole in the sheet and to touch and feel, and then to describe the object. You put your hand in and touch what is clearly part of an animal. It is thin, flat and flexible. You think of a ray, or maybe even the wing of a bat…

Unbeknown to you the animal is an elephant, and you are feeling an ear. The others, when they reach out, touch the trunk, tail, leg, and body of the elephant. Everyone has completely different ideas of what it might be.

You leave the room and put all your descriptions together. Just as you make the connections, the elephant trumpets, confirming your deductions.

In the same way, all our techniques for observing the environment are only ‘holes in a sheet’.

Water physico-chemistry

The physical and chemical characteristics of a particular body of water are most accurately called water physico-chemistry, more loosely known as water chemistry or water quality. The definition of water quality used in this book includes physico-chemistry as well as microbial and radiological characteristics. Water in aquatic ecosystems can be found as surface water, interstitial water (between sand grains) and groundwater.

Water physico-chemistry includes a variety of variables:

- system variables: characteristic of particular sites or regions e.g. temperature, pH, dissolved oxygen concentration, total suspended solids (TSS) and total dissolved solids (TDS - which include inorganic salts and ions)
- nutrients: so called because they are food for plants and microbes e.g. phosphorus and nitrogen
- toxic substances: single substances or mixtures in concentrations that are poisonous to living organisms e.g. metal ions, ammonia, pesticides and herbicides. Organisms may be able to tolerate low concentrations of toxic substances, but may be negatively affected, or even die, when subjected to higher concentrations.

Water quality monitoring

Physico-chemical monitoring, usually called *water quality monitoring*, is the norm in pollution control and water quality management the world over. It is the approach that water resource managers and users know best. In water quality monitoring, the chemical composition of effluent streams, whole effluents, and receiving waters is measured and analysed on a regular basis. General and special standards for a selected range of individual variables have to be met as end-of-pipe criteria (DWAF 1995). There are drawbacks to the method, however. Because the usual time-interval for sample collection is a month, it is difficult to accurately model concentration-duration. Also the patchy distribution of monitoring sites, differing periods of data collection, and limited range of variables analysed, all mean that the physico-chemical data is at best representative and is always incomplete. This is a major reason for adding biomonitoring and ecotoxicology to gain an understanding of pollution.

Instream water quality monitoring

South Africa has a national network of water quality monitoring sites. These were selected some years ago to meet the pollution control requirements of the 1956 Water Act and were mainly located upstream and downstream of point sources. They were not located so as to characterise the natural water quality of aquatic ecosystems. These data, kept on DWAF water quality databases, have limitations, such as:

- Water samples are usually only collected monthly and therefore the highest and lowest measures may be missed. There is a limited capacity to monitor the frequency and duration of interim concentrations.
- In rivers, water quality monitoring sites are often at the outflow of dams rather than instream. The chemical character of the river water may be different from that of the dam.
- The water quality of wetlands is very seldom monitored.
- The data record may be short or interrupted.
- There is a limited range of variables measured. Some ecologically important variables, such as TSS and organic toxins, are normally not measured.
- Monitoring site selection may be more influenced by accessibility than chemical relevance.

Despite these limitations, the water quality monitoring records are the best data source available to show the history of South African surface waters.

When biomonitoring data are used together with chemical data, considerably more insight is gained into the link between the chemistry of the water and ecosystem health.

Effluent water quality monitoring

End-of-pipe water quality monitoring is done routinely, mainly as a chemical analysis of individual variables. The range of variables measured may be different from those measured routinely instream, and is dictated by the nature of the effluent.

This form of monitoring is also limited. Effluents are complex mixtures and the concentration of each component changes with the addition of other variables and changes again, depending on the water chemistry of the receiving water (interactions include synergism, antagonism or additive effects). Industrial effluents are frequently discharged to sewers and are mixed with domestic sewage before discharge. Sewage microbes and the organic composition of the sewage can change the chemical characteristics of the effluent.

Pollution control based on general and special limit values is of limited use in controlling the effects of discharging complex chemical mixtures because:

- Mixtures can contain substances that may be difficult or prohibitively expensive to identify.
- There may be too many chemical components to characterise.
- Substances that are present below chemical detection limits can still have a negative effect on biota.
- Mixtures can change in chemical composition because of biological processes.
- Mixtures can have environmental effects substantially different from the sum of their individual component effects.

Despite all these limitations, water quality monitoring records provide important information about the basic chemical character of effluents. When toxicity test data are used together with chemical data, considerably more insight is gained into the link between the chemistry of the effluent and the health of the ecosystem.

Biologically important dimensions

When physico-chemical data are interpreted, it is important to take account of the real exposure of the organism to the chemical stress. There are three biologically important dimensions which apply to flow and water quality:

magnitude (concentration) [for flow, magnitude = discharge]

frequency (how often a particular concentration/flow occurs)

duration (how long a concentration/flow persists)

Biomonitoring

Living things – the plants, algae, invertebrates and fish that make up the aquatic biota – are always in the water, at least for the aquatic stage of their life-history. They experience the cumulative results of all chemical interactions that affect them, including the full frequency and duration of high and low chemical concentrations. They respond to the whole integrated chemical condition. If the chemical conditions are favourable, the biota have the potential to thrive. If chemical conditions approach or exceed their tolerance limits, they will diminish or disappear.

Organisms respond to the whole range of stressors, not only chemistry – so responses are not always easy to interpret. But biomonitoring has become an accepted way of measuring overall ecosystem health (Wright et al. 2000).

Biomonitoring is based on the fact that different organisms have different tolerance levels (see the section on ecotoxicology below). In any biological sample collected from an ecosystem, the presence or absence of sensitive organisms, or simply a change in community composition, can indicate a change in water chemistry that may not be detected by the chemical data record. For example the organisms would respond if damaging effluent had been discharged between monthly chemical monitoring samples.

Invertebrates, fish, algae, the riparian vegetation and the geomorphology can all be monitored to assess aquatic ecosystem health (Uys et al. 1996, Hohls 1996, Dallas 1997, WRC 2001, 2002, 2003). But the most useful are invertebrates, because there are so many of them, they have a diverse range of tolerances, and they have shorter life-cycles and more rapid response times. Invertebrates also have the advantage of being mainly sedentary, and remaining in one area. Fish are also useful indicators of pollution, but they are fewer, larger and generally respond negatively only to higher concentrations. And being mobile, they can swim away from temporarily unfavourable conditions.

In South Africa, biomonitoring has only been used relatively recently, even though aquatic biomonitoring methods were pioneered here 30 years ago (Chutter 1972, 1998). The River Health Programme, which runs in many parts of the country, relies on biomonitoring. Currently, efforts are underway to extend the methods of biomonitoring rivers to monitoring of other aquatic ecosystems (Mangold 2001). Some of the rapid bio-assessment methods, such as the South African Scoring System (SASS), can be undertaken by people with fairly basic training (Dickens and Graham 2002). There are also new biomonitoring methods emerging which allow invertebrates to be rapidly identified to the equivalent of species level and measure a more sensitive response. These techniques can and do provide a real-time, integrated indication of how biota are experiencing the chemical environment.

Biomonitoring offers crucial evidence of ecosystem health response. It shows whether the community composition has changed, and whether the altered community composition comprises tougher organisms. But biomonitoring also has its limitations. It can raise an ecosystem health "red flag", but does not identify the cause of the problem. The causes could be many – changes in habitat because of flow changes or structural damage, or high concentrations of any particular variable or mixture. Links to changes in water quality can be inferred through correlations with water quality data. We begin to find causal links when chemical data, biomonitoring and ecotoxicity data all indicate the same thing.

Diagnosis : the thermometer analogy

The fish and invertebrates in aquatic ecosystems act as a biological thermometer. They can indicate health, and they can indicate when health deteriorates – but they cannot tell you what the problem is. For that you need a diagnosis. Consider the following analogy:

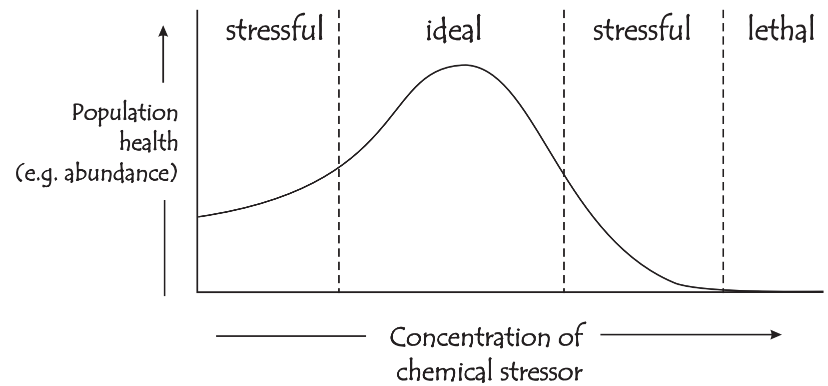
If your child shows signs of being sick, one of the first things you do is to take his or her temperature. If the child has a high temperature you may take her to the doctor for further investigations. The thermometer provides you with a rough index of human health – a high temperature means a person is not well. But it cannot identify the cause of the problem.

Ecotoxicology

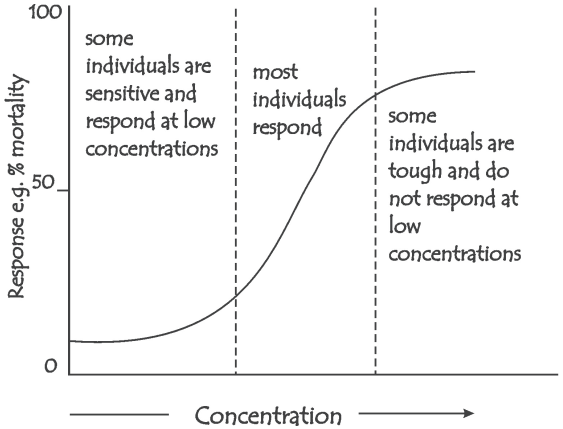
Ecotoxicology is the study of the effects of chemical solutions and mixtures on living organisms. Selected organisms, or communities of organisms, are exposed to single substance solutions or complex mixtures under controlled experimental conditions. The concentrations are carefully controlled and responses are reported as statistical probabilities.

Tolerance limits

All ecosystems accommodate and adjust to changes in water quality, but only up to a point. Living organisms can adapt to high concentrations of some variables. Natural physical, chemical and biological processes can break down and transform some waste substances. Each organism has a specific tolerance to each variable and the organism will only be abundant within its tolerance range. It will be less abundant at the boundaries of its tolerance range, and it will not survive beyond these boundaries. Biological interactions such as competition and predation also affect the abundance and distribution of organisms.



Tolerance of a population to a chemical stressor



Concentration response relationship

When they are near the boundaries of their tolerance limits, organisms use a good deal of their energy coping with the stress of the poor conditions in which they find themselves. This leaves them with less energy for essential activities like feeding and reproduction, and makes them more vulnerable to competition and predation. The ability of an organism to live and compete effectively is called its *fitness*. At quite low concentrations, sometimes at even undetectable concentrations, pollutants can affect an organism's fitness. Low concentration effects that do not kill the animal but affect its performance, are known as *chronic effects*. Chronic effects influence the relative abundance and composition of aquatic biological communities.

Ecotoxicology provides a quantifiable, causal link between the chemical concentrations that are routinely monitored in water resources and the instream biological responses that are now being increasingly monitored. An understanding of these causal links can assist resource quality managers in setting RQOs, and also help water resource users to meet end-of-pipe licence requirements and instream RQOs.

Ecotoxicology is used world-wide. Test results have been used to set water quality guidelines for aquatic ecosystems in the USA, Canada, Australia, New Zealand, Europe as well as South Africa (ANZECC and ARMCANZ 2000, AQUIRE 1994, CCREM 1987, DWAF 1996a). Ecotoxicology is also used to set instream criteria and end-of-pipe criteria in the form of toxicity endpoints.

In South Africa, the use of ecotoxicology is not yet widespread, but is increasing. For example, there are plans to implement the 'direct estimation of environmental effect potential' approach (DEEEP)(DWAF 2003), which specifically targets the management of complex mixtures termed 'whole effluents' (Grothe et al. 1996).

Toxicology terminology

Aquatic toxicology is the study of the effects of chemicals, materials and substances on aquatic organisms and ecosystems (Rand 1995). These studies include laboratory-based toxicity tests as well as studies of organisms in the context of ecosystem function. Generally *toxicology* refers to laboratory-based tests, while *ecotoxicology* is used when there is a greater degree of environmental realism, and testing is linked to ecosystem structure and function.

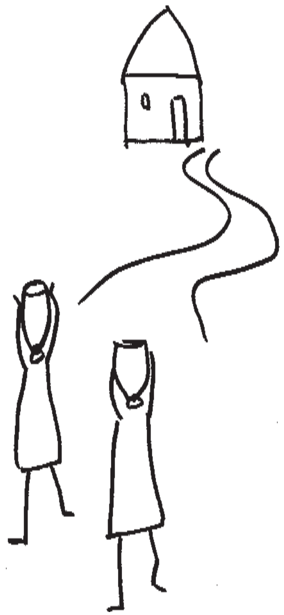
In summary:

- water chemistry provides information about water chemistry composition
- biomonitoring provides information about biotic composition
- ecotoxicology provides insights into why the biota respond in the way they do to the water chemistry

Courses

Among others, courses in biomonitoring and applied aquatic ecotoxicology are offered by the Unilever Centre for Environmental Water Quality at Rhodes University and a variety of partners. Email enquiries to **ucewq@iwr.ru.ac.za**

Further training courses and details can be found at **http://www.csir.co.za/rhp/**



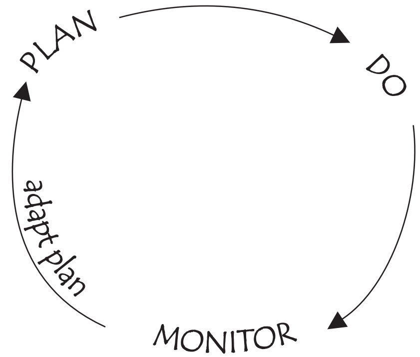
3. EWQ application in the National Water Resources Strategy

"Water for people and people for water"

The National Water Resource Strategy (NWRS) (DWAF 2002a (draft)) is a comprehensive document which sets out how DWAF intends to implement the NWA over the next 10 to 20 years. The NWRS was drafted by DWAF and was subject to an extensive national consultation process. Stakeholder comments are being incorporated, and the final document will be complete late in 2004.

The NWRS promotes a strategic adaptive management style (Rogers 2000). This flexible approach involves:

- Step 1 **plan** (using best available information)
- Step 2 **do** (implement the plan)
- Step 3 **monitor** (check to see if the plan is working)

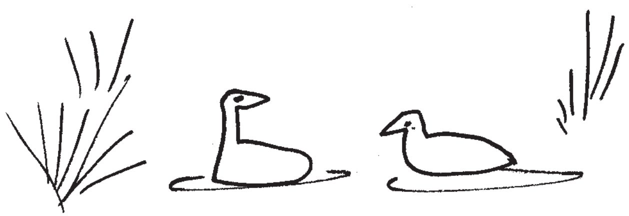


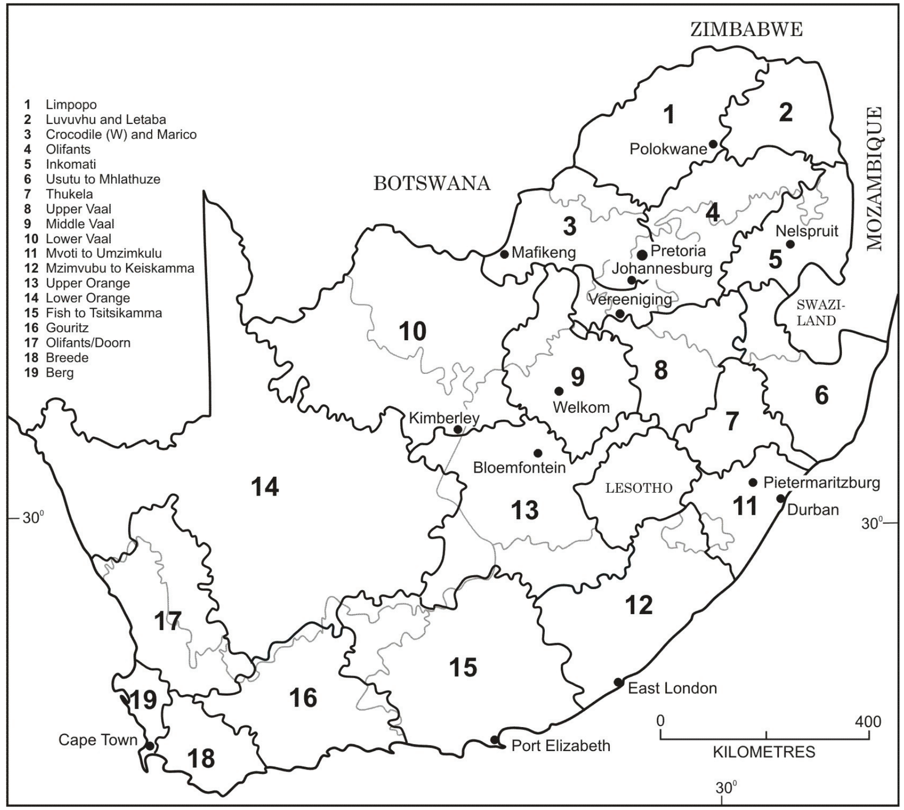
SAM
Strategic Adaptive Management

If monitoring indicates the plan is not working (for example if key objectives are not met), then management returns to Step 1 and modify the plan. If monitoring indicates the plan is working, then management cycles between Steps 2 and 3 until the need to re-plan arises. This cyclical shift between steps is the adaptive part of the model, and ensures that management learns as it goes.

Catchments – the units of water resource management

A key feature of the NWRS is the identification of 19 Water Management Areas (WMAs) for South Africa. A WMA can either include a major catchment with its component sub-catchments, such as WMA 14 (the Lower Orange River) or several smaller catchments, such as WMA 15 (the Fish to Keiskamma Rivers). The NWRS provides maps of each WMA, and further subdivides them into component sub-areas made up of quaternary catchments, which are the smallest units of water resource management. Each WMA will, in time, have its own Catchment Management Agency (CMA) to take responsibility for water resource management in that area. The CMAs will be regional institutions accountable to the Minister of Water Affairs and Forestry for water resource management. Until these CMAs are in place, the regional DWAF offices are undertaking regional water resource management responsibilities.





Water Management Areas

Water resource and water quality management decisions also have to be made at smaller scales than WMAs and catchments. Within each WMA, the NWA requires ‘significant’ water resources (all but very small resources) to be classified, and an ecological Reserve assigned to each one. Each classified resource unit is defined as an area that would naturally have had a characteristic flow pattern, structure type and water quality. The resource can be logically managed as a unit, and an ecosystem health class can be assigned to it. This ecosystem class defines the RQOs that will guide management decisions.

The methods for the classification process are given in the ecological Reserve determination procedure (DWAF 2002b, Palmer et al. 2004). The process requires that rivers should be divided into river reaches, and river reaches subdivided into water quality resource units. A water quality resource unit can be defined as a length of river for which a single description of water quality can be given, whether in a natural state or an impacted state.

Procedure to identify water quality resource units

The basic procedure to identify the extent of a water resource unit consists of three steps:

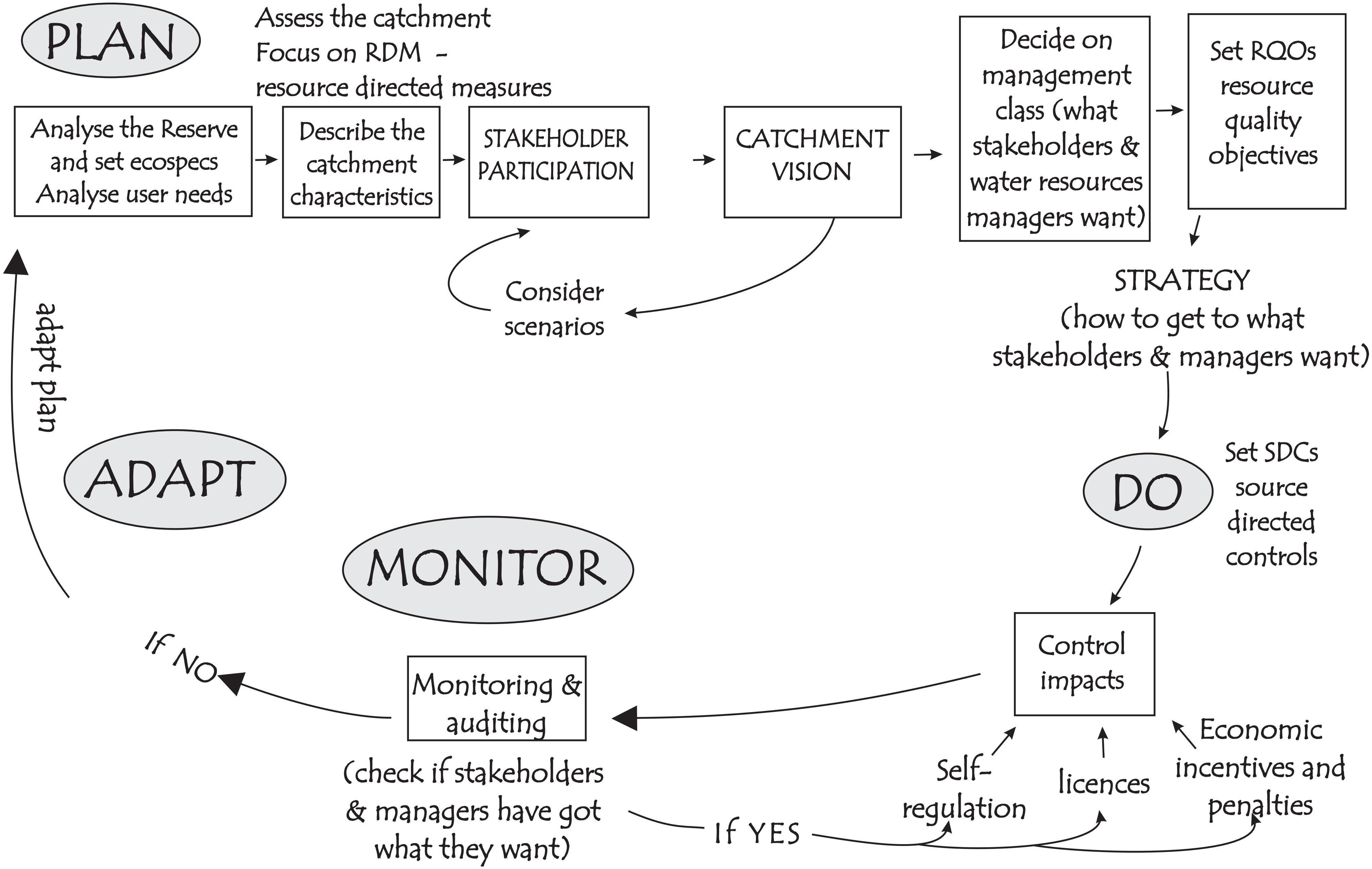
(1) Map the area and identify reservoirs. A dam wall forms the upstream boundary of a water quality resource unit and the inflow point into the next reservoir downstream forms the downstream boundary.

(2) Divide the main river channel at its Level 1 Ecoregion boundaries (Kleynhans 1999). The Level 1 delineation of ecoregions for South Africa has been derived from terrain and vegetation, with some consideration of altitude, rainfall, runoff variability, air temperature, geology and soil. The Level I Ecoregions can be downloaded as image files (jpegs) or Arc View shape files from:

www-dwaf.pwv.gov.za/IWQS/gis_data/ecoregions/get-ecoregions.htm

(3) Include additional resource unit boundaries to take account of major tributaries and urban/industrial point sources that might modify the river to a large degree and thus warrant a new water quality resource unit.

Each resource unit will require water quality data, thus DWAF water quality monitoring points should be noted. Ideally there will be an upstream point to provide data for reference conditions and a downstream site to provide present-state data. If there are no existing physico-chemical data, information from equivalent catchments/sites can be extrapolated. It is also valuable to have a biomonitoring site within the resource unit.



IntegratedWater Resource Management – a water quality perspective

Strategic adaptive management in catchments

Strategic adaptive management is the model used by van Wyk et al. (2003) to demonstrate IWRM. Here we describe each step (Plan–Do–Monitor–Adapt), followed by a text box which explains how EWQ is applied in that step.

STEP 1: PLAN

Catchment Assessment Study

A catchment assessment study includes several stages, each with a focus on the resource and involving the application of RDM. The output from the study is a catchment management strategy, including a water quality management strategy, that is informed by RQOs.

Analyse the Reserve and set ecospecs

The basic human needs Reserve is approached from a human health perspective, and relies on the delivery of treated potable water. Conditions for the basic human needs Reserve are classified as Ideal, Acceptable, Tolerable or Unacceptable. It is not possible nor advisable to manage instream water quality to meet drinking water standards.

The ecological Reserve is determined using an approved methodology (DWAF 1999a, 2000a, Palmer et al. 2004). The methodology requires quantifying the flow, habitat and water quality requirements of all ecosystems in the water resource so that they remain at, or attain, a selected level of ecosystem health. The current classification system for ecosystem health (soon to be revised) recognises that ecosystems are in one of four states – Excellent, Good, Fair or Poor – and can be managed to be in one of three states – Excellent, Good, or Fair (if they are currently

in a Poor state they should be rehabilitated to at least a Fair state). Rehabilitation is very expensive, so it is always cost-effective to put real effort into preventing an ecosystem from deteriorating into a Poor state.

There is still debate about how to classify ecosystems that have been totally modified, for example canalised rivers. There are limited ecological objectives that can be achieved in these systems, and they will probably be classified as Modified, and appropriate RQOs will be developed.

Water quality and water quantity should always be considered in combination. Part of the process of determining an ecological Reserve is specifying environmental flows to meet particular ecological requirements. Every recommended environmental flow component performs a specific ecological or geomorphologic function. (However, environmental flows are *not* recommended to solve pollution problems or to provide dilution flows).

In an ecological Reserve assessment procedure, after environmental flows for each class have been specified, a water quality specialist will use a modelling procedure to evaluate whether the water quality ecospecs will still be met at the recommended environmental flow. If the flow is lower and reduced dilution means water quality will be poorer, then SDCs need to be stricter.

This information is recorded in the ecological Reserve analysis and goes forward to the water quality scenario-planning phase and ultimately into the catchment management strategy.

Analyse the Reserve and set ecospecs: the role of EWQ (Scherman et al. 2003)

Water chemistry:

An ecological Reserve assessment takes account of a minimum set of water quality variables:

system variables – temperature, dissolved oxygen, pH, TSS (total suspended solids)

inorganic salts – sodium chloride, sodium sulphate, calcium chloride, calcium sulphate, magnesium chloride and magnesium sulphate

nutrients – total phosphate (TP), total inorganic nitrogen (TIN)

toxic substances – as listed in DWAF (1996a) Aquatic Ecosystem Guidelines

In certain instances, additional variables may be included, for example it may be necessary to pay attention to fluoride or some other toxicant. The RDM method manual (update in preparation, see also Palmer et al. 2004) provides default class-concentration relationships for low confidence assessments, and methods for higher confidence assessments.

Biomonitoring:

For each resource unit, at least the aquatic invertebrates are measured, using a recognised biomonitoring method such as SASS (Dickens and Graham 2002). Biomonitoring measures such as SASS and ASPT (average score per taxon) scores are related to each ecological class.

For each water quality reach, the class for water chemistry is compared with the class for biomonitoring. If the water chemistry class is better than the biomonitoring class, some factor other than the routinely measured variables is affecting the biota. In such cases the first thing to check is habitat. A low range of habitats could be present at the biomonitoring site, or the habitat could be structurally degraded, or available habitat could be reduced because of flow reductions.

If there are no apparent habitat-related problems, then land-use should be evaluated to assess whether there is likely instream toxicity. If there is mining, heavy industry, intensive agriculture, a sewage treatment works that receives industrial effluent, or urban-industrial storm-water runoff, there may be metal, pesticide or other sources of instream toxicity. Instream toxicity should then be evaluated using the standard suite of a crustacean (*Daphnia*), a fish (*Poecilia/Tilapia*), and an alga (*Selanastrum*) (DWAF 2003).

Ecotoxicology:

The ecological Reserve manual for water quality includes default tables that relate chemical concentrations to ecological health class (Palmer et al. 2004). The excellent class is the same as the aquatic ecosystem guideline value (DWAF 1996a). The relationship between ecological health class and chemical concentration is derived from toxicity test results (Jooste 2002). Additional site-specific toxicity tests can also be undertaken for higher confidence assessments (DWAF 2000b).

Summary:

Water quality ecospecs can now be framed in terms of physico-chemical and biological endpoints. The ‘present ecological state’ of each resource unit can be described for each variable in terms of concentration (water quality magnitude) as well as the pattern of concentrations through time (the frequency and duration of particular concentrations). In the case of toxicants, the chemical concentration boundaries can be derived from ecotoxicity results. The biological status of the resource can then be evaluated using a set of biomonitoring techniques, with, for example, SASS and ASPT scores being linked to class boundaries. In this way the water quality part of an ecological Reserve assessment is explicitly based on an EWQ approach (DWAF 2002b).

Analyse user needs

The three main consumptive kinds of water resource users are bulk domestic users, agricultural users and industrial users. Recreation is an important non-consumptive use with specific requirements. The water quality requirements of these user sectors are provided in the DWAF (1996b, c, d, e, f, g) water quality guidelines, and are classified as being Ideal, Acceptable, Tolerable or Unacceptable.

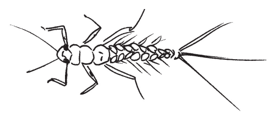
> **Analyse user needs: the role of EWQ**
>
> EWQ is not applied in this stage.

Describe catchment characteristics

This stage of a catchment assessment involves gathering and integrating information and making it accessible and available to stakeholders and water resource managers. The specialists involved in the analyses of the Reserve and user needs make recommendations in this process. Interaction between specialists, stakeholders and managers is crucial here, when a catchment vision is being created by evaluating various scenarios. This stage leads to a decision about which ecological health class will provide the RQOs for future management.

Examples of information feeding into this stage:

- The basic human needs Reserve analysis provides information on the quantity (a minimum of 25 litres per person per day) of water that must be available to people. Water used by people for drinking, cooking and personal hygiene must be treated to the degree needed for human health (DWAF 1996b). At its most basic, this requires sterilising river water with household bleach.
- The ecological Reserve analysis provides quantitative and descriptive ecospecs for a set of variables for each class, as well as information about the present state of ecological health of each reach. Ecospecs can then be compared with userspecs, and protective RQOs can be developed. (Note: methods for integrating ecospecs and userspecs have still to be developed.)
- A socio-economic assessment which evaluates the goods and services offered by the resource in its present state. Each resource class is associated with a particular range of natural goods and services. The economic benefit derived from resource use can be assessed, as well as the economic value of the resource as used for water supply and waste disposal. The value of other services can also be assessed – biodiversity conservation, recreation, aesthetic and spiritual value.



Options for goods & services offered by water resources

EXCELLENT

1 Aesthetic & spiritual opportunities
2 Biodiversity
3 Nature conservation
4 Recreation
5 Supply of natural products
6 Flood control

7 Abstraction

GOOD

1 Aesthetic & spiritual opportunities
2 Biodiversity
3 Nature conservation
4 Recreation
5 Supply of natural products
6 Flood control

7 Abstraction
8 Waste disposal

FAIR

4 Recreation
5 Supply of natural products
6 Flood control

7 Abstraction
8 Waste disposal

POOR

6 Flood control

7 Abstraction
8 Waste disposal

These comparisons and assessments together make up a social, economic and bio-physical assessment. The integrated picture can then be considered in the context of institutional capacity and lines of responsibility, so that effective implementation can be planned. Existing policies, plans and programmes within the catchment should be taken into account so that conflict and overlap are minimised.

Describe catchment characteristics: the role of EWQ

This is a complex stage and EWQ has a specialised role. Firstly, the biophysical attributes of the water resource are described and communicated.

Water chemistry:

The present ecological state (PES) stage of the ecological Reserve process provides information on the current knowledge of water chemistry in each water quality reach. PES concentrations can be compared with those for alternative ecological classes.

Biomonitoring:

Biomonitoring endpoints and habitat integrity measures (Dickens and Graham 2002) provide insights into the biological status of each reach.

Ecotoxicology:

Any instream ecotoxicity test results will pinpoint specific toxicity problems.

Results from the three EWQ approaches are then integrated to describe the present and potential water quality status of each water resource unit. Information presented in this way is understandable and can be effectively used in public participation procedures.

Existing plans and programmes in the catchment are likely to include a water quality monitoring programme for the capture of physico-chemical data and may include the national biomonitoring programme, the River Health Programme. In the future it is likely that a toxicity monitoring programme will also be included. Any development plans and economic empowerment plans can now be considered. Most development options, such as Industrial Development Zones, water-borne sanitation, and even building of new schools, have water-related implications.

Stakeholder participation and catchment visioning

Using the information gathered during the Reserve determination, user needs analysis and catchment assessments, stakeholders can now participate with specialists and water resource managers in the process of 'catchment visioning'. The stakeholders – people from catchment management agencies (CMAs), water user associations (WUAs), local government (municipalities), non-governmental organisations (NGOs) and others – express what they want from the water resources in the catchment, in terms of both level of protection and level of use required.

It is important to note that while the National Water Act requires stakeholder input, the final decisions about resource classification, management objectives and licence conditions are made by the Minister of Water Affairs and Forestry, or DWAF officials delegated by him/her to do so.

Stakeholder participation and catchment visioning: the role of EWQ

The vision for the catchment should encompass both the socio-economic aspirations of the people within the catchment and the ongoing ecological health of the aquatic ecosystems in the catchment. The ecological health vision should take account of the many interactions in the catchment, including ground-surface water, upstream-downstream, quality-quantity, and flow-habitat structure. The vision should include both the present ecological, social and economic conditions and the desired future state of the catchment.

Integrating all of these is difficult, because water is a limited resource for which there will be competition. Hence it is vitally important to follow the guidance of the National Water Act and view the ecosystem as the resource from which user-needs are to be met now and in the future. Ecosystem health is an investment in continued goods and services. Users will necessarily compete for water use and will need to demonstrate that there are optimal benefits for their selected uses of the water.

For stakeholders to participate effectively in the visioning process, they need information on which to base their decisions. They need to understand which ecosystem goods and services are associated with which use options. It is here that multi-criteria decision-making analysis can be useful (Farolfi et al.2004) as it provides stakeholders with ways to take into account many factors, compare them, and evaluate options.

In the next step, stakeholders in the catchment need to agree on the management class for the resource. The class will guide the development of the water use allocation schedule and licensing system in the catchment (for both abstraction and waste disposal).

The visioning process lays the foundation for consensual decision-making that will ensure both resource protection and optimal resource use. EWQ has an important role to play here, providing combined chemistry, biomonitoring and ecotoxicity information to understand the role of water quality in ecosystem health.

Consider scenarios

Scenarios offer a means of visualising the future and examining the alternatives. Scenarios are option assessment tools built using quantitative and descriptive information. They can be developed into models that simulate and evaluate alternative management options and conditions.

Consider scenarios: the role of EWQ

EWQ plays a central role in water quality scenario planning. At this stage, the water quality consequences of recommended environmental flows are considered. Bear in mind that a recommended environmental flow regime may allow additional water abstraction, which means reduced dilution capacity and probably deteriorating water quality. Environmental flows are not recommended for dilution, but allocation of dilution flows may be a temporary management option while SDCs are reassessed/enforced.

Scenario planning is a tough 'reality check' stage. It is a stage when stakeholders, specialists and water resource managers and may find they have conflicting or unrealistic visions. They may find, for instance, that they cannot have both a high ecological health and maximum economic development. Water resource managers also have a tough assignment at this stage. DWAF is the custodian of water resources, the 'public trustee' of our most precious natural resource. Government has a responsibility to both protect the resource and to ensure it is used for social and economic benefit.

Scenario planning forces participants to choose and prioritise. This can be a painful and difficult process. Several decision-making tools are being developed to allow stakeholders and managers to consider complex scenarios including bio-physical, social and economic factors (Farolfi et al. 2004).

EWQ provides a clear picture of the relationship between water quality and ecosystem health. In addition to the integrated flow and EWQ information, social and economic information is also required.

Resource classification

"As the public trustee of the nation's water resources the National Government, acting through the Minister, must ensure that water is protected, used, developed, conserved, managed and controlled in a sustainable manner and equitable manner, for the benefit of all persons and in accordance with its constitutional mandate."

National Water Act Chapter 1, 3(1)

Under the NWA, the government acts as the public trustee of the nation's water resources, and as such it has the responsibility of finally deciding on the class for each water resource unit.

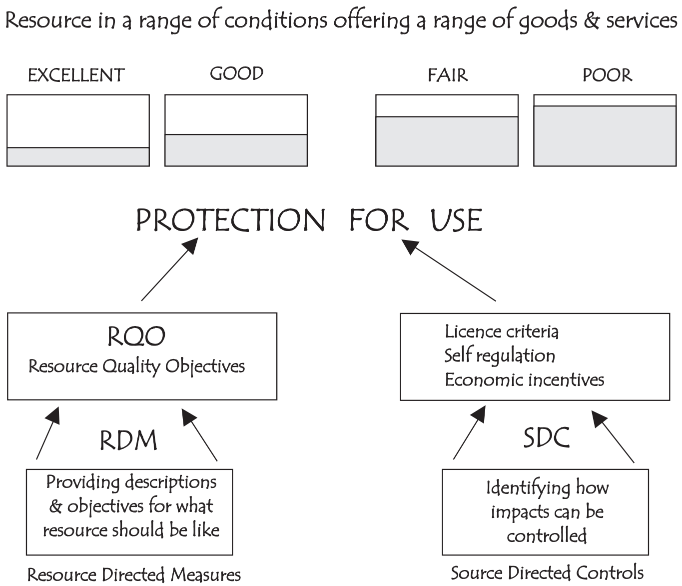
Excellent	Good		Fair	Poor	RESOURCE CLASS
Minimal	Slight		Heavy	Unacceptable	USER IMPACT
A	B	C	D	E&F	
Unmodified	Slightly modified	Moderately modified	Considerably modified	Critically modified	ECOLOGICAL CONDITION

- **Each ecological class has a set of flow and water quality ecospecs which define its objectives**
- **Different user impacts are associated with each ecological class**
- **The final management class objectives are Resource Quality Objectives (RQOs) which are made up of ecospecs and appropriate userspecs**
- **Sustainability is achieved when management actions result in the instream RQOs for the selected class being met :**
  - **Plan - set RQOs**
  - **Do - implement Source Directed Controls**
  - **Monitor - check if RQOs are met**

Alternative possible management class names and areas of relevance

The decision-making process towards selecting a class involves defining RQOs for each of the classes. There is a specific Reserve for each class – and a resultant specific volume (distributed in time and space) and quality of allocatable water. This volume includes allocations for both abstraction and waste disposal, and includes the interaction between flow and quality. *Classification is therefore at the heart of the scenario planning process, and selecting a class is a critical and pivotal decision.*

The information used to decide on the class includes: Reserve assessments, social and economic conditions, opportunities within the catchment, and inputs from stakeholders. Once scenarios have been considered, the class is decided, and this determines the appropriate Reserve and the associated RQOs. These in turn determine the management objectives and plans for the resource. RQOs may be both qualitative-descriptive and quantitative-numerical.



Links between resource protection, classification and resource use

Resource classification : the role of EWQ

A major outcome from the catchment visioning process is the agreed management class. Each resource unit (e.g. tributary, river, wetland, aquifer) is assigned a management class. Excellent and Good classes entail stricter SDCs and less waste disposal and abstraction, but with more potential for recreation, biodiversity conservation, ecotourism and meeting aesthetic and spiritual needs. A Fair class offers more options for direct economic benefit from abstracted water use and waste disposal. Classification is the central action in balancing resource use and resource protection.

Resource classification presents difficult choices for stakeholders. Let us look at two examples of potentially difficult situations:

1) The resource is already over-allocated, and is in a Poor, or only just Fair class. Here it will be extremely difficult for stakeholders to accept that the social, environmental and economic return on the continued over-use of the resource will continue to decrease. This situation requires a brave shared vision where stakeholders agree to invest in the future by accepting that the resource cannot sustain current use and that the type of water use will have to change. Stakeholders and managers will need to decide together what these changes should be, and the time-frame of their implementation.

2) The resource is in a Good or even an Excellent condition, but the stakeholders perceive that their development opportunities will be curtailed if they do not develop the resource for abstraction and waste disposal. Again this requires brave and visionary decision-making. There are relatively few water resources in a Good state, and even fewer in an Excellent state. Everyone benefits from these through recreation, biodiversity conservation, pleasure and spiritual renewal. Therefore the stakeholders in those areas should have some benefit from maintaining those classes.

EWQ contributes directly to the classification process (Palmer & Jang 2002). It is possible to define resource classes in terms of each of the EWQ components – water quality, biomonitoring and ecotoxicity endpoints – but by themselves each of these is of limited value. Ecospecs based on the integrated use of all three approaches have a much greater chance of delivering the desired environmental conditions than the use of any of them separately.

Strategy

The final stage, and outcome, of the Plan step of the IWRM model is the development of a catchment strategy, with a water quality component. The strategy is a clear plan for how to achieve the agreed RQOs. The water quality component takes account of both point and non-point sources of pollution, and includes the water quality impacts of urban, peri-urban and settlement areas.

In developing the strategy, first assess any gap between the present state of the resource and the management resource class that has been decided. If the resource quality needs to be improved, a time-frame for improvement should be agreed upon, with a set of interim RQOs that will lead, over the specified time, to meeting the class-related RQOs.

The next step is to use the interim RQOs to set related incremental management objectives for pollution sources, so that the condition of the resource is directly related to the inputs from pollution sources. Source Directed Controls (SDCs) are then set. Implementation of SDCs should result in meeting RQOs.

Incremental SDCs will be linked to the incremental RQOs, and adopted by each of the water-use sectors. Each water-user sector can then plan the measures it needs to take for incremental

improvement, and put forward a sectoral water quality management plan. Finally, within each sector, individual sources of impact take responsibility for their impact and develop their own individual water quality management plan. Thus controls are planned at catchment, sector and individual source scale. This attention to scale of organisation will ensure that both the collective and individual nature of impact-responsibility is catered for.

Once all the strategy is in place, The IWRM cycle moves from the ‘plan’ phase to the ‘do’ phase.

STEP 2: DO

Control impacts (SDCs)

Each step in the strategy to control impacts is taken. Each water-user sector implements the measures for incremental improvement or water resource development. Each action is described in the sectoral water quality management plan. Within each sector, individual polluters take responsibility for their impact and implement their individual water quality management plan. Controls are therefore implemented at catchment, sector and individual source scale. Incremental SDCs and RQOs will clearly direct decisions along this hierarchy of options. Criteria and goals may be expected to change with time.

There are three main mechanisms to ensure implementation.

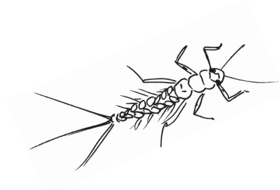
- *licensing*
  Government (DWAF), as the public trustee, imposes licences that limit use – both abstraction and discharge. Compliance depends on a combination of self regulation and enforcement.

- *self regulation*
  With increasing globalisation, many industries are part of multinationals and/or have international markets. For these industries, first world environmental requirements apply and provide an incentive for self regulation. Self regulation outside of international constraints depends on informed and motivated users that understand and 'buy into' the concept that resource protection is in their own interests. If polluters have been part of the scenario development for their catchment, and understand which ecosystem goods and services they are getting with their choice of class, they may become sufficiently motivated to comply with licence criteria voluntarily.
- *economic incentives and penalties*
  This is the 'carrot and stick' approach. There can be fines or levies for non-compliance and rebates for compliance. Details of these economic incentives should be part of the strategic plan, and could include:

Market-based management instrument	A waste discharge charge system.
Regulatory management instruments	Waste discharge licences, the Environmental Management Programme Report process, landfill permits.
Self-regulatory management instruments	Implementation of ISO 14001, certification.

The implementation mechanisms are managed at three levels:

Pollution prevention	Impact on the water resource is prevented by pre-emptive management, such as disposal of wastes to sealed land-disposal sites.
Impact minimisation and remediation	Impact on the resource is minimised, for example by use of a cleaner production technology. Impacts that do occur are remediated, e.g. wetlands may be used to remediate the impact of excess nutrients.
Water resource use	Resource-use for waste disposal involves acceptance of a level of impact, and assessing the capacity of water resources to transport, dilute and process wastes. This form of use is controlled by licensing.

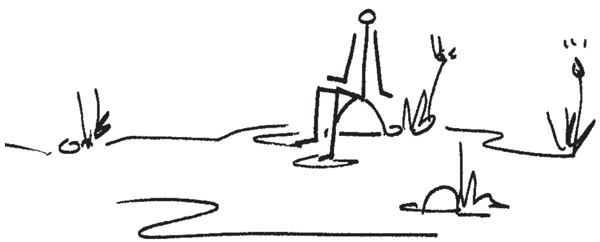


Control impacts (SDCs): the role of EWQ

In the past licence criteria were routinely set in terms of chemical concentrations. DWAF is now steadily moving towards extending this to include toxicity-based licence criteria – particularly for complex wastes (DWAF 2003). Any waste water containing more than 15% by volume industrial waste is defined as a complex industrial waste – this includes the waste water from many STWs.

Complex industrial mixtures are excluded from the General Authorisation (DWAF 1999b) to discharge without a licence. Therefore all complex industrial wastes that are discharged into a resource are subject to SDC by licence. DWAF already has in place a policy and technical guideline for the implementation of toxicity-based licensing of complex wastes.

DWAF is also including biomonitoring endpoints in licences, as a requirement to meet instream RQOs Biomonitoring endpoints indicate whether the outcome of the chemical and/or toxicity-based control has been successful. There is huge potential to further develop this integrated use of EWQ in pollution control.



STEP 3: MONITOR

Monitoring and auditing

This step has elements of both RDM and SDC:

- monitoring has the resource as its focus (RDM)
- auditing focuses on the impact source (end-of-pipe) (SDC).

Monitoring involves checking that the instream RQOs are met. Auditing involves checking end-of-pipe discharge for compliance with licence criteria.

It is likely that DWAF will put in place a monitoring programme specific to the ecological Reserve, so as to ensure compliance with both Resource Directed Measures and Source Directed Controls. It has been recommended (Palmer et al. 2004) that this should include an extended range of variables such as instream toxicity, toxicants, temperature, suspended solids and nationally routine biomonitoring. Any extension of national monitoring efforts should also consider the issues of sampling frequency and the geographic location of sampling stations (Jooste pers.comm.).

Monitoring and auditing: the role of EWQ

If all three aspects of EWQ are specified in both RQOs and licence criteria, and all three are aspects of both RDM and SDC, then automatically there will be three aspects to monitoring – the chemistry will be monitored, ecosystem health will be monitored using biomonitoring, and ecotoxicity will be monitored. In the same way compliance can be audited using chemical, biological and ecotoxicological criteria.

The advantages of the threefold approach remain the same – each type of information provides a different perspective and the combined use of all three offers the best option for achieving the selected resource quality condition.

Adaptive water quality management

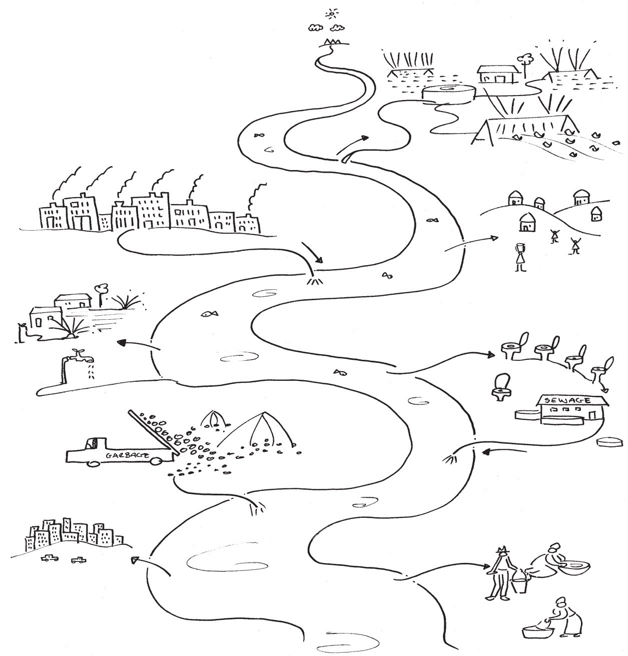
Management is by nature iterative. Objectives are achieved incrementally and goals are repeatedly re-set. The only certainty is that change will happen, and management is essentially an attempt to control the direction and magnitude of change.

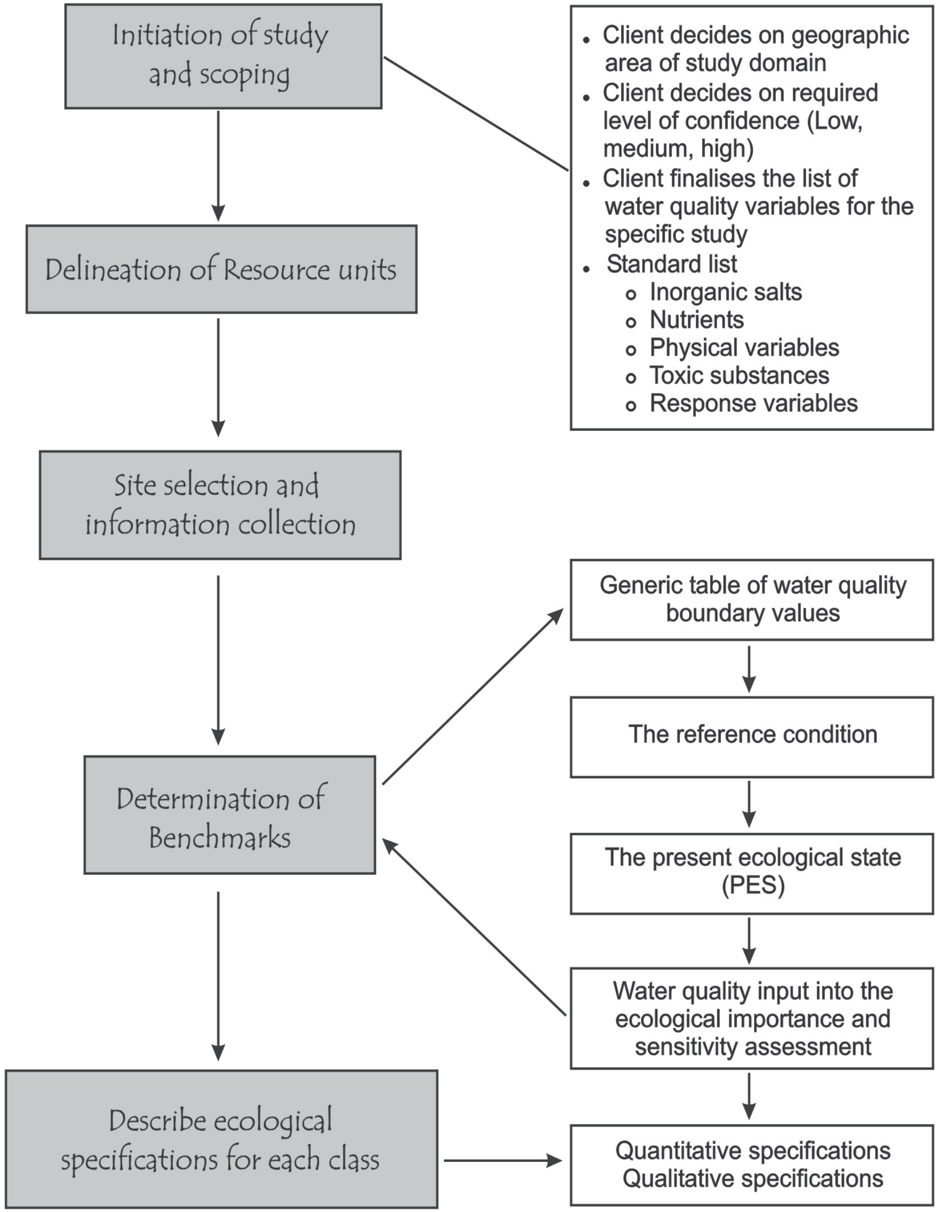
Adaptive management involves an evaluation of the monitoring and auditing against the objectives set in the planning phase. As long as objectives are met, and stakeholders accept the goods and services offered by the resource and its associated class, the monitoring and auditing and implementation of SDCs continues.

However, the lifespan of a licence is limited (5 to 25 years) before it is subject to review. With time, the needs and requirements of people within the catchment may change. There may be a need to review the entire water quality management plan. When this happens, the process cycles back to the planning phase and the whole process is repeated.

Case study: EWQ applied to salts in the ecological Reserve for the Olifants River, Mpumalanga

The Olifants River in Mpumalanga was the first river for which a detailed ecological Reserve assessment for water quality was done in South Africa (DWAF 2000a). The method has subsequently been further developed (Palmer et al. 2004). (This latter document should be used as the water quality methods manual until it is superseded by a formal DWAF methods manual). The assessment undertaken in the Olifants study, particularly in relation to salts, provided the first indications of the value of EWQ approach. In this case study the assessment of salts in the Olifants River is presented in terms of the steps of the National Water Resources Strategy described in part 3.





Water Quality process in an ecological Reserve determination

STEP 1: PLAN
Catchment Assessment Study

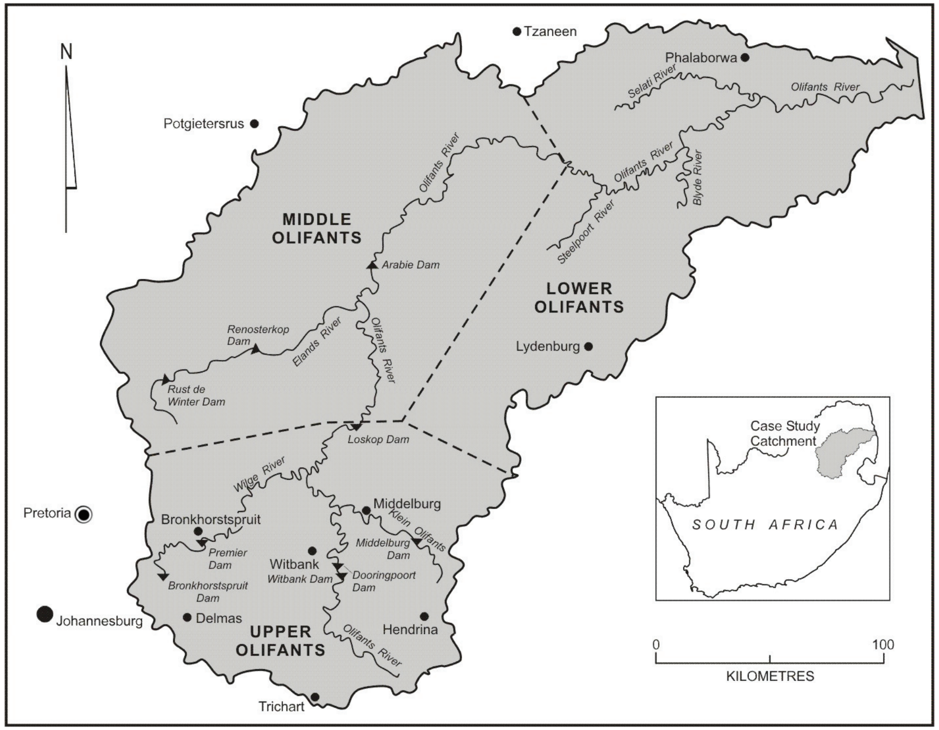
Analyse the Reserve and set ecospecs

Follow the stages in water quality in an ecological Reserve assessment flow diagram.

Initiation of study and scoping

The Olifants River catchment was divided into the upper, middle and lower Olifants, and specific tributaries and main-stem river reaches were then specified as being part of the study:

- Upper Olifants which is the catchment upstream of Loskop Dam and includes the upper Olifants, Klein Olifants, and Wilge Rivers.
- Middle Olifants which is the catchment downstream from Loskop Dam to just downstream of the Mohlapitse River and includes the middle Olifants, and the Elands River.
- Lower Olifants which is the Olifants River downstream of the Mohlapitse River, up to the border of South Africa and Mozambique and includes the Steelpoort, Blyde, and the Selati Rivers.



Olifants River Catchment

Delineation of resource units / water quality reaches

Each water quality reach reflected a length of river for which a single set of objectives (RQOs) could be derived. Reaches were therefore bounded by tributary inflow, dams and/or major towns.

Site selection and information collection

DWAF water quality monitoring points were identified and the data assessed.

Examples of water quality reaches identified along the main stem of the Olifants River, in the Upper catchment.

Reference sites = least impacted record in the reach
PES (present ecological state) site = current status of reach.
In the complete study all reaches in the study were described (DWAF 2000a).

River reach (delineated by segment numbers)	Description	Comments
Olifants 1 – 8	Olifants River from its source to the confluence with the Steenkoolspruit.	The upper reaches of the Olifants River are relatively undisturbed with dryland agriculture being the main land-use and some coal mining at the bottom end of the reach. Reference site: B1H006Q01 PES site: B1H018Q01
Olifants 9 – 13	Olifants River from the Steenkoolspruit confluence to the inflow into Witbank Dam	This reach of the Olifants is highly impacted by coal mining and power generation activities in the catchment through which it flows, as well as poor quality water in the Steenkoolspruit. Reference site: B1H018Q01 PES site: B1H005Q01
Olifants 14 – 27	Olifants River downstream of Witbank Dam to the Klipspruit confluence	This reach is negatively impacted by water from the Spookspruit (due to coal mining activities) and the Klein Olifants River. There are no routine DWAF monitoring stations in this reach which could be used to assess the PES.

Describe water quality data

The adequacy of the water quality data were described (DWAF 2000a):

“There are some 119 DWAF monitoring points distributed unevenly over the study area. The upper and lower Olifants River study area has good or moderate to good distribution of monitoring points. In the middle Olifants River there is a poor distribution of monitoring points, especially in the old homeland areas.

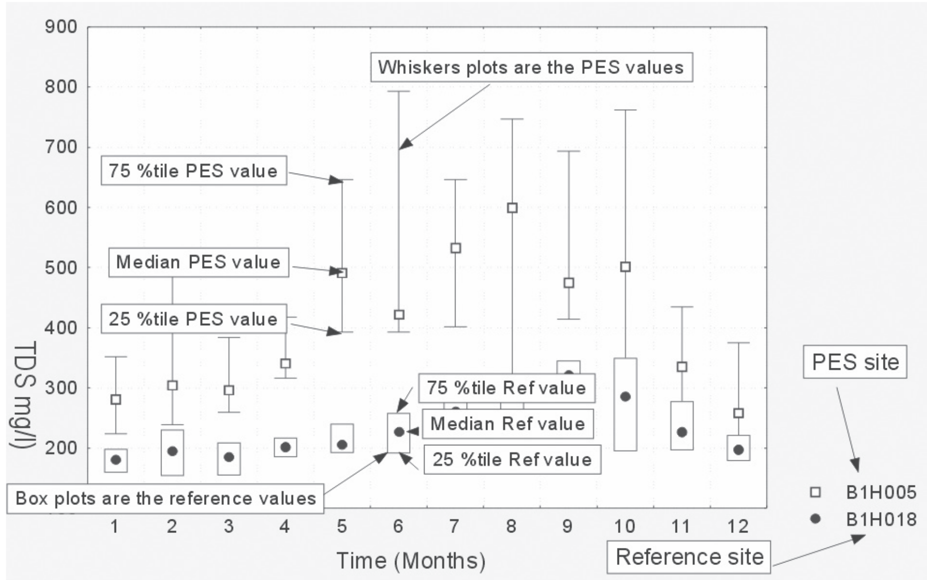
Upper Olifants: There are some 40 monitoring points in the upper Olifants catchment. Of these, 25 are situated in the Olifants and Klein Olifants River catchments upstream of the Wilge River confluence, 11 are in the Wilge River catchment, and one monitoring station between the Wilge River confluence and the inflow into Loskop Dam. where there are three in-lake monitoring points. Weaknesses in the distribution of monitoring points are that the Wilge River upstream of the confluence with the Bronkhorstspruit has no monitoring points and the same applies for the main stem Olifants River between Witbank Dam and Loskop Dam where there are no routine water quality monitoring points.

Middle Olifants: There are some 25 sampling points in the middle Olifants study area. These are distributed on the main stem Olifants River, mostly up to Arabie Dam, and on the Moses and Elands Rivers. The coverage of water quality monitoring points is very poor in the former homeland of Lebowa and none of the tributaries like the Lepellane, Nkumpi and Motsephiri have any routine monitoring points on them.

Lower Olifants: There are some 51 DWAF sampling points in the Lower Olifants study area. About 17 of these are in the Steelpoort River catchment, about 11 in the Blyde River catchment, about 7 in the Selati River catchment and the remainder is distributed over the main stem Olifants and minor tributaries. The most serious weakness in the current monitoring programme is the absence of routine monitoring points in the Olifants River between B5H002Q01 (Olifants at Zeekoegat) and B7H009Q01 where the Olifants enters the Lowveld. There is also concern about the absence of a routine monitoring point in the middle Selati River which makes it difficult to assess the degree of change in water quality upstream of the Phalaborwa mining complex.”

Analyse water quality data

Box and whisker plots, and/or scatter diagrams were developed for each data set (DWAF 2000a):



“A comparison was made between the statistics of the monthly TDS concentrations observed at the reference site and the present ecological state (PES) site. The reference site values were represented as a box plot for each month and the PES site values were represented as whisker plots for each month. The top bar of the box (or whisker) represented the 75th percentile value for the month, the bottom bar was the 25th percentile and the middle marker was the 50th percentile or median value. Fifty percent of the observations in a specific month therefore fell within the whiskers or box plot. In the margin, the DWAF station number of the reference site (round marker) and PES site (square marker) was given.

Data used to describe reference conditions for many water quality river reaches were the best available reference data. These data did not represent the unimpacted state, but rather the best available estimate of the unimpacted state."

Development of a method for determining ecospecs for salts

Early on in the study the water quality team travelled through the catchment. It was evident that mining was a major land-use that was likely to impact on water quality. All the DWAF water physico-chemical data were collected, and it was clear the TDS (total dissolved solids – a measure of salinity) was very high in many reaches, and that sulphate ions contributed to this.

The problem arose that there was no formal method to relate salt, TDS or ion concentrations to different classes. So a sequence of methods was developed and applied.

- *The % deviation method*

The DWAF (1996) water quality guidelines for aquatic ecosystems provided guidelines for single-substance toxicants on the basis of toxicity test results, but for salinity the guideline was simply that it should not exceed 15% of the "natural" range. (At that time salts were considered "system variables" and part of the natural suite of abiotic conditions, whereas now they are recognised as toxicants (Kefford et al. 2002).)

The water quality team therefore identified a reference or "natural" site, and an impacted or "present day" site in each water quality reach in the Olifants River. The median monthly TDS concentration was compared between the reference and the impacted site and the % difference noted. As a preliminary guide we suggested that the following % difference would relate to specific classes:

<table>
<tr><th colspan="2">Ecological Health Class</th><th>Salinity - % deviation from the natural (Excellent / A Class) condition</th></tr>
<tr><td>A</td><td>Excellent</td><td>15</td></tr>
<tr><td>B</td><td rowspan="3">Good

Fair</td><td>20</td></tr>
<tr><td>C</td><td></td></tr>
<tr><td>D</td><td>30</td></tr>
<tr><td>E/F</td><td>Poor</td><td>40</td></tr>
</table>

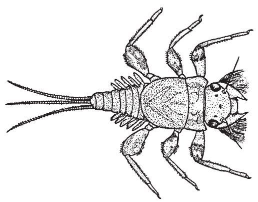
When this was applied to the Olifants River salt data, nearly all the reaches had to be classified as Poor. Most of the recorded salinities at impacted sites had been more than 40% higher on average than they would have been in the natural condition.

- *Links between biomonitoring and classification*

In the meantime the macroinvertebrate specialist in the team had related SASS scores (biomonitoring) to classes for the Olifants River:

Total SASS score & average score per taxon (ASPT) related to river classes		
Class	SASS score	ASPT
Excellent	> 175	>7
Good	120 -175	6 – 7
Fair	60 –120	4.8 – 5.9
Poor	< 60	<4.8

When the biomonitoring results were assessed, it was clear that while there were reaches in which the biological indicators showed a Poor class, there were also reaches in each of the other classes. This meant that 40% salinity increases above the natural were within the tolerance limits of many fish and invertebrates. As a result the team began to reconsider the salt-toxicant question. There was evidence of the toxicity of salts, and indeed of different salts having different toxicity effects (Goetsch and Palmer 1997, Palmer and Scherman 2000). We therefore collected large numbers of nymphs of the mayfly *Tricorythus discolor* from a reference site in the Upper Olifants and, using sodium sulphate as a model for mining-influenced salinisation, undertook a series of salt tolerance tests.



Tricorythus tinctus (Ephemeroptera, Tricorythidae)

- *Site specific salt toxicity method*

From this we developed a relationship between salts tolerance endpoints and classes. This relationship was subsequently refined:

Specific toxicity endpoint related to ecological health classes (Scherman et al. 2003)		
Class		Toxicity endpoint
A	Excellent	Lowest measurable 10 day toxicity: < lower 95% confidence limit of the 10 day LC1
B	Good	Measured 10 day toxicity = 10 day LC1
C	-------------- Fair	
D		Measured 4 day toxicity = 4 day LC1
E/F	Poor	> 4 day LC1

In the Olifants River study the actual recommended salinities were based on the tolerance responses of the mayfly *Tricorythus discolor* for the whole river except for the Blyde River tributary. The Blyde is the last remaining tributary of the Olifants with very low, naturally occurring salinities. To be conservative, the boundary values for the Sabie River were used for the Blyde. If the Olifants River salt ecospecs were recalculated, the method described by Palmer et al. (2004) would be followed.

Relationship between river class and salinity for all river reaches in the Olifants study area except the Blyde River (The experimental basis for these values is given in DWAF 2000a)		
Assessment class	Electrical conductivity (mS/m)	Total dissolved salts (mg/litre)
A	20-35	130-195
B	35 – 45	195-295
C	45 – 80	295-520
D	80 – 120	520 – 780
E/F	> 120	>780

Relationship between river class and salinity for the Blyde River (The experimental basis for these values is given in DWAF 2000a)		
Assessment class	Electrical conductivity (mS/m)	Total dissolved salts (mg/litre)
A	8-17	50-100
B	17-30	100-195
C	30-40	195-260
D	40-50	260-325
E/F	>50	>325

When these salinity concentrations for each river reach were compared with the biomonitoring classes for the equivalent reaches, the match was very close – the class indicated by the biomonitoring result matched the class indicated by the salt toxicity result. This was most encouraging.

It was then apparent that there were a few resource units where the biomonitoring indicated a 'Poor' condition even though the salinity was 'Good'. This led to a further use of ecotoxicology.

The land-use around the resource units with a 'Poor' biomonitoring status was assessed and those units where there was mining (risk of metal ion toxicity) or intensive agriculture (risk of pesticide toxicity) were noted. The toxicity of the river water in those resource units was tested, and in two instances the river water was found to be toxic. This allowed a conclusion that in those resource units there was a chemical problem, but it was related to toxicity other than to salinisation.

Since then salts have been recognised as toxicants (Kefford et al. 2002) and the need for toxicity-based classification accepted. The combined use of water chemistry, biomonitoring and ecotoxicology should now be routinely part of ecological Reserve assessments.

- *EWQ in ecological Reserve assessments*

Several comprehensive ecological Reserve studies have followed the Olifants River, and there as been a steady development in methods and their application. An interactive Decision Support System has been developed which guides any user through the ecological Reserve process (Hughes 2004). The integrated, EWQ approach is described in the Water Quality section (Palmer et al. 2004)

- *Species sensitivity distribution method*

DWAF has since developed a more sophisticated link between tolerance responses and classes (Jooste 2002).

Analyse user needs

This was not done as part of the Olifants study.

Stakeholder participation and catchment visioning

Stakeholders were involved in the Olifants study, but did not actively participate in catchment visioning. Ecological specialists presented results and a classification, which were accepted by stakeholders.

Consider scenarios and Resource classification

Hughes (2004) describes the process of considering scenarios and classifying the resource. For water quality, scenario development is based on the work of Malan and Day (2002).

Remaining steps

The last part of Step 1, and Steps 2 and 3 were not undertaken in the Olifants study. They are:

STEP 1: PLAN (last part)	Strategy Development
STEP 2: DO	Control impacts (SDCs)
STEP 3: MONITOR	Monitoring and auditing Adaptive water quality management

However the Olifants study did supply a list of issues that emerged from the study, which would be used as part of the remaining aspects of an adaptive management cycle.

Summary of water EWQ issues that emerged from the ecological Reserve in the Olifants River

(modified from the conclusion to Palmer and Rossouw, 2000a)

SDCs

Source Directed Control of water quality is imperative if the resource is to be adequately protected. If SDCs take longer to implement than the recommended environmental flows, water resource managers should be alerted to river reaches that may require intervention management. An example is the use of dilution to solve water quality problems that threaten resource health and integrity. In the final analysis, it is the approach to water quality management, and the effective implementation of SDCs in relation to the implementation of environmental flows, that will ensure integrated resource protection in the Olifants River catchment.

Water quality refugia and 'hot spots'

Throughout the catchment there are reaches and tributaries with particularly good water quality which play an important role in the improvement of downstream water quality conditions. They act as refugia for biota from adjacent, more impacted, reaches. In the integrated management of the catchment, the vital role of these good quality river reaches should not be underestimated, nor should the dependence of downstream river health on them be overlooked. Tributaries and river reaches that play this critical role include: the Wilge River, the Mohlapitse River, the upper reaches of the Selati River and the Blyde River.

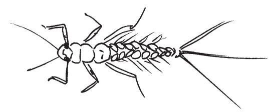
Likewise there are reaches and tributaries that are severely impacted and have very low water quality. These impact negatively either on receiving impoundments or on downstream reaches. Effective SDCs in these reaches would significantly improve catchment water quality. This category includes the Steenkoolspruit River, the river reaches flowing into Witbank

and Middelberg dams, and reaches downstream of Arabie Dam, the lower reaches of the Steelpoort River, the Moses River, and especially the Klip River and the lower reaches of the Selati River.

Conclusion

The study concluded that water quality is of key importance in the management of the Olifants River, and that the effective implementation of SDCs will be the determining factor in the achievement of resource objectives in several key river reaches.

The study provided an excellent example of the need to consider both water quality and water quantity in ecological Reserve determinations and the catchment management operations which follow.



Appendix 1: Water Quality

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Water quality is a huge topic and subject of many books. The most comprehensive South African reference is: The effect of water quality variables on aquatic ecosystems: a review (Dallas and Day 2004). This appendix comprises selected chapter summaries from this book.

Aquatic ecosystems and water quality

Water quality is the combined effect of the physical attributes and chemical constituents of a sample of water for a particular user. Functional aquatic ecosystems usually support a variety of organisms, such as primary producers, primary consumers and secondary consumers, within different trophic levels. Rivers are longitudinal systems driven largely by the flow of water and are divided into zones, which are distinct with respect to their physical, chemical and biological characteristics. Wetlands are depositing systems that accumulate sediment and include a wide variety of aquatic ecosystems from riverine floodplains to high-altitude rain pools and from tree-covered swamps to saline lakes. Regional differences in rivers and wetlands arise as a result of differences in climate (and thus temperature, mean annual precipitation, mean annual evaporation, etc), geomorphology (gradient, erosion), geology and biota. These differences need to be considered when establishing guidelines for the protection of aquatic ecosystems.

Within each region or zone, community composition is determined by water quality, the type of habitat (biotope) available, the degree of water movement, temporal variations in the availability of water, and the historical distribution of species. Water quality variables potentially affecting aquatic ecosystems may be physical (turbidity, suspensoids, temperature) or chemical (non-toxic: pH, TDS, salinity, conductivity, individual ions, nutrients, organic enrichment and dissolved oxygen; and toxic: biocides and trace metals). Each variable has an effect, either beneficial or detrimental, on aquatic organisms; and the overall effect when more than one variable is involved is dependent on whether they act synergistically, antagonistically or individually. The effect of each variable on individual organisms is also influenced by the tolerance limits of the organism. In addition to individual variables, aquatic ecosystems are often the ultimate receivers of whole effluents, which consist of a combination of water quality variables.

Temperature

The thermal characteristics of running waters are dependent on various hydrological, climatic and structural features of the region, catchment area and river. Running waters in regions of seasonal climates exhibit daily and seasonal temperature patterns, in addition to longitudinal changes along a river course. All organisms have a temperature, or range of temperatures, at which optimal growth, reproduction and general fitness occur. Changing water temperature may expose aquatic organisms to potentially lethal or sublethal conditions.

Anthropogenic causes of temperature changes in river systems include those resulting from thermal pollution, stream regulation and changes in riparian vegetation. An increase in water temperature decreases oxygen solubility and may also increase the toxicity of certain chemicals, both of which result in increased stress in the associated organisms. Many life cycle characteristics of aquatic organisms are cued into temperature, i.e. temperature is the cue for migration, breeding, emergence, etc. Temperature changes affect metabolic processes and life cycle patterns by altering reproductive periods, rates of development and emergence times of aquatic organisms. Differences in temperature tolerance amongst the

biota, and regional and seasonal temperature differences, should be considered when establishing guidelines for the management of water temperature in rivers.

Turbidity and suspended solids

The immediate visual effect of a change in turbidity is a change in water clarity. An increase in turbidity or suspended solids affects light penetration, which may have far-reaching consequences for aquatic biota. The natural seasonal variations in rivers often include changes in turbidity, the extent of which is governed by the basic hydrology and geomorphology of the particular region.

Erosion of land surfaces in catchment areas by wind and rain is a continuous and historically natural process. Land-use practices such as overgrazing, non-contour ploughing and removal of riparian vegetation accelerate this erosion, however, and result in increased quantities of suspended solids in associated rivers.

Increases in turbidity can, and often do, result from other anthropogenic processes, such as release of domestic sewage, industrial discharge (including mining, dredging, pulp and paper manufacturing) and physical perturbations such as road and bridge construction, dam construction, road use and reservoir management. If turbidity increases resulting from human inputs are as infrequent as natural flooding, the stream community may tolerate them. Continuous high-level inputs, on the other hand, may have very serious consequences for the riverine biota. As light penetration is reduced, primary production decreases and food availability to organisms higher in the food chain is diminished. Suspensoids that settle out may smother and abrade riverine plants and animals. Community composition may change, depending on which organisms are best able to cope with this alteration in habitat.

Predator-prey interactions are affected by the impairment of visually-hunting predators. Nutrients, trace metals, biocides and other toxins adsorb to suspended solids and are transported in this form. Few studies on turbidity effects have been conducted in South Africa, primarily because turbid rivers are fairly common in this country and are thus not considered to be problematic.

pH and alkalinity

pH is determined largely by the concentration of hydrogen ions (H^+), and alkalinity by the concentrations of hydroxyl (OH^-), bicarbonate (HCO_3^-) and carbonate (CO_3^{2-}) ions in water. Addition of acid or alkali to a water body alters pH. Since pH is a log scale, a change of one unit means a ten-fold change in hydrogen ion concentration. Further, in very pure waters pH can change rapidly because the rate of change is determined by the buffering capacity, which in turn is usually determined by the concentration of carbonate and bicarbonate ions in the water.

The pH of natural water is determined by geological and atmospheric influences. Most fresh waters are relatively well buffered and more or less neutral, with pH ranging around 6 to 8. pH determines the chemical species (and thus potential toxicity) of many elements in water. For instance, aluminium is mobilized following acidification. Changing the pH of water changes the concentration of both H^+ and OH^- ions, which affects the ionic and osmotic balance of aquatic organisms.

Relatively small changes in pH are seldom lethal, although sublethal effects such as reduced growth rates and reduced fecundity may result from the physiological stress placed on the organism by increased energy requirements in acid or alkaline waters. Human-induced acidification of rivers is normally the result of industrial effluents, mine drainage and acid precipitation. Alkaline pollution

is less common but may result from certain industrial effluents and anthropogenic eutrophication.

The effects of altered pH on riverine biotas have been investigated by means of toxicity tests, artificial streams and field studies. Such studies indicate that a change in pH from that normally encountered in unpolluted streams may have severe effects on the biota but that the severity of the effects depends on the magnitude of change. Some streams are naturally far more acidic than others and their biotas are adapted to these conditions. Water quality guidelines require that the Target Water Quality Range for pH be stated in terms of the background site-specific pH regime. Guidelines are thus case- and site-specific and take diel and seasonal variation into account. pH values should not be allowed to vary from the range of the background pH by more than 0.5 of a pH unit, or by more than 5%.

Conductivity, total dissolved solids (TDS) and major ions

Material dissolved in water is commonly measured as total dissolved solids (TDS), as conductivity, or as salinity. TDS represents the total quantity of dissolved material, organic and inorganic, ionised and un-ionised, in a water sample. Conductivity is a measure of the ability of a sample of water to conduct an electrical current. TDS and conductivity usually correlate closely for a particular type of water. Salinity refers to the saltiness of water.

Natural TDS in rivers is determined by geological or atmospheric conditions. Anthropogenic activities such as industrial effluents, irrigation and water re-use lead to increases in TDS.

Very little information is available on the tolerances of freshwater organisms to increased TDS. Generally it is the rate of change rather than the absolute change that is important. Juvenile stages are often more sensitive than adults and effects may be more pronounced in upper mountain streams, where organisms are generally not tolerant of stress. Ions most commonly found in natural waters are the cations calcium, magnesium, sodium and potassium, and the anions bicarbonate, carbonate, chloride and sulphate. Their characteristics and importance with respect to aquatic systems are discussed.

The Target Water Quality Range for TDS is stated in terms of case- and site-specific TDS concentrations, taking into account background concentrations. TDS concentrations should not be changed by more than 15 % from the normal cycles of the water body under unimpacted conditions at any time of the year, and the amplitude and frequency of natural cycles in TDS concentrations should not be changed

Dissolved oxygen

Most aquatic organisms are dependent on water for their survival. The maintenance of adequate dissolved oxygen concentrations is critical for the survival and functioning of aquatic biota. Dissolved oxygen (DO), as mg l^{-1} or percentage saturation, fluctuates diurnally, depending on the relative rates of respiration and photosynthesis of aquatic animals and plants.

Factors causing an increase in DO include atmospheric re-aeration, increasing atmospheric pressure, decreasing temperature and salinity, and photosynthesis by plants. Factors causing a decrease in DO include increasing temperature and salinity, respiration of aquatic organisms, decomposition of organic material by micro-organisms, chemical breakdown of pollutants, re-suspension of anoxic sediments and release of anoxic bottom water. Generally, it is a depletion of DO that is observed in aquatic systems although super-saturation, i.e. in excess of 100%, may occur in eutrophic waters.

The significance to aquatic biota of dissolved oxygen depletion depends on the frequency, timing and duration of such depletion. Continuous exposure to concentrations of less than 80% of saturation is harmful, and is likely to have acute effects, whilst repeated exposure to reduced concentrations may lead to physiological and behavioural stress effects. Generally, if the rate of change is rapid, adverse effects on the biota will increase significantly. The extent to which any organism is affected by a decrease in dissolved oxygen is determined by its dependence on water as a medium. The oxygen requirements of fish and other aquatic organisms vary with type of species (particularly warm- or cold-water species), with life stages (eggs, larvae, nymphs, adults) and with different life processes (feeding, growth, reproduction) and size. If possible, many species will avoid anoxic or oxygen-depleted zones. Juvenile life stages of many aquatic organisms are more sensitive than adults to physiological stress arising from oxygen depletion, and in particular to secondary effects such as increased vulnerability to predation and disease. Prolonged exposure to sublethal, low oxygen concentrations may lead to changes in behaviour, blood chemistry, growth rate and food intake.

Many toxic constituents such as ammonia, cadmium, cyanide, zinc, etc, become increasingly toxic as DO concentrations are reduced. Current standards in South Africa use chronic and acute physiological effects on aquatic biota for assessing the effect of dissolved oxygen depletion on aquatic ecosystems. Criteria based on a Target Water Quality Range and Minimal Allowable Concentration use percentage saturation levels for protection of aquatic biota. Site-specific modifications are applied if local conditions require that control be more or less stringent.

Organic enrichment

Dissolved and particulate organic matter is naturally present in aquatic ecosystems. Anthropogenically-derived organic discharges, which originate from or are produced by living organisms, may result in organic enrichment of the receiving water body. Major sources of organic enrichment include domestic sewage, food processing plants, breweries and vegetable canning, animal feedlots, abattoirs and cattle grazing. Of these, enrichment by organic matter from sewage and sewage effluents is probably the most common and extensively documented type of pollution in rivers. Most organic material in sewage is not directly toxic to aquatic organisms.

The major effects of organic enrichment are a decrease in dissolved oxygen concentrations, an increase in turbidity and the concentration of suspended solids, an increase in nutrient concentrations and possible bacterial contamination of the receiving water body. Of these, reduced oxygen concentration, measured as Biological Oxygen Demand (BOD), is considered to have the most severe impact on aquatic biota. In fact, organic waste is commonly referred to as 'oxygen-demanding waste'. Aquatic assemblages typically respond to organic enrichment through changes in species composition, increased densities of taxa tolerant to enrichment, and decreased densities or elimination of taxa sensitive to enrichment. Characteristic chemical and physical changes occur below the point of organic effluent input, together with changes in micro-organisms and macroinvertebrates.

Both the duration and extent of the discharge (continuous versus episodic) and the river zone in which the enrichment occurs, influences the effect of the enrichment on the aquatic biota. Indicator species or taxa have been identified for most groups of organisms including bacteria, fungi, algae, protozoans and macroinvertebrates. Of these, macroinvertebrates are considered to be the best documented and understood indicators of organic enrichment.

Nutrient enrichment

Various plant nutrients are required for normal plant growth and reproduction. It is nitrogen and phosphorus, however, which are most commonly implicated in excessive plant growth resulting from nutrient enrichment (eutrophication) of aquatic systems. Most nutrients are not toxic (exceptions include nitrite and ammonia), even in high concentrations, but when present in aquatic systems in these high concentrations, they may have a significant impact on the structure and functioning of biotic communities.

Climatic and catchment characteristics influence initial nutrient concentrations in rivers. Anthropogenic sources of nutrients may be of the point-source type (e.g. sewage treatment works, industry, intensive animal enterprises) or nonpoint-source (e.g. agricultural runoff, urban runoff, atmospheric deposition) or urban runoff. Agricultural activities such as land clearing and fertilizer application are considered significant contributors to eutrophication of aquatic ecosystems.

On entering an aquatic system, phosphorus is dissolved in the water column (as PO_4^{3-} ion) or adsorbed onto soil and other particles. High concentrations of phosphorus are likely to occur in waters that receive sewage and leaching or runoff from cultivated land.

Nitrogen occurs abundantly in nature and is an essential constituent of many biochemical processes. Inorganic nitrogen may be present in many forms including ammonia (NH_3), ammonium (NH_4^+), nitrites (NO_2^-) and nitrates (NO_3^-). On entering aquatic systems, nitrates are rapidly converted to organic nitrogen in plant cells. Nitrite is an intermediate in the conversion of ammonia to nitrate, and is toxic to aquatic organisms. Un-ionised ammonia (NH_3) is also toxic to aquatic organisms and its toxicity increases as pH and temperature increase.

Several management options are available for reducing the input of nutrients into aquatic ecosystems. Current water quality guidelines are designed to ensure that the trophic status of a water body does not change in a negative direction, e.g. from an oligotrophic to eutrophic state. The ratio of total inorganic phosphorus to total inorganic nitrogen is used to establish trophic status. Site-specific conditions need to be considered when calculating Target Water Quality Ranges. Guidelines for ammonia are given in the form of chronic and acute toxicity values.

Biocides

Biocides are chemicals that kill living organisms. They are used in the control of pests, usually associated with agricultural crops and vector-borne diseases. The most commonly used biocides are herbicides, fungicides and insecticides. Potential sources of biocides in aquatic systems include direct application (for pest control), industrial effluents, sewage, leaching and runoff from soil, and deposition of aerosols and particulates.

Studies have concentrated on biocide residues in the biotic and physical environment, bioaccumulation, determination of tolerance (acute and chronic) limits of aquatic organisms and the effects of biocides on whole communities. The nature, modes of action and toxicity of biocides vary considerably. Generally, organochlorine insecticides (e.g. DDT, dieldrin) are the most hazardous with respect to the natural environment and their use has thus been banned in many countries. These biocides are persistent in the environment, concentrating in organisms and thus through food chains. Methods for the detection and quantification of biocides are complex and expensive. Analyses are complicated by the small quantities of biocides found in water and the variety of breakdown products, with variable toxic properties, of most biocides.

Trace metals

In most natural waters, trace metal concentrations are very low, and thus any increase exposes aquatic organisms to levels not previously encountered. Contamination of water bodies with trace metals is therefore of significance and should be carefully monitored and controlled. Sources of trace metals include geological weathering, atmospheric sources, industrial effluents, agricultural runoff and acid mine drainage.

A number of chemical and physical factors modify the toxicity and uptake of trace metals. These include the chemical species of the metal, the presence of other metals and organic compounds, the volume of the receiving water, substratum type, dissolved oxygen, temperature, hardness, pH, and salinity. Biological factors (e.g. life history stage, age, sex, tolerance levels), influence an organism's susceptibility to pollutants.

The overall ecological consequences of trace metal contamination of aquatic ecosystems is a reduction in species richness and diversity and a change in species composition. The selective elimination of less tolerant species, with the resultant reduction in competition and predation, may result in an increase in the abundance of more tolerant species. The degree of change is related to the concentration of the metal(s) and the type (chronic, acute, constant, intermittent) and timing (in relation to season and thus flow rate) of exposure.

Appendix 2: Biomonitoring in rivers

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This appendix is an edited exerpt from a lecture presented by Dirk Roux on the National Biomonitoring Short Course: Aquatic Biomonitoring in Water Resources Management, 10-14 February 2003

Understanding the Concepts

Aquatic biomonitoring

Measuring only physical and chemical water quality variables cannot provide an accurate account of the overall condition of an aquatic ecosystem. Chemical monitoring alone is insufficient to detect, for example, the cumulative effects on aquatic ecosystems resulting from multiple stressors. Many factors other than chemical water quality have an influence on the ecological state of an ecosystem – examples would be habitat changes, dams or weirs that alter streamflow, water abstraction, and the introduction of exotic species. Effective management of aquatic ecosystems must address all these factors.

A worldwide trend since the 1990s has been the introduction of in-stream biological monitoring to water resources management. This type of monitoring, usually called biomonitoring, is now recognised as an important component in the assessment of water resources. Biomonitoring of fish or invertebrate communities is an integrated and sensitive tool for diagnosing the condition of ecosystems and assessing ecological impacts. Data from biomonitoring can drive and direct the processes of decision-making and management.

Different biomonitoring programmes are developed for different purposes, including

- surveillance of the general ecological state of an aquatic ecosystem
- assessment of an impact (both before and after the impact, or upstream and downstream of the impact) – both diffuse and point-source impacts
- audit of compliance with ecological objectives or regulatory standards
- detection of long-term trends in the environment as a result of any number of perturbations

Stressor and response monitoring

Biomonitoring can be used in two distinct ways, depending whether you are monitoring a *stressor* or monitoring a *response*. A stressor is any physical, chemical or biological entity or process that induces adverse effects on individual organisms, populations, communities or ecosystems.

Stressor monitoring focuses on the stressors that cause pollution and ecological change by linking stressors to biological responses. Predictive ability is, however, only possible where a specific stressor is known to cause a specific biological effect. Such cause-effect relationships can be determined in the laboratory under controlled conditions, but extrapolation to the real environment should be made with caution.

Environmental *response monitoring* focuses on the response of the environment to a disturbance. A disturbance can be defined as any event that disrupts ecosystem, community or population structure. Response monitoring looks at the effects resulting from the disturbance. It is limited in that it tends to say *that* something is wrong rather than *why* something is wrong. To know why, we need to know something of the relevant cause-effect relationship.

Both stressor-oriented and response-oriented approaches have different uses and benefits, so in practice both should be used together. The table below summarises the characteristics of the two approaches.

	Stressor-oriented approach	**Response-oriented approach**
Monitoring focus	Stressors causing environmental change, i.e. mainly chemical and physical inputs to aquatic systems.	Effects resulting from natural or human disturbances, e.g. changes in the structure and function of biological communities.
Management focus	Water quality regulation: Controlling stressors by regulating their sources (end-of-pipe focus).	Aquatic ecosystem protection: Managing the ecological integrity of aquatic ecosystems (ecosystem or resource focus).
Measurement end points	Concentrations of chemical and physical water quality variables, e.g. pH, dissolved oxygen and lead.	Structural and functional attributes of biological communities, e.g. diversity and abundance of fish species.
Assessment end points	Compliance or non-compliance with set criteria or discharge standards.	Degree of deviation from benchmark or desired biological condition.

Ecological integrity

Integrity generally refers to a condition of being unimpaired. *Biological integrity* is defined as the ability of an ecosystem to maintain a community of organisms having a species composition, diversity and functional organisation similar to that of the natural state.

Habitat integrity is defined as the presence of physico-chemical and habitat characteristics similar to that of the natural state. The habitat integrity of a river provides the conditions for a certain level of biological integrity to be realised.

Habitat integrity and biological integrity together constitute *ecological integrity*. For a river, ecological integrity is therefore the ability of the river to support and maintain a balanced, integrated composition of physico-chemical habitat characteristics, as well as biotic components, on a temporal and spatial scale, that is similar to the natural characteristics of ecosystems of the region.

Ecological indicators and indices

Indicators can be used to measure change. Ecological indicators are characteristics of the environment, both biotic and abiotic, that provide quantitative information on the condition of ecological resources. The in-stream biological condition of a river ecosystem can be described by indicators of geomorphological characteristics, hydrological and hydraulic regimes, chemical and physical water quality, riparian vegetation and other factors. Aquatic communities are good indicators of ecological integrity because they integrate and reflect the effects of chemical and physical impacts over extended periods of time.

When designing a monitoring programme, attention should be given to indicators that represent the larger ecosystem and are practical to measure. Indicators will vary depending on the type of aquatic ecosystem being assessed. For example, benthic macroinvertebrates and fish are often used to assess flowing waters, plants are used for wetlands, and algae and zooplankton for lakes and estuaries. The design of a biomonitoring programme should be tailored depending on whether a wetland, lake, stream, river or estuary is being assessed.

The focus on biological indicators and biomonitoring does not mean that other ecological indicators should be ignored. Information derived from non-biological indicators usually supports interpretation of biological results. Protecting ecological integrity requires the monitoring and protection of physical and chemical habitats. For this purpose, qualitative and quantitative information on habitat characteristics is required.

Ecological indices allow us to summarise complex ecological data. Appropriate indicators, for example selected fish community characteristics, need to be tested and justified, and linked to measurements that can be used to describe ecological condition.

Reference conditions

Ecosystems are naturally dynamic, and their evolutionary histories and capabilities are never static in either structure or function. Hydrological regimes include variability on many time scales, not only the normal range of conditions at a site, but also the extremes of floods and other infrequent events. From an ecological point of view there is nothing abnormal about these extremes, they are a natural and often crucial part of ecosystem dynamics.

The challenge of interpreting the results from an ecosystem-monitoring programme lies in distinguishing between natural and unnatural changes. Resource managers need to know if an ecosystem is responding in some way that is outside its natural range of variation. This would allow remedial steps to be taken before such change becomes permanent.

One way of distinguishing between natural and unnatural changes is to establish a 'natural' benchmark or reference condition with which similar monitoring sites can be compared. This requires a procedure for comparing the state of an ecosystem with a reference condition. Both the state of the assessed ecosystem and the reference conditions have to be made explicit.

Reference conditions and Ecoregions

In South Africa, establishing reference conditions is complicated by a large range of ecosystem types. The variability among natural surface waters, resulting from vast climatic, landform, land cover (vegetation), soil type and other geographic differences, favours the use of area-specific rather than national reference conditions. Such reference conditions should describe, within the relevant geographic area, the characteristics of those river segments which are least impaired by human activities. Area-specific reference conditions allow environmental conditions at any assessment site to be compared with conditions expected in undisturbed streams or rivers of similar size and habitat type located in the same area.

As completely undisturbed environments are virtually nonexistent, and even remote waters are impacted by factors such as atmospheric pollution, some countries (for example the USA) use 'minimally impacted' sites to define the 'best attainable reference condition'. Difficulties arise in areas where the best sites are already considerably modified. In such cases expert knowledge and extrapolation techniques may be required to construct a hypothetical 'best attainable' condition.

River Health Classification

Once appropriate reference conditions have been set for a particular area, standardised measurements of ecological integrity can be used for the site being assessed and the data compared against these reference conditions. On a calibrated scale of river health, the reference condition represents the top end and an almost sterile system the lowest possible state. An area-specific calibration of ecological state of any site in the area can then be made, rating the site anywhere between the reference condition and the lowest possible state.

In South Africa a river health classification scheme is used to standardise the output of different indices as well as to allow comparison of the health of different river systems. Each index is calibrated so that its results can be expressed as a river health class. River health classes can be expressed in terms of ecological and management perspectives, as shown in the table following:

River Health Class	Ecological perspective	Management perspective
Excellent	No or negligible modification of instream and riparian habitats and biota	Protected rivers; relatively untouched by human hands; no discharges or impoundments allowed
Good	Ecosystems essentially in good state; biodiversity largely intact	Some human-related disturbance but mostly of low impact potential
Fair	Sensitive species may be lost; lower abundances of biological populations are likely to occur; or sometimes, higher abundances of tolerant or opportunistic species occur	Multiple disturbances associated with need for socio-economic development, e.g. impoundment, habitat modification and water quality degradation
Poor	Habitat diversity and availability have declined; mostly only tolerant species present; species present are often diseased; population dynamics have been disrupted (e.g. biota can no longer breed or alien species have invaded the ecosystem)	Often characterised by high human densities or extensive resource exploitation. Management intervention is needed to improve river health – e.g. to restore flow patterns, river habitats or water quality

The National River Health Programme (RHP)

The Department of Water Affairs and Forestry initiated the design and implementation of the River Health Programme (RHP) in 1994. The programme was designed to expand the ecological information available for managing rivers in South Africa. It provides a systematic framework for quality controlled collection and assessment of river health data, and for reporting on the results.

A phased approach was used for the design and implementation of the RHP with the following key objectives:

- measure, assess and report on the ecological state of the main rivers of South Africa (published as State of River reporting; SOR)
- identify areas of sustainable water use and areas of unacceptable ecological deterioration
- develop the information base to support scientifically and ecologically sound decision-making regarding the utilisation of the country's river systems
- educate the public at large regarding the health of the country's rivers

RHP site selection

The RHP is designed to allow comparison between reference and monitoring sites. *Reference sites* are relatively unimpacted sites that can be used to define the best physical habitat, water quality and biological parameters for each kind of river. *Monitoring sites* are sites identified as important in assessing the condition of a river or reach experiencing an impact on water quality or habitat degradation. In the case of SOR reporting, however, monitoring sites are randomly selected impacted or unimpacted sites that reveal the range of conditions in their types of rivers.

Indices used in RHP

Indices that are in use include:

The South African Scoring System (SASS) for aquatic invertebrate fauna:

A variety of invertebrate organisms (snails, crabs, worms, insect larvae and adults, mussels) require specific habitat types and water quality and flow conditions for at least part of their life cycles. Changes in the structure of invertebrate communities are a sign of changes in overall river conditions, because most invertebrate species are fairly short-lived and remain in one area during their aquatic life phase. This makes them particularly good indicators of localised conditions in a river over the short term. The SASS index, based on the presence of families of aquatic invertebrates and their sensitivity to water quality changes, is currently in its fifth stage of development. It has been widely tested and used in South Africa as a biological index of water quality. SASS results are expressed both as an index score (SASS score) and the average score per recorded taxon (ASPT value).

The Fish Assemblage Integrity Index (FAII):

Fish, being relatively long-lived and mobile, are good indicators of long-term influences on a river reach. The numbers of species of fish that occur in a specific reach, as well as factors such as different size classes and the presence of parasites on the fish, can be used as indicators of river health. This index categorises fish communities according to an intolerance rating which takes into account trophic preference and specialisation, requirement for flowing water during different life-stages, and association with habitats with unmodified water quality. Results of the FAII are expressed as a ratio of observed conditions versus conditions that would have been expected in the absence of human impacts. The FAII index has been applied and published, and is being further developed and refined for different parts of South Africa.

The Riparian Vegetation Index (RVI):

Healthy riparian zones (river banks) maintain channel form and serve as filters for light, nutrients and sediment. Changes in the structure and function of riparian vegetation commonly result from changes in the flow regime of a river, exploitation for firewood, or use of the riparian zone for grazing or ploughing. The RVI determines the status of riparian vegetation within river segments based on the qualitative assessment of a number of criteria – vegetation removal, cultivation, construction, inundation, erosion/sedimentation and alien species of vegetation. This is expressed as percentage deviation from natural or unmodified riparian conditions.

The Index of Habitat Integrity (IHI):

Habitat availability and diversity are major determinants of aquatic community structure. Adverse changes in biological communities may be attributed either to deterioration in water quality or to habitat degradation, or both. Loss of habitats is regarded as the single most important factor that has contributed towards the accelerating extinction of species in the last century. Examples of river habitat types are pools, rapids, sandbanks, stones on the riverbed, and vegetation fringing the water's edges. As the availability and diversity of habitats are major determinants of whether a given system is acceptable to a specific suite of biota or not, knowledge of the availability and quality of habitats is very important in an overall assessment of ecosystem health. The IHI has been developed to assess the impact of major disturbances on river reaches. These disturbances include water abstraction, flow regulation, and bed and channel modification. This index accounts for both the condition of the riparian zone and the in-stream habitats.

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Appendix 3: Ecotoxicology

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This appendix is based on a lecture presented by Nikite Muller on the National Biomonitoring Short Course: Aquatic Biomonitoring in Water Resources Management, 10-14 February 2003.

Introduction

Aquatic toxicology is the study of the effects of chemicals, materials and substances (together known as chemical stressors) on aquatic organisms and ecosystems (Rand, 1995). These studies include laboratory-based toxicity tests as well as field-based studies of organisms within ecosystems. Generally *toxicology* refers to laboratory-based tests, while *ecotoxicology* refers to a greater degree of environmental realism where testing is linked to ecosystem structure and function.

Chemical stressors can be single chemicals, complex effluents, any manufactured or natural materials or activities which affect animals, plants and microbes. Toxicity tests are used to assess the effects of exposure to chemical stressors. They involve exposing an organism, or preferably a range of organisms, to a test substance and determining the response.

Although responses of organisms can be either positive or negative, toxicology and ecotoxicology mostly focus on negative responses. Negative effects can occur over exposure periods ranging from hours to months. Responses can range from sub-organisms (such as production of enzymes), through organisms (death, changes in behaviour, growth) to changes in communities (such as the disappearance of a particular species).

The goals and uses of toxicology and ecotoxicology include:

- identification of chemical stressors
- prediction of the chemical concentrations when negative impacts occur
- development of water quality criteria

Water Quality Criteria - Water quality criteria can be expressed either as chemical concentrations derived from toxicity tests or more directly as toxicity units. These criteria can be used in both RDM and SDC.

Toxicity-based criteria - The Water Quality Guidelines for Aquatic Ecosystems (DWAF,1996) are an example of toxicity-based, chemical concentration criteria. The Guidelines give concentration ranges for each toxicant, derived from toxicity test results. Monitoring and auditing are done by chemical analyses.

Toxicity units - Criteria can be specified in toxicity-units instead of concentrations. This is particularly suitable for complex mixtures. Monitoring and auditing are done by ongoing toxicity testing.

RDM and SDC - Ecospecs, Resource Quality Objectives (RDM) and/or licence criteria (SDC) can be specified in chemical concentrations or toxicity units.

Aquatic toxicology is a multi-disciplinary science focusing on chemical, physical and biological processes. These processes examine factors which affect environmental concentrations of chemicals and determine how toxic agents act in the environment (as well as the effects of the environment on toxicants). To understand the effects of toxicants and estimate their effects on aquatic biota, researchers have to use a combination of aquatic ecology, physiology, biochemistry, histology, behaviour and environmental chemistry.

Toxicity tests can be acute (short term tests, up to 96 hours in duration) or chronic (longer terms test for 10 days or more). Acute tests usually use mortality as the end point. Chronic tests usually use sub-lethal end-points such as changes in growth, reproduction or behaviour. Acute tests provide rapid and reliable methods for screening chemicals with unknown toxicity and frequently form the basis for further testing in sub-lethal and chronic toxicity tests. Tests can either be *proactive* (‘will there be an effect?’) or *reactive* (‘has there been an effect?’)

Proactive testing is the use of worst-case testing – using the most sensitive species, most sensitive life-stages, the most severe laboratory exposures – knowing that these are not real case situations. Worst case testing is used to reduce uncertainty, because if there are no effects when testing the most sensitive species, then it is reasonable to conclude that ecosystem effects are unlikely. However if worst case testing produces an effect, this is a warning that a potential problem exists and that something should be done before it becomes critical.

Reactive testing evaluates whether the pollution conditions being tested have the potential to affect organisms in the local ecosystem. This is done by site-specific testing. It is particularly important to select appropriate test species and test end-point effects such as growth or death. In an ideal situation, the organisms that need protecting (the *key taxa*) should be tested. If these species are unaffected by the pollution, we can infer that the structure and function of the ecosystem will also be unaffected. It is important to test a range of organisms, as different organisms have different responses to different contaminants. An organism's sensitivity can also vary during its life and with previous exposure, so comprehensive testing should be undertaken, with a range of species.

The advantages and disadvantages of toxicity tests are highlighted in the table below:

Advantages	Disadvantages
A holistic approach, integrating effects of all stressors (especially useful for investigating whole effluents).	Tests may not indicate which stressors are causing the observed effect.
Tests can be simple and cost-effective.	Tests can be too simple and result in environmentally unsound answers.
The effect on the selected organisms is observed at the exposures tested, allowing a cause-effect relationship to be established.	Not all organisms, exposures and end-points can be tested.
Tests are normally carried out under controlled laboratory conditions.	Field conditions are different from laboratory conditions and extrapolating results from laboratory to field is complex.

Sources of toxicity

Toxicity reflects the potential of a chemical or mixture of chemicals to have a harmful effect on living organisms. This harmful effect can be damaging to the structure and functioning of biological systems and may result in death. Substances that cause these responses are known as toxicants.The toxicity of a substance is a function of its concentration, its chemical properties and how long organisms are exposed to the substance/toxicant.

Toxicants can be introduced into water resources in two ways. *Non-point sources* (also known as diffuse sources) include agricultural runoff, contaminated groundwater, urban/settlement runoff, atmospheric fallout. *Point sources* are localised sources – effluent discharges from industry, hazardous waste sites, municipal sewage treatment works and spills. Unlike non-point sources, their location and quantity can be identified accurately and their quality more easily managed.

Defensibility

Toxicity tests allow for regular, defensible measures of the toxicity of different chemicals/mixtures and the responses (sensitivities) of different species to the same chemical. This is possible because of standardised acute and chronic toxicity tests that use a particular suite of test organisms and ensure that toxicity test results are reliable, replicable and comparable.

Standard toxicity tests

Reliability of the test describes the repeatability of the test – the variability in results obtained from a number of tests performed by the same operator in the same laboratory using the same equipment.

Replicability of the test describes the reproducibility of the test – the variability in results obtained from a number of tests performed by different operators in different laboratories with different equipment.

Comparability results from high reliability and replicability.

Principles of toxicology: the dose-response relationship

There are three main assumptions in toxicology that are fundamental to the understanding, interpretation and application of toxicity data:

- There is a cause-effect relationship: the effect seen in the organism can be attributed, either directly or indirectly, to the toxicant being examined.

- There is a dose-response, or concentration-response, relationship, where:
  - the effect is a result of the toxicant reaching the site of action in the organism
  - the amount of toxicant reaching the action site is a function of the amount of toxicant to which the organism is exposed
  - the size of the effect is proportional to the amount of toxicant reaching the action site

- The effects can be quantified, and are reproducible (hence the development of standardised toxicity tests).

Factors affecting toxicity

There are a number of abiotic and/or biotic factors that affect toxicity:

Exposure: For an effect to take place, sufficient of the chemical must reach an action site within the organism for long enough. This is known as exposure. Exposure is affected by: the kind and

concentration of the toxicant, the duration of exposure, and the route of exposure (such as ingestion or adsorption through body surfaces). Exposure can be either *acute* or *chronic*. Acute exposure is short, with high concentrations of the toxicant, resulting in an immediate effect over a short period of an organism's life cycle. Chronic exposure involves low concentrations over a prolonged period resulting in more subtle effects that manifest themselves over a prolonged period of an organism's life cycle.

Organism response: Species differ in their response to different substances. The accessibility of the toxicant to the organism is influenced by a number of factors: species behaviour (for example, the ability to avoid the toxicant), differences in metabolism and excretion, organism genetics and prior exposure to toxicants (their adaptability), dietary factors (nutritional status and physiological and biochemical functions), age of the organism (young neonates usually being more susceptible) and general health of the organisms.

Chemical: Toxicity of a chemical can be influenced by its composition or structure, and the presence of impurities. Its ability to dissolve in water and adsorb onto other bodies and chemicals present in the water, as well as the pH and temperature of the water, affect toxicity. These factors also affect the persistence of chemicals in the environment, their transformation into breakdown products, their availability to organisms and their fate in the water column.

It is important to consider that in the natural environment, toxicants are seldom present in isolation. Organisms may be exposed to a number of different toxicants simultaneously and the presence of these different toxicants may result in toxicological interactions.

Toxicological interactions between two or more toxicants result in a biological response that is quantitatively or qualitatively different from that expected from the actions of each of the toxicants alone.

Interactions between toxicants can be:

- *additive* - exposure to two or more chemicals results in a response that is the simple additive of the individual responses
- *synergistic* - the combined effect of two chemicals is much greater than the sum of the effects of the individual chemicals
- *antagonistic* - where two chemicals, applied together, interfere with each others' actions
- *potentiation* – where a toxicant only has an effect when applied together with another chemical

Toxicity testing

The objective of a toxicity test is to measure, as accurately as possible, the range of chemical concentrations that produce a selected, readily observable, quantifiable response in groups of the same test species under controlled laboratory or field conditions. The experimental design determines the details of the toxicity test and there are a number of choices which can be made which will be guided by the central question being addressed.

Although there may be differences between individuals in a population, these differences are natural and reflect the genetic make-up of the population as well as any differences in condition between individuals. This variability is an inherent component of any toxicity test. Other factors affecting variability are dependent on toxicity test procedures and can be assessed via intralaboratory and interlaboratory comparisons.

Intralaboratory precision: This reflects the ability of trained people within the same laboratory to obtain consistent results repeatedly using the same test on the same species using the same chemical. This gives a measure of reliability of the toxicity test within that laboratory.

Interlaboratory precision: This reflects the measure of reproducibility of a method when conducted by a number of laboratories using the same method, the same species and the same chemical. This gives a measure of the replicability of the test method, and tests the reliability of the method as well as the people doing the testing.

Intralaboratory results tend to be less variable than interlaboratory tests. This is mostly because within a single laboratory the same people are undertaking the tests and therefore perpetuating the same errors or quirks of undertaking the test. Intra- and inter-laboratory variability are excellent measures of good laboratory practice. Intralaboratory variability provides a good measure of how reliable a laboratory is in performing routine toxicity tests, and is a factor in laboratory accreditation.

Selecting a toxicity test

There are a number of criteria that are used to assess the appropriateness of a toxicity test procedure. A selected test should be:

- standardised, have a clear protocol, a sound statistical basis, and be widely accepted by the scientific community
- repeatable – it must be possible to obtain similar results, within boundaries of specified variability, whenever the test is undertaken
- of realistic duration, both for the test organism and for the concentration range selected
- sensitive and realistic in design to detect and measure effects
- planned with a minimum of 6 concentrations (including the control), in order to obtain proper regression predictions
- as predictive as possible of field conditions
- cost-effective.

The appropriateness of a toxicity test may be especially important for compliance monitoring. For example, industries undertaking routine toxicity tests of their effluent need to know whether they will pass or fail tests because of their effluent rather than because of flaws in the method.

Extrapolating to field conditions
Some studies show that laboratory results can reasonably be extrapolated to field conditions, while others indicate that laboratory tests may be overprotective. Broadly, the closer the experimental conditions are to field conditions, the more likely the results are to apply. For example receiving water can be used as the test medium, indigenous organisms can be used as test organisms, and whole effluents can be used instead of testing component chemicals. Variability and test-cost increases with closer approximation to the field condition, and so does the variability of the results. Appropriate test selection depends on the application of the results.DWAF has a policy for the assessment of complex industrial effluents called DEEEP (Direct Estimation of Ecological Effect Potential). The DEEEP approach is based on applying a sequence of toxicity test procedures, starting with the cheapest, simplest and most protective, through tests including aspects of 'reality', leading up to a detailed environmental risk assessment. In line with the 'polluter pays' principle, the water user can choose to reduce effluent toxicity and therefore the complexity and cost of compliance monitoring, or can discharge a more toxic waste which has been more rigorously tested.

The decision about which toxicity test to use will be determined by the purpose of the test. For example, the experimental design for answering whether an industry effluent discharge meets with its discharge compliance licence will be quite different to establishing the toxicity of a new chemical to the aquatic environment, or assessing the suitability of a new toxicity test species as an appropriate test organism. Each test will have advantages and disadvantages.

Statistical considerations
The statistical approach to analysing the data will influence the number of concentrations necessary for a toxicity test. Once the minimum number of concentrations has been identified, other factors can influence the inclusion of additional concentrations: laboratory space, number of organisms and number of people who can help run the toxicity test. A toxicity test requires a range of exposure concentrations that typically increase in strength. Organisms can be exposed in fewer, replicated, concentrations, or else with increased number of concentrations but no replicates of each concentration.

The replicated design is mainly used to assess tolerance variability within the test population. The regression design is more common and is used to provide the most accurate estimate of specified levels of response, for example estimating the LC50 (the concentration at which 50% of the test population is expected to die).

Control exposure
Different control treatments can be used in toxicity tests, depending on the test substance, and also the question being addressed. It is important to establish which control is to be used before embarking on the toxicity test.

Negative control: This is an untreated control, exposing test organisms in the same dilution water as the remainder of the test concentrations. This is done to ensure that the test organisms are not responding to something in the dilution water. It provides the baseline for the test and a point of correction for interpreting the test results. It is used to assess the inherent background effects of the test, such as laboratory conditions, health of organisms and quality of the diluent used.

Positive control: This is also known as a reference control. It is a control which contains a chemical to which the response of the test organism is known and defined. This control is used to ensure that the test organisms are responding in a typical manner, allowing the researcher to detect any changes in the test population, particularly with regard to any changes in sensitivity. This type of control is frequently used to test the reproducibility of toxicity test data, assess precision of test data, perform interlaboratory calibrations, compare relative toxicities of different substances, and determine health and sensitivity of test organisms. A negative control will still need to be included as part of the toxicity test.

Test solvent control: This is also known as vehicle control and is only used if the chemical tested required a solvent in order to dilute it first. It is used to check whether the organisms are responding to the solvent or in fact to the chemical being tested. It needs to be used in conjunction with a negative or positive control. The maximum solvent is added to the diluent water, and provides a baseline for the test. Ideally the solvent should not have an effect on the test organisms.

Experimental endpoints

Test endpoints may be lethal (death) or sublethal. Sublethal endpoints could be reproductive output; change in growth rate or organism size; production of stress proteins or other biomarkers; changes in physiology such as increased heartbeat or altered blood physiology; changes in behaviour; accumulation of compounds in various tissues such as the liver or fat-bodies; changes in

morphology; and the development of abnormal growths or cancers. Lethal endpoints are usually used in acute tests, and sub-lethal endpoints for chronic tests. Lethal endpoints are expressed as LC (lethal concentration) or EC (effect concentration) values. EC is sometimes used because immobility is used as a surrogate for death, and it is not always possible to identify the difference between a dead and an immobile organisms. Sublethal measures may be expressed as NOEC, (no observed effects concentration) or LOEC (lowest observed effects concentration) values.

Test organisms

It is important to select appropriate test organisms in suitable test systems in order to obtain meaningful, relevant and ecologically significant results. Test organisms can be either s*tandard laboratory-reared organisms* or *site-specific, wild-caught organisms* (indigenous) (Scherman and Palmer 2000). It is important to consider the ethics of using animals in experiments.

Desirable characteristics of test organisms are:

- species representing a broad range of sensitivities
- widely available and abundant species
- species that are representative of the receiving ecosystem
- recreationally, commercially or ecologically important species
- species which can withstand handling under laboratory conditions
- species which can be cultured under laboratory conditions
- species for which there is some existing biological information

It may be necessary to conduct tests with several species from different taxonomic groupings and different levels in the food chain in order to obtain information on the natural variability in response to the test substance.

Test systems
Organisms can be exposed to the selected toxicant in one of four systems, each with advantages and disadvantages.

Static test: Test organisms are exposed in still or standing water; the toxicant is added to the diluent (dilution medium), placed in the test chamber (size can vary) and the test organisms are added to the toxicant. There is no change of water for the duration of the test, the test organisms are not fed and the test solution is not aerated; as a result, these tests tend to be of short duration.

Recirculating test: The organisms are exposed to the toxicant in a chamber in which the test solution is pumped through a filter which does not reduce the toxicity of the toxicant but maintains the levels of oxygen and nutrients.

Renewal test: The test solution and control water are replaced at intervals. This can be applied to both static and recirculating tests, and is usually applied to chronic, sub-lethal test exposures to prevent the build-up of potentially toxic metabolic products.

Flow-through test: In these systems the test solution passes through the chambers in which the test organisms are kept only once: this flow-through can be either continuous or intermittent (to simulate a pulsed dosing of an effluent discharge). The test solution can be either prepared once at the beginning of the test, or fresh solutions can be prepared as required. This usually depends on the toxicant – a highly volatile toxicant will obviously have to be prepared more frequently.

Static tests are the least complicated, usually the cheapest, and require the least volume of test solution (an advantage for waste disposal). However, they do have drawbacks:

- The test toxicant may become degraded, volatilise, or absorb onto the test chamber so the test solution concentration decreases through the duration of the test.
- If the test toxicant has a high oxygen demand, oxygen will be depleted from the solution rapidly and organisms may respond to the oxygen deficiency rather than the toxicant.
- Build-up of metabolic products may interfere or react with the toxicant.

- ***Test diluent***

There are various sources of diluent: reconstituted laboratory water, dechlorinated tap water, site-specific water from a reference site. There are a number of criteria for assessing the suitability of a diluent, namely whether it is adequately available, acceptable to the test organisms, or of uniform quality.

- ***Types of toxicity tests***

Toxicity tests are categorized according to their length of exposure, the test situation and the effects to be measured. These tests may have different test endpoints, and different exposure periods, depending on the selected test organism. The statistical approach differs for the different test types.

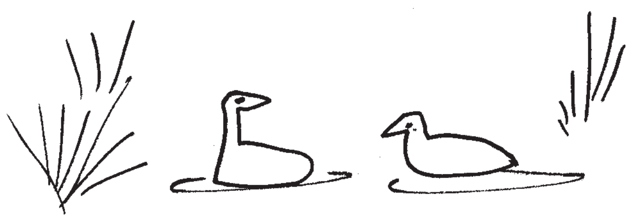
Acute toxicity tests are used to evaluate the effects, measured as mortality, immobility or growth (in algae) of short-term exposure to a chemical for a predetermined time period, usually 48 hours or 96 hours. If the acute toxicity test is allowed to continue until equilibrium is reached (no more mortality), then the test is known as a *time-independent test*.

Chronic toxicity tests allow the long-term evaluation of sublethal concentrations of chemicals. In full chronic toxicity tests, the organism is exposed for its full life-cycle (either from egg to egg, or from adult to adult and egg). Partial life cycle toxicity tests involve sensitive life-stages such as the reproductive and growth phases.

Short-term sublethal tests are often misleadingly referred to as chronic tests, but they are of much shorter duration than chronic tests and focus on the most sensitive life stages of the test organisms.

Early life stage tests are a variation of chronic and short-term sublethal tests in that they only test the early life stages of selected organisms. Usually only the egg, larvae, embryo or fry stages are exposed.

Bioaccumulation tests measure toxicants that are stored in body tissues such as fat or the liver. Bioconcentration is the process through which organisms accumulate chemicals in their tissues through gills or epithelial tissues. Bioaccumulation includes bioconcentration, but also refers to accumulation through food. Biomagnification is the total process, including bioconcentration and bioaccumulation, through which chemicals increase in concentration in organism tissues as they pass through several trophic levels.



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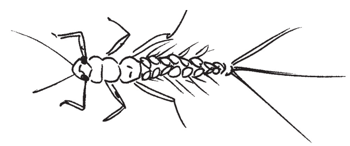

Acronyms and Glossary

abiotic not pertaining to living organisms: environmental features like temperature, rainfall, etc.

abundance the number of organisms in a population, combining 'intensity' (density within inhabited areas) and 'prevalence' (number and size of inhabited areas)

acclimation the process whereby an organism becomes accustomed to artificially imposed conditions

acute having a sudden onset, lasting a short time

acute toxicity test short-term toxicity test of 4 days or less: mortality is the response measured

adaptation a characteristic of a living organism that contributes to its ability to survive in its particular way of life: also the evolutionary process of aquiring adaptations

antagonism a phenomenon in which the toxicity of a mixture of chemicals is less than that which would be expected from a simple summation of the toxicities of the individual chemicals present in the mixture

anthropogenic caused by human activity

aquatic relating to water

ASPT *see average score per taxon*

assimilative capacity the capacity of a water body to accommodate, through processes such as dilution, dispersion and chemical and biological degradation, a quantity of substances without causing any known impairment of use

average score per taxon (ASPT) SASS score divided by the number of taxa

bilharzia a human parasitic disease caused by a small fluke whose intermediate host is one of a number of species of freshwater snail

bioaccumulation accumulation of any material within the body of a living organism

bioavailability the extent to which a particular constituent is available in the biota

biochemistry the scientific study of the chemistry of living cells, tissues, organs and organisms

bioconcentration the phenomenon whereby a chemical substance accumulates in an organism by direct contact with the surrounding medium

biodiversity the diversity of life from a taxonomic, ecological or genetic point of view

biology the scientific study of living organisms

biomagnification the phenomenon whereby a chemical substance accumulates in an organism through different trophic levels in the food chain

biomarker the use of physiological, biochemical, and histological changes as indicators of exposure

biomonitoring monitoring of living organisms, usually as indicators of habitat integrity

biota the living organisms of a region or system

biotic pertaining to living organisms (as opposed to abiotic)

biotope an area of uniform environmental conditions

catchment the land area from which a river or reservoir is fed; a drainage basin (known as 'watershed' in American usage)

cause-effect relationship the effect or response in question is clearly a direct or indirect result of the exposure of the organism(s) to the toxic agent(s) being examined

cholera an acute intestinal infection caused by ingestion of contaminated water or food

chronic effect long-term response

chronic toxicity test involves a stimulus that is lingering or continues for a long period i.e. from several weeks or month to years, depending on the life cycle of the organism

colloid in non-crystalline solid state

CMA Catchment Management Agency

concentration-response curve a curve describing the relationship between different exposure concentrations of a material and percentage response of the exposed test population

contaminant a foreign agent that is present (e.g. in water, sediment) which may produce a physical or chemical change but may not cause adverse biological effect

control a treatment in a toxicity test that duplicates all the conditions of the exposure treatments but contains no test material. The control is used to determine the absence of toxicity of basic test conditions

Crustacea crabs, prawns, amphipods

dilution water (diluent) water used to dilute the test material in an aquatic toxicity test in order to prepare either different concentrations of a test chemical or different percentages of an effluent for the various test treatments

dose-response curve similar to concentration-response curve except that the exposure dose (the quantity) of the chemical administered (e.g., by injection) to the organism is known

DWAF Department of Water Affairs and Forestry, South Africa

EC *see electrical conductivity*

ecological risk assessment the process of identifying and quantifying risks to nonhuman biota and determining the acceptability of those risks

ecology the study of the interrelationships between organisms and their environments

ecospecs ecological specifications

ecosystem / ecological health a descriptive non-specific term for the combination of all factors, biotic and abiotic, that make up a particular environment and its organisms

ecotoxicology the scientific study of harmful effects caused by man-made chemicals to the natural environment, especially effects on populations, communities, and ecosystems; an essential part of ecotoxicology is the study of the movement of potentially toxic substances through food webs and through the water cycle

effluent that which flows out (usually discharge waste water)

electrical conductivity (EC) the measure of electrical current conducted which depends on the ions in solution, and is also therefore a measure of the total quantity of salts dissolved in a sample of water

end-point the adverse biological response that is measured, and used as criteria for effects

environment all the physical, chemical and biological factors and conditions that influence an object

EWQ environmental water quality

enzyme a protein that acts as a biological catalyst

equilibrium in a thermodynamic sense, an indication that both a steady state of flux and an equivalence in chemical activity have been reached in compartments or phases separated by a membrane or boundary across which the chemical fluxes occur.

erosion the weathering and denuding action of wind, water, ice, etc.

eutrophication the process whereby high levels of nutrients result in the excessive growth of plants

fauna collective term for the animals living in a particular area or period

fitness the contribution made to a population of descendants by an individual relative to the contribution made by others in its present population

flow-through system an exposure system for aquatic toxicity tests in which the test material solutions and control water flow into and out of test chambers on a once-through basis either intermittently or continuously

genetic the branch of biology that studies heredity and variation in organisms

geomorphology the branch of science that deals with the external structure (morphology) of the land and the bottom of the sea

habitat the combination of biotopes that makes up the living space of an organism

hazard a state that may result in an undesired event, the cause of risk. In ecotoxicology: the potential for exposure of organisms to chemicals at potentially toxic concentrations constitutes the hazard

hazard assessment determination of the existence of a hazard

herbicides chemicals used for killing plants

histology the branch of biology that studies the microscopic structure of animal and plant tissues

hydrology the branch of science that deals with the properties, distribution and circulation of water on earth

immobility the quality of not moving; remaining in place

indigenous living or growing naturally in a particular area, but not naturally confined only to that area

in situ performing experiments or tests with intact tissues

invertebrate animal without a backbone

IWRM Integrated Water Resource Management

LC lethal concentration

lethal causing death by direct action

Lowest Observed Effect Concentration (LOEC) the lowest concentration of a material used in a toxicity test that has a statistically significant adverse effect on the exposed population of test organisms compared with the controls

malaria disease caused by parasites that are transmitted through the bite of an infected *Anopheles* mosquito; marked by paroxysms of chills and fever

mesocosm artificial, experimental stream or lake, or an artificially closed part of a stream, lake or the sea

microcosm usually a laboratory-based experimental system mimicking a part of the natural environment

morphology structure (usually of n organism)

mortality death-rate

National Water Act (NWA) the 1998 legislation relating to the management and use of South Africa's waters

nature conservation the preservation and careful management of the environment and of natural resources

negative control untreated water control, consisting of a group of organisms with the same dilution water and the same conditions and procedures

NGO non-governmental organisation

no observed effect concentration (NOEC) the highest concentration of a material in a toxicity test that has no statistically significant adverse effect on the exposed population of test organisms compared with the controls

non-point source diffuse area from which pollutants leak, usually into aquatic systems

nutrients elements required for life processes: nitrogen, phosphorus and potassium are probably the most important nutrients

NWA *see National Water Act*

NWRS National Water Resource Strategy

organic containing carbon and relating to, or derived from, living organisms

organism a living thing

pathogens a microorganism or virus that causes disease

PES present ecological state

pesticides a chemical used for killing pests

pH a measure of activity or hydrogen ion activity in a solution

physiology study of the internal processes and activities of organisms

point source a single identifiable point at which an effluent enters a water body

pollutant a harmful material that makes an environment less fit for the organisms to occupy it

pollution the degradation of natural systems by the addition of harmful substances

population a group of individuals of the same species living in the same area, interacting and interbreeding

positive control a material known from previous experience to produce a defined effect on the test organism

predation the consumption of one organism, in whole or in part, by another, where the consumed organism is alive when the consumer first attacks it

rain gauge an instrument to measure the quantity of rain

RDM Resource Directed Measures

receiving waters waters receiving effluents

regression analysis method helpful in ascertaining the probable form of the relationship between variables, its objective usually to predict or estimate the value of one variable corresponding to a given value of another variable

RHP River Health Programme

riparian pertaining to a river bank

risk the probability of a prescribed undesired effect

RQO Resource Quality Objective

runoff rainfall that runs over the surface of the ground rather than filtering into it

salinity saltiness: the mass of dissolved inorganic solids in a kilogram of water

salt in common language, sodium chloride, but also any chemical that dissociates into ions in solution

SASS score sum of the number of families (taxa) present at each sampling site against each taxon present

SDC Source Directed Control

sedentary attached or not moving

sediment fragmentary material (sand, silt, mud, etc.) weathered from rocks and (recently) deposited

sedimentation the process whereby sediments are deposited

sewage waste material carried by sewerage systems (pipes) to waste-water treatment plants

South African Scoring System (SASS) a system for the rapid bioassessment of water quality of rivers using invertebrates

sterilising the procedure of making some object free of live bacteria or other organisms, usually by heat or chemical means

STW Sewage Treatment works

sub-lethal below the concentration that directly causes death: producing less obvious effects on behaviour, biochemistry and/or physiological function

substrate stationary surface upon which other things can attach, for example cells in culture on a plastic or glass substrate, or invertebrate larvae settling on a patch of bare rock (a hard substrate), or worms burrowing into mud or other sediment (a soft substrate)

synergism when the effect of two substances given together is greater than the sum of their individual effects

taxonomy the science of classification of living organisms

TDS total dissolved solids

TIN total inorganic nitrogen

tolerance the ability of an organism to withstand the adverse effects of pollution

total suspended solids (TSS) a measure of all particulate material in a sample of water

toxicant an agent or material capable of producing an adverse response in a biological system, seriously injuring structure and/or function or producing death

toxicity test the means by which the toxicity of a chemical or other test material is determined. A toxicity test is used to measure the degree of response produced by exposure to a specific level of stimulus (or concentration of chemical)

TP total phosphorous

TSS see total suspended solids

unequivocal endpoint unmistakable endpoint, e.g. mortality: the organism is dead or not

userspecs user specifications : objectives for water quality that will meet the needs of different users

water quality the value or usefulness of water, determined by the combined effects of its physical attributes and its chemical constituents, and varying from user to user

wetlands an area of soils that are periodically or permanently waterlogged: usually dominated by emergent vegetation

WMA Water Management Area

WRC Water Research Commission

WUA Water User Association

xenobiotic a foreign chemical or material usually not produced in nature and not normally considered a constitutive component of a specified biological system

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