THE DEVELOPMENT AND APPLICATION OF ECOLOGICAL RISK ASSESSMENT IN SOUTH AFRICAN WATER RESOURCE MANAGEMENT

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by

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Abstract

The provision of goods and services by aquatic ecosystems plays an important role in socio-economic development and livelihoods in the southern African region. Water resource management in South Africa developed from an agrarian and pastoral focus up to 1956 to also supporting mining and industrial activities. This led to the introduction of the resource water quality objectives and pollution prevention approaches, which balanced the needs for development and protection. Prior to 1994, access to water resources was limited to riparian property owners and a minority of the population who controlled industrial and mining activities. The establishment of a democratic government amplified the need for accelerated socio-economic development, with equity, efficiency and sustainability being the principles of such development. New approaches were needed, which could achieve these development objectives and secure the resource base for future generations.

An overview of the scientific process highlighted a risk based approach as potentially supporting the much needed balance between development and protection. The aims of this thesis is to develop a framework and process for the application of ecological risk assessment to water resource management in South Africa, to use case studies to draft guidelines for ecological risk assessment and to assess the degree to which ecological risk assessment can contribute to effective water resource management in South Africa.

The United States Environmental Protection Agency's guidelines for ecological risk assessment were identified amongst international best practice as meeting the requirements for local application. A framework was drafted for ecological risk assessment in South Africa, with the main phases being to agree on objectives, formulate the analysis plan, analyse information, characterise risk and manage risk. Modifications from the Environmental Protection Agency's process include the order of activities in the first phase, the explicit testing of hypotheses and clarification of the evaluation of existing data or collection of new data.

An industrial effluent case study was used to assess the applicability of the proposed framework. The case study dealt specifically with the assessment of risks posed by current conditions and long term licence conditions. The framework was found to be useful to identify weaknesses in the established monitoring programme and to evaluate lines of evidence to assess the degree to which the stated conditions would have unacceptable

consequences. The study highlighted several weaknesses in the suggested framework, of which the most critical is the interpretation of the risk hypothesis as a testable null hypothesis. It became clear that cause-effect relationships should be stated as the risk hypothesis, whereas the assessment should evaluate expressed or expected conditions against a risk profile for a given stressor to benefit fully from the risk assessment approach. Changes to the framework terminology were suggested as well as nested feedback loops to allow for iterative processes where new information becomes available.

The proposed guidelines incorporate the learning from the case study application as well as feedback from a peer review process. The guidelines incorporate the suggested actions under each phase as well as notes providing the rationale for each step. Three case study outlines were provided to assist users with the interpretation of the guidelines in different applications.

The proposed guidelines are applied in an ecological Reserve determination case study, which specified the ecological water quality requirements. The study found that a risk-based approach was followed in the development of the water resource management policy, but the Reserve determination method is generally hazard based, with site specific modifications of the target values being allowed on a conservative basis. The case study highlighted a lack of readiness of water resource managers to accommodate scientific results expressed as probability distributions in support of management decisions.

The thesis is concluded with a discussion of the key learning points of the ecological risk assessment development process. The evaluation highlights the move from stating and testing a null hypothesis to stating the risk hypothesis and evaluating the stated conditions against a risk profile. Several implementation challenges are highlighted, with specific recommendations made for adopting the proposed guidelines.

Declaration

In accordance with the regulations for the award of the degree of Doctor of Philosophy, I declare that the work presented in this thesis is my own original research. I conducted the work in Chapter 1 and 2 as part of CSIR funded research projects. While many people were consulted, all substantial contributions are appropriately referenced. The work presented in Chapter 3 was based on an ongoing biomonitoring programme, which was funded by AEL. Clean Stream Environmental Services coordinated the monitoring programme, while Ecosun and the CSIR collected much of the raw data and did the laboratory analyses. I completed all data analyses and interpretation. The work presented in Chapter 4 is based on CSIR and WRC funded research projects that I managed and executed. The projects included international study tours and I also organised local workshops. Dr. Murray was contracted to facilitate a process analysis of ERA. The recommendations of the analysis were published and served as an input to this thesis. The work presented in Chapter 5 is entirely my own work, based on water quality and climatologic data, which were sourced from the relevant government departments. Neither the whole, nor any part of the thesis, has been, is being, or will be submitted for a higher degree from any other university.

Several manuscripts arising from the research work have been published.

Claassen M (1999) Ecological Risk Assessment as a framework for Environmental Impact Assessment. In: Water Science and Technology 39: 10-11

Claassen M, Strydom WF, Murray K and Jooste S (2001) Ecological Risk Assessment Guidelines. WRC Report number TT 151/01. pp 21 + xii

Claassen M, Strydom WF, Murray K, Jooste S, Palmer CG (2001) The Development and Application of Guidelines for Ecological Risk Assessment in South Africa. In: Linkov, I., Palma Oliveira, J.M., eds. “Assessment and Management of Environmental Risks”. Kluewer, Amsterdam. pp 440

Claassen M, Wade PW (2001) Ecological Risk Assessment in Water Resource Management. African Journal of Aquatic Science 26 (1)

Jooste S, Claassen M (2001) Rationale for an Ecological Risk Approach for South African Water Resource Management. Water SA 27 (3): 283-292

Murray K, Claassen M (1999) An Interpretation and Evaluation of the US Environmental Protection Agency Ecological Risk Assessment Guidelines. Water SA 25 (4): 513-518

Preface

Dedication

This thesis is dedicated to Liezl, whose unselfish support provided me with the opportunity.

Acknowledgements

Over the years, the ideas, comments and inputs of many people contributed to the content of this thesis. Without repudiating the value of these inputs, the following specific people and organisations are thanked for their roles:

Dr Jane Harris, who introduced us to the concept and supported our pursuit thereof,

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Dr Nikite Muller who contributed to finalising the thesis, and

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1. Water Resource Management

This chapter provides an introduction to ecosystem concepts and expands the concepts in the context of aquatic ecosystems (Figure 1.1). A brief history of water resource management in South Africa is concluded with a description of its current state and key challenges. An overview of the risk assessment paradigm provides the basis for discussing the potential application of the ecological risk assessment to water resource management. An outline of the aims of the thesis concludes the chapter. A draft framework for ecological risk assessment (ERA) in Chapter 2 is applied to a case study in Chapter 3, with the proposed ERA guidelines (Chapter 4) being applied to a Reserve determination case study in Chapter 5. The thesis is concluded with a critical evaluation in chapter 6.

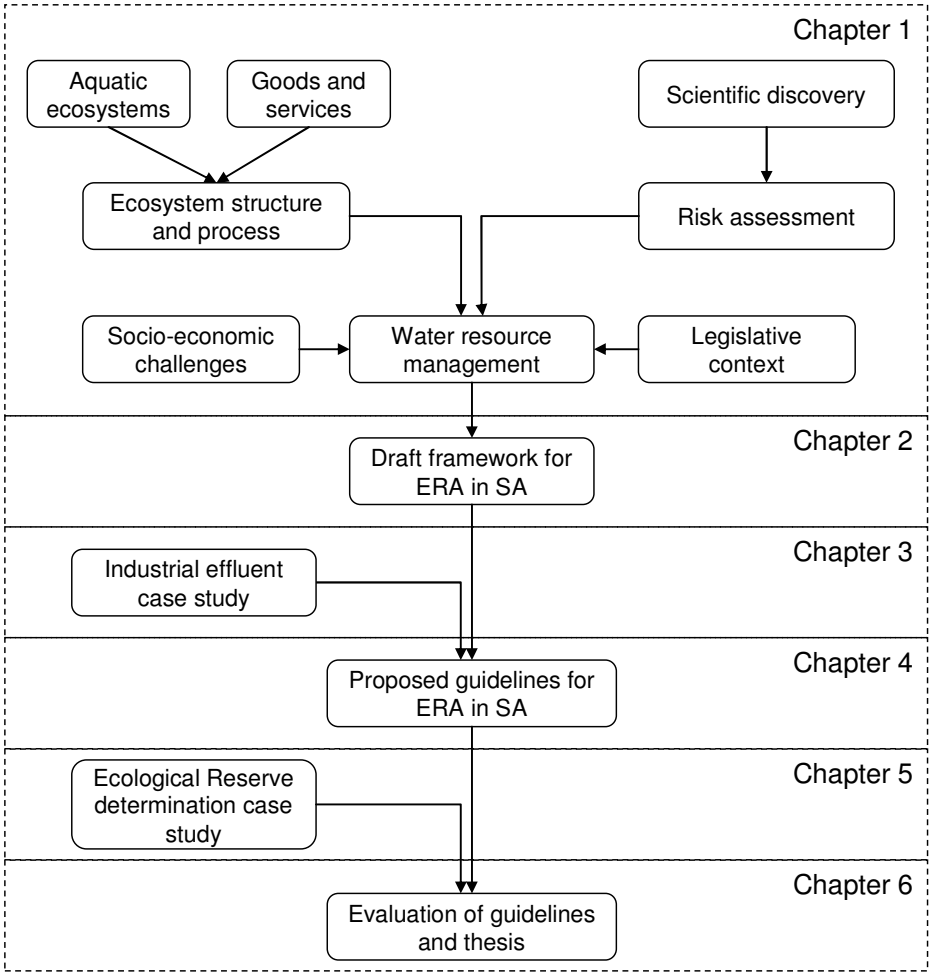


Figure 1.1: The framework of the thesis indicating the main sections and the respective chapters where the sections are discussed.

1.1. Ecosystems

Sustainable utilisation of natural resources requires a balance between meeting the needs of present generations while ensuring sufficient protection to serve the needs of future generations. An important requirement for sustainability is a theoretical understanding of ecosystem structure and function. Such theories, that describe, explain and organise scientific facts, laws and relationships, are the basis for determining adequate protection measures and developing utilisation strategies. A strong theoretical basis helps to achieve a balance between the cost of "knowing everything" and the limitations of partial knowledge by focussing attention on relevant ecological knowledge.

Ecology is defined as the science of the interrelations between living organisms and their environment (Odum, 1971). Ecological units (ecosystems) are made up of biotic and abiotic elements. The abiotic elements, consisting of energy (kinetic, thermal, light and chemical) and material (solids, fluids and gasses), provide the context for living systems. Biotic elements make use of this environment to feed, grow, reproduce, adapt and survive. Important aspects to consider in ecology are the spatial and temporal scales of these processes.

In a quest to make advances in understanding ecosystems, disciplines and sub-disciplines have been identified, all focussing on different levels of organisation (spatial scales) and response times (temporal scales; Figure 1.2; Forman and Godron, 1986). The realisation of the limitations of this approach led to further research, with the aim of bridging the gaps between scales (Pickett, et al. 1994). Landscape ecology was pioneered in response to a need for a wider spatial perspective (Forman and Godron, 1986). In contrast to most ecological studies, which focussed on interactions within homogeneous units, landscape ecology considers interactions within units as well as interactions between units. A landscape is defined as a heterogeneous land area composed of a cluster of interacting ecosystems that is repeated in similar form throughout. Key landscape elements are patches, corridors and matrices (networks), with patches being non-linear surface areas differing in appearance from its surroundings, corridors being routes or boundaries between patches and matrices represent larger areas characterised by connectivity which dominate landscape dynamics (Forman and Godron, 1986). Ecological assessments need to focus on appropriate scales, depending on the

objectives. Measurement and prediction of the response of ecosystems should match the scale of the impact that is being evaluated.

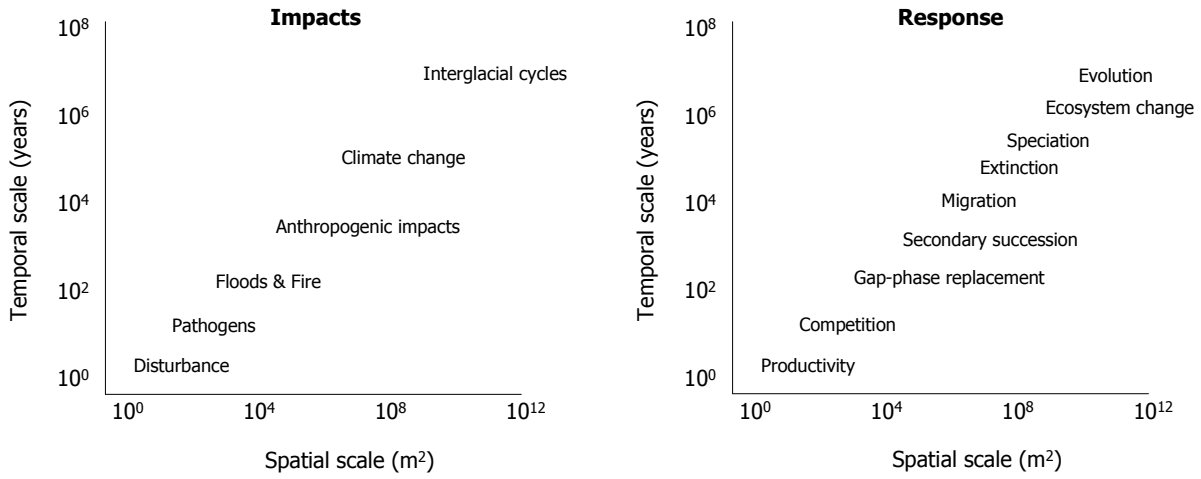


Figure 1.2: Examples of spatial and temporal scales of impacts and ecosystems' response (modified from Forman and Godron, 1986).

As discussed above, landscapes consist of biotic and abiotic elements at different levels of biological organisation, which contribute both individually and cumulatively to the overall landscape. This creates a multivariate environment within a multidimensional context, which has been the motivation for many attempts to model ecosystem dynamics. The application of systems analysis to underpin ecosystem theory followed various approaches, including control -, information -, network -, thermodynamic -, synergetic - and hierarchical theory (Muller, 1997). Each of these approaches has unique characteristics, strengths, weaknesses and potential applications. Recent advances in measuring techniques (physical, chemical and biological) and interpretation techniques (information systems and modelling) further support the application of theoretical approaches. Ulanowicz and Abarca-Arenas (1997) criticised mechanistic views of ecosystems dynamics, stating that probabilistic analyses are better suited to describe directional behaviour. Further problems that are associated with the application of ecosystem theories include the extensive studies required to validate models (which is not always feasible) and non-theoretical approaches, which lead to fragmented and often useless conclusions (Muller, 1997). A key question lies in the philosophical approach to the theoretical models. Although ecological principles are necessary, they are not sufficient to

deal with relationships between humans and their environment. To this end cultural, social and economic aspects also need to be included in analyses.

1.1.1. Aquatic ecosystems

The above overview of ecological concepts stresses the importance of temporal and spatial scales to ecosystem processes and highlights the complexity brought about by the multidimensional, multivariate nature of ecosystems. Focussing more specifically on aquatic ecosystems, it is important to characterise and understand their structure and function.

Ecosystem structure can be described as the spatial relationships, among distinctive ecosystem elements, specifically the distribution of energy, materials and species in relation to size, shapes, numbers, kinds, and configuration of the ecosystems (Odum, 1971). Ecosystem function adds to this by specifying the interactions among spatial elements, specifically the flow of energy, materials and species among the components of ecosystems (Forman and Godron, 1986). The structure of ecosystems depends on the physical template (provided by geomorphological and climatic processes), the chemical signature of the system, and the interrelated biotic elements that are adapted to utilize this environment.

The functioning of aquatic ecosystems is primarily dependent on the water cycle. This cycle (Figure 1.3) determines the spatial and temporal patterns of water availability throughout atmospheric, terrestrial, subterranean and surface water environments. The temporal frequency and patterns of water movement is governed by climatic features (seasonality of precipitation and evaporation) and the physical environment (soil, slope, vegetation, channel shape, etc.). These variables give rise to different types of aquatic systems (Table 1.1).

The temporal and spatial variability of physical attributes such as light, temperature, current, turbidity and suspended solids has significant effects on aquatic ecosystems. The ability of ecosystems to convert light energy to chemical energy (photosynthesis) is largely dependent on a suitable physical habitat for plant communities, access to sufficient light and the availability of chemicals needed for the conversion. Biotic processes are dependent on the

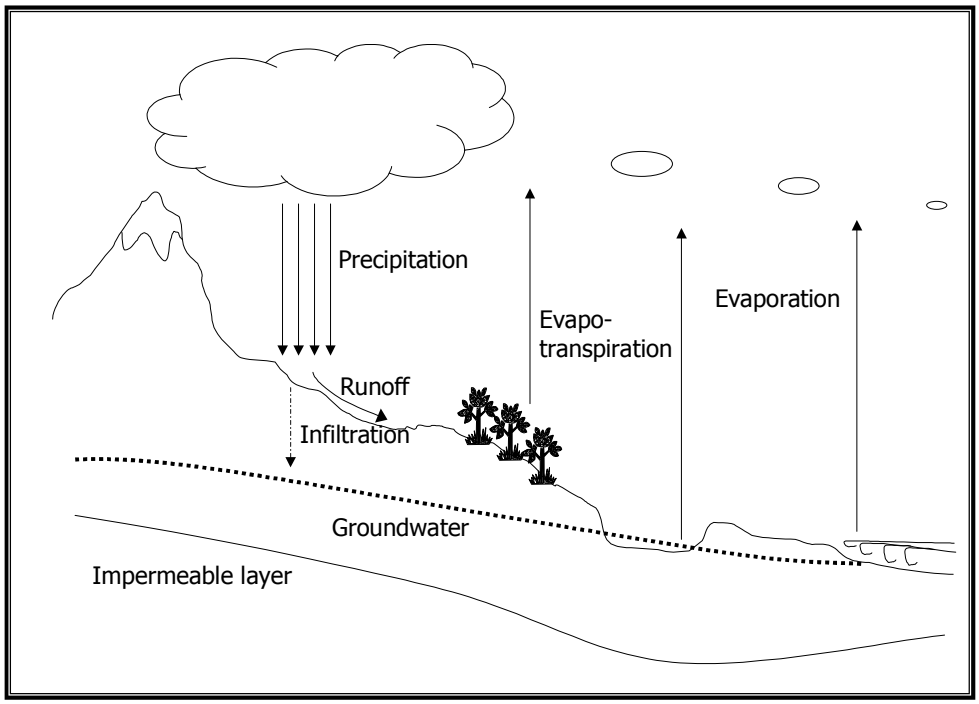


Figure 1.3: The movement of water through the environment, as illustrated by the water cycle.

Table 1.1: Physical and climatic features of inland aquatic ecosystems.

Type of system	**Physical template**	**Key climatic drivers**
Lotic systems (ephemeral or perennial)	Drainage pattern	Seasonal precipitation
Lentic systems (wetlands, lakes and impoundments)	Natural or artificial sinks	Inflow, precipitation, evaporation and evapotranspiration
Aquifers	Subterranean geology	Infiltration, decant and evapotranspiration
Estuaries	Ocean-river interface	Inflow, precipitation, evaporation and tides

fixation of light energy by primary producers as a source of energy. Townsend (1980) suggested a simplified model of the conversion and transfer of energy through aquatic ecosystems (Figure 1.4). The sources of energy are light and organic inputs from terrestrial ecosystems. Biota utilize organic matter according to their functional role, such as shredders that consume course particulate matter, collectors that exploit fine particulate organic matter and grazers feeding on microphytes (Vannote, et al., 1980). Predators prey on all three of these groups and on one another (Barnes and Mann, 1980).

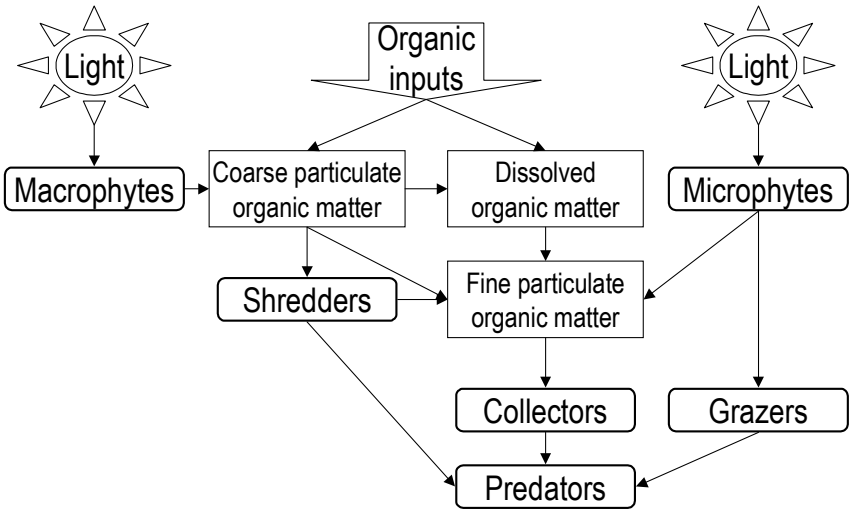


Figure 1.4: A simplified model of community energy flow in a lotic ecosystem (adapted from Townsend, 1980).

The ability to capture and circulate energy in ecosystems is dependent on the availability of several chemicals and chemical compounds. Carbon is the most basic element required in all organic compounds. Carbon is sequestrated through the process of photosynthesis (Figure 1.5), circulated within and between biota as organic molecules and converted to energy when needed which releases the carbon as CO_2 (Townsend, 1980). Under anaerobic conditions, C can also be mineralised to CH_4. Oxygen is released in the photosynthetic process, but used again in the process of respiration to release energy.

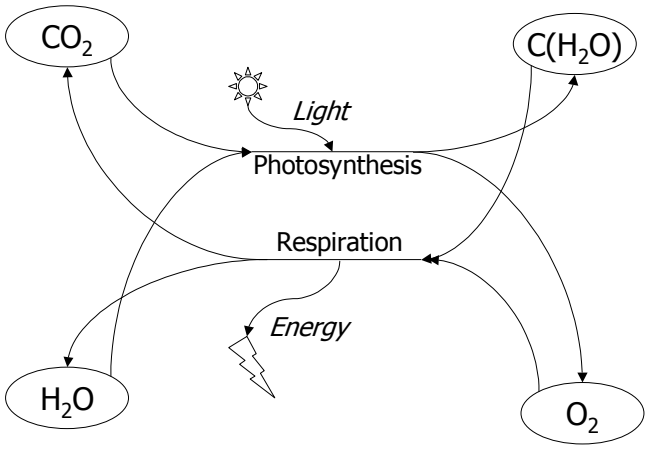


Figure 1.5: The basic elements, primary processes and products resulting from the sequestration of carbon in the environment (Townsend, 1980)

Nitrogen is an essential element in ecosystems, not because of its direct role in the capture and transfer of energy, but because it is an integral part of protein and nucleic acid molecules. Although nitrogen is the most abundant element in the atmosphere, it is usually in a gaseous form (N_2), which cannot be assimilated by most organisms (Ricklefs, 1979). The nitrogen cycle, presented in Figure 1.6, shows how nitrogen is converted from NH_3, through NO_2 to NO_3 by nitrifying bacteria (Conn et al., 1987).

The role of phosphorus in limnology has been extensively studied (Reynolds and Davies, 2001). The interest in phosphorus stems from its major role in biological metabolism and the relatively small amounts thereof in the biosphere (Wetzel, 1975). The biological importance of phosphorus is due to it being a component of nucleic acids and its pivotal role in intracellular molecular synthesis and transport (Reynolds and Davies, 2001; Figure 1.7). The only significant form of inorganic phosphorus in aquatic systems is orthophosphate (PO_4), while it is inaccessible in most other forms such as soluble unreactive P, reactive particulate P and unreactive particulate P (Arms and Camp, 1986; Reynolds and Davies, 2001). Sulphur occurs in many essential biochemical compounds and is utilized for this purpose by most biota in its reduced form (Barnes and Mann, 1980). Sulphate reducing bacteria use sulphate as a source of sulphur for the synthesis of amino acids, thus making it available to other biota

(Figure 1.8). The occurrence of sulphur species in natural waters is dependent on the pH and redox as illustrated in Figure 1.9 (Wetzel, 1975). The availability of H_2S and SO_4^{2-} are thus dependent on prevailing environmental conditions.

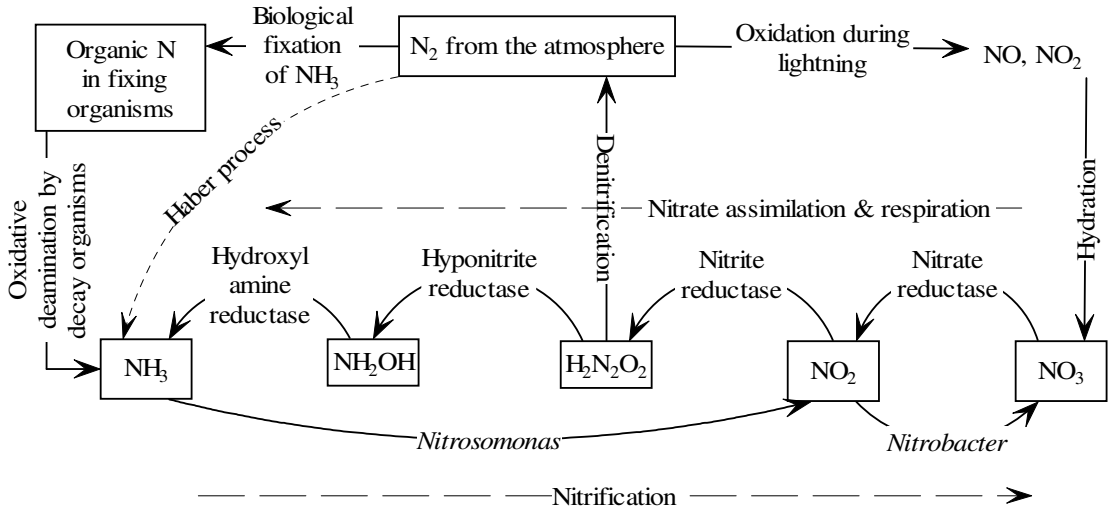


Figure 1.6: A process diagramme, illustrating the conversion of nitrogen from N_2 to NO_3 and NH_3 (Conn et al., 1987).

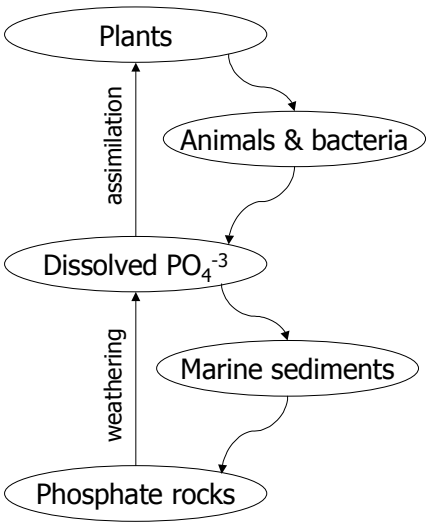


Figure 1.7: The conversion of phosphate to dissolved phosphorus, and its movement in the environment (Reynolds and Davies, 2001).

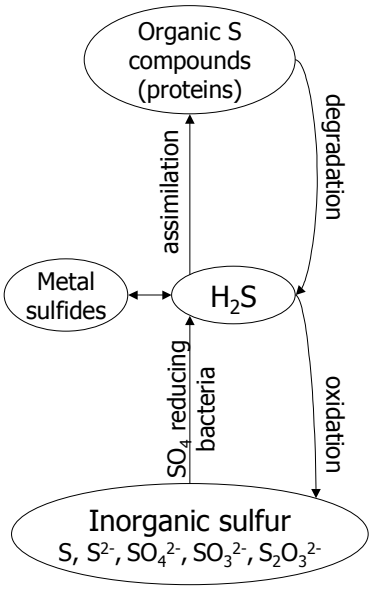


Figure 1.8: The processes involved in the conversion of inorganic sulphur to organic sulphur compounds in the environment (Barnes and Mann, 1980).

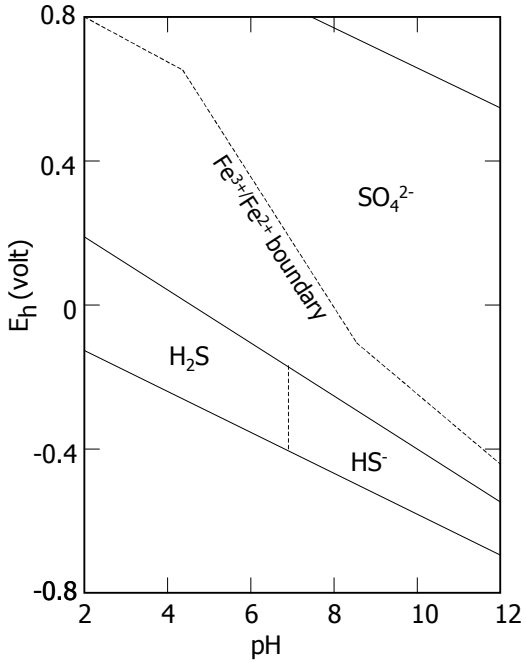


Figure 1.9: The speciation of sulphur in relation to Redox and pH (Wentzel, 1975).

The chemicals mentioned are not the only ones important for ecosystems, but are the primary drivers for ecological processes. A large number of essential microelements are also needed for the biotic processes. It is important to note that most chemicals, be they essential or non-essential, natural or man-made, can be harmful at high doses.

An integrated approach to ecological studies (landscape ecology) was discussed in section 1.1. River systems are, however, unique in the sense that there is strong unidirectional flow of material and organisms. The river continuum concept (RCC) was developed to deal with implications of theses changes over space and time. The approach shares the basic philosophy of landscape ecology, but focuses strongly on the longitudinal differentiation of rivers (Vannote, et al., 1980). The RCC concept was introduced as an attempt " *..to build a single synthetic framework to describe the function of lotic ecosystems from source to mouth, and to accommodate the variation among sites that results from differences in their terrestrial setting"*. Characteristic changes in geomorphological and hydrological features along the length of a river act as a template upon which biological communities become adapted. These changes are relatively predictable and therefore also the biological communities associated and adapted to these different conditions (Ladle, 2001). The RCC describes the structure and function of communities along the river system, specifically energy inputs, organic matter transport, energy storage, use of energy by the stream's functional feeding groups and fluvial geomorphic processes (Table 1.2).

Table 1.2: The characterisation of river sections related to energy sources, dominant functional groups and characteristics of the respective sections described in the RCC (Vannote, et al., 1980)

Section	**Energy**	**Functional feeding groups**	**Characteristics**
Headwater	Hetertrophic (riparian vegetation)	Shredders, collector-gatherers	Shading riparian vegetation Low diversity
Medium streams	Autotrophic (macrophytes, algae)	Collector-gatherers, scrapers (grazers)	Diverse temperature High diversity
Large rivers	Heterotrophic (organics from upstream)	Collector-gatherers (filter feeders)	Macrophytes abundant Lower diversity

Reader (1998) stated that: *"Climatic change undoubtedly has a major effect on the distribution and population size of all living species, but evidence from Africa indicates that competition for resources has had more influence than climate on the origin and evolution of species"*. The resources that are referred to are those which are needed for successful reproduction. A brief summary of these aspects will provide the context for discussion of goods and services offered by ecosystems (section 1.1.2). The units of ecological organization that are used for discussing these attributes are populations, communities and ecosystems. A population is a group of organisms of the same species, located at a particular time and space and share a gene pool through reproductive processes (Odum, 1971; Forman and Godron, 1986). Several populations may be functionally associated to form a community, which, together with other communities and the abiotic environment, constitute an ecosystem. Many ecosystem characteristics are, however, based on population dynamics (Ray, 2001).

Feeding in the broadest sense of the word relates to the acquisition of materials (organic and inorganic) needed for biotic processes (Figure 1.4). Primary production is effected by terrestrial, semi-aquatic and aquatic macrophytes, of which some are rooted and some floating. Microphytes include benthic algae and phytoplankton. All of these groups occupy different habitats with different physical and chemical attributes. Heterotrophs span a large array of organisms, from unicellular protozoa, to fungi, invertebrates, fish and mammals. The strategies employed by consumers differ vastly, but includes grazing and scraping, shredding and collecting (Whitton, 1975). Predators show a similar diversity of faunal groups than consumers, with as many feeding strategies. These trophic levels have significant implications for spatial and temporal patterns of growth, reproduction and adaptation. According to Arms and Camp (1986) ecosystems seldom have more than four or five trophic levels. This is because not all foods available at specific trophic levels are eaten, not all foods that are eaten are useful and energy is used at each level (often inefficient). The comment of Reader (1998) about competition for resources driving evolutionary processes is particularly true in the case of food. The competition amongst populations for the same food is very often the driver for ingenious adaptations, such as morphological features, feeding specialisation, territorialism and migration. These adaptations are geared towards more successful reproduction, to ensure the survival of the species.

Barnes and Mann (1980) identified two reproductive strategies at a population level, which also apply to aquatic ecosystems. Populations that reproduce at a rate that is consistent with the carrying capacity of the resources follow a *K-strategy*, whereas *r-strategists* maximise the rate of reproduction. These two strategies (representing the extremes of a continuum) have significant consequences related to production, biomass, energy expenditure, population stability and adaptation, which is specifically true for aquatic ecosystems (Table 1.3). Regardless of the strategy followed, all organisms need to be competitive in an environment where physical, chemical and biological stressors (including humans) abound. A summary of how these forces act on organisms is presented in Figure 1.10.

Table 1.3: Comparison of r and K and reproduction strategies (Barnes and Mann, 1980; Odum, 1971; Ricklefs, 1979).

Attribute	***r*-strategy**	***K*-strategy**
Strategy	Exponential growth rate	Carrying capacity
Consumption	Higher resource requirement	Lower resource requirement
Development	Rapid	Slow
Production:Biomass	High ratio (energy spent on reproduction)	Low ratio (energy spent on growth)
Life cycle/time	Shorter	Longer
Adaptation	High rate	Low rate
Reproduction	High numbers, low survival	Low numbers, high survival
Occurrence	Early colonisation	Stable, competitive environment

1.1.2. Goods and services provided by aquatic ecosystems

On a per capita basis, humans, especially those in the northern industrialized countries and those in large cities of the southern countries, are consuming more resources than the planet can regenerate, and filling waste sinks at a more rapid rate than the planet can assimilate (Princen, 1999). The fact that the value of ecosystems to our global economy is not recognized or measured well has broad policy implications. The importance of the ecosystem may often be ignored in bottom-line policy decisions (Alexander et al., 1998). As an example, many landowners and property developers are unaware of the biological value of sites, and with little biological monitoring and limited legal protection, aquatic ecosystems in urban locations are frequently drained and developed (Wood et al., 2001).

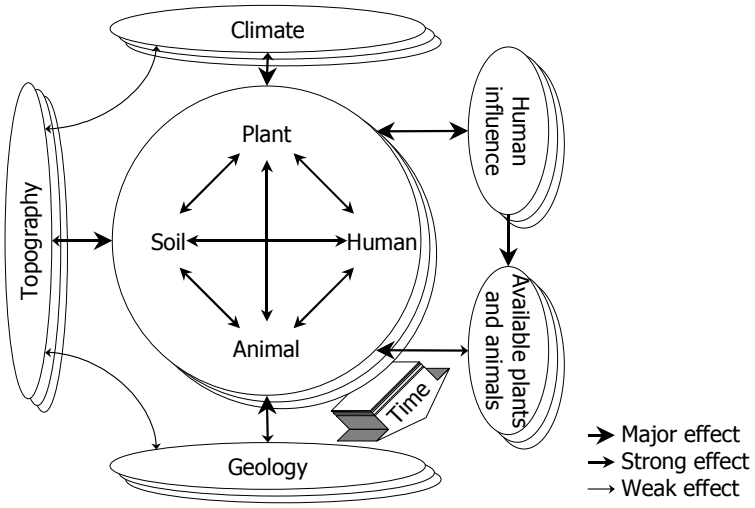


Figure 1.10: A conceptual diagramme of the forces acting on organisms in the environment (adapted from Atkinson, 2001).

Water has also been viewed as a commodity, something that can be contained, transported and traded, where in fact water resources are not just the commodity, "water", but rather the whole ecosystem, of which water is one component. The way in which we perceive and value water resources should reflect both societal values and ethics and the specific characteristics of this complex resource. Ecological integrity, which gives a water resource its resilience (ability to recover from change), is an essential element contributing to the value of the resource. In this context, a broader definition of a water resource has been proposed by the South African Department of Water Affairs and Forestry (DWAF, 1999), according to which, a water resource is an ecosystem which includes the physical or structural aquatic habitats (both instream and riparian), the water, the aquatic biota, and the physical, chemical and ecological processes which link habitats, water and biota. It is the ecosystem that provides us, not only with the water (which we see as a commodity), but also with many other services and benefits associated with ecosystem functions.

Ecosystem services are typically unpriced or not priced correctly at their marginal value because of a lack of private, organized markets for such services (Alexander et al., 1998), although they do contribute utility to individuals and therefore have value (Loomis et al., 2000). The ecological value of water resources (global natural resources, forested catchments,

rivers, national water resources, ponds and wetlands) has been difficult to quantify (Alexander et al., 1998; Creedy and Wurzbacher, 2001; Guo et al. 2001, Loomis et al., 2000; McMahon and Postle, 2000; Wood et al., 2001; Woodward and Wui, 2001). Several approaches have, however, been used to value ecosystem services. Woodward and Wui (2001) identified several methods for the valuation of wetlands viz. net factor input, replacement value, contingent value, travel cost and hedonic pricing. In this meta-analysis of valuation methods, it was found that derived value is less sensitive to the method employed, but depend more on reducing uncertainties in the assessments. In an application of the contingent valuation method Loomis et al. (2000) evaluated respondents' willingness to pay for specific services (dilution of wastewater, natural purification of water, erosion control, habitat for fish and wildlife and recreation) of the Plains River under current and restored conditions. The differential between respondents' willingness to pay for the current and for restored services outweighed the cost of restoration in that specific case. Seeking the maximum amount that could feasibly be paid for global ecosystem services Alexander et al. (1998) determined maximum surplus (world output minus subsistence) and total complementary value. The latter being sub-divided as complementary land value (gross agricultural value minus human inputs) and complementary labour value (total wage bill minus subsistence bill). These values in Table 1.4 show that 88% of the world GDP in 1987 was attributable to ecosystem services.

Table 1.4: Value of global ecosystem services (extract from Alexander et al., 1998)

Measure	**Annual value (1987 US$ x 10^9)**	**% of 1987 world GDP**
Maximum surplus	16 200	88
Total complementary value	7 965	44
- Complementary land value	*765*	*4*
- Complementary labour value	*7 200*	*40*

Princen (1999) advocated a focus on consumption rather than production (demand management rather than supply management). Supporting this notion, Rennings (2000) described eco-innovations as the development and application of new ideas, behavior, products and processes that contribute to a reduction of environmental burdens, or to meeting sustainability targets (Figure 1.11). These innovations can be at the level of technology, organization, society or institutional framework.

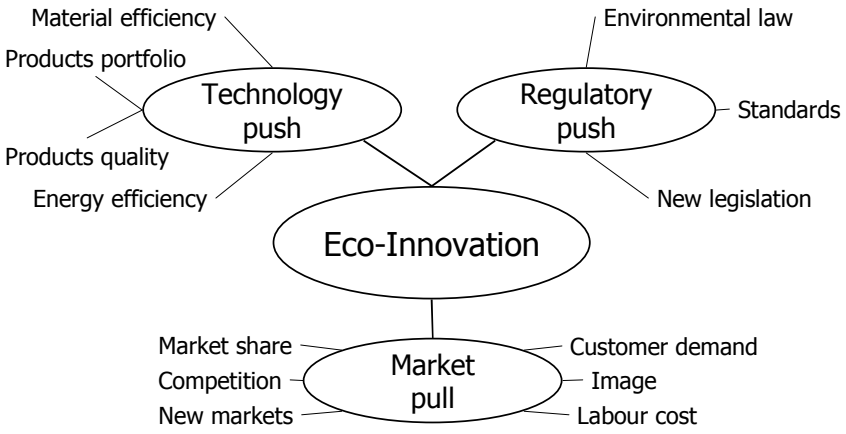


Figure 1.11: A system diagramme of the determinants for eco-innovation (Rennings, 2000)

Some of the services provided by natural resources as discussed by Costanza et al. (1997), Mander (personal communication), Loomis et al. (2000) and Palmer et al. (2002) are:

- Water for drinking and basic human needs
- Water for industrial use
- Irrigation
- Stock watering
- Transport (people and goods)
- Assimilation of waste products
- Subsistence or commercial supplies of biotic and physical components
- Opportunities for recreation
- Maintenance of habitats and ecological processes for ecosystem conservation
- Natural purification of water
- Retention and storage of water
- Control of floodwaters and erosion control
- Climate regulation
- Aesthetic and spiritual services

These services, which support resource based socio-economic development, rely on hydrological, biological and ecological processes, and require at least some degree of maintenance of the natural structure and character of aquatic ecosystems discussed previously.

1.2. Water Resource Management in South Africa

Water has been as a source of international conflict for centuries. Accounts of such disputes can be traced to Sumeria around 3000BC. Religious animosities, ideological disputes, political borders and economic development were mostly at the root of the conflicts. This is not surprising, since water is the lifeblood of social and economic development and there are currently 263 basins that either cross or demarcate international political boundaries (UNEP, 2002). In the last century, there were at least 21 instances recorded where military conflict between nations ensued from disputes over water (Gleick, 1998). Southern Africa is no stranger to such conflicts, with water resources being highly variable and unreliable. Rivers in the region often transect various countries or form the boundaries between countries. Shared river basins such as the Okavango (Angola, Namibia and Botswana), Kunene (Namibia and Angola), Orange (Lesotho, South Africa and Namibia), Incomati (South Africa, Swaziland and Mozambique) and Limpopo (Botswana, Zimbabwe, South Africa and Mozambique) have lead to disputes about entitlements to water, water abstraction, hydropower, water pollution and land ownership (Turton, et al., 2003).

Water resources within South Africa met the modest demands put on it prior to the nineteenth century. Sustainable use in the higher rainfall eastern areas and nomadic subsistence in the drier western regions ensured that water was not a limiting resource. Following international trends, modern agricultural practices were introduced in the 20th century (Gleick, 1998). These monoculture methods were not only more intensive, but they also required vast amounts of water. This need was addressed through the construction of dams and canals. Rapid population growth coupled with industrial and mining development put further demands on the finite resource. The Irrigation and Conservation of Waters Act (Act 8 of 1912) consolidated and amended the provincial laws in the Union of South Africa relating to the use of water from public streams for domestic, irrigation and industrial purposes. The Act provided for the establishment of facilities for irrigation and domestic use of water. The key aspects of this Act were the distinction between public and private water and the establishment of riparian rights. The use of private water (defined as that which originated from private land) was not regulated, except for specified historically established uses. The Act was set in a utilitarian paradigm, with the key objective being to supply specific users with sufficient water.

The Water Act (Act 54 of 1956) further regulated water use in 1956 by repealing the Irrigation and Conservation of Waters Act of 1912 and consolidating various other financial and irrigation acts that related to water. Although the Act provided for the control of water pollution and the more effective protection of the water resources of the country, it was still set in the paradigm of riparian rights (rights to water use based on land ownership). Through its link to land ownership, this policy sustained the inequitable, undemocratic and discriminatory use of the resource. Although the 1956 Act was largely a response to industrialisation, the need for pollution control required amendments. The uniform effluent standard approach, which was followed up to 1989, was not entirely satisfactory. This prompted the application of the combined receiving water quality objectives (RWQO) and pollution prevention approach (Neytzell-de Wilde, 1992). The effluent standards approach amounted to effluent producers having to comply with minimum effluent standards, based on the control of individual substances (uniform general standards and special effluent standards). Exemptions to the standards could only be granted if satisfactorily motivated on technological and/or economic grounds and justified by the RWQO approach (by substituting with site-specific effluent standards). The RWQO policy also provided for site-specific standards that could be stricter than the general and special effluent standards (DWAF, 1991). The RWQO approach focused on the receiving water quality instead of emission quality from a pollution source in decisions concerning pollution control. It required that sources, both point and diffuse, be controlled to achieve the desired quality in the receiving water (DWAF, 1995a).

There was a realisation that certain chemicals present major threats to the environment due to their toxicity, persistence and capacity for bioaccumulation. The pollution prevention approach was adopted to control the handling and disposal of hazardous substances (DWAF, 1995a). Prevention strategies included effluent standards based on "BATNEEC" (best available technology not entailing excessive cost) and required polluters to carry out all other functions according to best practice and in a way that renders any emissions that do occur, harmless and inoffensive to people and the environment as a whole (DWAF, 1991). In line with its precautionary approach, DWAF adopted a hierarchy of decision-making for considering any application for the discharge of an effluent to a receiving water body. All options for preventing and minimizing waste through source reduction, recycling, detoxification and neutralization of wastes had to be thoroughly investigated. If, after all the

practical options to prevent or minimize waste had been exhausted, there was still waste or an effluent, it was required that it meet whichever was the strictest of minimum effluent standards or receiving water quality based effluent standards. Exemptions from the minimum effluent or RWQO-based standards were considered under special circumstances, but required sufficient justification on technological, economic and socio-political grounds (DWAF, 1995a).

Although the above policies may have been effective in reducing pollution, they were not effective for comparative evaluation of different uses (DWAF, 1998). Optimal resource use, at a time when the demand was increasing and the social and economic issues were increasingly complex, required a shift in thinking. Around the same time, the global paradigm for water resource management shifted significantly. Previous approaches focused on capturing a larger portion of the hydrological cycle to meet growing demands. Projections used population growth, and extrapolated existing levels of use per capita to determine future demands. It soon became clear that conventional engineering solutions on the supply side were not sustainable. Resource managers were turning to efficiency improvements and demand management in a holistic strategy to meet future needs (Gleick, 1998). The new policy on water resource management in South Africa was drafted in this context (DWAF, 1997). The analysis of the development and implementation of this policy in the next section explores the rationale for the changes.

The context for the use and management of water resources in South Africa has been reset in the South African Constitution (Act no. 108 of 1996). The Bill of Rights (Chapter 2 of the Constitution) specifies among others things that every person shall have the right to:

- Equality before the law and that no person shall be unfairly discriminated against
- Life and respect for and protection of his or her dignity
- An environment which is not detrimental to his or her health or well-being and to have the environment protected
- Have access to sufficient food and water
- Access to all information held by the state or by another person and that is required for the exercise or protection of any rights

The Constitution also specifies aspects related to co-operative governance in Chapter 3, which refers to infrastructure and mechanisms for resource management. These principles rendered most of the preceding acts, related to water resources, unconstitutional. A new paradigm for water resource management was established in the National Water Act (NWA, Act No. 36 of 1998), with related environmental policies (DEAT, 1996a and DEAT 1996b) also having implications for the water sector. The constitution and related acts specifically promote the equitable and sustainable use of water resources. The NWA therefore provides for sufficient water for basic human needs (drinking, cooking and hygiene) and for the quality, quantity and pattern of water to maintain ecosystem functions as basic rights. These rights are supported by fundamental changes to the concept of water ownership, with water now being a public asset, water resource protection being a fundamental requirement, and the government being a public trustee of the resource.

The purpose of the NWA is to ensure that the nation's water resources are protected, used, developed, conserved, managed and controlled in ways that take into account of relevant factors. Some of these include meeting the basic human needs of present and future generations, promoting the efficient, sustainable and beneficial use of water in the public interest, and protecting aquatic and associated ecosystems and their biological diversity. Resource quality is defined in the NWA (Act No. 36 of 1998) as the quality of all the aspects of a water resource including instream flow (quantity, pattern, timing, water level and assurance), water quality (physical, chemical and biological characteristics), instream and riparian habitat (character and condition) and aquatic biota (characteristics, condition and distribution). The management of resource quality, thus, means the ability to define these aspects, measure them and provide information that could be used to support decisions (which are typically multi-criteria) in an integrated water resource management framework.

The protection of water resources receives specific attention in Chapter 3 of the NWA. The first stage in the protection process is the development of a system to classify the nation's water resources. Water resources will be grouped into classes representing different levels of protection according to the classification system. The protection required for a specific class is expressed as the risk of irreversible change in the state of ecosystem integrity (MacKay, 1998). This system provides the basis for considering specific development options in the context of the long-term protection of a water resource. The highest class (least consumptive

utilization, lowest risk) will include water resources of high conservation importance or those that support important and sensitive uses (such as cultural sites). The lower classes (more consumptive utilization, high risk) would be applicable to resources where there are high demands on water for socio-economic development and where the conservation value of the system is not very high. The classification of a water resource requires a formal process of negotiation and consensus-seeking among all stakeholders and the DWAF as the public trustee. Stakeholder groups should be representative of water users, industries, agriculture, the public sector, special interest groups, local and regional government, as well as other government departments responsible for resource protection and development (MacKay, 1998). The stakeholders should come to agreement on the level of protection that will be afforded to the resource, with an understanding of the limitations and opportunities that the agreed level of utilization holds.

Within the specified classes, the Reserve needs to be determined. The Reserve consists of a basic human needs component, which specifies the basic water needs of present and future generations, and an ecological component, which is specified to sustain aquatic and associated ecosystems. Contrary to the previous policies, potable water use is no longer seen as competing with other users, but enjoys special protection. Likewise, the maintenance of aquatic ecosystems is not considered to be a use of the resource, but rather protecting the resource to sustain use. The resource quality objectives of all or part of each water resource considered "significant" must then be determined. In determining resource quality objectives, a balance must be sought between the need to protect and sustain water resources on the one hand (related to the Reserve), and the need to develop and use them on the other. Assessment methods should provide information that will support management decisions in this context.

In the context of water resource protection, the NWA specifies measures related to the utilisation of the resource. The source directed controls (Chapter 4 of the NWA) define water use very broadly, to include activities that could affect water quantity (abstraction, storage, diversion, flow reduction and water discharge), water quality (waste discharge and recreation) or the biophysical components of the resource (altering the characteristics of the watercourse or catchment). These activities require authorisation, generally through licensing, in support of the water resource protection measures. The realisation that water resources can provide specific utilities, which can be equated to a specific economic value, is entrenched in

the NWA through the establishment of tradable permits. This in itself is a paradigm shift from the previous philosophy. Accepting and accommodating the monetary value (perceived or real) of water resource use has the potential to create a competitive environment for resource use. Market forces will thus determine the most efficient and beneficial use of allocated water, within the parameters of the NWA and the regulatory authorities.

Within the ambit of management, the NWA also proposes a progressive approach. Water resources management has historically been through command-and-control, with hierarchical central government functions dominating. This approach has now made way for participative governance at regional and local levels. Catchment management agencies (CMA's) will form the central body for water resource management institutions. A broad range of stakeholders represented on these agencies, participate in the operational aspects of catchment management, with ministerial approval only required for critical aspects. New water management areas are not delineated by political boundaries, but follow catchment boundaries. Unfortunately, these were not aligned with local government boundaries therefore, even though this method of demarcation allows holistic management of the water resources, it will require significant levels of cooperative governance to be effective.

1.2.1. Implementation challenges

Policy is defined as a systematically defined course of action selected from alternatives in the light of given conditions, that guide and determine present and future decisions, with the intention of achieving a stated objective or set of objectives. The policy process has four main elements (Wilson, 2000):

- Problem identification;
- Policy formulation;
- Implementation; and
- Monitoring and evaluation.

The NWA was based on a set of principles (DWAF, 1997), which is translated into policy. The implementation of such a policy requires a hierarchical matrix of activities. This process can be characterised in terms of the level of activity and the resources required (Figure 1.12). The cycle starts with the development of new policy. A core of competent people is needed to

conceptualise the policy and develop and source methods and formulate the policy. The development of a broader knowledge base (capacity) in the policy arena creates an environment where the new policy can be adopted. Competence at the strategic (planning) level is then needed to develop a plan to deploy the policy. Approaches to strategy development are formulated and used, whereupon the strategy (implementation plan) is diffused to a broader based of competent people and resources (capacity). Business plans are then drafted at the operational level. The execution of these plans is dependent on the development or acquisition of technical tools, which include monitoring and evaluation systems. The availability of enough competent people and resources (capacity) is a prerequisite to final implementation of the policy.

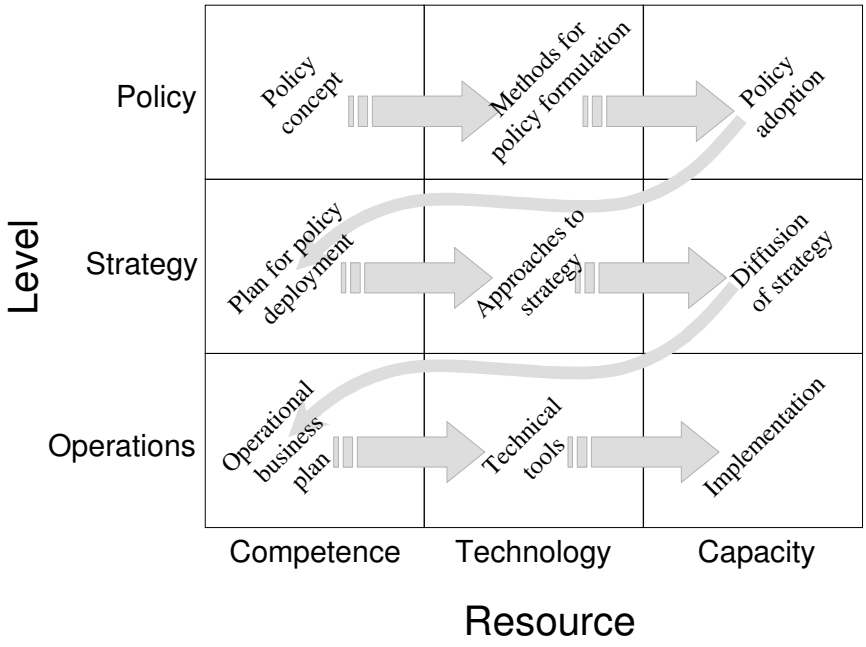


Figure 1.12: The steps of the water resource policy implementation process, as they relate to the levels of actions and the resources required.

In the South African context, The White Paper on a National Water Policy (DWAF, 1997) and the National Water Act (Act 36 of 1998) are the products of policy formulation, whereas the adoption of the policy was promoted through national workshops. Diffusion of the plan to deploy the policy is published in the form of a National Water Resources Strategy (DWAF,

2002b) and has already been initiated (DWAF, 2002c; van Wyk et al., 2002). Catchment management strategies will now be developed, which will provide the basis for operational business plans (DWAF, 2002b).

DWAF (1998) identified issues and criteria for prioritising areas for the implementation of catchment management in South Africa (Table 1.5). During a workshop in 1998 (Claassen, 2002) needs related to the role of ecological risk assessment (ERA) in water resource management were identified (Table 1.6). These issues relate primarily to strategic and operational issues and require the development of new technologies and capacity for diffusion and implementation.

Table 1.5: Issues and criteria for prioritising catchment management (DWAF, 1998).

The need for catchment management in a particular catchment	
• Sensitivity of the receiving environment • Requirements of water users • Acceptable risk of impact • Type and severity of the water resource problem	• Social, economic and environmental effects of water resource problems • Urgency for management • Understanding of problems and effects • Complexity of the catchment • Need for wider integration
The resources available to support catchment management	
• Human • Financial	• Equipment
The capacity and motivation for implementing catchment management	
• Technical • Managerial	• Administrative • Political will
Local support for a catchment management initiative	
• Existing catchment management initiatives • General awareness	• Sectoral interest • Stakeholder representivity • Legitimacy of the process
DWAF's requirement to gain catchment management experience	
• Integration • Institutional/resources	• Social/economic • Land use/physical

1.3. Scientific Discovery

The development of a scientific process should be based on a sound philosophical approach and should specifically comply with the requirements of the scientific method. Key characteristics of the scientific method are that it is falsifiable (can potentially be disproved) and it displays causality (deals with the underlying causes of observations). The steps in a typical research process are summarized in Figure 1.13 (Scholes, 1996).

Table 1.6: Needs related to ERA in water resource management in South Africa (Claassen, 2002)

A reliable classification system in accordance with the NWA	
Effective communication at all levels	
Reserve determination • Process for determining the Reserve	• Process of consensus seeking
Capacity (enough skilled people)	
Understanding water resource management process	
Understanding rules for changing classification	
The development of risk-based policy	
Enforcement • ERA policy • Decision support systems	• Enforcement
Assign risks to hazards for water resource classes • For monitoring, control and enforcement	• Managements' response to hazard is dependant on risk
Dependant on the development of ERA and risk management competence	

In conceptualising an approach to developing a scientific method, it is important to explore the nature of scientific knowledge. The development of scientific knowledge is based on a cumulative process of reporting, reviewing and accepting (or rejecting) specific contributions. This scientific knowledge can expand in breadth and in depth. Growth in breadth is characterized by incremental improvement of existing knowledge. Such contributions are readily accepted (provided they survive peer review), but their significance is limited by the confines of the existing paradigm. Another type of growth is needed to change the paradigm.

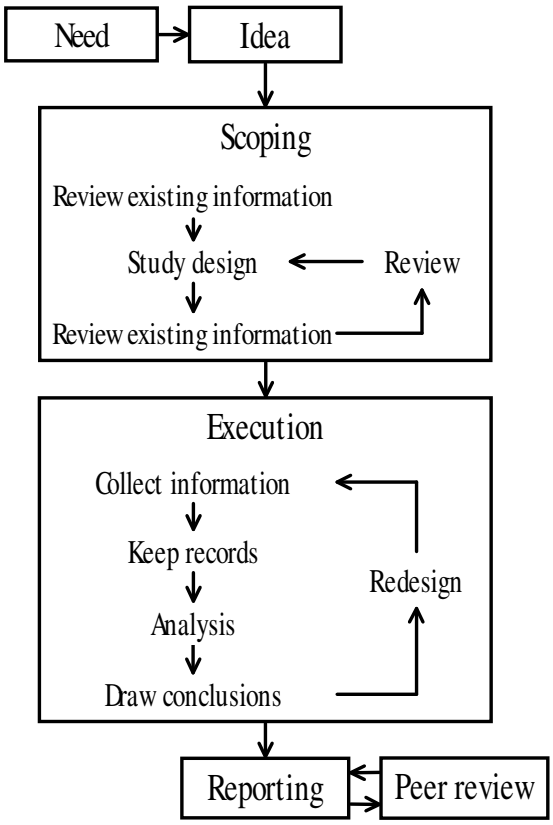


Figure 1.13: The basic steps in the research process (adapted from Scholes, 1996)

Contributions to scientific depth are characterized by new theories involving the unobservable. Although these contributions are often heavily criticised, their impact may be significant. Once accepted, these new hypotheses are strengthened by a renewed growth in breadth of science. Iterations of expanding on scientific depth and breadth may lead to scientific maturity (Bunge, 1965). This cycle may be obvious in retrospect, but deep theories sometimes have an embryonic stage in which their depth is far from apparent (Popper, 1965).

Characteristics of deep theories are the occurrence of high level constructs, the assumption of mechanisms, and a high explanatory power. Such constructs are necessary to describe hypothetical mechanisms, which are in turn necessary to explain the behaviour of the system, and eventually the appearance it presents to the observer. Logical and semantic clarity concerning fundamentals are acquired by first analysing, then criticising and eventually reconstructing a whole body of ideas, grown in a spontaneous and usually wildly fashion (Bunge, 1965). In the late 1960's, it was said that thinking in terms of cause and effect was

being replaced by thinking in terms of functional relationships and probabilistic correlations. These developments do not suggest that philosophical problems are obsolete, but rather that they enable us to present such problems with an increased degree of clarity and precision (von Wright, 1971).

Logical reasoning can be either through deduction, which deduces specific conditions from general models, or induction, which deploys actual data to infer general models (Salmon, 1984). More recent developments in the scientific method (Gauch, 2003) highlight the role of probability theory, notably the likelihood of events occurring (frequentist approach) or the belief that events may occur (Bayes's theorem).

1.3.1. Risk assessment

The realisation that the future is not just a reflection of the past, a function of random events or in the hands of the gods, defined an important landmark for modern man. Given this understanding, it still took a long time to develop the tools and competences to capitalize on it. Gambling has been practiced from as early as 3500 BC (Bernstein, 1996). Such games of chance were precisely about risk-taking (that is betting on the occurrence of a future event). Initially, an expectation that a specific event will occur was the basis for decisions. In this paradigm, 'professional' risk assessors in ancient Babylon (around 3200 BC) offered advice on difficult decisions (American Chemical Society, 1998). The ability to quantitatively consider odds came only with the development of a numbering system and the use of the abacus from 450 BC. The development of the Hindu-Arabic numbering system (including a zero) between 1000 and 1200 AD made proper calculation of probabilities possible. Subsequent developments in mathematics allowed for more sophisticated analyses, although these were mostly applied to academic and gambling problems. Halley initiated the application of risk in actuarial science in the 1690's (Halley, 1693), although the application of his work found favour only towards the end of the 18th century. The occurrence, frequency, timing and magnitude of events such as death or property loss affected claims, but predicting these events was not yet possible. The need to determine the probability of events and their associated magnitudes prompted the further development of actuarial techniques. In the 20th century, stockbrokers traded in markets where the outcomes of transactions were uncertain. Again, the use of probabilistic analysis (risk assessment) provided a basis for

decision-making (risk management). In this application, it became clear that absolute risk was not the only criterion for decision-making, which introduced the notion of risk perception.

Willet defined risk assessment in 1901 as the *"objectified uncertainty regarding the occurrence of an undesired event"* (quoted in Suter, 1993). Views from a century later expanded slightly on this notion, stating that risk assessment defines the probability of an undesired effect, expressed in the context of associated uncertainties (EPA, 1998). These approaches focus on the objective aspects of risk assessment, involving data, facts and statistics (risk analysis). An ongoing problem with risk assessment is that society and experts may differ considerably in their views of the relative significance of a specified risk. An infinite knowledge of ecosystems structure and behaviour may allow for an accurate prediction of a system's response and the service that can be provided under various conditions, but says little about the acceptability of such attributes to society. This requires risk analyses to be free of value judgments, specifically because the assessors' values and ethics may influence choices on method and data. The interpretation and application of results are necessarily more subjective, involving social values in judgments and decisions. The views of society should contribute to the context of risk management, where diverse groups and individuals may provide essential information and insights about the risk situation. The relevance of losses, harms and consequences to interested and affected parties will thus affect choices in a risk situation (Stern and Fineberg, 1996). The criteria for considering the social acceptability of specific risks may for instance focus on the protection of health, the availability of technologies to reduce the risk, or consider both options in a balanced approach (American Chemical Society, 1998). Although there is growing support for the use of risk assessments to bring the best available science to decisions making, some critics view the acceptance of risk, however small, as undesirable. A more realistic view is that risk is inherent in human activities. The choice is rather in balancing the benefits of development against the cost and effort of reducing the associated environmental risks.

1.3.2. Risk perception

Hazards are physical, chemical or biological attributes that can potentially result in adverse effects, whereas risk assessments evaluate the probability that such hazards will actually result in the undesired effects. The criteria for defining undesired effects, however, originate

from human perceptions. People may intrinsically ascribe to the value and importance of healthy ecosystems or they may be interested in how changes to ecosystems influence their utility of the resource. These considerations are more at home in the ambit of social science, which requires an understanding of thought processes.

In developing the *psychology of the mind* approach, Neethling and Rutherford (1996) concluded that psychological functioning rests on three principles: the mind, thoughts and consciousness. They concluded that although the mind and consciousness are fixed, thoughts are highly variable and controllable. Glicken and Fairbrother (1998) investigated the process of knowing (thoughts), and specifically the evolution of thinking, and identified the following stages:

- In a view of *empiricism*, they stated that data can only be gathered through the senses, and that these data are the limit of thoughts.
- *Modernism* expands this view to include truth, thus enriching the data with logical, scientific laws and laws of nature. In a modernistic paradigm, ecosystems are individual units connected by energy flows.
- *Rationalism* provides for systems theory to be included in the thought process, suggesting that it is the essence of things that are important, rather than their attributes. The truth now becomes a perception of the observer rather than a characteristic of the observed.
- *Postmodernism* carries this view even further by advocating that the observer creates his perceptions through filters of personal history and experience.

Economics, aesthetics, lifestyle preferences and cultural issues therefore influence societal values. These values, together with technical information about ecological attributes, determine to a large extent society's importance rating of various ecosystem components and the conditions that are deemed acceptable (Gentile, 1998). A survey conducted by McDaniels et al. (1997) characterised lay perceptions of ERA in water resources. A key conclusion of the study was that lay people perceived activities that are beneficial to humans as presenting less of a risk to the environment. They also expressed hazards that were potentially controllable as presenting lower risks. The study supported the view that lay people and experts perceive risk differently. This perception has important implications for the risk assessment, risk communication and risk management strategies.

1.3.3. Risk management

Management refers to the activities of identifying and evaluating alternative options, deciding on a course of action and implementing the decision. These activities are conducted in the context of social, economic, environmental and political issues. Since we cannot eliminate all risks associated with anthropogenic activities, tradeoffs (which may be based on risk-benefit, cost-benefit, or risk-risk evaluations) are typically part of risk management (Stern and Fineberg, 1996). Inherent variability due to stochastic processes often characterise natural systems and information available at the time of making a decision is also often incomplete (uncertainty). The use of a risk-based approach therefore has specific implications for management.

Risk assessments are forecasts of future events that provide a description of the likelihood of a future event occurring in the context of associated variability and uncertainty (Warren-Hicks, 1999). If we consider the use of probability in the actuarial domain, it would not make sense to painstakingly determine probabilities and consequences of events and then not use the information to manage risk. Similarly, risk management related to environmental issues should accommodate and consider probabilistic assessments in support of decisions. Discussions on risk assessment often mention risk-based management, but the real meaning of this has rarely been analysed. Risk assessments can be used at different management levels and in a variety of ways. As an example, risk-based priority setting makes use of comparative risk assessment and risk ranking to develop management plans. An important characteristic of risk management is the ability to integrate risks from different sources. Such analyses allow the allocation of resources in such a way as to minimise risk (Garetz, 1993).

Current developments in risk analysis allow us to describe anthropogenic activities and their associated risks. An understanding of social values and ethics, the political environment and economic consequences provides the context for risk evaluation and management. The ability to deal with risk, coupled with the need for effective resource utilisation justifies the application of risk assessment in environmental management.

1.3.4. Application of risk assessment in an ecological context

Risk assessment consists mainly of probabilistic analyses in the context of variability and uncertainty and linking the outcome to decisions, in the context of societal values. The application of these principles to ecosystems is particularly appealing, since it can deal with the complexities in such systems, accommodate both natural variability and uncertainty and consider societies' values and expectations (US DoE, 1996). Uncertainty describes the nature and extent of unknowns in a risk assessment. The sources of uncertainty include a lack of data about the types of stressors and the exposure to them, inadequate information about dose-response relationships, a poor understanding of distributions over time and space, and uncertainty about the methods used to calculate risk (US DoE, 1996). Variability describes the expected distribution of stressor measures, exposure scenarios, exposure-effect relationships, cumulative effects and indirect effects resulting from stochastic or random processes and associated diversity. An understanding of risk perception, as discussed in section 1.3, is vital for appropriate risk assessment, risk communication and risk management.

The United States Environmental Protection Agency (US EPA) proposed a risk-based approach for ecosystem assessment and management (EPA, 1992), but practitioners are often reluctant to use this approach. The main reasons given are that:

- ERA is different from engineering or mathematical risk assessment and should not be formulated in the same way,
- it is not appropriate to use a particular mathematical construct because it is not clear what approach (such as probabilistic analysis or fuzzy logic) is most useful for ERAs, and
- ERA uses a weight-of-evidence approach that requires the professional judgement of qualified ecologists and does not lend itself to a quantitative approach (Kelly and Roy-Harrison, 1998).

Although these perceptions have not been supported by factual evidence, assessors have focussed more on hazard assessments, while confining ecological effects assessments mostly to qualitative analyses. This approach has limited the impact of such assessments in decision-making processes. Managers have been cautious of qualitative ecological information, while

favouring quantitative economic and social information for decision-making.

Karr and Chu (1997) critiqued the application of ERA, arguing that ERA will miss its mark if it relies on inappropriate substitutes such as chemical measures and subsequent hazard assessments. They further warned against the inappropriate use of pollution control methodologies, commenting that most risk assessments still follow the single-source-single-stressor approach. Moore (1998) added to this view by stating that the assessment of environmental effects at higher levels of ecological organisation will improve relevance. Such an integrative approach (taking account of complex stressor conditions and ecological complexity) requires a thorough understanding of ecosystem theories (Muller, 1997).

1.3.5. Application of risk assessment to water resource management

The regulatory framework for water resource management in South Africa is aimed at optimising socio-economic development, while providing sufficient protection of the resource to ensure the long-term sustainable development. The dilemma for water resource managers is that decisions must be made while knowledge about ecosystems and their response to stresses are incomplete. This problem is compounded by the stochastic nature of natural systems, which makes accurate predictions even more difficult. The ability to deal with uncertainty and variability provides an opportunity to apply risk assessment to water resource management. Gentile (1998) stated that information on social values should be combined with technical information about ecological relationships to frame questions about what is important in an assessment and how much change society is willing to tolerate, while Roux et al. (1999) emphasized the role of stressor and response monitoring in the context of water resource management. These needs are addressed in ERA, since socio-economic issues are considered in the planning phase of the ERA, while exposure and effects assessment are explicit steps in the analysis phase. Hart (1998) and Hart et al. (1999) pointed out that the application of a risk-based approach to the development of water quality guidelines and management should provide an effective means of protecting biodiversity and ecological integrity. ERA could therefore be considered as a tool in implementing water resource management policy in SA. The specific applications could include the technical aspects of water resource classification, methods to support decision-making and a need for increased capacity for implementation.

1.4. Aims and Chronology of this Thesis

This chapter introduces ecosystems and in particular aquatic ecosystems. The history and state of water resource management in South Africa is followed by a discussion of risk assessment and its potential application in an ecological context. This provides the basis for evaluating the use of the risk assessment paradigm for water resource management in South Africa.

Chapters 2 to 5 of the thesis present work that was conducted and published between 1997 and 2001. The chapters and sections represent the chronological sequence of the development, application, refinement, publication and evaluation of the South African Ecological Risk Assessment Guidelines (Claassen et al., 2001b). An international review, leading to the development of a framework for ERA in South Africa (Chapter 2), is followed by the evaluation of the framework in a complex industrial effluent study (Chapter 3) and the development of the South African ERA Guidelines (Chapter 4). The Guidelines are applied in an assessment of ecological water quality requirements (Chapter 5) and the thesis is concluded with a critical assessment of the work in the context of reported applications (Chapter 6).

The specific aims and approach of the thesis are to:

- Develop a process and framework for the application of ERA to water resource management in South Africa. This is done through:
    - Defining the context and challenges to water resource management in South Africa,
    - Describing international best practice in ERA, and
    - Adapting international best practice towards a framework for ERA, which is relevant to local needs.
- Use case studies to draft guidelines for ERA by:
    - Applying an industrial effluent case study to the ERA framework to assess its relevance and the appropriateness of specific actions,
    - Drafting guidelines for ERA, with case study examples to aid in communication, and
    - Applying the guidelines to assess ecological water quality requirements

(Ecological Reserve).

- Assess the degree to which ecological risk assessment can contribute to effective water resource management in South Africa.

2. Approach to Ecological Risk Assessment in South Africa

The need for a common understanding of ecological risk assessment (ERA) in South Africa led to an examination of published ERA processes. These processes were evaluated through workshops with international experts and local scientists and stakeholders. Best practice elements of these processes were integrated and adapted to suit the South African context and conditions. The objective was to develop a framework, which could be discussed, applied and evaluated as a precursor to the development of more comprehensive guidelines. In considering the development of a framework for ERA in South Africa, international approaches were assessed to ensure that the framework complies with the requirements of the scientific method, that issues relevant to South Africa water resource management are considered and the approach provide clear guidance on how to conduct an ERA.

2.1. International Developments

The principles of risk assessment are well established (Bernstein, 1996; Stern and Fineberg, 1996; American Chemical Society, 1998). Although these principles have been applied in the actuarial sciences and the field of engineering, their application in environmental sciences has only gained momentum in the last decade (Suter, 1993; Karr and Chu, 1997).

Many environmental statutes, implemented by the US EPA since the 1970's, regulated and reduced point source releases to the environment. Risk assessment emerged as a regulatory paradigm in the early 1980s, at a time when regulatory and policy decisions were being influenced by ecological impact measures. The use of ecological information for decision making expanded slowly through the 1980s. In the mid to late 1980s, tools and methods for conducting ecological risk assessments began to be standardized (Suter, 1983; Calow, 1998). The EPA's Science Advisory Board recommended that ERA be the cornerstone for decision-making within environmental management. Their report "Future Risk: Research Strategies for the 1990's" (EPA, 1988) emphasized the need for a fundamental shift in EPA's approach to environmental protection. The proposed move was from conventional approaches to focussing on the resources at risk, their composition within a landscape, multiple stressors and multiple assessment endpoints. In 1992, the EPA published the "Framework for

Ecological Risk Assessment" as the first statement of principles for ecological risk assessment (EPA, 1992), and in 1998 published the "Guidelines for Ecological Risk Assessment" (EPA, 1998). These documents not only describe single-species, chemical-based risk assessments, but also techniques for assessing risks to ecosystems from multiple stressors and multiple endpoints. In the rest of the world, the value of the ERA process has only been considered more recently.

The Department of the Environment, Transport and the Regions generally leads policy to control risk to the environment in the UK and published "A Guide to Risk Assessment and Risk Management for Environmental Protection" (DOET&R, 1995). This guidance has been followed in reports, for instance, on dioxin emissions. Although the basic approach follows that proposed by the EPA (1992), significant attention is given to the precautionary principle[1]. Legislation in most other European Union countries also emphasise technological standards to achieve improvement. The European approach to ERA for pesticide registration followed a similar approach, but allowed for a cost-benefit balance and in-use monitoring (Greig-Smith, 1992). The precautionary principle is, however, not ideally suited for applications where substances are persistent and may build up in the environment, since it generally does not cater for cumulative effects. Risk assessment and management is also more difficult to fit within a precautionary paradigm, because the presented information often does not represent the full cause-effect spectrum.

The draft Australian/New Zealand Standard on Risk Management of 1994 defines risk as follows: *Risk arises out of uncertainty. It is the exposure to the possibility of such things as economic or financial loss or gain, physical damage, injury or delay, as a consequence of pursuing a particular course of action.* The Management Advisory Board of the Australian Public Service identifies a five step generic process for managing risk (Australian Academy of Science, 1995). These are:

- Establish the context
- Identify the risks
- Analyse the risks

1 The precautionary principle guards against erroneously allowing an activity, if in fact such activity will have unacceptable consequences. In statistical terms, the analysis is protected against a Type I error.

- Assess and prioritise risks
- Treat the risks

The Australian and New Zealand Environment and Conservation Council and Agriculture and Resource Management Council of Australia and New Zealand (2000) also followed a risk-based approach to the development of Australian and New Zealand guidelines for fresh and marine water quality.

Skivington's (1992) discussion of motivations for risk management focused on risk perception and the cost of protection. In developed countries, the public typically has an unsympathetic attitude towards companies causing adverse environmental impacts, while this is not necessarily true of developing countries. These attitudes have impacts on potential markets. There is also ever-tightening legislation affecting local and international trade. ERA is important for environmental decision-making because of the high cost of eliminating environmental risks associated with human activities and the necessity of making regulatory decisions in the face of uncertainty (Calow, 1998; Stern and Fineberg, 1996).

In an evaluation of the United States ERA guidelines (EPA, 1998) Murray and Claassen (1999) found that the approach generally considered issues relevant to water resource management in South Africa and provides clear guidance on conducting ERAs when compared to other approaches (DOET&R, 1995; Greig-Smith, 1992; MPP-EAS, 1999). The evaluation suggested that the sequencing of tasks be clarified and found that the US EPA guidelines were not explicit in following the scientific method of testing the null hypothesis. A specific requirement of the South African context that is not adequately covered in the guidelines is the provision of consultation and feedback during the quantification of effects. Previous attempts to establish ERA in South Africa did not adequately address these issues (Jooste et al., 1999; Jooste and Claassen, 2001b; DEAT, 2002).

2.2. Draft Framework for Ecological Risk Assessment in South Africa

The draft framework for conducting ecological risk assessment in South Africa (Figure 2.1) is based in the US EPA guidelines (EPA, 1998) with modifications relevant to the South African context (Murray and Claassen, 1999; Claassen, 2000).

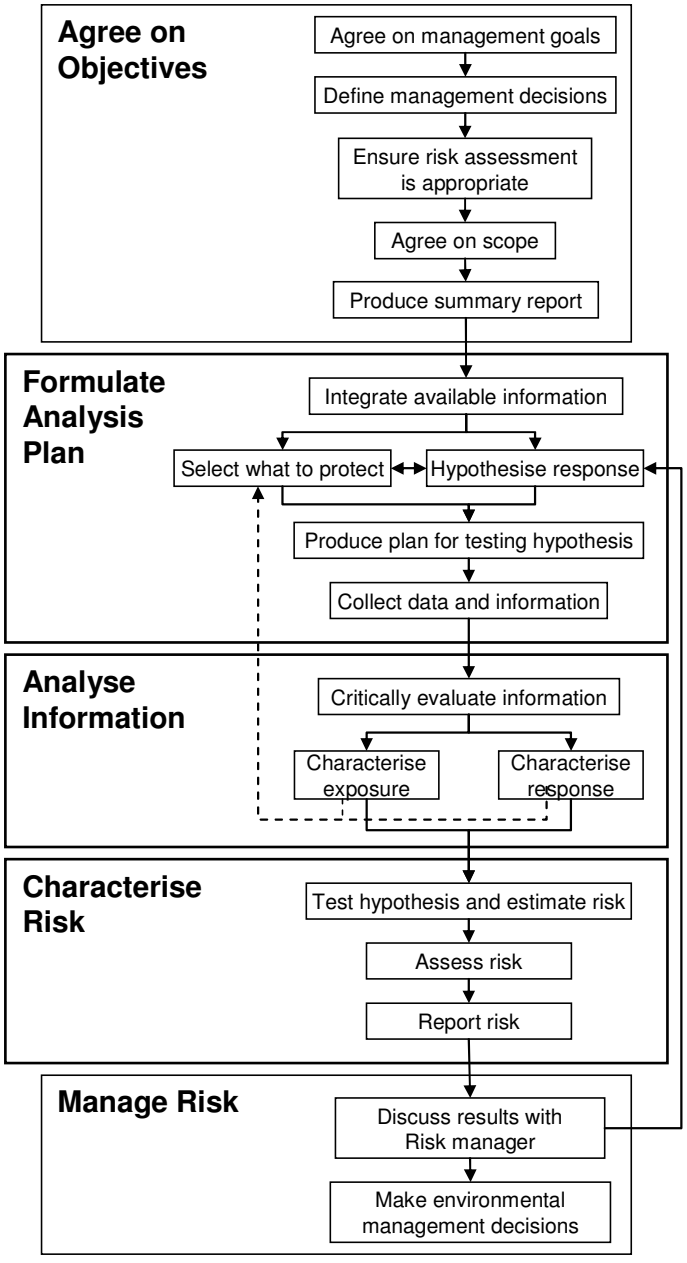


Figure 2.1: Actions in the draft ERA framework for South Africa (adapted from Murray and Claassen, 1999)
(foldout on page 195)

2.2.1. Agree on objectives

An ERA should be a process of sound scientific integrity. The ERA should take account of relevant political, economic and social issues, though it should not be biased or compromised by them. Accordingly, the formal assessment should be preceded by interaction between the risk manager, stakeholders and the risk assessor.

The US EPA guidelines (EPA, 1998) specify the first step in planning as determining if a risk assessment is the best option for supporting the decision. In the evaluation of the approach, it was established that management goals have been established and the management decisions (options) have been defined prior to assessing the appropriateness of the risk assessment.

Agree on management goals. Establishing the goals is primarily the task of the risk manager. The risk assessor, however, needs to ensure that the goals can be represented by definitive ecological values, in agreement with the risk manager.

Define management decisions. The more explicitly the management decisions that are to be supported by the risk assessment can be defined, the better the risk assessment is likely to be aligned with those decisions. The options available to managers are important in the assessment.

Ensure risk assessment is appropriate. The next important issue is whether a risk assessment will enable managers to make informed environmental decisions, compared to other approaches.

Agree on scope of risk assessment. Both parties need to be clear on constraints of data availability, scientific knowledge, financial resources and spatial and temporal scales. Of particular importance is the maximum uncertainty that the risk manager will tolerate. The lower the tolerance the more extensive the assessment is likely to be.

Produce summary report. Ideally, a summary report of this dialogue should be produced prior to the assessment, which will provide a point of reference for subsequent work.

2.2.2. Formulate analysis plan

Integrate available information. Issues including the sources of stressor and stressor characteristics as well as exposure mechanisms and time frames must be addressed. Information on the ecosystem potentially at risk needs to be evaluated as well the likely ecological effects (responses) of the ecosystem to the stressor. Key information necessary for planning the assessment should be collected.

Select what to protect. The risk assessor must identify potential assessment endpoints. These include both the ecological entity considered to be of value (e.g. a species) and the characteristic of that entity that is potentially at risk (e.g. reproduction success). The ecological relevance of the endpoints, their susceptibility to the particular stressors and their relevance to management goals are important selection criteria.

Hypothesise responses. Risk hypotheses are predictions of relationships between stressor, exposure and the response of the assessment endpoints. To facilitate clear communication one should also develop a corresponding diagram of stressors, endpoints, responses, exposure routes and ecosystem processes. This conceptual diagram should represent the risk hypotheses.

Produce plan for testing hypotheses. The risk assessor should describe how the risk hypotheses will be assessed. There are various measures that should be selected at this point. One group consists of measures of effect that evaluate the response of the assessment endpoint when exposed to a stressor. Another constitutes measures of exposure which establish mechanisms by which exposure occurs. A third group comprises measures of ecosystem and receptor characteristics which affect the assessment endpoints. The analysis plan should also include how data will be analysed or modelled and how results will be presented. Finally the analysis plan should be discussed with the risk manager to ensure that the results are indeed those that the manager requires to make sound decisions. It may be necessary to iterate a number of times through the steps of this stage.

Collect data and information. The plan should clearly identify the data that needs to be measured and the information that needs to be collated.

2.2.3. Analyse information

The second formal stage of an ERA comprises the following actions:

Critically evaluate information. This activity is a more detailed examination of existing information than that carried out as the first step of the first stage of formulating the analysis plan. First the risk assessor must critically evaluate existing studies. The strengths and limitations of data from various sources must be established. These sources include laboratory and field studies, indices, experience from similar situations, structure activity relationships and models. The purpose and scope of existing studies should be carefully compared with those of the risk assessment. Each study must have been conducted properly. The next step is to evaluate uncertainty. What is known and not known about exposure and effects should be described and, preferably, quantified. Potential sources of uncertainty include unclear communication, errors in the information itself, gaps in the data, uncertainty about a quantity's true value and model uncertainties. An important aspect is to distinguish between natural variability and lack of knowledge. The risk assessor may also need to measure new data if necessary.

Characterise exposure. To describe the stressor source, the risk assessor must describe the place where it is released or the action that produces it. If the original source no longer exists then the current origin of the stressors is defined as the source (like sediments contaminated by an industrial plant that no longer operates). The intensity and timing of stressor generation must also be addressed. The next step is to describe the stressor spatial and temporal distribution. Pathways that stressors take from the source must be evaluated. Chemical stressors will require an assessment of the media between which they may partition. The attributes of physical stressors, like the size of suspended solids, may influence their fate. Other physical stressors, like filling a wetland or flooding a valley, will not involve pathways but rather evaluation of secondary stressors. Biological stressors may disperse by diffusion or jump dispersal (erratic spread over time). Ecosystem characteristics will influence all the above. It is important to identify secondary stressors caused by the primary stressor, which can significantly influence the result of a risk assessment. The final step is to describe the exposure (i.e. stressor and receptor contact). This is a critical step because without exposure there can be no risk. It involves describing how, when, where and to what degree the stressor

and receptor will occur simultaneously. Both contact and uptake must then be considered. Finally, with this information, the risk assessor must integrate into an exposure profile which is a summary of what has been learned.

Characterise Responses. The first task is to clearly identify applicable effects of the stressor on the ecosystem. This may involve further examination of existing studies and should confirm that the effects are consistent with the assessment endpoints and the conceptual model. The second task is to perform an ecological response analysis. This stressor response analysis should relate stressor levels to ecological effects, preferably quantitatively. It should also establish cause and effect relationships (causality). Finally it should link measures of effects with assessment endpoints. Sometimes the latter cannot be monitored directly. In this case, sound and explicit linkages between those effects that can be measured and the assessment endpoints are needed. These can be based on expert judgement but are preferably based on empirical or process models. The final task is to integrate into a stressor response profile which is a summary of what has been learned. Information gathered at this stage may necessitate returning to an improved formulation of the analysis plan, for example, to modify the endpoints selected.

2.2.4. Characterise risk

This is the final formal stage of an ERA. The US EPA guidelines document (EPA, 1998) is not explicit in referring back to the stated risk hypothesis. In developing the framework for ERA in South Africa, it was suggested that this link be made explicit.

Test hypotheses and estimate risk. The risk assessor must determine the likelihood of adverse effects to assessment endpoints by integrating exposure and effects data and evaluating any associated uncertainties. The assessor uses the exposure and stressor response profiles developed in stage two according to the analysis plan produced in stage one. It is at this point that the previously defined hypotheses are tested. Risk estimates can be obtained in one or more ways. First, they can be expressed qualitatively based on professional judgement (low, medium and high or yes and no). Secondly, they can be expressed as single point estimate usually as a ratio of two numbers. Typically this would be an exposure concentration divided by an effects concentration and are commonly used for chemical

stressors. Thirdly, they can incorporate the entire stressor response relationship. This is appropriate when the stressor level is related to the magnitude of response by a curve. Fourthly, they can incorporate variability in exposure or effects. Variability in exposure can be used to describe risks to moderately or highly exposed members of a population. Variability in effects can be used to describe risks to average or sensitive population members. These provide a convenient means of comparing different risk management options. Fifthly, risk assessors can use process models upon which to base risk estimates. Models are mathematical expressions that represent our understanding of the mechanistic operation of the system. They have the major advantage of allowing "what if" scenarios to be examined. Finally, risk assessors can perform field studies and base estimates directly on the results.

Assess risk. It is essential that a technical narrative accompany the estimated risk. Its first task is to evaluate lines of evidence. An attempt should be made to use fundamentally different (i.e. independent) approaches in support of the conclusions, for example, quotients and field studies. The second task is to determine whether changes are adverse. The assessor must evaluate the nature and intensity of the effects, the spatial and temporal scales and the potential for recovery.

Report risk. The results of the risk assessment should be presented clearly and concisely. It should include a degree of detail appropriate to the kinds of management decisions that need to be taken.

2.2.5. Manage risk

Discuss the results with the risk manager. The risk manager needs to ensure that the necessary environmental management decisions can be soundly supported by the results of the risk assessment. If not, then another more detailed risk assessment may be requested and a new analysis plan formulated. A risk assessment process is iterative by nature. It is possible that the process will be completed first at a rather superficial level. If results are not sufficiently sound to support the required management decisions then, resources permitting, the assessment may be repeated at a more detailed level. Individual stages may also require internal iteration before the required results are obtained.

Make environmental management decisions. The risk manager uses the results along with other relevant social, legal, political or economic information to make decisions on how to proceed. This may include invoking mitigation measures, monitoring progress and communicating results to the public.

2.3. Discussion

The drafting of a framework for ERA in South Africa followed the approach of the US EPA guidelines (EPA, 1998). The South African framework placed specific emphasis on what needs to be done (actions). There are two areas where the draft framework for ERA in South Africa deviates from the US EPA guidelines. The first is in the sequence of the "Agree on objectives" phase. In the case of the South African draft framework, explicit reference is made to agreeing on the management goals and defining the management decisions that are to be supported before a decision is taken on whether ERA is an appropriate approach. Secondly, the South African draft framework makes explicit reference to testing the risk hypothesis in the "Characterise risk" phase. The framework is applied to an effluent discharge case study in Chapter 3, on the basis of which changes are incorporated and the framework is expanded to provide text which motivates why each action is required (Chapter 4). International forums were used to discuss developments with peers and to get reviewer's comments on the proposed framework (Claassen et al., 2001a).

3. Industrial Effluent Case Study

The proposed South African framework for ERA (Chapter 2) was evaluated through applying it to a case study. The selected a case study was sufficient in scope to evaluate all the steps in the ERA process, provided sufficient technical detail to evaluate the technical approach and was representative of practical applications. The case study does not represent an ideal case, but represented the limitations encountered in real life cases. The approach, analyses and results of the case study are presented, and the South African framework for ERA is evaluated on the basis of the study.

3.1. Introduction

With gold as the catalyst that fuelled the industrial awakening of SA, the discovery of the Witwatersrand Reef in 1886 resulted in Johannesburg becoming the largest market for dynamite in the world. The construction of the ”Zuid Afrikaansche Fabrieken voor Ontplofbare Stoffen Beperk”, a company formed expressly to supply dynamite to the mines, started in April 1895. The formation of African Explosives and Industries (later African Explosives and Chemical Industries) in 1924 paved the way for the establishment of the biggest commercial explosives factory in the world. Today, African Explosives Limited (AEL) is one of the world's largest manufacturers and suppliers of commercial explosives and initiating systems (AEL, 2002).

The proposed framework for ERA in South Africa (Chapter 2) was applied to AEL’s effluent monitoring programme. The broad objectives were to assess and quantify the impacts of AEL's operations on the receiving waters, in the context of the regulatory requirements and in support of pro-active management initiatives. An ERA is predictive when the characteristics of the stressor are known and the expected magnitudes of the consequences are determined. In cases where the consequences are expressed, the assessment can be retrospective, and aimed at characterising the stressor profile that lead to a specific condition. In the case of AEL, some information about the stressors (effluent), the consequences (ecosystem characteristics) and the mechanisms (toxicity) were available. The assessment was thus

carried from both retrospective and predictive perspectives, which also allowed for an audit approach to be followed. This approach used exposure, dose-response and effects data to verify the conceptual model and the appropriateness of regulatory standards. The method proposed by the United States Environmental Protection Agency (EPA, 1998) was adapted (Chapter 2) and what follows is an account of the assessment within the revised framework (Figure 3.1).

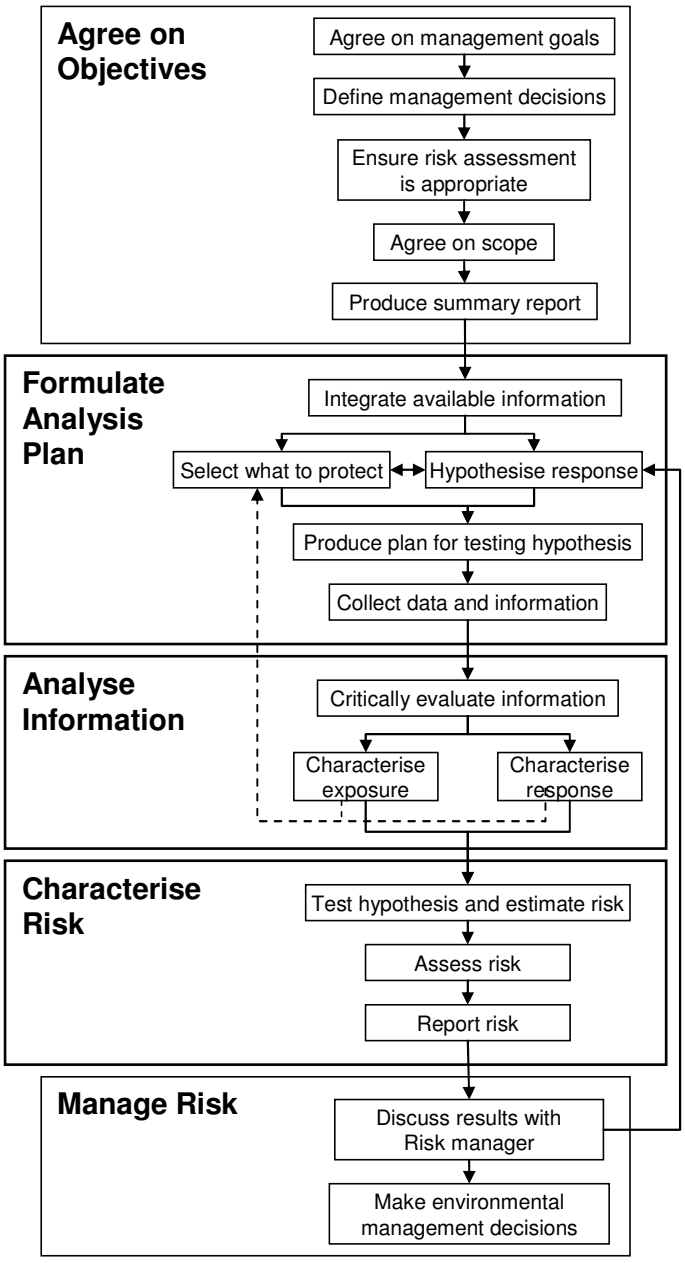


Figure 3.1: The South African draft framework for ERA (adapted from Murray and Claassen, 1999).

3.2. Agree on Objectives

3.2.1. Agree on management goals

The current management of AEL is singularly focussed on achieving the business strategy through the stringent adherence to the value system. The values that drive AEL's strategy and business processes are the following (AEL, 2002):

- Protecting you and your environment
- Service beyond expectations
- Innovative products and services
- Investment in quality
- "Respect for individuality
- Encouraging growth and self-advancement
- Continuous pursuit of service excellence
- Integrity and honesty beyond reproach

These principles culminated in the AEL group stating their commitment to environmental responsibility in their 2002 Safety Health and Environment performance targets (AEL, 1995). These targets briefly state that AEL will:

- Introduce waste minimization programmes in all AEL companies by 1997
- Reduce solid hazardous waste per unit of production by 50% of 1995 volumes
- Reduce non-hazardous waste per unit of production by 30% of 1995 volumes
- Reduce water usage per unit of production by 15% of 1995 volumes
- Reduce energy consumption per unit of production by 15% of 1995 volumes
- Ensure that the necessary remediation of all of AEL's sites is defined, progressed and reported on in accordance with an approved prioritised programme by 1997

AEL's commitment to sound environmental management practices is in line with the intent and spirit of the National Water Act (NWA; Act 36 of 1998). The NWA provides the legislative context on which the management goals of DWAF are based. The NWA defines water as a public asset, which needs to be managed on a sustainable basis to the benefit of all

the people of SA. The sustainability of management practices relates to source directed controls (SDC) and resource directed measures (RDM) in the NWA. RDM means that sufficient water (the quality and quantity of physical, chemical and biological components) needs to be maintained to sustain the ecological functioning (the ecological Reserve) at a specified level (according to the management class) and provide for the basic human needs of people that are, or may be, supplied from the specific resource. The resources that are not needed for these basic functions are available for allocation. SDC provide for the management of sources of pollution or impacts. This assessment deals specifically with risks related to the ecological functioning of the resource (RDM), although the information may also be used support SDC.

AEL obtained a discharge exemption permit for the disposal of effluent from DWAF at the end of May 1997, which serve to give effect to AEL's and DWAF's management objectives (1706B, Appendix A). The permit required compliance to water quality and quantity specifications at a site downstream of AEL (W6) and at two AEL discharge streams (W5 and W20; Figure 3.2 and Figure 3.3). Temporary relaxation was granted on an annual basis for W5 and W20 to allow for the implementation of cleaner technologies (Table 3.1).

Table 3.1: Permit specifications for AEL at W5, W20 and W6 (Figures 3.2 and 3.3).

	Variables										
	Flow	pH	EC	NO_3	NO_2	NH_3	SO_4	F	COD	PO_4	Na
	m^3/h	-log $[H^+]$	mS/m	mg/ℓ-N			mg/ℓ				
Permit specifications											
W5	250	>5.5<8.0	<120	<12	<1	<2	<200	<2	<50	<1	60
W20	10	>5.5<8.0	<120	<12	<1	<2	<200	<2	<50	<1	90
W6	-	>5.5<8.0	<120	<6	<0.5	<1	<200	<1.5	<50	-	-
Temporary relaxation W5											
From 1/7/1996	400	-	195	51	-	73	400	12	-	2.2	130
From 1/7/1997	330	-	195	43	-	61	400	8	-	1.4	130
From 1/7/1998	290	-	195	34	-	45	400	8	-	1.4	130
From 1/7/1999 to 30/6/2002	280	-	160	25	-	35	200	6	-	1.4	60
Temporary relaxation W20											
From 1/7/1996	46	-	310	120	-	23	770	1.1	-	0.9	260
From 1/7/1997	46	-	310	120	-	23	770	1.1	-	0.9	260
From 1/7/1998	46	-	160	15	-	11	650	1.1	-	0.9	104
From 1/7/1999 to 30/6/2002	10	-	150	10	-	10	590	1.1	-	0.9	90

Figure 3.2: Geographic perspective of AEL and monitoring sites.

(foldout on page 196)

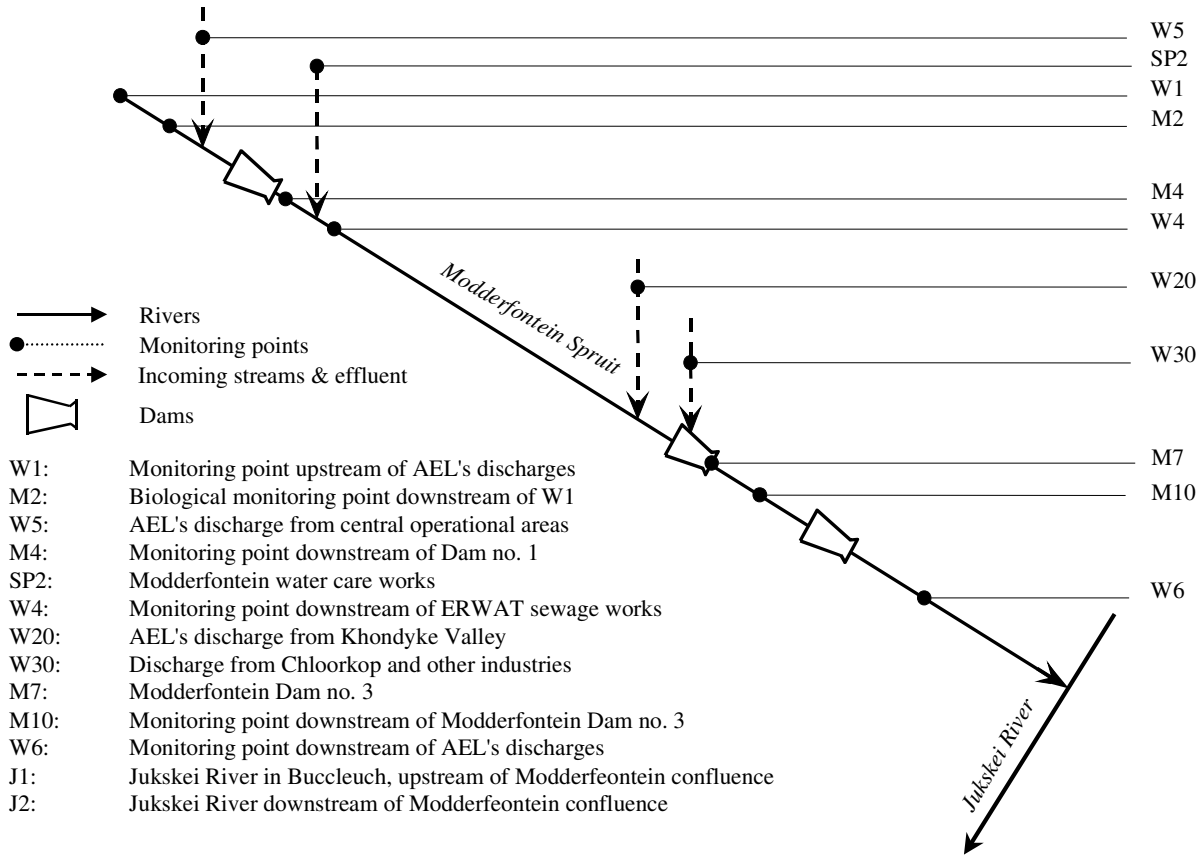


Figure 3.3: Schematic presentation of AEL study area and monitoring sites.
(foldout on page 197)

A biomonitoring program is stipulated as part of the permit specifications, to "qualify and quantify the biological impacts due to the exemptee's {AEL} activities on the water environment along and downstream of the Modderfontein Spruit[2]". This programme should include "the compilation of a sequential database from which the extent and frequency of the future biomonitoring can be developed and consistently improved to serve as a reliable site specific biomonitoring program". SASS4 monitoring (Thirion et al., 1995) and monthly toxicity testing (Appendix B) is specified upstream and downstream of the discharge of W5 and W20, with toxicity tests also to include W1, W5, W6 and W20. A water chemistry and flow monitoring programme is also specified in the permit according to the variables and monitoring frequencies specified in Appendix A for W1, W5, W6 and W20.

2 “Modderfontein Spruit” is the name of a stream that runs past the AEL plant in the Modderfontein suburb. “Modderfontein” can be directly translated as “fountain of mud” and “Spruit” as “brooklet”.

3.2.2. Define management options

The management options that have been identified in discussion between the risk assessor (the author) and the risk manager (AEL environmental manager) are:

- Comply with the permit specifications
- Negotiate permit specifications with DWAF
- Pro-actively reduce AEL's impact on the receiving environment
- Participate in catchment management activities
- Compile information towards the environmental impact assessment (EIA) of AEL operation on the Hartebeespoort Dam, as specified in the permit

3.2.3. Ensure appropriateness of ERA

ERA was considered an appropriate method to evaluate the water quality aspects and the biomonitoring results from AEL's monitoring programme. Water quantity (flow) issues were considered where it had an impact on water quality and habitat. It should be noted that the impacts of flow alterations (from natural) could have significant impacts on ecosystems, but this stressor was not was identified as a priority by DWAF. The ERA approach allows for a probabilistic analysis of water quality (exposure assessment) and evaluation of monitoring results (effects assessment). Characterising the relationship between exposures and effects provides the capability to predict the response to anticipated future exposures. The ERA framework allows for a screening assessment (comparing water quality to literature data and confirming with monitoring that the results are relevant), with the option of more detailed site-specific analysis such as toxicological analysis to assess the relationship between water quality with the response of species that occur in the system.

3.2.4. Agree on scope

The effluent discharge permit specifies water quality standards within AEL's boundaries. This includes site W1 as the upper boundary and W6 as the downstream limit. The permit does, however, require a full impact assessment if the quality standards cannot be complied with by 2002. Such an assessment is to include the Hartbeespoort Dam and the users of water from the dam. The impact assessment should thus provide information regarding the

significance of AEL's operations on the Modderfontein Spruit, the Jukskei River and the Braamfontein Spruit.

Historical information is important insofar as it relates to the water quantity, water quality and ecological status of the relevant systems. The actual assessment used recent monitoring information to determine the likelihood of impact, and this information is used to make predictions regarding future scenarios.

The study did not attempt to address social, political or economic issues except where it was essential for the development of the assessment plan or the evaluation of options.

The agreed objectives of the ERA were to determine the probability and magnitude of impacts of AEL's operations on aquatic ecosystems in the Modderfontein Spruit, specifically considering the current conditions, permit specifications and future scenarios for variables specified in the permit and on a whole effluent basis

3.2.5. Produce summary report

The preceding description is a summary of the outcome of the "Agree on Objectives" phase, and was presented to AEL before the planning of the assessment commenced. The report provided strong arguments for the use of a risk based approach and in addition to agreeing to the approach, AEL commissioned additional monitoring to strengthen the assessment.

3.3. Formulate Analysis Plan

3.3.1. Integrate available information

The purpose of this step is to inform the planning process. The policy environment within which the assessment was done was complicated due to a transition from old to new legislation. The original permit was granted in terms of section 21(4) of the Water Act (Act 54 of 1956) "*in respect of the purification or treatment of water used for industrial purposes, including any effluent resulting from such use and the disposal of the purified or treated*

water, including water recovered from any effluent" (Appendix A). The permit was negotiated in the paradigm of the pollution prevention approach and receiving water quality objectives (RWQO; DWAF, 2002a). With the support of technological and economic justification and justified by the RWQO approach, exemptions to the general and special effluent standards were granted. The promulgation of the NWA brought a dramatic change to the context for water resource management, specifically regarding the protection of the resource. Participation in catchment management is of critical importance in this framework, therefore the assessment had to give due consideration to issues that would contribute to engagement in catchment management. AEL's own environmental health and safety and general management policies (section 3.2) also affected the evaluation. In addition to the regulatory context, the site-specific issues were also considered during this stage.

The following potential sources of stressors have been identified in previous studies (Rall et al., 1995; DWAF, 1995b; van Veelen and Venter, 1996; Du Preez, 1997):

- AEL's effluent discharge (W5)
- AEL's non-point source pollution (W20)
- Power generation industries (upstream of W1)
- Residential runoff (upstream of W1)
- Water treatment works (M5, SP2)
- Discharge from other industries (W30)
- Groundwater (not included in this assessment)

The following stressors specified in the effluent discharge permit were the focus of the assessment:

- Flow
- pH
- Electrical conductivity
- Nitrate and nitrite
- Ammonium
- Sulphate
- Fluoride
- Chemical oxygen demand
- Phosphate
- Sodium

Other potential stressors, such as organic compounds, metals and solid waste, were also evaluated in accordance with the requirements of the regulator. The stressors were measured *in situ*, which represents the conditions to which aquatic ecosystems are exposed.

The ecosystem at risk in the Modderfontein Spruit has been described by DWAF (1995b), Rall et al. (1995), van Veelen and Venter (1996) and du Preez (1997). The system is highly modified from its original state, with effluent contributing to the consistent flow (little seasonal fluctuation) and modified water quality. Previous studies found only four fish species in the system, with the riparian vegetation and instream habitat also being severely modified. The ecosystem was affected by water quality, including high nutrient loads with the lack of suitable habitat compounding the problem.

The following species (Class *Osteichthyes*) represent the historical distribution of fish in the upper reaches of the Jukskei River (DWAF, 1995b):

Barbus anoplus	Chubbyhead barb
Clarias gariepinus	Sharptooth catfish
Tilapia sparmanii	Banded tilapia
Pseudocrenilabrus philander	Southern mouthbrooder

During 1993 and 1994, DWAF (1995b) and Rall et al. (1995) reported the presence of the following organisms (Barnes, 1987) in the Modderfontein Spruit:

Tubifex spp.	(Class: Oligocheata; Order: Tubificida; Family: Tubificidae)
Daphnia spp. (Water fleas)	(Class: Branchiopoda; Order: Diplostraca)
Macrocyclops spp.	(Class: Copepoda; Order: Cyclopoida)
Potamonautus warreni (Freshwater crab)	(Class: Malacostraca; Order: Decapoda)
Chironomidae (Family) (True flies)	(Class: Insecta; Order: Diptera)
Coenagrionidae (Family) (Damselflies)	(Class: Insecta; Order: Odonata)
Hemiptera (Order) (True bugs)	(Class: Insecta)
Cyprinus carpio (Common carp - exotic)	(Class: Osteichthyes)
Clarias gariepinus (Sharptooth catfish)	(Class: Osteichthyes)
Tilapia sparmanii (Banded tilapia)	(Class: Osteichthyes)
Gambusia affinis (Mosquito fish - exotic)	(Class: Osteichthyes)

3.3.2. Hypothesise response

The objective of the study was to determine the impact of AEL's operations on the receiving aquatic ecosystem. The objective could be achieved through developing a set of hypotheses, undertaking the studies required to inform the testing of the hypotheses and finally testing the hypotheses. It is important to note that the purpose in probabilistic assessments is not to reject (or accept) the hypothesis, but rather to express the degree to which the evidence points to adverse ecological effects. The hypotheses are best represented in a matrix (Table 3.2), with the temporal parameters presented on the one axis and stressor descriptions on the other.

The hypotheses were evaluated in the context of the conceptual diagram presented in Figure 3.4. The diagram distinguishes between sources, stressors, exposure routes, endpoints and measures, and provides potential causal links between these elements. It is important to identify significant elements and links, since evidence may be biased if key contributing factors are not identified.

3.3.3. Select what to protect

The assessment endpoints were identified during the development of the risk hypotheses. A summary of these endpoints are presented in Figure 3.4, with a description of the ecological entities considered to be of value, and their characteristic that is potentially at risk, being provided in Table 3.3. Although these endpoints are scientifically relevant to the study, the measures are not ideal. While acute response can be used as a first tier screen for harmful effects, the absence of acute toxicity should not be seen as proof that no harmful effects exist. The endpoints do represent different trophic levels in the ecosystem, from primary producers (algae) to consumers (invertebrates) and top predators (fish). The endpoints are relevant from a management perspective, since the public can relate to the presence of fish, while macro-invertebrates provide an effective monitoring endpoint and algae provide an important indicator for regulatory agencies. A problem with *in situ* measures are that specific stressors cannot be easily identified, but it does give an indication of the effects due to multiple stressors, similar to the analyses used in whole effluent evaluations.

Table 3.2: A summary of the testable case study hypotheses as a function of stressors (instream conditions or whole effluent) and temporal conditions (current, permitted and future conditions).
(foldout on page 198)

		Stressors	
		1. Specified variables at W6	2. Whole effluent
Temporal	A. Current conditions[3]	**1A** "Current values of specified variables do not pose an unacceptable risk to aquatic ecosystems"	**2A** "The current toxicity of effluents do not pose an unacceptable risk to aquatic ecosystems"
	B. Permit values	**1B** "Permitted values of specified variables do not pose an unacceptable risk to aquatic ecosystems"	**2B** "The toxicity of effluents at permitted values do not pose an unacceptable risk to aquatic ecosystems"
	C. Future scenario[4]	**1C** "Likely future values of specified variables do not pose an unacceptable risk to aquatic ecosystems"	**2C** "Likely future toxicity of effluents do not pose an unacceptable risk to aquatic ecosystems"

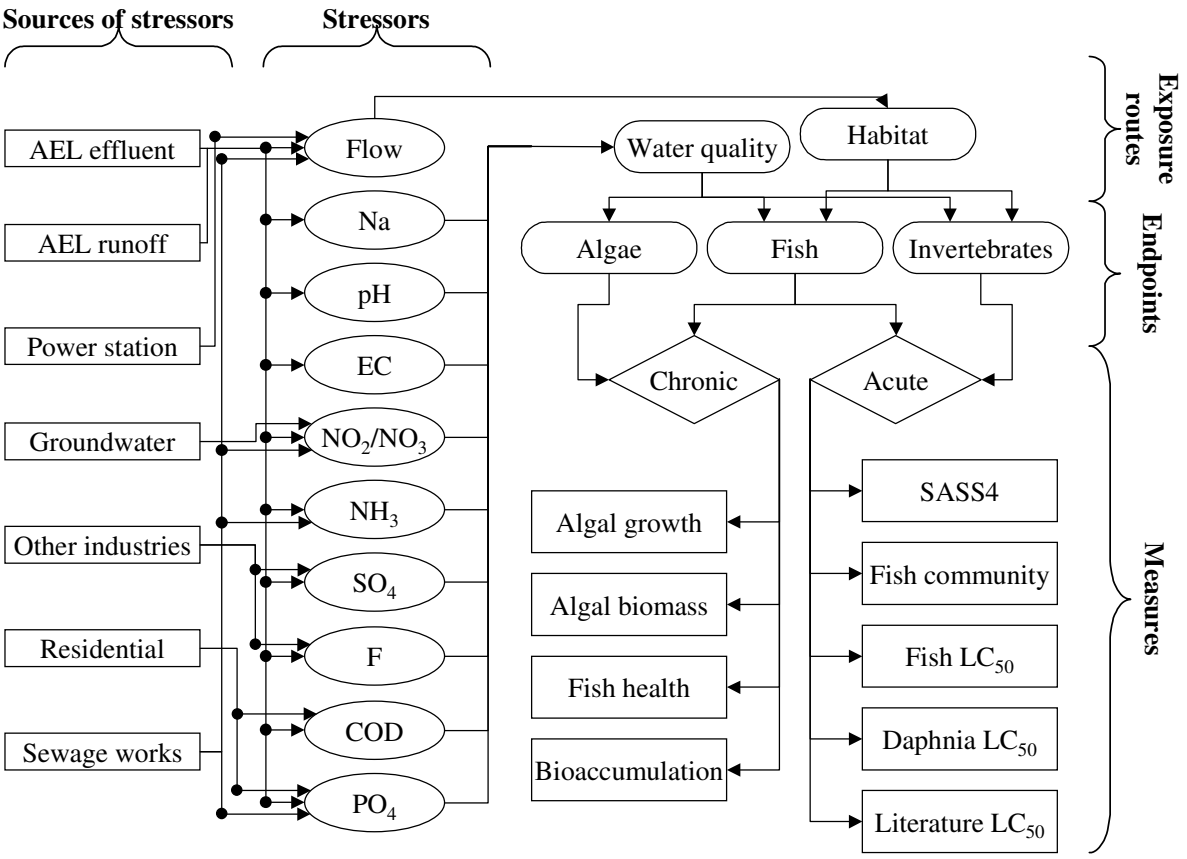
Specific phrases in the hypotheses have the following meanings:

Specified variables:	Variables regulated by the effluent permit (Appendix A) at W6, W20 and W30. (pH, EC, Nitrate, Nitrite, Ammonia, Sulphate, Fluoride, COD, Phosphate, Sodium and Flow)
Unacceptable risk:	Acute effects in the receiving water or effluent, chronic effects in receiving waters that threaten the sustainability[5] of populations or any stressor that threatens the sustainability[5] of the aquatic ecosystem.
Aquatic ecosystems	Includes all of the aquatic organisms in the Modderfontein Spruit and their interaction with the physical environment, where the flow of energy leads to clearly defined trophic structure, biotic diversity and material cycles.
Whole effluent:	Although the effluent at W20 and W30 are permitted on the basis of water quality parameters, the effluent permit also specifies that toxicological analyses and biological monitoring must be conducted. The hypothesis will be evaluated by taking all available information into account.
Permitted values:	This relates to the license conditions for 1/7/1998 to 30/6/1999, when the study was conducted
Future scenario:	This relates to the permit specifications from 1/7/1999 to 30/6/2002. Here the hypotheses are stated as likely future values, since compliance is not guaranteed – especially given evidence of historical non-compliance.

3 Since AEL are not meeting their licence conditions, current conditions and permit values represent different hypotheses.

4 Future scenario refers to the licence conditions without temporary relaxation.

5 The ability of the populations and ecosystems to sustain production and reproduction



LC_{50}: The concentration at which 50% of a test population show acute effects. The LC_{50} for literature was selected (rather than NOEC or LOEC) to serve as a comparison with site-specific toxicity assays.

Fish health: The health of a fish community, expressed by measures of abundance and diversity

SASS4: South African scoring system, version 4 (Thirion et al., 1995)

Figure 3.4: A conceptual model, showing the relationship between stressor sources and endpoint measures.

Table 3.3: Endpoints selected for the assessment and measures of effect.

Assessment endpoint	**Characteristics measured**
Macro-invertebrates	Benthic - Diversity and abundance (SASS4) *Daphnia pulex* - Acute response (LC_{50} bioassay)
Fish	Diversity and abundance Bioaccumulation (metals) *Poecilia reticulata* - Acute response (LC_{50} bioassay)
Plants	Planktonic algae - Biomass (chlorophyll-a) *Selenastrum capricornutum* - Chronic response (growth bioassay)

3.3.4. Produce plan for testing hypothesis

Unacceptable risk was defined as acute effects in the receiving water or effluent, chronic effects in receiving waters that threaten the sustainability of populations or any stressor that threatens the sustainability of the aquatic ecosystem. (Table 3.2 footnote) The testing of the hypotheses to assess the risk posed by the variables specified in the permit was done through a comparison of toxicity data from the literature with permit values at W6, as presented in Table 3.4. Acute toxicity data were obtained for a representative range of aquatic species (EPA, 2000), with dose-response profiles being drawn up for variables of concern. The values presented in Table 3.4 were plotted on the response profiles to determine the potential risk to representative species. The results were also compared with data from biomonitoring and bioassays to confirm its relevance. The conditions upstream of AEL were also assessed and compared with downstream conditions to determine AEL's impact. The lines of evidence are presented in Figure 3.5. The response profile and actual monitoring data could be used to support management decisions related to future regulatory requirements.

Table 3.4: Current, permitted and likely future values for variables at W6.

	Flow	**pH**	**EC**	**NO_3**	**NO_2**	**NH_3**	**SO_4**	**F**	**COD**	**PO_4**	**Na**
	m^3/h	-log $[H^+]$	mS/m	mg/ℓ-N			mg/ℓ				
Current state[6]											
50th percentile	981	6.9	1530	43.0	-	13	360	3.1	32.5	0.7	137
90th percentile	1553	>4.4<7.3	1654	55.8	-	21.4	420	4.6	51.5	1.1	163
99th percentile	2109	>4.0<7.4	1695	59.2	-	37.1	486	5.0	87.2	1.8	188
Permit specifications											
Until 30/6/2002	-	>5.5<8.0	<120	<6	<0.5	<1	<200	<1.5	<50	-	-
Future scenario											
From 30/6/2002	-	>5.5<8.0	<120	<6	<0.5	<1	<200	<1.5	<50	-	-

"-" Not available

6 Bi-weekly sampling during 1998 (n=23)

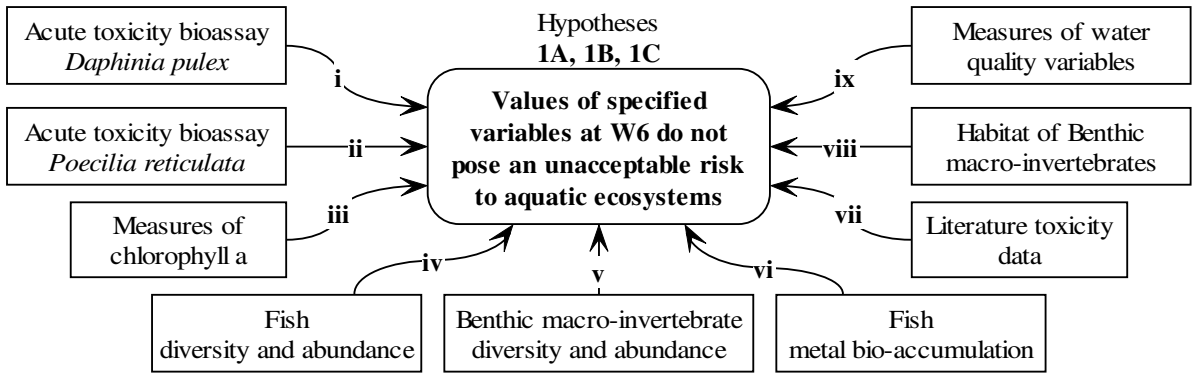


Figure 3.5: Lines of evidence that are used for evaluating risk posed by selected variables (Table 3.1) in the Modderfontein Spruit.
(foldout on page 199)

The hypotheses were tested according to the values for W5 and W20 specified in Table 3.5 and Table 3.6 respectively. The lines of evidence that were used to evaluate the hypotheses are presented in Figure 3.6. The hypotheses that deal with the risks on a whole-effluent basis were tested by conducting whole-effluent toxicity tests and supported by comparing specific variable concentrations with published toxicity values (Table 3.7).

Table 3.5: Current, permitted and possible future values for variables at W5.

	Variables										
	Flow	pH	EC	NO_3	NO_2	NH_3	SO_4	F	COD	PO_4	Na
	m^3/h	-log $[H^+]$	mS/m	mg/ℓ-N			Mg/ℓ				
Current status											
50th percentile	301	4.7	325	102	-	115	776	11.8	176	5.5	212
90th percentile	407	>2.1<9.0	600	200	-	210	1260	19.8	457	10.8	304
99th percentile	544	>1.7<12.4	998	450	-	450	2040	27.9	823	16.0	890
Permit specifications											
From 1/7/1998 To 30/6/1999	290	>5.5<8.0	195	34	<1	45	400	8	<50	1.4	130
Future scenario											
From 1/7/1999 to 30/6/2002	280	>5.5<8.0	160	25	<1	35	200	6	<50	1.4	60
From /7/2002	250	>5.5<8.0	<120	<12	<1	<2	<200	<2	<50	<1	60

"-" Not analysed

Table 3.6: Current, permitted and possible future values for variables at W20.

	Variables										
	Flow	pH	EC	NO_3	NO_2	NH_3	SO_4	F	COD	PO_4	Na
	m^3/h	-log $[H^+]$	mS/m	mg/ℓ-N			mg/ℓ				
Current status											
50th percentile	22.9	4.9	3410	82	-	10	700	1.1	60	0.7	257
90th percentile	55.3	>3.2<6.6	3804	180	-	25	808	1.5	145	1.6	310
99th percentile	86.5	>2.8<8.2	4195	529	-	241	866	2.4	445	7.7	354
Permit specifications											
From 1/7/1998 to 30/6/1999	46	>5.5<8.0	160	15	-	11	650	1.1	<50	0.9	104
Future scenario											
From 1/7/1999 to 30/6/2002	10	>5.5<8.0	150	10	<1	10	590	1.1	<50	0.9	90
From 1/7/2002	10	>5.5<8.0	<120	<12	<1	<2	<200	<2	<50	<1	90

"-" Not available

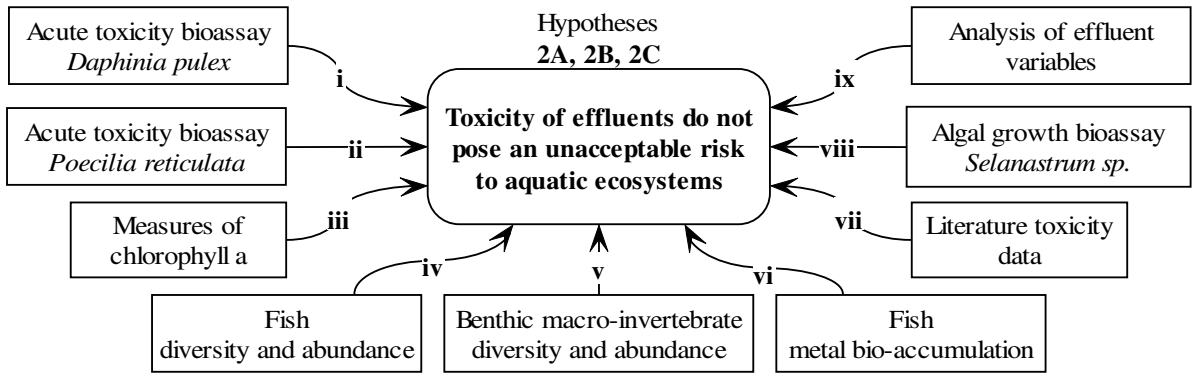


Figure 3.6: Lines of evidence that are used for evaluating risk posed by selected variables (Table 3.1) in whole effluent discharge.
(foldout on page 199)

3.3.5. Collect data and information

This stage of the assessment presents the data collected and specifies which part of the analysis plan was supported by the data. The evaluation of evidence is presented in section 3.5.1.

Various lines of evidence were used to test the hypotheses that "Current, permitted and future values of specified variables do not pose an unacceptable risk to aquatic ecosystems" (hypotheses1A, 1B and 1C, Table 3.2). The first and second lines of evidence (i and ii in Figure 3.5) relate to acute toxicity of the river water at W6 to *Daphinia pulex* and *Poecilia reticulata* respectively. The results obtained from screening analyses are presented in Table 3.7. The assays were conducted at a monthly interval during the study period according to the method presented in Appendix B (Slabbert et al., 1998).

Table 3.7: Screening bioassays of water at Modderfontein Spruit sites.

Bioassays	***Daphnia pulex**** **(% mortality after 48 hrs)**					***Poecilia reticulata**** **(% mortality after 96 hrs)**				
	W1	**M4**	**W4**	**W6**	**M10**	**W1**	**M4**	**W4**	**W6**	**M10**
June 1997	25	5	5	0	-	0	0	0	0	-
July 1997	0	0	0	0	-	0	0	0	0	-
August 1997	0	0	0	0	-	0	0	0	0	-
September 1997	30	80	25	0	-	0	40	0	0	-
October 1997	0	20	0	65	0	0	0	0	0	0
November 1997	0	0	0	0	0	0	0	0	0	0
December 1997	30	0	0	30	0	0	0	0	0	0
January 1998	0	0	0	45	0	0	0	0	0	0
February 1998	0	0	0	0	0	0	0	0	0	0
March 1998	0	0	0	0	0	0	0	0	0	0
April 1998	0	20	0	0	0	0	0	0	0	0
May 1998	0	0	0	0	0	0	0	0	0	0
June 1998	0	0	0	0	0	0	0	0	0	0
July 1998	0	0	0	0	0	0	0	0	0	0
August 1998	0	0	0	0	0	0	0	0	0	0
September 1998	0	0	0	0	0	0	0	0	0	0
October 1998	0	0	0	0	0	0	0	0	0	0
November 1998	0	10	0	10	0	0	0	0	0	0
December 1998	0	5	0	0	0	0	0	0	0	0
January 1999	45	0	0	0	0	0	0	0	0	0
February 1999	0	5	0	0	0	30	0	0	0	0
March 1999	0	0	5	0	0	0	0	0	0	0
April 1999	0	5	0	0	0	0	0	0	0	0
May 1999	0	0	5	15	5	0	0	0	0	0

- No mortality in control experiments

The assays represent an objective, independent evaluation of standard laboratory organisms' response to the river water. The use of replicates reduces the possibility of analytical errors. The assays are not designed to quantify the toxicological response (i.e. determine NOEC, LC_0, LC_{50} etc.), but to determine whether the sample induces an acutely toxic response to the test organisms within the test duration. Any acute response (>0% mortality) is viewed as

unacceptable according to the criteria in Table 3.2. *Daphnia pulex* occurs in the study area, but the laboratory culture does not represent the gene pool of the Modderfontein Spruit. *Poecilia reticulata* is an exotic fish species, which is used to represent the potential response of fish.

Chlorophyll-a concentrations were recorded at W6 from October 1997 onwards, as an indication of planktonic algae biomass. The results from the analyses (line of evidence iii in Figure 3.4) are presented in Table 3.8. The chlorophyll-a measures are useful for describing primary production, because it is a rapid, cheap and sufficiently sensitive method, which usually correlates well with primary production and phytoplankton biomass (Eloranta and Eloranta, 1977). Because primary production is system and season-specific, comparisons between sites and over time were used to evaluate the hypotheses that "Current, permitted and future values of specified variables do not pose an unacceptable risk to aquatic ecosystems" (hypotheses 1A, 1B and 1C, Table 3.2), rather than to use benchmarks values (generic guideline values) or data from other systems.

Table 3.8: Chlorophyll-a measures (µg/ℓ) at Modderfontein Spruit sites.

	W1	**M4**	**W4**	**M10**	**W6**
October 1997	7	79	43	14	14
November 1997	1	14	20	3	6
December 1997	8	3	9	6	9
January 1998	6	57	43	26	12
February 1998	1	26	34	152	72
March 1998	2	2	95	83	109
April 1998	3	9	9	60	97
May 1998	58	7	5	71	149
June 1998	6	12	13	3	11
July 1998	13	279	221	1	5
August 1998	4	242	136	10	48
October 1998	0	6	18	9	17
November 1998	3	19	18	21	19
December 1998	1	38	66	140	108
January 1999	4	40	41	230	101
February 1999	6	61	8	26	17
March 1999	2	109	104	71	53
April 1999	2	6	3	55	21
May 1999	1	30	32	50	14
Mean	*7*	*55*	*48*	*54*	*46*
Variance	*164*	*6123*	*3123*	*3777*	*2049*

Fish were collected in a dam upstream of W6, at M7 [7]. The diversity and abundance (Table 3.9) provide information (line of evidence iv in Figure 3.4) towards evaluating the hypotheses that "Current, permitted and future values of specified variables do not pose an unacceptable risk to aquatic ecosystems" (hypotheses 1A, 1B and 1C, Table 3.2). The essence of biological monitoring is that one cannot protect the health, condition or quality of an entire natural system without information about the condition of that system and the organisms that inhabit it (Cairns and van der Schalie, 1980).

Table 3.9: Fish diversity and abundance at M7 during April 1998.

Species recorded	Abundance
Clarias gariepinus - Sharptooth catfish	4 (26 minutes gill-net catch effort)
Tilapia sparmanii – Banded tilapia	1 (26 minutes gill-net catch effort)

The diversity and relative abundance of benthic macro-invertebrates and associated habitat, as assessed with the South African Scoring System, version 4 (SASS4; Thirion et al., 1995), Habitat Quality Index (HQI; Thirion et al., 1995) and Habitat Assessment Matrix (HAM; Thirion et al., 1995) supported the evaluation of hypotheses that "Current, permitted and future values of specified variables do not pose an unacceptable risk to aquatic ecosystems" (hypotheses 1A, 1B and 1C, Table 3.2) through lines of evidence v (benthic macro-invertebrate diversity and abundance) and viii (habitat of benthic macro-invertebrates) in Figure 3.4. These results are listed in Table 3.10a-c. During the risk assessment, it was found that the reference site used in the programme did not represent natural conditions. An alternative site was suggested, which was used from June 1998 onwards.

The accumulation of metals in fish tissues (representing line of evidence vi in Figure 3.4 and Figure 3.5) was assessed in April 1999. The data (Table 3.11) do not represent fish health directly, but confirm exposure to the metals of interest in support of evaluating the hypotheses that "Current, permitted and future values of specified variables do not pose an

7 The presented results on fish diversity and abundance do not represent a comprehensive assessment. In accordance with the criteria in the preface to Chapter 4, the case study presents a realistic scenario, where available data are not always ideal. A premise of ERA is the ability to evaluate all data as lines of evidence, and not just those which, in and by itself, lead to conclusive findings.

unacceptable risk to aquatic ecosystems" (hypotheses 1A, 1B and 1C, Table 3.2). Comparisons to other studies are used to determine the significance of the results.

Table 3.10a: Habitat Quality Index (HAM; Thirion *et al.*, 1995) scores at Modderfontein Spruit sites.

Sites	Modderfontein sites						Reference
	W1	M2	M4	W4	W6	M10	Sites *
June 1997	67	62	66	64	71	84	87
August 1997	61	87	74	73	88	82	92
October 1997	72	73	85	73	96	87	87
December 1997	86	79	76	82	87	76	75
February 1998	73	67	75	79	82	81	80
April 1998	73	72	78	75	81	68	84
June 1998	73	65	78	69	72	76	43
August 1998	70	63	74	71	79	81	79
October 1998	66	65	82	70	83	75	114
December 1998	76	69	73	80	89	88	72
February 1999	67	64	65	74	79	80	73
April 1999	67	63	75	70	72	73	77

* Braamfonteins Spruit at the River Club Golf Course until April 1998 and at Randpark from June 1998

Table 3.10b: Habitat Assessment Matrix (HQI; Thirion *et al.*, 1995) scores at Modderfontein Spruit sites.

Sites	Modderfontein sites						Reference
	W1	M2	M4	W4	W6	M10	Sites *
June 1997	68	57	72	68	83	83	95
August 1997	59	58	77	70	77	65	92
October 1997	69	55	74	75	84	77	78
December 1997	82	66	78	75	83	79	84
February 1998	72	68	74	77	86	86	78
April 1998	71	68	83	70	89	85	84
June 1998	76	61	77	83	82	81	47
August 1998	74	66	79	70	81	86	81
October 1998	75	70	74	67	94	84	95
December 1998	77	67	82	73	90	90	75
February 1999	75	62	77	71	81	83	89
April 1999	64	63	73	73	75	77	77

* Braamfontein Spruit at the River Club Golf Course until April 1998 and at Randpark from June 1998

Table 3.10c: South African Scoring System (SASS4; Thirion *et al.*, 1995) scores at Modderfontein Spruit sites.

Sites	Modderfontein sites						Reference
	W1	M2	M4	W4	W6	M10	Sites *
June 1997	3	9	10	8	19	21	20
August 1997	12	3	4	8	20	23	20
October 1997	23	3	18	17	17	24	72
December 1997	19	14	11	10	32	24	53
February 1998	31	25	44	10	32	40	51
April 1998	26	9	60	27	37	36	40
June 1998	48	11	44	28	40	45	86
August 1998	25	14	15	13	40	34	58
October 1998	14	27	17	20	50	35	53
December 1998	18	13	62	14	45	47	59
February 1999	20	18	55	38	34	52	67
April 1999	25	13	58	19	40	58	50

* Braamfontein Spruit at the River Club Golf Course until April 1998 and at Randpark from June 1998

Concentrations of selected metals in fish from the Modderfontein Spruit are listed in Table 3.11. The comparative body loads in fish for various South African rivers (Heath and Claassen, 1999) and the Modderfontein Spruit (ranked by mean, ± standard deviation) are as follows:

Chromium (µg/g dry weight):
Modderfontein (4.4 ± 2.2) > Letaba (3.6 ± 8.4) > Crocodile (3.2 ± 6.1) > Olifants (2.0 ± 1.6)

Molybdenum (µg/g dry weight):
Modderfontein (2.9 ± 1.4) - no data for other rivers

Nickel (µg/g dry weight):
Modderfontein (4.6 ± 5.6) > Crocodile (2.1 ± 4.0) > Letaba (1.7 ± 1.8)

Strontium (µg/g dry weight):
Modderfontein (47.7 ± 31.2) - no data for other rivers

Zinc (µg/g dry weight):
Luvuvhu (200 ± 125) > Olifants (170 ± 130) > Berg (135 ± 104) > Modderfontein (119 ± 61) > Sabie (114 ± 60) > Letaba (95 ± 46) > Crocodile (84 ± 73)

Literature data on toxic effects of the specified variables, obtained from the AQUIRE database (EPA, 2000), are summarised in Tables 3.12a-f. The data support the evaluation of the hypotheses that "Current, permitted and future values of specified variables at W6 do not

pose an unacceptable risk to aquatic ecosystems" (hypotheses 1A, 1B and 1C; Table 3.2). The water quality data presented in Figure 3.7 are compared with toxicity data from the literature in accordance with line of evidence vii (Figure 3.4). The analysis of the data is discussed in section 3.5.

Table 3.11: Metal concentrations in fish tissues at M7 during April 1999 (dry weight).

Scientific name	**Tissue**	**Cr** (μg/g)	**Mo** (μg/g)	**Ni** (μg/g)	**Sr** (μg/g)	**Zn** (μg/g)
Clarias gariepinus (1)	Liver	3	5	2	32	182
	Muscle	3	3	2	98	49
	Whole	8	<3	11	92	124
Clarias gariepinus (2)	Liver	6	6	4	26	180
	Muscle	5	3	3	19	52
	Whole	10	<3	23	68	262
Clarias gariepinus (3)	Liver	5	4	3	16	142
	Muscle	4	3	3	11	67
	Whole	2	<3	2	82	125
Clarias gariepinus (4)	Liver	3	3	3	12	103
	Muscle	4	4	3	13	53
	Whole	5	<3	4	74	132
Clarias gariepinus (5)	Liver	3	<3	2	67	142
	Muscle	2	<3	1	49	45
	Whole	3	4	3	56	130

Table 3.12a: Summary of acute toxicity of nitrate (LC_{50}) to various species (EPA, 2000).

Scientific name	**Common name**	**Taxa –Class**	**Time**	**mg/ℓ N**
Gambusia affinis	Western mosquitofish	Osteichthyes	96h	3
Daphnia magna	Water flea	Crustacea	48h	9
Poecilia reticulata	Guppy	Osteichthyes	96h	27
Caenorhabditis elegans	Nematode	Nematoda *	96h	44
Lepomis macrochirus	Bluegill	Osteichthyes	96h	58
Streptocephalus proboscideus	Fairy shrimp	Crustacea	24h	76
Brachionus calyciflorus	Rotifer	Rotifera *	24h	76
Polycelis nigra	Planarian	Turbellaria	48h	328

* Phylum

Table 3.12b: Summary of acute toxicity of sulphate (LC_{50}) to various species (EPA, 2000).

Scientific name	Common name	Taxa –Class	Time	mg/ℓ SO_4
Streptocephalus proboscideus	Fairy shrimp	Crustacea	24h	98
Brachionus calyciflorus	Rotifer	Rotifera *	24h	623
Dreissena polymorpha	Zebra mussel	Bivalvia	24h	151
Daphnia magna	Water flea	Crustacea	48h	2462
Ceriodaphnia dubia	Water flea	Crustacea	48h	2584
Pimephales promelas	Fathead minnow	Osteichthyes	96h	2665
Lepomis macrochirus	Bluegill	Osteichthyes	96h	4031
Gambusia affinis	Western mosquitofish	Osteichthyes	96h	4193
Nitzschia linearis	Diatom	Protista **	120h	4330
Lepomis macrochirus	Bluegill	Osteichthyes	24h	5140
Gambusia affinis	Western mosquitofish	Osteichthyes	96h	75767
Oncorhynchus mykiss	Rainbow trout	Osteichthyes	96h	83795

* Phylum ** Kingdom

Table 3.12c: Summary of acute toxicity of ammonia (LC_{50}) to various species (EPA, 2000).

Scientific name	Common name	Taxa –Class	Time	mg/ℓ N
Hypophthalmichthys nobilis	Carp	Osteichthyes	96h	0.2
Hypophthalmichthys molitrix	Silver carp	Osteichthyes	96h	0.3
Oncorhynchus mykiss	Rainbow trout	Osteichthyes	48h	0.3
Cyprinus carpio	Common carp	Osteichthyes	96h	0.4
Polycelis tenuis	Turbellarian	Turbellaria	48h	0.6
Lymnaea stagnalis	Great pond snail	Gastropoda	48h	1.0
Baetis rhodani	Mayfly	Insecta	48h	1.3
Physa fontinalis	Bladder snail	Gastropoda	48h	1.3
Chironomus riparius	Midge	Insecta	48h	1.4
Limnodrilus hoffmeisteri	Tubificid worm	Annelida	48h	1.6
Enallagma sp.	Damselfly	Insecta	48h	1.7
Asellus aquaticus	Aquatic sowbug	Crustacea	48h	2.1
Brachionus rubens	Rotifer	Rotifera *	24h	2.6
Hydropsyche angustipennis	Caddisfly	Insecta	48h	2.7
Daphnia pulex	Water flea	Crustacea	48h	3.4
Daphnia magna	Water flea	Crustacea	48h	3.4
Clarias batrachus	Walking catfish	Osteichthyes	96h	3.5
Brachionus calyciflorus	Rotifer	Rotifera *	24h	3.8
Carassius auratus	Goldfish	Osteichthyes	48h	57
Ictalurus punctatus	Channel catfish	Osteichthyes	48h	232

* Phylum

Table 3.12d: Summary of acute toxicity of fluoride (LC_{50}) to various species (EPA, 2000).

Scientific name	Common name	Taxa –Class	Time	mg/ℓ F
Hydropsyche occidentalis	Caddisfly	Insecta	48h	46
Oncorhynchus mykiss	Rainbow trout	Osteichthyes	96h	49
Streptocephalus proboscideus	Fairy shrimp	Crustacea	24h	70
Salmo trutta	Brown Trout	Osteichthyes	96h	74
Pimephales promelas	Fathead minnow	Osteichthyes	96h	93
Daphnia magna	Water flea	Crustacea	48h	126
Brachionus calyciflorus	Rotifer	Rotifera *	24h	183
Gambusia affinis	Western mosquitofish	Osteichthyes	96h	189

* Phylum

Table 3.12e: Summary of acute toxicity of phosphate (LC_{50}) to various species (EPA, 2000).

Scientific name	Common name	Taxa –Class	Time	mg/ℓ PO_4
Gambusia affinis	Western mosquitofish	Osteichthyes	96h	109
Clarias gariepinus	Sharptooth catfish	Osteichthyes	96h	141
Daphnia magna	Water flea	Crustacea	48h	781

Measures of water quality at W6 are presented in Figure 3.7. The data support the evaluation of the hypotheses that "Current, permitted and future values of specified variables do not pose an unacceptable risk to aquatic ecosystems" (hypotheses 1A, 1B and 1C, Table 3.2) through line of evidence ix (Figure 3.4). The data are used in section 3.5 to characterise the response.

Lines of evidence employed in support of evaluating the hypotheses that "Current, permitted and likely future toxicity of effluents do not pose an unacceptable risk to aquatic ecosystems" (2A, 2B and 2C; Table 3.2) are presented in Figure 3.5. Two lines of evidence (i and ii) relate to acute toxicity of whole effluent to *Daphinia pulex* and *Poecilia reticulata*. The results of the bioassays at W5, W20 and W30 are provided in Table 3.13. Chlorophyll-a concentrations recorded at W1, M4, W4 and M10 indicate planktonic algal biomass. The results from the analyses (line of evidence iii in Figure 3.5) are presented in Table 3.8. Information on fish sampled at M7 (Table 3.9) provide information towards line of evidence iv (fish diversity and

abundance) in Figure 3.5. The diversity and relative abundance of benthic macro-invertebrates, as assessed with the SASS4 method, supports the evaluation of the hypotheses through lines of evidence v in Figure 3.5, with the results listed in Tables 3.10 a-c. The accumulation of metals in fish tissues, representing line of evidence vi in Figure 3.5, is reported in Table 3.11. The analyses and interpretation of data are reported on in section 3.5.

Table 3.12f: Summary of acute toxicity of sodium (LC_{50}) to various species (EPA, 2000).

Scientific name	**Common name**	**Taxa –Class**	**Time**	**mg/ℓ Na**
Hydropsyche occidentalis	Caddisfly	Insecta	96h	26
Streptocephalus proboscideus	Fairy shrimp	Crustacea	24h	46
Dugesia sp.	Turbellarian	Turbellaria	48h	70
Gambusia affinis	Western mosquitofish	Osteichthyes	96h	73
Clarias gariepinus	Sharptooth catfish	Osteichthyes	96h	294
Micropterus treculi	Guadalupe bass	Osteichthyes	96h	341
Oncorhynchus mykiss	Rainbow trout	Osteichthyes	96h	367
Ceriodaphnia dubia	Water flea	Crustacea	48h	401
Lepomis macrochirus	Bluegill	Osteichthyes	96h	541
Daphnia magna	Water flea	Crustacea	48h	653
Stenonema rubrum	Mayfly	Insecta	48h	983
Nais variabilis	Oligochaete	Annelida	48h	1011
Xenopus laevis	Clawed toad	Amphibia	120h	1147
Poecilia latipinna	Sailfin molly	Osteichthyes	48h	1165
Lepomis macrochirus	Bluegill	Osteichthyes	24h	1352
Physa heterostropha	Pond snail	Gastropoda	48h	1455
Carassius auratus	Goldfish	Osteichthyes	96h	1986
Culex sp.	Mosquito	Insecta	48h	2008
Gambusia affinis	Western mosquitofish	Osteichthyes	96h	2153
Asellus aquaticus	Aquatic sowbug	Crustacea	48h	2203
Lepomis macrochirus	Bluegill	Osteichthyes	96h	2543
Limnodrilus hoffmeisteri	Tubificid worm	Annelida	48h	2734
Erpobdella punctata	Red leech	Hirudinea	48h	2950
Helisoma campanulatum	Ramshorn snail	Gastropoda	48h	2950
Anguilla rostrata	American eel	Osteichthyes	96h	4836
Poecilia reticulata	Guppy	Osteichthyes	96h	5180
Pimephales promelas	Fathead minnow	Osteichthyes	96h	5335
Carassius carassius	Crucian carp	Osteichthyes	24h	5409
Argia	Damselfly	Insecta	48h	10228

Literature data on the toxic effects of the specified variables support the hypotheses (2A, 2B and 2C, Table 3.2) through line of evidence vii. A summary of the data obtained from the AQUIRE database (EPA, 2000) is presented in Tables 3.12a-f. Algal growth inhibition tests provide information in support of line of evidence viii in Figure 3.5. The definitive bioassays and algal growth bioassay results for W5, W20 and W30 are presented in Table 3.13 and 3.14 respectively.

Table 3.13: Definitive bioassays of samples at Modderfontein Spruit sites.

Bioassays	***Daphnia pulex* (% effluent inducing LC_{50} after 48 hrs)**			***Poecilia reticulata* (% effluent inducing LC_{50} after 96 hrs)**		
Sites	**W5**	**W20**	**W30**	**W5**	**W20**	**W30**
June 1997	53	>100	>100	24	>100	>100
July 1997	6	19	>100	19	>100	>100
August 1997	22	>100	38	>100	63	16
September 1997	>100	99	34	>100	>100	>100
October 1997	>100	63	>100	>100	63	>100
November 1997	33	48	>100	31	>100	>100
December 1997	7	90	27	6	>100	>100
January 1998	6	>100	63	16	>100	>100
February 1998	19	>100	24	38	>100	75
March 1998	3	>100	100	3	100	100
April 1998	100	32	>100	100	100	>100
May 1998	32	31	38	>100	75	100
June 1998	81	35	>100	>100	>100	>100
July 1998	92	100	20	>100	>100	75
August 1998	>100	56	>100	>100	>100	>100
September 1998	9	6	46	25	10	>100
October 1998	3	38	3	3	>100	50
November 1998	3	4	21	22	40	>100
December 1998	3	15	>100	3	20	>100
January 1999	19	22	68	25	20	>100
February 1999	28	50	>100	58	>100	>100
March 1999	19	25	70	65	>100	>100
April 1999	41	33	3	>100	>100	9
May 1999	9	92	3	38	>100	9

- Where the LC_{50} is not induced with undiluted effluent, it is indicated as >100%

Table 3.14: Algal growth inhibition test of water at Modderfontein Spruit sites.

Bioassays	***Selenastrum capricornutum* (% effluent inducing EC_0)**			***Selenastrum capricornutum* (% effluent inducing EC_{50})**		
Sites	**W5**	**W20**	**W30**	**W5**	**W20**	**W30**
October 1997	>100	0.78	13	>100	4.61	>100
November 1997	50	<0.78	50	>100	>100	>100
December 1997	50	<0.78	<3.13	>50	16	8.3
January 1998	25	<0.39	50	>100	29	>100
February 1998	<0.04	<0.78	50	>0.16	9	>100
March 1998	100	0.39	100	>100	0.39	100
April 1998	0.39	1.56	0.39	>100	100	50
May 1998	0.39	1.56	3.13	16	100	100
June 1998	<0.39	0.39	0.39	>100	>100	>100
September 1998	>100	3.13	>100	>100	77	>100
December 1998	<0.39	<0.39	0.39	<0.39	4.69	15.5
January 1999	25	<0.39	50	78	29	>100
March 1999	0.024	0.10	0.024	36	17	8.9
May 1999	<0.39	1.56	3.13	15.8	>100	>100

3.4. Analyse Information

3.4.1. Critically evaluate information

The strengths and weaknesses of the data used in the assessment are summarised in Table 3.15. From the analysis it can be seen that none of the data sources provide a complete picture. It is only through the combination of various sources that the weaknesses can be overcome.

3.4.2. Characterise exposure

The stressors (Table 3.1) were released through AEL's effluent (W5 and W20), other point sources (W1, SP2 and W30) and diffuse sources (Figure 3.3). The intensity, pattern and timing of the ecosystem's exposure to the stressors are presented in Figure 3.7. While weekly and bi-weekly samples were taken, temporal aspects such as diel cycles and short term fluctuations are not adequately represented. The mechanisms and pathways of stressors dispersion from the source are important. Given the importance of inorganic nitrogen as a stressor, the nitrogen cycle (Figure 1.6) is also considered.

Table 3.15: Characteristics of data used in the assessment.

Data	**Strengths (✓) and weaknesses (✘)**
Water Quality	✓ Measured at site of exposure to ecosystem ✓ Variables of concern analysed ✓ Analytical precision very high ✘ One sample per month (variability not represented) ✘ Data on all identified stressors not available
Invertebrate - SASS4 assessment	✓ Measures receiving ecosystem ✓ Rapid method ✓ Measures abundance and diversity ✘ Identification only at family level ✘ Does not consider community structure and function ✘ Does not identify stressor ✘ Sensitive to habitat changes ✘ Replication is often very difficult ✘ Low sampling frequency to allow recovery
Fish - Diversity and abundance	✓ Measures receiving ecosystem ✓ Integrates effects (high in food chain) ✓ Measures abundance and diversity ✓ Identification at species level ✘ Does not consider community structure and function ✘ Does not identify stressor ✘ Only monitored on an annual basis
Algae - Chlorophyll a	✓ Rapid method ✓ Good indicator of primary production ✘ Does not identify algae (diversity)
Bioaccumulation - *Clarias gariepinus*	✓ Confirms exposure to metals ✘ Baseline levels are not known ✘ Monitoring and analyses are expensive
Toxicology - *Daphnia pulex*	✓ Indicates toxic nature of water ✓ Standard and relatively cheap method ✓ *Daphnia pulex* is indigenous ✘ Laboratory culture different to wild population ✘ Laboratory different to in-stream conditions ✘ Screening assay lacks resolution of definitive assay
Toxicology - *Poecilia reticulata*	✓ Indicates toxic nature of water ✓ Standard and relatively cheap method ✘ *Poecilia reticulata* is an exotic species ✘ Laboratory culture and conditions ✘ Screening assay lacks resolution of definitive assay
Toxicology - *Selenastrum capricornutum*	✓ Indicates effect of water on algal growth ✓ Relevant for eutrification studies ✘ Growth stimulation and inhibition affect results ✘ Laboratory culture and conditions ✘ Assay not commonly used
Toxicology - Literature data	✓ Reflect effects on range of species ✘ Laboratory conditions not comparable to field ✘ Species not indigenous ✘ LC_{50} endpoint has limited use

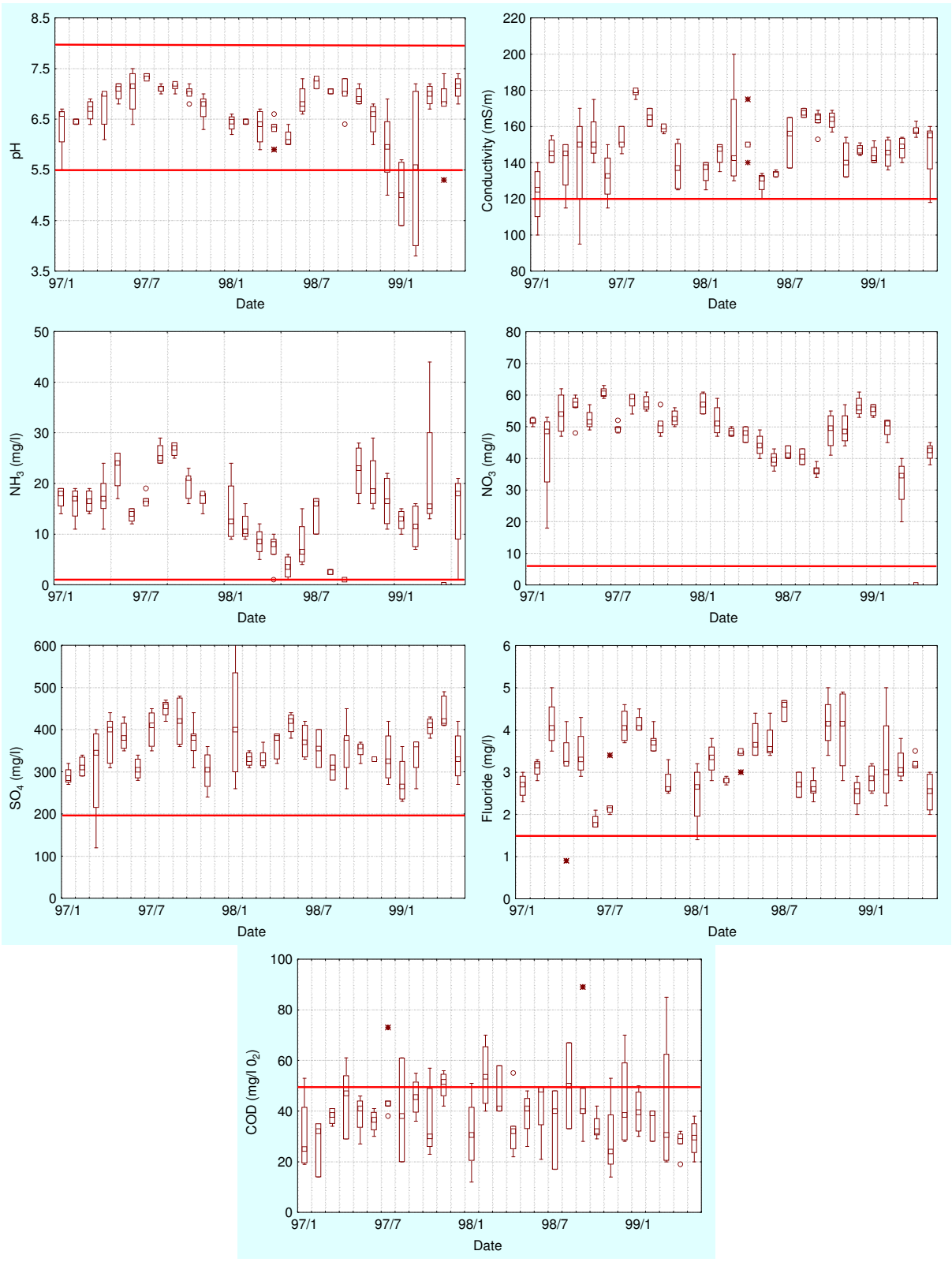


Figure 3.7: Water quality at W6 for January 1997 to May 1999 indicated as median, 5th, 25th, 75th , and 95th percentiles, with outliers. (permit specification indicated by red horizontal lines).

3.4.3. Characterize response

The stressor sources and stressors are linked to the endpoints and measures through the exposure routes in accordance with the conceptual model in Figure 3.4. The model provides the basis for evaluating expressed (biological monitoring) and expected (toxicological analyses) ecological responses. The dose-response relationships provide information towards the expected ecological response through relating stressor levels (water quality variables) to ecological effects (literature LC_{50} values). These relationships were used to evaluate the hypotheses that "Current, permitted and future values of specified variables do not pose an unacceptable risk to aquatic ecosystems" (Table 3.2) through line of evidence vii (Figure 3.5).

Figure 3.8 provides the key to comparing exposure and response profiles. Firstly, the cumulative frequency of exposure (water quality) is plotted against the left (y_1) axis. The interpretation of this analysis can be explained by the blue dotted lines marked as "*(a)*". The relationship simply means that the variable concentration was lower than 300 mg/ℓ (x-axis) for 23% of the time (y_1-axis), or conversely, that 300 mg/ℓ (x-axis) was exceeded for 77% of the time (compliment of y_1-axis). Similarly, the cumulative frequency of the response information (LC_{50} values) is plotted against the right (y_2) axis. The interpretation is that the blue dotted lines marked "*(b)*" indicate that the LC_{50} is expressed for 50% of the represented species at 1000 mg/ℓ of the variable. The permit specification indicated by the vertical red line (marked *"c"*) shows that the measured values for the variable (green symbols) always exceeded the value, with the LC_{50} of 24% of represented species being expressed below this concentration.

The cumulative frequencies of measured water quality were compared with the cumulative LC_{50} data for each constituent (Figure 3.9). In accordance with the above, an overlap between expose data and effects data on the *x*-axes means that the water quality for the specific variable exceeded the LC_{50} values of the species in the overlapping area. For example, the cumulative distribution for sulphate shows that the permit specification was exceeded 100% of the time. This concentration is also higher than the LC_{50} values for the fairy shrimp and zebra mussel. A comparison between the literature data (Table 3.12 a-f) and water quality in the effluent streams (Tables 3.5 and Table 3.6) are also used to evaluate the hypotheses that

"Current, permitted and likely future toxicity of effluents do not pose an unacceptable risk to aquatic ecosystems" (2A, 2B and 2C in Table 3.2) through line of evidence vii in Figure 3.5. The analysis and evaluation is reported on in section 3.5.

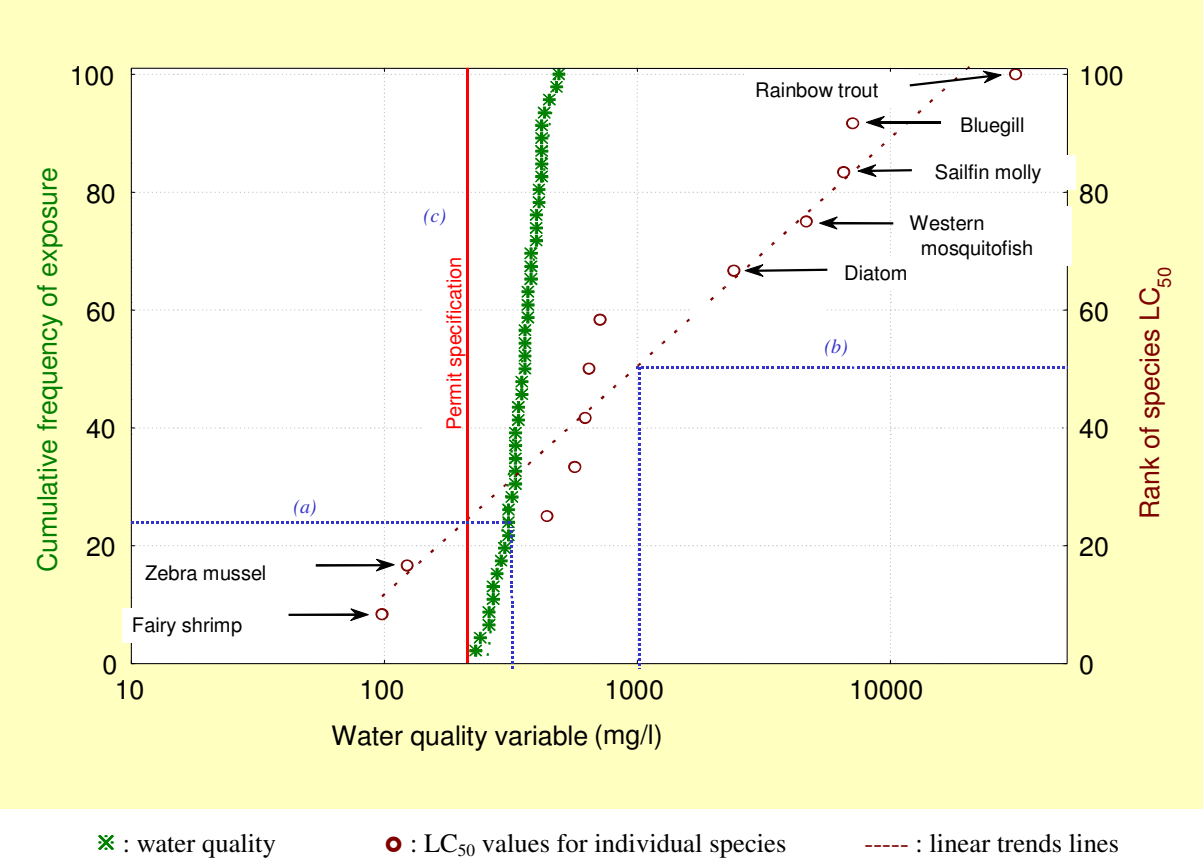


Figure 3.8: A key to interpreting the exposure and response exceedence curves, which are presented in Figure 3.9 (adapted from EPA, 1998).
(Permit specifications are provided for variables listed in the permit.)

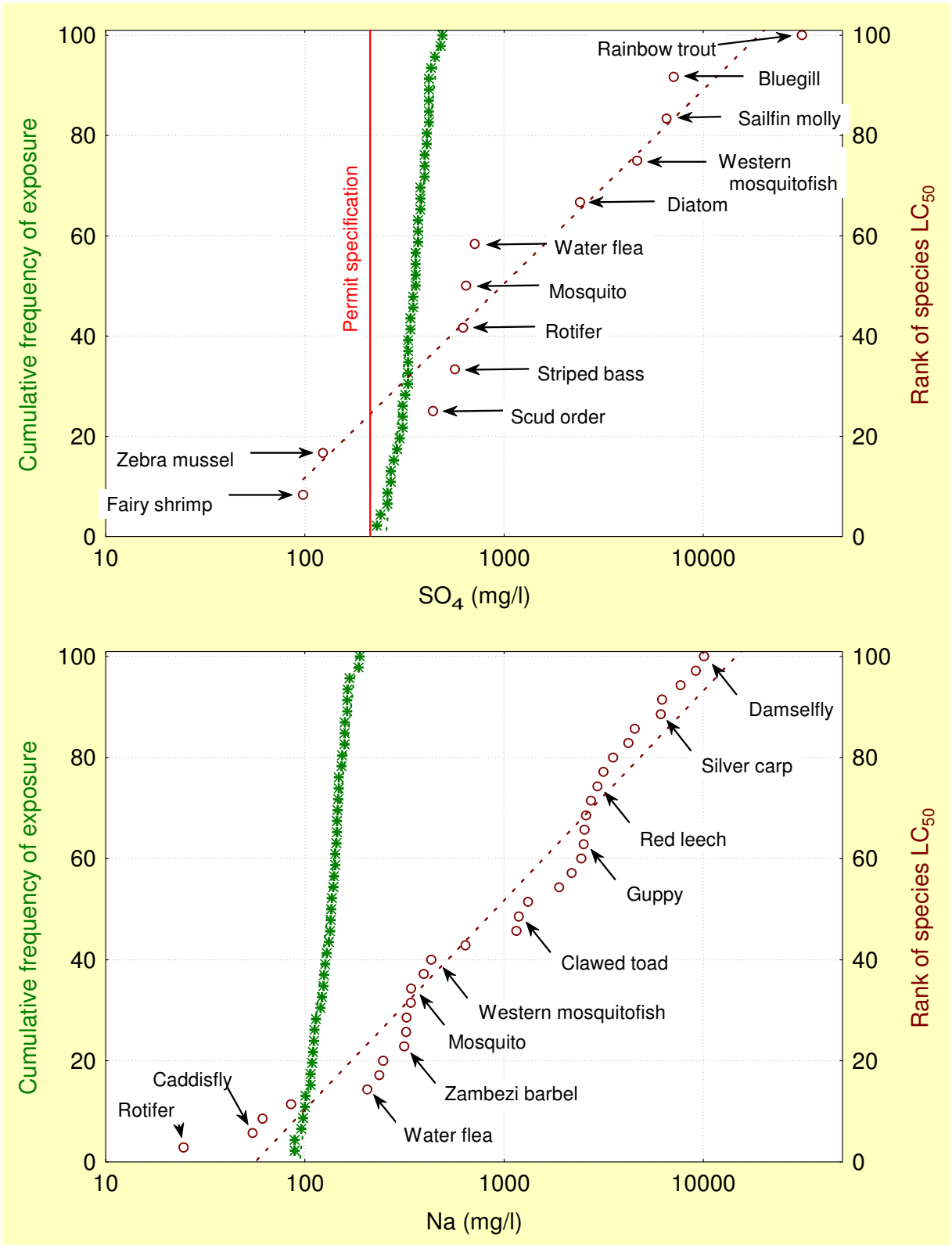


Figure 3.9: Exceedence values for literature toxicity data and water quality at W6.

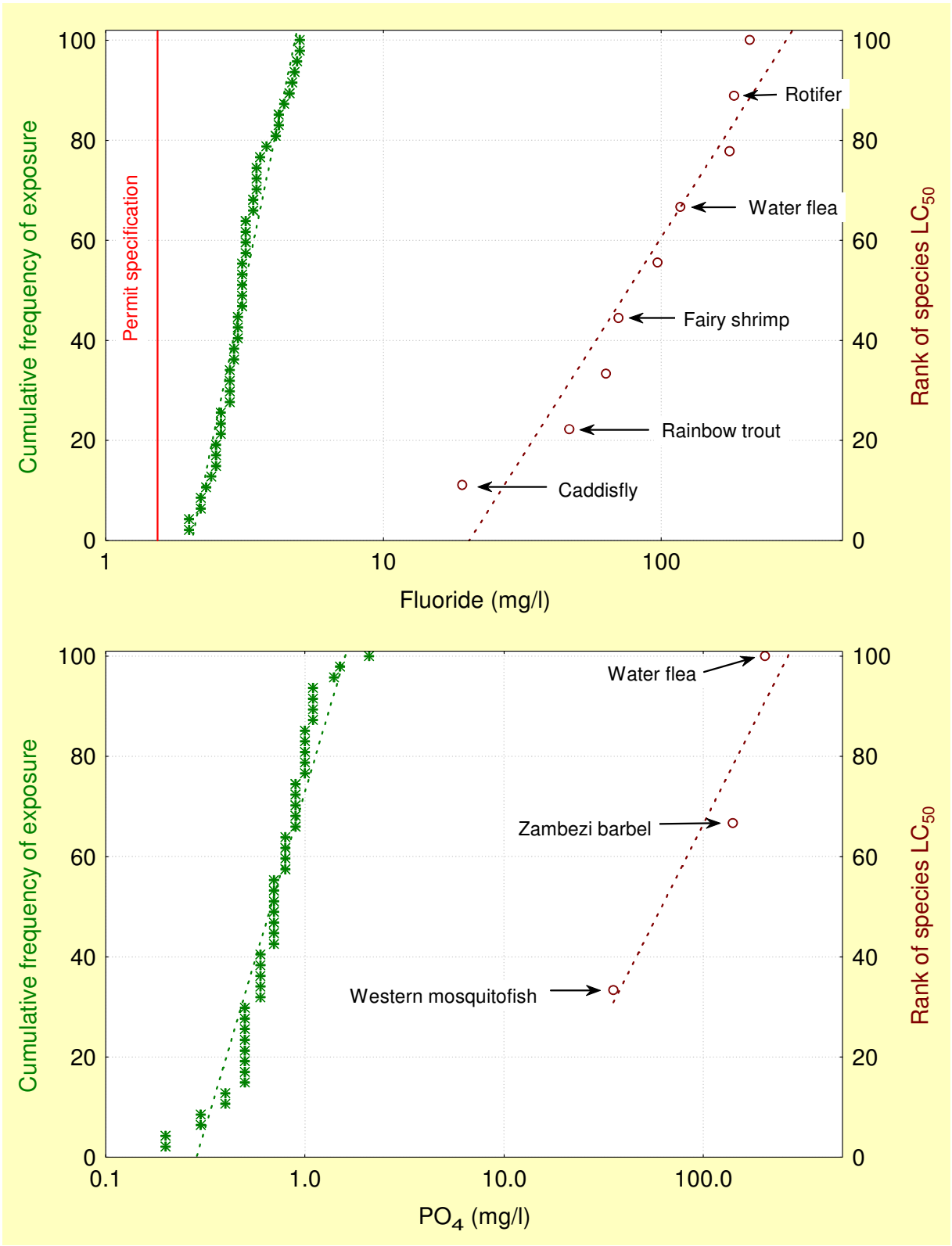


Figure 3.9 cont.: Exceedence values for literature toxicity data and water quality at W6.

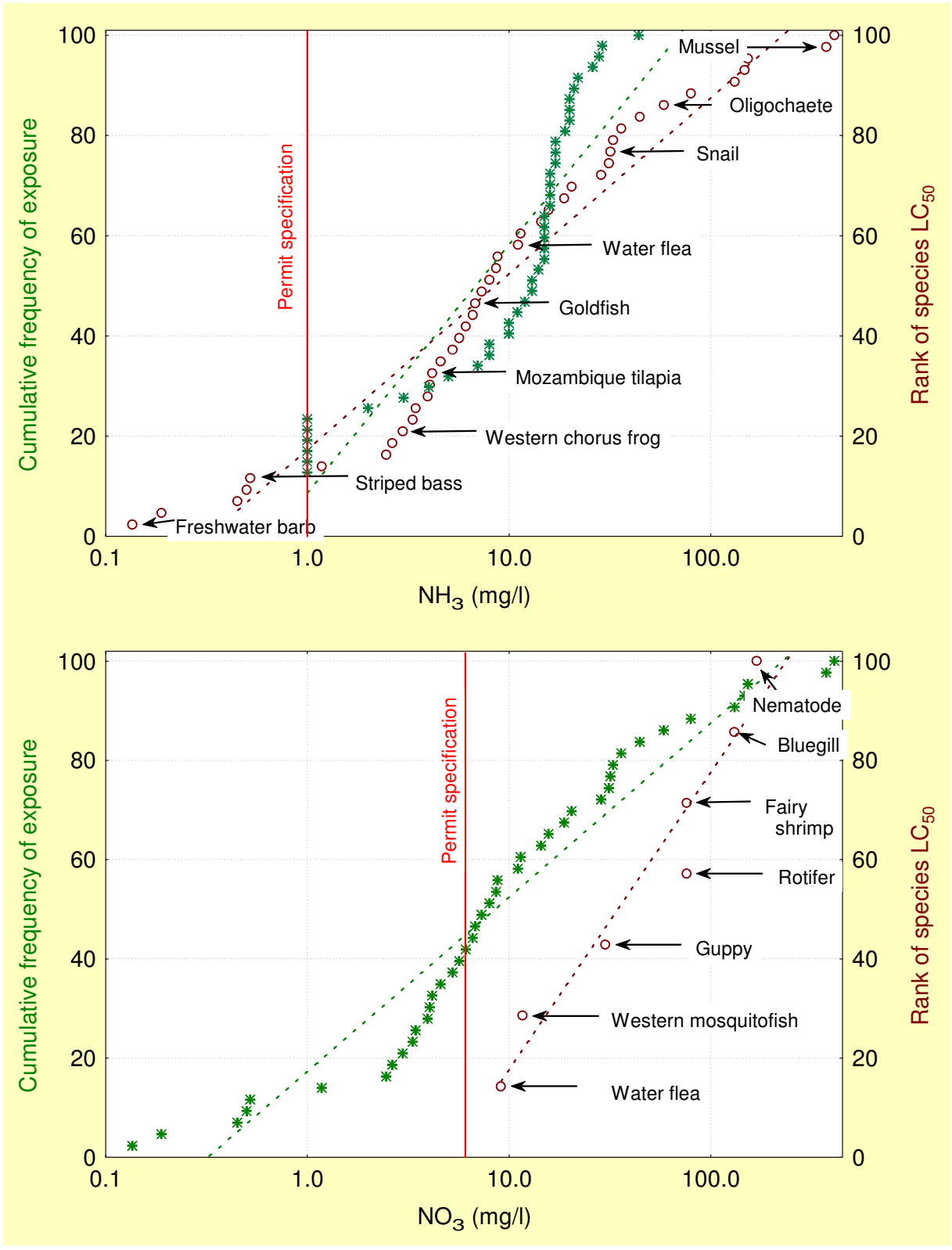


Figure 3.9 cont.: Exceedence values for literature toxicity data and water quality at W6.

Other sources of response information include:

- Toxicity bioassays
    - *Daphnia pulex*

Acute toxicity of water at W6 and of effluents to *Daphnia pulex* (Table 3.7 and Table 3.13) was assessed to evaluate hypotheses 1A-C (Figure 3.5) and hypotheses 2A-C (Figure 3.6) respectively, in accordance to line of evidence i.

    - *Poecilia reticulata*

Acute toxicity of water at W6 and of effluents to *Poecilia reticulata* (Table 3.7 and Table 3.13) was assessed to evaluate hypotheses 1A-C (Figure 3.5) and hypotheses 2A-C (Figure 3.6) respectively, in accordance to line of evidence ii.

    - *Selanastrum capricornutum*

Growth inhibition or stimulation characteristics of effluents to *Selanastrum capricornutum* (Table 3.14) were assessed to evaluate hypotheses 2A-C (Figure 3.6) in accordance to line of evidence viii.

- Biological monitoring
    - Chlorophyll-a

Chlorophyll-a values were used as a proxy for primary production, with the values in Table 3.8 being used to evaluate hypotheses 1A-C (Figure 3.5) and hypotheses 2A-C (Figure 3.6) in accordance with line of evidence iii.

    - Fish

The measured diversity and abundance of fish (Table 3.9) were used to evaluate hypotheses 1A-C (Figure 3.5) and hypotheses 2A-C (Figure 3.6) in accordance with line of evidence iv.

    - Macro-invertebrates

An assessment of the diversity and abundance of macro-invertebrates (Table 3.10c) were used to evaluate hypotheses 1A-C (Figure 3.5) and hypotheses 2A-C (Figure 3.6) in accordance with line of evidence v.

    - Bioaccumulation

The bioaccumulation of metals (Table 3.11) was used as evidence of exposure to evaluate hypotheses 1A-C (Figure 3.5) and hypotheses 2A-C (Figure 3.6) in accordance with line of evidence vi.

- Habitat

The habitat available to instream organisms (Table 3.10 a-b) was assessed, firstly as a contributing factor to faunal diversity and abundance, but also to evaluate hypotheses 1A-C (Figure 3.5) in accordance with line of evidence viii.

Each line of evidence is characterised by intrinsic variability and has uncertainties associated with the data. The use of independent lines of evidence strengthens the risk assessment in much the same way in which multivariate statistical analyses are strengthened by independent data. The role of each line of evidence is discussed in more detail in section 3.5.

3.5. Describe Risk

3.5.1. Assess risk and evaluate hypotheses

The hypotheses (Table 3.2) were tested through analysing the respective lines of evidence (LoE; Figures 3.5 and 3.6). It is important to reiterate here that the hypotheses are tested in a risk assessment paradigm, which expresses the likelihood that the hypothesis can be rejected, rather than a statistical (binary) statement of rejecting or not rejecting the null hypothesis. Where the evidence is overwhelmingly in favour of rejecting the hypothesis, it is stated as a high probability. In cases where the evidence may suggest that the hypothesis be rejected or accepted, but the evidence is not strong, a moderate probability is stated. For evidence that give a weak indication that the hypothesis should be rejected or accepted, the likelihood is expressed as low.

In addition to the evaluation of probability, a qualitative assessment on the confidence (uncertainties) of each assessment is also made. A high confidence suggests that more information or different analyses are unlikely to yield a different outcome. Moderate confidence indicates that some assumptions are made that, if proven to be false, could affect the outcome of the analysis. Low confidence denotes evidence with tenuous links to the hypothesis, major assumptions or insufficient data to draw conclusions.

Hypothesis 1A: "Current values of specified variables do not pose an unacceptable risk to aquatic ecosystems"

LoE i: The water samples taken from W6 were acutely toxic to daphnids during October 1997, December 1997, January 1998 and May 1999, during which times 65%, 30%, 45% and 15% of the respective test populations died (Table 3.7). According to the definition of unacceptable risk (Table 3.2 legend), acute effects in receiving water are unacceptable.

Probability: There is a high probability the hypothesis can be rejected.

Confidence: High

LoE ii: The water samples taken at W6 were never acutely toxic to guppies (Table 3.7). The hypothesis could therefore not be rejected on the basis of LoE ii. A limitation of hypothesis testing is illuminated in this evaluation, since it is unlikely that a hypothesis would be statistically rejected on the basis of a single proxy indicator with very few analyses.

Probability: There is a low probability the hypothesis can be rejected.

Confidence: High

LoE iii: For the analysis of chlorophyll-a data (Table 3.8), the values at W6 (downstream of AEL) are compared with those at W1 (upstream of AEL). The chlorophyll-a concentrations at W6 were highly variable during the study period, with a variance of 2049, as opposed to a variance of 164 at W1. Peaks occurred between February 1998 and May 1998 and between December 1998 and January 1999. In addition to the high variability, chlorophyll-a concentrations at W6 (mean = 46.4 µg/ℓ) were also significantly higher than at W1 (mean = 6.7 µg/ℓ). The *t*-test for dependent samples prove the significance of the difference with $p = 0.00053$. The impact of elevated algal production on the sustainability of the aquatic ecosystem is viewed as unacceptable.

Probability: There is a high probability the hypothesis can be rejected.

Confidence: Moderate

LoE iv: Both the diversity and abundance of fish at M7 were lower than those reported during previous surveys in the Moderfontein Spruit and Jukskei River (DWAF, 1995; Rall *et al.,* 1995; van Veelen and Venter, 1996; du Preez 1997; Table 3.9). More specifically, *Pseudocrenilabrus philander* and *Gambusia affinis* were expected to occur at M7. The absence of *P. philander,* an indigenous species, provides strong evidence that the conditions pose an unacceptable risk to fish diversity and abundance. Although *Gambusia affinis* is not an indigenous species, its absence supports the notion that the risk to fish diversity and abundance are unacceptable.

Probability: There is a moderate probability the hypothesis can be rejected (since a threat to the sustainability of representative populations was viewed as unacceptable (Table 3.2 legend)).

Confidence: Moderate

LoE v: The diversity and abundance of aquatic macro-invertebrates (as measured with SASS4) was very poor to poor (Table 3.10c). When comparing the upstream (W1) and downstream (W6) sites, there is a significant difference between mean SASS scores (t-test; $p = 0.007$), with the mean values of the downstream scores (33.8) being better than those upstream (20.0). The results from the analysis are consistent with the evidence from the habitat assessment (LoE viii), with conclusive evidence that the downsteam habitat is of a better quality than the habitat upstream. The lower SASS scores at W1 can thus be attributed to the poor habitat, with the better SASS score at W6 being a consequence of relatively good habitat. There is also a link between primary production (LoE iii) and aquatic invertebrates, since increased primary production provides additional food for primary consumers, and will hence influence abundance and diversity. Such changes are however not always positive, as it may lead to unnatural community composition. A potential weakness of using indices that are affected by multiple variables (such as SASS) is demonstrated by this phenomenon.

Probability: There is a low probability the hypothesis can be rejected.

Confidence: Moderate

LoE vi: Little is known about the natural levels of metals in fish tissues. The bioaccumulation of metals in fish listed in Table 3.11 can be compared with similar data from other studies (listed in section 3.3.5, before Table 3.11). According to the analysis, chromium and nickel levels in fish tissues from the Modderfontein Spruit were much higher than in the other rivers. The elevated metal levels in fish tissue could have a negative impact on the sustainability of the fish populations

Probability: There is a low probability the hypothesis can be rejected.

Confidence: Low

LoE vii: The comparison of literature toxicity values (Table 3.12 a-f) with actual water quality (Figure 3.9) shows that sodium, sulphate, nitrate and ammonia pose a significant acute risk to the aquatic ecosystem. The risk is expressed as the likelihood of occurrence and the response of the endpoint if it does occur. For sodium, the present levels of exposure (90-110 mg/ℓ) exceed the LC_{50} values for the caddisfly, fairy shrimp, a tubellarian and the western mosquitofish (in one of two experiments). The risk of not having sustainable populations of these species (or species of similar sensitivity) is 100%. Of added importance is the fact that the western mosquitofish (*Gambusia affinis*) previously occurred in the river system, but is now absent. A similar situation is presented for sulphate, with the risk (50% of the population dying within the exposure period) to fairy shrimp and zebra mussel being 1. (Risk is expressed on a scale of 0-1, with 0 being no risk and 1 being absolute certainty of expression). Nitrate concentrations often exceed the LC_{50} values of tested species. For example, the nitrate levels exceed the LC_{50} level for *Daphnia spp.* and *Gambusia affinis* 40% of the time, for guppies 30% of the time and for bluegill sunfish 10% of the time. Ammonia (unionised ammonia, which has been normalized for pH and temperature) poses a significant acute risk to the ecosystem, since the levels at which the LC_{50} is expressed, is very closely aligned with the present exceedence curve for the levels of exposure (Figure 3.9). The risk posed by ammonia is thus 1 for most of the tested species (at least 50% of individuals in populations will die, given the levels of exposure). It should be noted that LC_{50} values provide an extremely conservative estimate

of population impact. Impacts will occur at much lower concentrations than those at which the the LC_{50} values are reached.

Probability: There is a high probability the hypothesis can be rejected.

Confidence: High

LoE viii: The availability of in-stream habitat as measured by HAM and HQI (Tables 3.10a-b) was poor, mainly due to accumulated fine sediment, a lack of natural vegetation cover and benthic algal growth. A comparison between the habitat assessment matrix (HAM) for the upstream (W1) and downstream (W6) sites indicate a significant difference between means (t-test; p = 0.00002), with the mean for W6 (83.8 %) being higher than at W1 (71.8 %). The analysis for the Habitat Quality Index (HQI) yields a similar result with the respective means being 70.9 % (W1) and 81.6 % (W6) and the results from a *t*-test indicating that the means are significantly different (p = 0.001). Although the conditions improve downstream, the available habitat is still limiting to aquatic communities.

Probability: There is a moderate probability the hypothesis can be rejected.

Confidence: Moderate

LoE ix: The water quality at W6 as presented in Figure 3.7 shows that the permit condition were exceeded for pH, conductivity, ammonia, nitrate and chemical oxygen demand. This line of evidence assumes that the permit values offer sufficient protection, whereas the relationships between exposure and effects in Table 3.8 suggest that it may not.

Probability: There is a high probability the hypothesis can be rejected.

Confidence: High

The preceding section shows that there is a high probability that the null hypothesis can be rejected (based on four lines of evidence), with the probability of rejecting the hypothesis being supported with moderate confidence on the basis of a further two lines of evidence. The evidence thus shows that it is unlikely that the current values of specified variables do not pose an unacceptable risk to aquatic ecosystems.

Hypothesis 1B: "Permitted values of specified variables do not pose an unacceptable risk to aquatic ecosystems"

LoE i-vi: The results from toxicity tests on daphnids could not be linked directly to the effect of water quality at permit specifications, as there was never a period where all the variables met the permit specifications. The evidence from LoE ii-vi is also not directly applicable to the hypothesis for the same reason.

Probability: There is a low probability these hypotheses can be rejected.

Confidence: Low

LoE vii: The comparison of literature toxicity values (Table 3.12 a-f) with permitted water quality (Figure 3.9) shows that sulphate, nitrate and ammonia pose a significant acute risk to the aquatic ecosystem. For sulphate, the permitted level of exposure (200 mg/ℓ) presents an absolute risk to fairy shrimp and zebra mussel. The permit specification for nitrate does not exceed the LC_{50} values of tested species. Ammonia poses a significant acute risk to the ecosystem at the permitted levels of exposure, since it exceeds the LC_{50} values of at least 10% of the tested species (Figure 3.9). The risk posed by ammonia is thus close to 1 for sensitive species. The sustainability of populations will be under threat, given the permitted levels of exposure. Again, it should be noted that the LC_{50} values provide an extremely conservative estimate of population impact.

Probability: There is a high probability the hypothesis can be rejected.

Confidence: High

LoE viii-ix: The habitat assessment is not applicable to future water quality scenarios, nor is measurement of water quality possible.

Probability: There is a low probability these hypotheses can be rejected.

Confidence: Low

Hypothesis 1C: "Likely future values of specified variables do not pose an unacceptable risk to aquatic ecosystems"

LoE i- ix: The analysis is the same as for hypothesis 1B, since the permit specifications are also seen as the likely future scenario for W6.

Table 3.16 provides a summary of the evidence for evaluating hypotheses 1A, 1B and 1C. The evidence suggest a high probability that hypothesis 1A should be rejected, with six out of nine lines indicating unacceptable risk. The evaluation of hypotheses 1B and 1C are supported on the basis of LoE vi, with the hypotheses being rejected in both cases.

Table 3.16: Summary of the lines of evidence for hypotheses 1A, 1B and 1C.

	Line of evidence								
	i	**ii**	**iii**	**iv**	**v**	**vi**	**vii**	**viii**	**ix**
1A "Current values of specified variables do not pose an unacceptable risk to aquatic ecosystems"	H (h)	L (h)	H (m)	M (m)	L (m)	L (l)	H (h)	M (m)	H (h)
1B "Permitted values of specified variables do not pose an unacceptable risk to aquatic ecosystems"	L (l)	L (l)	L (l)	L (l)	L (l)	H (h)	L (l)	L (l)	L (l)
1C "Likely future values of specified variables do not pose an unacceptable risk to aquatic ecosystems"	L (l)	L (l)	L (l)	L (l)	L (l)	H (h)	L (l)	L (l)	L (l)

H/M/L – High, Medium or Low probability of rejecting the hypothesis, (h/m/l) – high, medium or low confidence

Hypothesis 2A: "The current toxicity of effluents do not pose an unacceptable risk to aquatic ecosystems"

LoE i: The water at W5 and W20 was acutely toxic to daphnids more than 80% of the time and often at up to thirty times dilution (Table 3.13). The definition in the legend of Table 3.2 states that any acute effects in effluent are unacceptable.

Probability: There is a high probability the hypothesis can be rejected.

Confidence: High

LoE ii: The water at W5 and W20 was acutely toxic to fish (*Poecilia reticulata*) more than 50% of the time (Table 3.13) at up to thirty times dilution. As with LoE i, the acute effects constitutes and unacceptable risk.

Probability: There is a high probability the hypothesis can be rejected.

Confidence: High

LoE iii: Chlorophyll-a values at M4, W4, M10 and W6 were highly variable (respective variances: 6123, 3123, 3776, 2049) while values at W1 were less variable (variance of 164). There were significant differences between sites, as shown by Kruskal-Wallis analysis of variance ($p = 0.0006$). Cluster analysis (Figure 3.10; K-means) shows that M4 and W4 (directly downstream of W5 effluent) are similar, M10 and W6 (downstream of W20 effluent) are similar and W1 (upstream site) clusters closer to M10 and W6, although still some distance from them. This analysis shows the impact of W5 and W20.

Probability: There is a moderate probability the hypothesis can be rejected.

Confidence: High

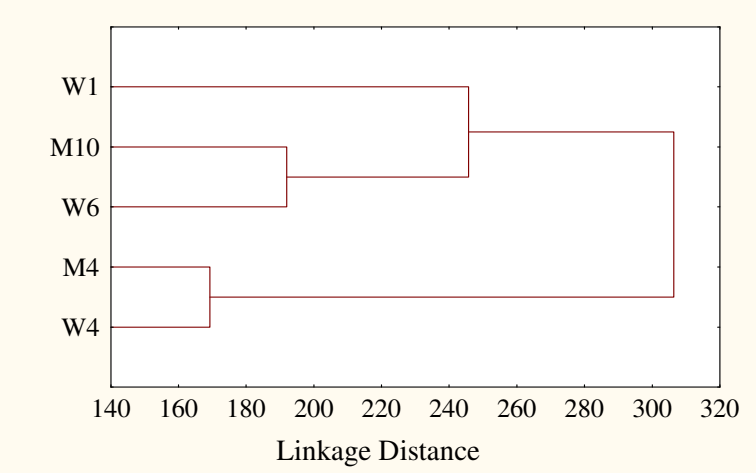


Figure 3.10: Cluster analysis of chlorophyll-a concentrations at various monitoring points

LoE iv, v and vi: The diversity and abundance of fish (Table 3.9), aquatic macro-invertebrates (Table 3.10c) and the bioaccumulation of metals in fish (Table 3.11) give an indirect indication of the effect of industrial effluent. This data cannot be directly linked to the toxic effect of W5 and W20

Probability: There is a low probability these hypotheses can be rejected.

Confidence: Low

LoE vii: The comparison of literature toxicity values (Table 3.12 a-f) with effluent quality (Tables 3.5 and Table 3.6) shows that nitrate, sulphate, ammonia and sodium may pose a significant acute risk to the aquatic ecosystem. For nitrate, the median concentrations (50^{th} percentile) for W5 (102 mg/ℓ) and W20 (82 mg/ℓ) are higher than the 85^{th} percentile of LC_{50} values of species tested (76 mg/ℓ, derived from Table 3.12a). The median concentrations for sulphate at W5 (776 mg/ℓ) and W20 (700 mg/ℓ) are higher than the 15^{th} percentile of LC_{50} values of species tested (458 mg/ℓ, derived from Table 3.12b), for ammonia at W5 (115 mg/ℓ) is higher than the 95^{th} percentile of LC_{50} values of species tested (66 mg/ℓ, derived from Table 3.12c), and for sodium at W5 (212 mg/ℓ) and W20 (257 mg/ℓ) are higher than the 10^{th} percentile of LC_{50} values of species tested (72 mg/ℓ, derived from Table 3.12f). The above comparisons constitute an unacceptable risk for effluent, as defined in Table 3.2 (legend).

Probability: There is a high probability the hypothesis can be rejected.

Confidence: High

LoE viii: The algal growth bioassays (Tables 3.14) indicate that the EC_0 was often at less than 10% effluent concentration, with the EC_0 being calculated at less than 0.03% effluent in March 1999. The EC_{50} was often at less than 100% effluent concentration, with less than 40% effluent being stated as the EC_{50} in March 1999. Although the evidence does not relate directly to acute effects in the effluent, the impact on algal growth (as supported by chlorophyll-a measures) would affect the sustainability of aquatic ecosystems.

Probability: There is a moderate probability the hypothesis can be rejected.

Confidence: Moderate

LoE ix: The water quality at W5, presented in Table 3.5, shows that the permit conditions were exceeded more than 50% of the time for pH, electrical conductivity, nitrate, ammonia, sulphate, fluoride, chemical oxygen demand, phosphate and sodium. The water quality at W20 (Table 3.5) shows that the permit condition were exceeded more than 50% of the time for pH, electrical conductivity, nitrate, sulphate, chemical oxygen demand and sodium, while the permit condition for ammonia, fluoride and phosphate were exceeded at least 10% of the time. Provided that the permit specifications fall within the range of acute toxicity, for sodium, sulphate and ammonia (Figure 3.9), the exceedence indicates that the risk is unacceptable (acute effects in effluent, Table 3.2 legend).

Probability: There is a high probability the hypothesis can be rejected.

Confidence: High

Hypothesis 2B: "The toxicity of effluents at permitted values do not pose an unacceptable risk to aquatic ecosystems"

LoE i-vi: The results from toxicity tests could not be linked to the effect of water quality at permit specifications, since the permit specifications for all the variables were never met. For the same reason, the evidence from LoE ii-vi is also not directly applicable to the hypothesis.

Probability: There is a low probability this hypothesis can be rejected.

Confidence: Low

LoE vii: Literature values on toxicity (Table 3.12 a-f) were compared with the permit specifications (1/7/1998-30/6/1999). For W5 (Tables 3.5) nitrate, ammonia, sulphate, fluoride and sodium pose an acute risk to the aquatic ecosystem, since the LC_{50} response is expressed for some of the test species below the levels specified in the permit (Figure 3.9). The values for W20 show that nitrate, ammonia, sulphate and sodium is specified in the permit (Tables 3.5) at levels which exceed the LC_{50} values of some of the tested species (Table

3.12 a-f).

Probability: There is a high probability the hypothesis can be rejected.

Confidence: High

LoE viii-ix: The habitat assessment is not applicable to future water quality scenarios, nor is measurement of water quality possible.

Probability: There is a low probability these hypotheses can be rejected.

Confidence: Low

Hypothesis 2C: "Likely future toxicity of effluents does not pose an unacceptable risk to aquatic ecosystems"

LoE i-vi and viii-ix: The evidence and resultant risk determined for hypothesis 2B also apply to hypothesis 2C.

LoE vii: A comparison of literature values on toxicity (Table 3.12 a-f) with the future scenarios (permit specifications for 1/7/1999 to 30/6/2000 and from 1/7/2002), showed that for W5 (Tables 3.5) and W20 (Tables 3.6) nitrate, ammonia and sulphate are specified at levels higher than the LC_{50} response levels for some of the test species. Any acute effects in effluent are, however, considered as an unacceptable risk (Table 3.2 legend)

Probability: There is a high probability the hypothesis can be rejected..

Confidence: High

Table 3.17 provides a summary of the evidence for evaluating hypotheses 2A, 2B and 2C. The evidence very strongly rejects hypothesis 2A, with six out of nine lines indicating unacceptable risk. Hypotheses 2B and 2C are only rejected on the basis of LoE vii, with the hypotheses being rejected with high confidence in both cases.

Table 3.17: Summary of the lines of evidence for hypotheses 2A, 2B and 2C.

	Line of evidence								
	i	**ii**	**iii**	**iv**	**v**	**vi**	**vii**	**viii**	**ix**
2A "The current toxicity of effluents do not pose an unacceptable risk to aquatic ecosystems"	H (h)	H (h)	M (h)	L (l)	L (l)	L (l)	H (h)	M (m)	H (h)
2B "The toxicity of effluents at permitted values do not pose an unacceptable risk to aquatic ecosystems"	L (l)	L (l)	L (l)	L (l)	L (l)	H (h)	L (l)	L (l)	L (l)
2C "Likely future toxicity of effluents do not pose an unacceptable risk to aquatic ecosystems"	L (l)	L (l)	L (l)	L (l)	L (l)	H (h)	L (l)	L (l)	L (l)

H/M/L – High, Medium or Low probability of rejecting the hypothesis, (h/m/l) – high, medium or low confidence

3.5.2. Evaluate risk

The lines of evidence presented in Table 3.16 and Table 3.17 provide strong support for rejecting hypotheses 1A and 2A. It can therefore be said that there is a high probability that the current values of specified variables in both the Modderfontein Spruit and AEL's effluents pose an unacceptable risk to aquatic ecosystems. Hypotheses 1B, 1C, 2B and 2C are supported by one line of evidence each, but evidence with a high level of confidence indicates a high probability that the hypotheses can be rejected. The conclusion is that the permitted and likely future values of specified variables at W6, W5 and W20 pose an unacceptable risk to aquatic ecosystems. Due to the single line of evidence for hypotheses 1B, 1C, 2B and 2C the analysis should be strengthened by experimental data. It can be concluded that the effects of the stressors are adverse, mostly indicating acute response. The effects are expressed throughout the study area and study period and are likely to have adverse downstream impacts.

3.5.3. Report risk

The discussions of the risks to downstream aquatic ecosystems associated with the operations of AEL in section 3.1.5 provide a clear picture of the risk. Communication to stakeholders or interested and affected parties should be done in the context of the services provided by the resource, thus explaining how it will affect the ability of the resource to provide for the needs

of present and future users. The services provided by the resources are characterised during the establishment of management objectives. In this instance, a human health risk assessment would have been a useful contribution.

3.6. Manage Risk

The risks should be managed in accordance with the new water resource protection policy (NWA). This implies a participative approach with stakeholder involvement in setting goals, cost-benefit analyses and decisions. Activities should be monitored to provide feedback as to the success of management actions and to change actions if needed.

3.6.1. Discuss the results with the risk manager

The results of the study were discussed with the risk managers to assess whether the assessment was sufficient in scope and confidence to assist in making management decisions.

3.6.2. Make environmental management decisions

The results were found to be of sufficient certainty and detail to inform management decisions. The manager should use the ERA results along with other relevant social, legal, political or economic information to make decisions. Given the results of the assessment, this should include mitigation measures. None of the feasible risk management options would result in an alteration of the risks, and would therefore not require another risk assessment. Preventative actions were found to be less damaging than no action. The information is presented in a way that allows comparative assessment of various risk hypotheses and considers a continuum in the stressor-response relationship (Figure 3.9).

3.7. Discussion

In setting the management objectives (permit specifications) for AEL, a balance was sought between the need to protect downstream environments and water users, and the optimisation

of socio-economic benefits that the industry provides. As a result, a combination of the pollution prevention approach (DWAF, 1995a), the RWQO's approach (DWAF, 1991) and the best available technology approach (BATNEEC; Azapagic and Clift, 1999) was used in setting objectives. These management objectives were therefore not risk-based. The monitoring programme that was implemented, also did not take the specific needs of risk-based assessment into account. More specifically, the selection of endpoints and measures (specified in the licence), as well as the spatial and temporal pattern of sampling, were not ideally suited to an ERA. The existing AEL programme did not include a detailed analysis of AEL's operations to determine likely stressors, nor did it include a comprehensive assessment of the catchment area. While both of these aspects should be included in the design of a monitoring programme (Roux, 2001), it did meet the thesis requirements of evaluating the ERA process in a realistic scenario, where data are often limiting.

The application of the ERA framework to AEL's monitoring programme provided the opportunity to adapt the programme so that management decisions could be better informed by the programme. The programme was changed in two ways. Firstly, the endpoints were expanded to include measures of primary production (chlorophyll-a and algal toxicity). Secondly, the frequency of biomonitoring was reduced. This was done because the initial frequency did not allow sufficient recovery of aquatic organisms between surveys and it also allowed the redistribution of project resources to other components, which was critical to the assessment.

The data that were collected over the study period allowed for an assessment with high level of confidence for hypotheses 1A and 2A (evaluating current conditions), while the evaluation of hypothesis 1B, 1C, 2B and 2C (evaluation of permit conditions and future scenarios) could only be done at low confidence. The original monitoring programme did not include these objectives. The programme was not sufficiently flexible to include extensive laboratory studies that would be needed to evaluate these conclusions with increased confidence.

The South African framework for ERA provided a practical framework for the assessment, but moreover served to identify weakness that could be addressed to strengthen the programme. Several aspects that were identified during the assessment were included in the South African Guidelines for ERA (Claassen et al., 2001b; Chapter 4). The most important

aspect was the lack of feedback loops between the different stages of the framework. In the first version, it was only during the last phase that the outcome was evaluated against the original objectives. In cases where the plan of the assessment was inadequate to meet the objectives, considerable time and effort would be wasted before the mismatch was detected. The addition of feedback loops allowed iterations of each phase, until the objectives of the specific phase was met. The case study also showed that the actions in the process needed to be separated from the supporting information, notes of clarification and examples. The distinction is explained on page 1 of the published guidelines document (Claassen et al., 2001b), which state that it should clarify communication and hence understanding of the process.

A specific criticism of the study concerns the use of ecological indicators. Ideally the suite of indicators should represent key information about structure, function, and composition of the ecological system (Dale and Beyeler, 2001). This study shares in stated concerns (Dale and Beyeler, 2001) about the use of ecological indicators as a resource management tool. The first concern is the small number of indicators used, which fail to consider the full complexity of the ecological system. Secondly, the ecological indicators that were used, originates from a management program that have long-term goals and objectives (Roux et al., 1999). The suite of indicators is therefore not ideally suited to the present regulatory context or the application to ERA. Thirdly, management and monitoring programs may lack scientific rigor because of their failure to use a defined protocol for identifying ecological indicators. The apparent discrepancies between permit conditions and expected ecosystem responses (toxicity data from the literature) at such concentrations illustrate this shortcoming. The discrepancy also shows that the process followed for setting the permit conditions did not take account of all relevant information. Suter (2001) highlights the differences between ecological indicators and assessment endpoints, concluding that risk assessments may use the results of monitoring studies, but only after disaggregating the indicators to their components and choosing those that are appropriate. The risk assessment was based on an existing and ongoing AEL monitoring programme, which did not follow such an approach (i.e. raw data were not reported). It is clear that disaggregated indicators would have increased the confidence of the assessment significantly. The conclusions from this study concur with Suter (2001) in suggesting that monitoring programs could be more useful if they used a risk-based approach to address important problems rather than simply tracking indicators.

In a baseline ERA of Elliot Ditch/Wea Creek, the EPA, Superfund Division, also applied hazard quotients (comparing measured values with benchmark values) and biological monitoring results to assess survival, reproduction and diversity of endpoints in accordance with a conceptual model (EPA 2001). Although the study referred to a testable hypothesis in the problem formulation stage, the hypothesis was never formally tested. While this approach is in line with the EPA guidance (EPA, 1998), it demonstrates a weakness in the EPA method by not clearly specifying the utility of establishing the risk hypothesis.

A few issues were raised during the AEL assessment, which were evaluated against the stated purpose of the South African ERA Guidelines document, being: "*This guideline document balances the need for a detailed manual to conduct ecological risk assessments and a framework document that will establish a common approach on which a broad range of environmental assessments can be based*" (Claassen et al., 2001b). The main comments in this regard were related to the levels of detail (specifically on exposure and effects assessment) required for the guidelines. It was concluded that the guidelines document should be generic enough to be applicable to a wide range of problems, including freshwater, marine, terrestrial and atmospheric environments and range from policy assessments to site-specific studies. It was also important to keep the document short enough so that managers and scientists alike could benefit from it. It was concluded that the document should provide an overarching framework for ERA in SA. The case study outlines presented in the Chapter 4 and the bibliography of key readings (Claassen et al., 2001b) were added to the guideline document to provide guidance with more technical aspects.

4. Proposed Ecological Risk Assessment Guidelines for South Africa

The development of a framework for ERA was based on international best practice, while taking South African needs into account (Chapter 2). The framework was applied to an industrial effluent case study (Chapter 3), where shortcomings of the proposed approach were identified. This chapter represents the proposed South African ERA Guidelines (Claassen et al., 2001b), which takes into account the lessons learned from the case study. It balances the need for a detailed manual and a framework document to establish a common approach for broad range of environmental assessments.

4.1. Introduction

An ERA is a process of sound scientific integrity. It should take account of relevant political, economic and social issues though should not be biased or compromised by them. The ERA methodology presented in this document distinguishes between actions in the process and the rationale and important notes. Communication and understanding of the process is supported by three hypothetical case study examples. The EPA (1998) definition for ERA, which was found to be robust through the development and application of the framework, is as follows: *"ERA is the process that evaluates the likelihood that adverse ecological effects may occur or are occurring as a result of exposure to one or more stressors".*

Risk in the context of ecological risk assessment and risk management is defined by the following necessary components:

- Subject: A hazard or stressor that initiates risk (Affected by what = stressor)
- Object: The target upon which the stressor or hazard is expected to have an effect (The effect on what = receptor)
- Effect: The type, magnitude and characteristics of the effect being assessed (what is happening to the object)
- Expression of likelihood: Probability of effect or other expression of expectation appropriate to the assessment

Risk management is an action (giving effect to a decision) where the decision is based on explicit knowledge on the likelihood of events and their consequences.

4.2. Agree on Objectives

A planning process, where the risk manager, stakeholders and the risk assessor agree on the objectives of the assessment, should precede the technical assessment (Figure 4.1).

4.2.1. Agree on management goals

Although risk management is performed independently of the technical assessment, the risk manager must effectively communicate the managerial goals and information needs to the assessor. Risk management can improve if the risk manager has access to appropriate ecological information, which can be accomplished by aligning the assessment to management goals. In the context of national legislation and international agreements, these management goals should support sustainable development and take account of stakeholder inputs and the socio-economic environment. The management goals should be related to adverse ecological effects in accordance with the definition of ERA and as such be represented by ecological values.

4.2.2. Define management options

The next step in the framework (Figure 4.1) is to define management decisions. In implementing the framework, it was found that it will be more productive to define management options towards designing an appropriate assessment. This will ensure that scarce resources are focussed at collecting appropriate information. The risk assessor and risk manager need to ensure alignment between the assessment and the management options. The problem needs to be articulate clearly in its human and environmental context and inputs should be accommodated from those who are likely to be affected by a decision. The decision should reduce and balance risks relative to their political, social, economic, legal, and cultural implications.

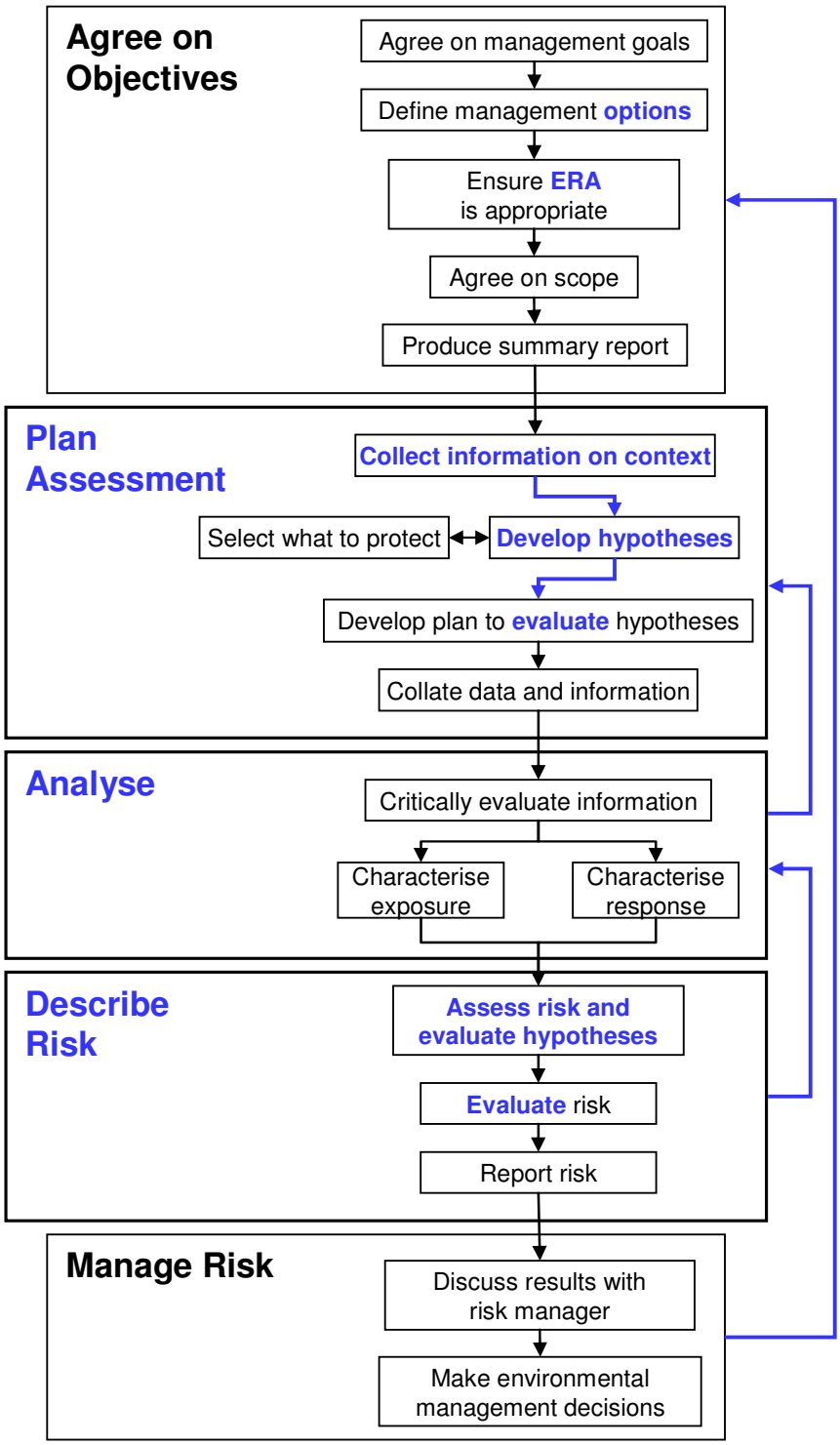


Figure 4.1: Revised process for ERA in South Africa (revisions indicated in **bold**). (foldout on page 200)

4.2.3. Ensure ERA is appropriate

A risk assessment provides the risk manager with a deeper understanding of the meaning and context of the risk associated with different management options. An expression of relevant risk, combining uncertainty and variability, improves the risk management process because it provides a sound scientific basis on which to base decisions. The purpose of this task is to determine whether an ERA will best enable managers to make informed environmental decisions, compared to other approaches, such as expert opinion, technological standards or a precautionary approach. Even if ERA will provide the best information for decisions, a risk management framework needs to be in place to accommodate and use results from the risk assessment.

A minor change from the framework (Figure 3.1) is the requirement to assess the appropriateness of ERA specifically, as opposed to the previous requirement to assess risk assessment as an approach. This has been included to ensure that the specific characteristics of ERA are appropriate to the assessment.

4.2.4. Agree on scope

The risk assessor and risk manager must agree on the scope of the ERA within the constraints of data availability, scientific knowledge, financial resources and spatial and temporal scales. It is important to define the uncertainty that the risk manager will tolerate, since higher confidence assessments may require more extensive assessments. The scope of the ERA may require the assessment to be at a screening level or a detailed, site-specific level. Managerial goals and information needs must be supported by the assessment, and should thus affect the scope. A clear scope will also lead to effective communication of the results to interested and affected parties.

4.2.5. Summary report

A summary report on the outcome of the "Agree on Objectives" phase should be produced. It will serve as a record of discussions and provide the terms of reference for subsequent work. The report will assist with clear communication between the risk manager, risk assessor and

interested and affected parties.

4.3. Plan Assessment

The development of an analysis plan is the first technical stage of an ERA. The language used for describing this stage was simplified from "formulate analysis plan" in the framework to "plan assessment".

4.3.1. Collect information on context

Information and data relevant to the assessment needs to be collected. Information related to environmental policy and the management context should be evaluated. The sources of stressors, stressors' characteristics and exposure mechanisms as well as spatial and temporal aspects need to be characterised. The characteristics of the ecosystem potentially at risk as well as the likely ecological effects of the stressors on the ecosystem also need to be described. It is important to understand the behaviour of ecosystems and its response to stressors because it promotes predictability, the interpretation of risk and reduces uncertainty. Ecosystem knowledge arises from monitoring, experimentation, modelling, etc. It also takes account of natural variability in the ecosystem. Knowledge of the stressor comes from chemical, physical or biological measures, modelling, experimentation and engineering design specifications. It should be focussed on the stressors' behaviour in the environment and take account of variability in the stressor system.

The task was described as "integrate available information" in the framework. This description led to confusion in the case study, since it was not clear whether new data related to the assessment were to be generated at this point. The updated description makes it clear that only information on the context is collected in the first step.

4.3.2. Develop hypotheses

Risk hypotheses are predictions of relationships between stressor, exposure and the response of the assessment endpoints. The risk hypotheses describe what will be evaluated during the

assessment. A cause-effect diagram of sources, stressors, exposure routes, end points, responses and measures representing the risk hypotheses should be drawn up. In-depth consideration should be given to ensuring all the important relationships are included, otherwise the uncertainty associated with the results of the risk assessment can be high. A good cause-effect diagram will facilitate clear understanding and communication. Examples of cause-effect diagrams are provided in Table 4.1.

Table 4.1: Examples of cause-effect diagrams highlighting the links between the sources of stressors and endpoint measures.

	Example 1	**Example 2**	**Example 3**	**Example 4**
Sources	Emission stacks	Effluent discharge	Construction	Erosion
Stressors	Heavy metals	Pesticides	Structure	Top soil loss
Exposure routes	Speciation/transport	Fate/dispersion	Migration barrier	Biome characteristics
Endpoint	Plant	Fish	Wildlife	Crops
Response	Growth	Death	Migration	Growth
Measure	Production	Abundance	Count	Yield
Ecosystem links	Herbivores	Kingfishers	Plants	Insects

4.3.3. Select what to protect

Endpoints are the definitive measures that scientifically and ecologically represent the broader management concerns. The ecosystem potentially at risk should be described according to functional and/or structural relationships (Figure 4.2). Potential assessment endpoints, which include valued ecological entities and the characteristic of the entities that are potentially at risk, should be identified. The endpoints should be scientifically relevant, which implies ecological and management relevance. Ecological relevance relates to endpoints helping sustain the natural structure, function and biodiversity of the ecosystem. Endpoints should be sensitive to the stressor under the amount of exposure likely to occur. Management relevance requires that the previously identified management decisions can be supported and hence the goals achieved. In this sense, the assessment endpoints should ideally be values that people care about.

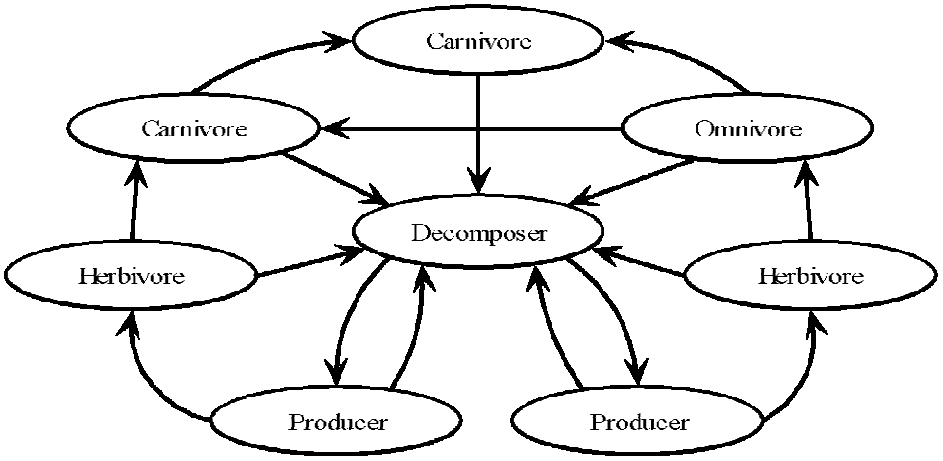


Figure 4.2: A simple ecosystem model.

4.3.4. Develop plan to evaluate hypothesis

An analysis plan needs to be developed that describes how the risk hypotheses will be assessed. Measures of exposure, measures of effect and measures of ecosystem and receptor characteristics need to be select and described. Measures of effect evaluate the response of the assessment endpoint when exposed to the stressor, whereas measures of exposure describe mechanisms by which exposure occurs and measures of ecosystem and receptor characteristics describe the assessment endpoints. Independent lines of evidence should be considered in the plan. It is important to describe the role of data analysis or modelling in the assessment, as well as how results will be presented. The analysis plan should comply with all the requirements for scientific integrity. The analysis plan needs to be discussed with the risk manager to ensure that the results will support sound decisions. The plan should clearly identify the data that need to be measured before the next stage is started.

4.3.5. Collate data and information

Detailed information that is relevant to the risk hypothesis and analysis plan should be compared and assessed. Aspects that need to be considered when collating data are variability (exposure and response), uncertainty (sampling error, unknown, hypothesis uncertainty, etc.) and data characteristics (including age of study, method employed, independence, replicates,

calibration, statistical significance, resolution and relevance).

The process of agreeing on objectives can be revisited if new information acquired during this phase is likely to bring about a different conclusion to the first phase of the assessment.

4.4. Analyse

4.4.1. Critically evaluate information

Existing studies should be critically evaluated and strengths and limitations of data should be evaluated. The purpose and scope of existing studies should be compared with those of the risk assessment and only data from studies that display due diligence and scientific rigour should be used. If the data required to reach the specified objectives demands it, new data should be obtained through measurements, modelling, experimentation, etc. Uncertainty should be evaluated by describing the exposure-effects relationships and quantifying what is known and not known. Potential sources of uncertainty include unclear communication, descriptive errors, gaps in the data, uncertainty about a quantity's true value and model uncertainties. There should be a clear distinction between natural variability due to stochastic processes and uncertainty due to lack of knowledge.

4.4.2. Characterise exposure

The place where the stressor is produced, the intensity and timing of stressor induction (spatial, magnitude and temporal dimension) and the mechanisms and pathways of stressors dispersion from the source should be evaluated. The mechanism, timing, location and magnitude of the exposure should be described. An exposure profile should be drawn up as a summary of what is known. Exposure assessment may include partitioning of chemicals, attributes of physical stressors, dispersion of biological stressors by diffusion or jump-dispersal. It is important to identify secondary stressors caused by the primary stressor since they can significantly influence the result of a risk assessment.

4.4.3. Characterise response

The relation between stressors levels and ecological effects should ideally be quantified. Ecological effects should be reflected at the expected and/or existing stressor levels. Causality should be established and an integrated stressor-response profile generated that integrates existing and new information. There should be a clear link between what needs to be protected (assessment endpoint) with what can be measured (measures of effect). Response analysis should include many different information sources. Lines of evidence that are developed in this way will strengthen the risk assessment.

New information that has been gathered or generated in this (analysis) phase may require another iteration of the "plan assessment" phase.

4.5. Describe risk

4.5.1. Assess risk and evaluate hypotheses

Testing the previously defined hypotheses allows the assessor to integrate measures of likelihood, variability and related uncertainties. The output is then strongly focussed on supporting the relevant decision. The nature, magnitude, extent and likelihood of adverse effects on assessment endpoints should be assessed. This is done by integrating exposure and effects data from the "analyse"-stage according to the analysis plan. Lines of evidence should be evaluated at this stage. Where independent approaches are used to arrive at conclusions, the assessment is likely to have higher confidence. Such approaches may include comparisons with literature or benchmark values, field studies and modelling.

Risk estimates can be obtained in many ways, including:

- Qualitative assessments, based on professional judgement.
- Single-point estimate, usually as a ratio of two numbers (actual value/benchmark value).
- Evaluating the relationships between the entire stressor and response profiles.
- Incorporating variability in exposure or effects.
- Using process models upon which to base risk estimates.
- Estimates can be based on results from field studies.

4.5.2. Evaluate risk

It is essential that a technical narrative accompany the risk assessment. The risks should be described in the context of the management options. The nature and intensity of the effects, the spatial and temporal scales and the potential for recovery should be considered.

4.5.3. Report risk

The report should facilitate communications of risk to policy makers in industry and government and interested and affected parties. This allows broader participation in, and scrutiny of, the process. Resource managers, the public and experts can differ considerably on the perception of risk and the significance thereof. The results of the risk assessment should be presented clearly and concisely. The approach to, and format of, risk reporting should be appropriate to the target audience.

4.6. Manage Risk

4.6.1. Discuss results with risk manager

The risk manager ensures that environmental management decisions are soundly supported by the risk assessment results. Another more detailed ecological risk assessment may be requested and a new analysis plan formulated, if it is needed for sound management decisions. Since an ERA process is iterative by nature, the assessment can initially conducted at a screening level. The results should be examined to decide if enough sound information is available to enable management decisions. The assessment may then be repeated at a more detailed level. Individual stages may also require internal iteration.

4.6.2. Make environmental management decisions

Once satisfied that the results are of sufficient certainty and detail, the risk manager can make decisions. The risk manager uses the results along with other relevant social, legal, political or economic information to make decisions on how to proceed. This may include invoking

mitigation measures, monitoring progress and communicating results to the public. A comparative risk assessment evaluates various risk hypotheses or considers a continuum in the stressor-response relationship. This enables a risk manager to set risk-based priorities. Resource allocation can then be focussed on risks that are more significant. A decision that alters risk may require another iteration of the ecological risk assessment process. Risk management may also mean that no action is taken, specifically when mitigation is more damaging.

4.7. Case Study Outlines

The following outlines of hypothetical case studies were developed to aid in communicating and implementing the guidelines.

4.7.1. Industrial effluent

Agree on objectives

Management Goals: Stakeholders were concerned about the perceived impacts of Egoli Industries' effluent on Hugem Park. Specific concerns were related to the endangered *Goldie sp*. Egoli Industries' goals were to:

- Determine the risk posed by their effluent to downstream ecosystems.
- Managing their effluent to protect the *Goldie sp*.
- Maintain good relationship with stakeholders.

Management Options: Egoli Industries had several management options. These were:

- Optimise their manufacturing process to attain minimum waste production.
- Use "best available technology" to attain reductions in metal containing effluent discharge.
- Negotiate with water users to reduce abstraction to increase the dilution of effluent.
- Employ other methods of waste disposal, e.g. recycling, drying, export, etc.

Appropriateness of ERA: ERA was considered appropriate because:

- It provides managers with an evaluation of various management options.
- Social, economic and ecological issues can be compared because the probability, magnitude and characteristics of combined effects are determined.

- It realistically addresses the complexity of problems through explicitly evaluating variability and uncertainty.

Scope of the study: The study was bounded by the following parameters;

Spatial: The Egoli industrial site and downstream Hugem National Park. The resolution was at the level of ecological communities.

Temporal: The study included historical data and considered the industry's lifetime.

Detail: The site-specific study should consider monthly water quality, the population status of *Goldie sp*. and relevant toxicological data (specifies resolution of data in exposure and effects).

Financial: The study had to be completed by three project members within 2 months. Local expertise was used where possible.

Summary report: A detailed record of the preceding "Agree on Objectives" phase was prepared.

Plan Assessment

Information: The following information was collected:

- Management context: Egoli Industries support pro-active environmental management.
- The legislation on biodiversity is the key regulatory consideration
- Egoli Industries' metal-containing (M^+) effluent is discharged into the river.
- The river transports M^+ to Hugem Park. M^+ can undergo chemical transformation during transport.
- The impacts are due to effects on fecundity and mortality of sensitive species.
- The high conservation status of Hugem Park is due to the occurrence of the endangered *Goldie sp*.

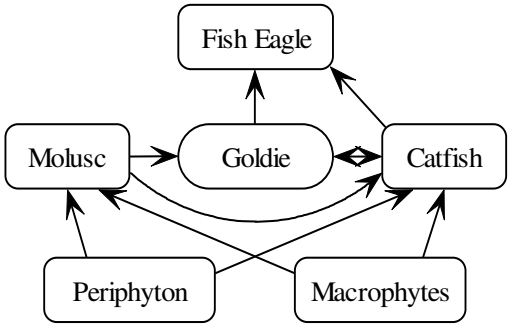
The cause-and-effect relationships (risk hypothesis) are presented in the following diagram.

The following questions are evaluated:

- Do current metal levels in the river pose an unacceptable threat to the *Goldie sp?*
- Do future metal levels in the riverpose an unacceptable threat to the *Goldie sp.*"

What to protect: The *Goldie sp.* was selected as the assessment endpoint because:

- It integrates ecological impacts, which confirms its ecological importance (diagram →).
- It is sensitive to the effects of the metal.
- Its endangered status makes it important for biodiversity and eco-tourism.



Plan to evaluate hypotheses:

- The current status was evaluated through compiling and comparing data on effluent quality, river water quality, toxicology and ecosystem structure.
- Fate and transport modelling and predictions based on eco-toxicology data were used to evaluate a range of possible future impacts.

Data and information: Data that was collated include:

- M^+ concentrations in the effluent and the river
- Chemical characteristics of the diluent water
- Observed laboratory transformations of M^+ species (from literature)
- Surveys of the *Goldie sp.* and associated ecosystems
- Toxicology of similar species
- The details of the management options

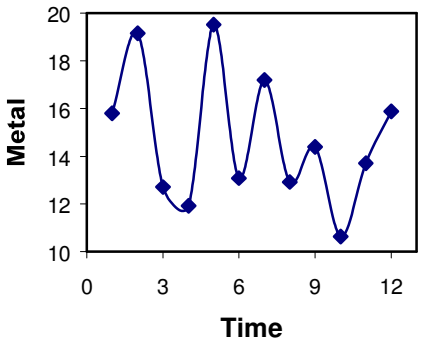
Analyze

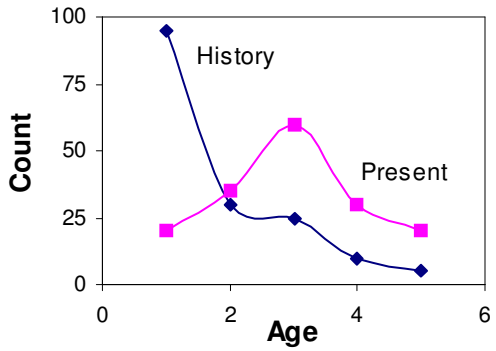
Evaluate information:

- Historical data was available on M^+ concentrations (and other important water quality determinants) in the effluent and the river. Data was collected at a weekly interval through acceptable analytical procedures. Possible reductions in M^+ were determined from the details of the management options.
- The status of the *Goldie sp.* and associated ecosystems were assessed prior to development. The current status of the *Goldie sp.* and associated ecosystem, the river flow and M^+ concentrations in Hugem Park was measured in this task.
- Fecundity and mortality data (toxicology) was available for the taxonomic group representatives.

Exposure:

As an aquatic species, the *Goldie sp.* is directly exposed to water (dermal, gills, digestive tract) and ingest contaminants together with food. The concentration of the bioavailable form of M^+ in the water is presented in the accompanying graph. The potential future M^+ concentration has been calculated through fate and transport modelling. It can range from 4 to 12 M^+ units at the site where *Goldie sp.* occur, depending on the management action.

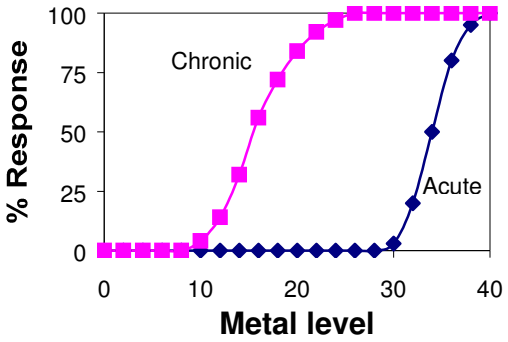




Responses:

The historical (prior to industrial activity) and present *Goldie* population structures are presented in the adjacent figure. Although the abundance is the same, the population structure is different.

The dose-response relationship for other species in the taxonomic group of *Goldie sp.* is presented in the adjacent figure. Chronic (inhibition of fecundity at age 3-4) and acute (mortality of age 1) effects are shown.



Describe Risk

Risk and hypotheses:

Comparing historical and present population data supports evaluation of the risk hypothesis. The current abundance of *Goldie sp.* is similar to historically records. The acute toxicity data supports the trend, with acute toxicity being indicated above 30 M+ units. The marked difference in population structure suggests chronic impacts. The evaluation is further supported by toxicological data, where chronic effects on other species in the taxonomic group are observed above 10 M+ units, with 100% effect on fecundity at 25 M+ units. Current metal values fluctuate between 10 and 20 units. This supports the evaluation that the

current metal levels affect the population structure. If the current trend continues, the *Goldie sp.* population will not be viable in 3 to 5 years time. The same data indicate that possible future levels will only affect fecundity at metal levels between 10 and 12 units. Acute effects are not expected under potential future scenarios. (Various statistical methods can be employed to quantify the risk)

Evaluate risk:

The evidence suggests that the current metal levels have a significant impact on the *Goldie sp.* population structure. No acute effect is indicated on the *Goldie sp.* population. Egoli Industries can institute management actions to limit in-stream metal concentration to 10 units.

Report risk:

The preceding evaluation should be reported in a format appropriate for the target audience

Uncertainties are due to:

- Unknown historical surveys methods
- Other gene pool used for toxicology
- Lack of analytical precision
- Lack of data on Goldie biology

Adsorptive capacity of in-stream particulates and sediments

Variability is affected by:

- River flow
- Effluent quality
- Other abstractions
- Seasonal trends
- Diurnal fluctuations in pH, temperature, DO and EC
- Goldie sp. susceptibility

Manage Risk

Discussion:

The results are discussed so that the risk manager is clear on the study characteristics, significance of the results and limitations.

Decision:

The manager should then be able to make effective decisions based on appropriate ecological and other relevant information. In this case, the analysis was sufficient to base a decision on; therefore, no further analyses are suggested.

4.7.2. Sustainable development

Agree on Objectives

Management Goals:

A state-owned property sustains a unique biome, which includes endemic species. The neighbouring community has been harvesting Fechit for the past 10 years, but due to the increasing needs of the community, the demand for Fechit has risen sharply. The conservation status of the area is high, with significant eco-tourism potential. The management goal is to: "Balance the development needs of the local community with eco-tourism potential and conservation priorities."

Management options:

- Stop or control the harvesting of Fechit
- Restock/replace Fechit in the area.
- Provide an alternative source of Fechit

Appropriateness of ERA: ERA can be used because:

- Different development options can be evaluated
- Cumulative effects can be assessed
- It provides an objective scientific evaluation

Scope of study:

Data availability: Very little is known about the specific area and associated ecosystems.

Scientific knowledge: Studies have been done on ecosystems with similar ecological characteristics.

Spatial scale: The boundaries of the study are the local community's property, the ocean and agricultural areas.

Temporal scale: The study should consider long-term effects (50-100 yrs).

Uncertainty: Because of the critical nature of the resource, very little tolerance (uncertainty) can be accommodated in the decision.

Summary report:

A detailed record of preceding discussions should be documented.

Plan Assessment

Information on context:

- Legislation regarding the protection of endemic species exists. The Act proposes

sustainable development as the minimum requirement.

- The frequency of harvesting and mass taken is recorded (once monthly, 50kg/ha)
- Harvesting methods have an impact on species that utilise similar habitat.

Cause-effect (risk hypothesis):

Fetchit harvesting ► Reduced production and abundance ► *N. demic* reduced

What to protect: Functional ecosystem model

Fechit (links to *other spp.*):

- Food source for *S. entails*
- Competes for food with *N. demic*
- Compete for habitat (nich) with *A. monarch, M. poster*
- *Creates habitat for* K. ritters, *D. gers, N. demic*
- Helps with dispersal of *D. rifters*

Endpoints are Fechit and *N. demic*

Fechit attributes: Abundance and production

N. demic attribute: Abundance

Key quastion:

Can Fechit be harvested without compromising the sustainability of Fechit and *N. demic* populations?

Plan to evaluate hypothesis:

1. Describe relationship between harvesting and Fechit
   - Harvesting data (kg/ha + frequency)
   - Detailed surveys (kg/ha)
   - Pilot studies (harvesting vs production)
   - Ecosystem modelling (sustainability of populations)
2. Describe relationship between Fechit and *N. demic*
   - Detailed surveys
   - Functional relationship (qualitative model)
   - Pilot studies (Fechit : *N. demic*)

Collate data:

Harvesting data are available – Survey methods known and acceptable

Need to collect other data – Use accepted methods to ensure <5% error in measurements.

Analyse

Evaluate information: Measure new data

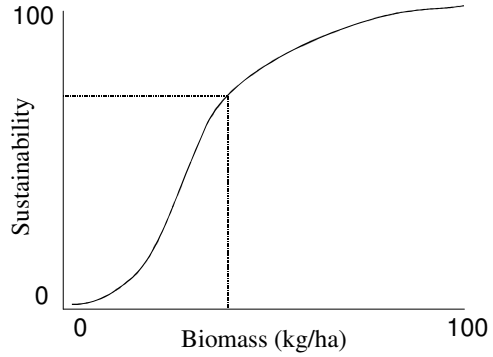
- Detailed surveys
- Pilot studies

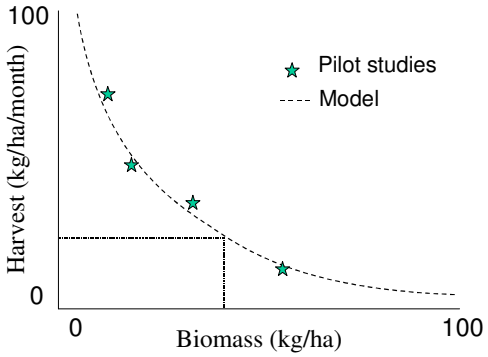
Characterise exposure:

- Current harvesting: 50kg/ha, once monthly
- Potential harvesting: 15kg/ha, weekly or 700 kg/ha, annually

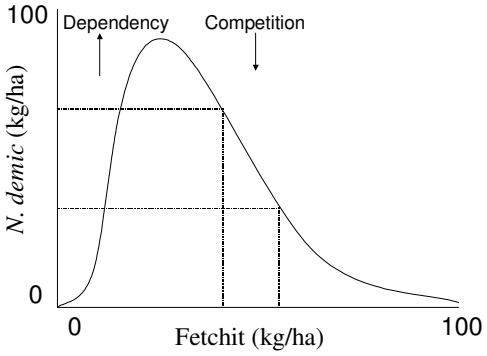
Characterise response:

An inverse relationship exists between harvesting and production. The figure shows modelled and actual data. The sustainability of the Fetchit population is affected by the biomass, with the relationship also indicated.





N. demic is dependant on Fetchit for habitat, but also competes for food with Fetchit. The relationship is depicted in the adjacent figure, with the optimal range indicated between the dotted lines.



Describe Risk

Assess risk:

A: Harvesting at 20kg/ha/month will ensure a biomass of acceptable sustainablity

B: For optimal *N. demic* population, need to manage for 300-700kg Fechit/ha (then *N. demic* = 10-25 kg/ha)

Uncertainties:

- Long term trends
- Seasonality
- Genetic diversity

Report risk: The preceding evaluation should be reported in a format appropriate for the target audience.

Manage Risk

Discussion: The results are discussed so that the risk manager is clear on the study characteristics, significance of the results and limitations.

Decision: The manager should then be able to make effective decisions based on appropriate ecological and other relevant information. In this case, the analysis was sufficient to base a decision on; therefore, no further analyses are suggested.

4.7.3. Marine pollution

Agree on objectives

Management Goals: An increasing incidence of crude oil spills threatened vulnerable coastal ecosystems. A management plan needed to be developed to:

- Reduce the likelihood of spills.
- Minimise vulnerable ecosystems' exposure to spilt oil.
- Optimise remediation of exposed ecosystems.

Management Options: Marine traffic and environmental authorities had the following options:

- Specify routes whereby potentially dangerous cargo can be transported.
- Control entry of high-risk vessels to sensitive areas.
- Reduce potential exposure to vulnerable ecosystems in the event of a spill.
- Mitigate impacts on vulnerable species in the event of exposure.

Appropriateness of ERA: An ERA would enable effective management decisions making because:

- The hazard could be characterised, which would lead to the institution of appropriate prevention actions.
- The evaluation of exposure routes and mechanisms would allow for the development

of an optimal hazard management programme.

- The integration of potential ecosystem responses and consequences would support the development of mitigation actions.

Scope of the study: The study was bounded by the following parameters;

Spatial: A 500 km buffer around two vulnerable coastal populations.

Temporal: The study considered current and potential future impacts.

Detail: The study was conducted at a detailed level, allowing the collection of site-specific information and the development of simulations.

Financial: 8 Experts and 20 support staff completed the study in 14 months.

Summary report: A detailed record of the preceding *Agree on Objectives* discussions was produced.

Plan Assessment

Information: The following information was collected:

- Global demand and supply of crude oil
- Frequency and timing of vessels passing through the study area
- Safety records of three classes of cargo vessels
- Characteristics of crude oil transported
- Ocean currents and characteristics that could effect spilt oil dispersion
- Susceptibility of two coastal populations to crude oil
- *Rocky* is dependent on habitat, which is adversely effected by spilt oil.
- *Diver* is directly affected through the toxic effects of crude oil.

Key question:

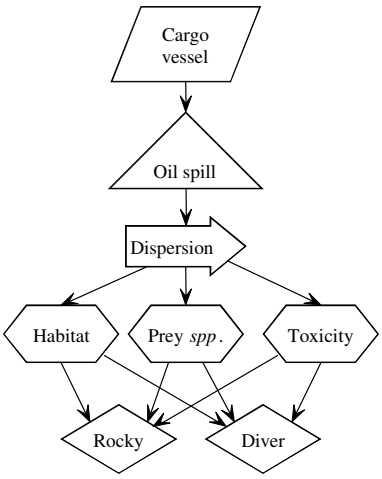
Do vessels carrying crude oil pose an unacceptable risk to *Diver* and *Rocky* populations?

Unacceptable was defined as:

- The probability of adverse effects being more than $1x10^{-3}$ (one in a thousand) annually.

Adverse effects were defined as

- Fatality to more than 5% of an exposed population or chronic effects in more than 25% of exposed populations.



The causal relationship between an oil spill and

adverse ecological effects was presented in the adjacent figure.

What to protect:

- *Diver* was selected as an assessment endpoint because they have a high conservation status, they integrate effects in the food chain (predators) and they are sensitive to crude oil exposure.
- *Rocky* was selected as an endpoint due to their importance as a food source for humans and their dependency on pristine habitat.

Plan to evaluate hypotheses:

- The likelihood of a spill (the hazard) occurring was determined through evaluating safety records of three classes of vessels (failures/1000 km travelled).
- The probability of exposure was determined through modelling the dispersion of spilt oil in the ocean.
- Pollutant levels that would induce acute and chronic effects were determined from historical and modelled information.

Data and information: Data that were collated include:

- Current and potential shipping routes, frequency of use and cargo type
- Safety records of vessels carrying crude oil
- Oceanographic and climate information
- A suitable simulation model and parameters
- *Diver* and *Rocky* sensitivity to crude oil

Analyse

Evaluate information:

Data was available at the required resolution and confidence for shipping routes and safety records and magnitude of spills.

The simulation model was calibrated to predict the dispersion and fate of spilt oil in the study area.

- There was uncertainty about the effect of global climate change on local conditions.

Assays were conducted to evaluate the susceptibility of *Diver* and *Rocky* to crude oil.

Exposure: The probability of a significant oil spill (> 10^6 units) was determined as follows:

- (Vessels per annum * Failures per 1000 km travelled)
    - Class A : (100 * 0.00001) = 0.001
    - Class B : (240 * 0.00005) = 0.012

- Class C : (35 * 0.0013) = 0.0455
- Summed probability of a significant spill (per annum) = 0.0585

- The oil concentrations that will reach the *Diver* and *Rocky* habitats can be simplified (hypothetically) to:

  $C = V/Br^2$ + (wind + current – biodegradation)

  - Where: C = Oil concentration (units/km^2) V = spilt volume
  - r = Population's distance from spill B = 22/7
  - Wind + current - biodegradation = distribution functions accounting for variability

- *Diver* was 30 km from the shipping route and *Rocky* 28 km

Responses: The populations' toxicological response to oil is described as follows (units oil/km^2):

No Observed Effect Concentration (NOEC) *Diver* = $2x10^1$, *Rocky* = $1x10^2$

Lowest Observed Effect Concentration (LOEC) D*iver* = $8x10^1$, *Rocky* = $3x10^2$

Concentration lethal to 5% of population (LC_5) *Diver* = $1x10^3$, *Rocky* = $5x10^2$

Concentration that induces chronic effects in 25% of population (EC_{25})

Diver = $4x10^2$, *Rocky* = $6x10^2$

Describe Risk

Risk and hypotheses:

The probability of a significant spill in the study area was 0.0585

- Significant exposure to the populations was:

  Diver : $4x10^2$ units/km^2 (chronic effects)

  Rocky : $5x10^2$ units/km^2 (acute effects)

- The expected exposures in the event of a spill was thus:

  C = $V/\Pi r^2$ + (wind + current – degradation)

  Diver : = $10^6/(22/7)*30^2$ + (± distribution)

  = 353 units/km^2 (± distribution)

  Rocky : = $10^6/(22/7)*28^2$ + (± distribution)

  = 378 units/km^2 (± distribution)

- The probabilities of significant effects were calculated through incorporating the distribution functions for wind, current and degradation (through Monte Carlo simulations):

Diver : Probability of > $4x10^2$ units/km^2 = 0.03

Rocky : Probability of > $5x10^2$ units/km^2 = 0.001

- The risks posed by crude oil vessels to the respective populations were calculated as the products of the likelihood of the hazard occurring and the probabilities of significant effects if it does.

  Diver : $0.0585 * 0.03 = 1.76 \times 10^{-3}$

  Rocky : $0.0585 * 0.001 = 5.86 \times 10^{-5}$

Evaluate risk:

- The risk posed by crude oil vessels to the *Diver* population is higher than the acceptable risk of $1x10^{-3}$.
- The risk posed to the *Rocky* population is acceptable in the context of the management thresholds.
- The risk to the *Diver* population was mostly affected by class C vessels and driven by chronic response.

Report risk: The calculated risks, together with the associated uncertainties, were reported in a clear yet concise format.

Manage Risk

Discussion: During discussions of the results, it was clear that the study provided adequate information to base a decision on.

Decision: The regulations for Class C vessels were upgraded to reduce the risk. Mitigation actions were put in place to rehabilitate the Diver population in the event of a spill.

4.8. Discussion

The ERA guidelines for South Africa (Chapter 4; Claassen, et al., 2001b) are based on the framework presented in Chapter 2, but modified according to peer and stakeholder comments as well as the findings from the case study presented in Chapter 3. The guidelines are applied to an ecological Reserve assessment case study (Chapter 5).

5. Application of ERA to an Ecological Reserve Determination (Water Quality)

5.1. Introduction

The ecological Reserve, as described in Chapter 2 (section 2.2), is based on risk principles (MacKay, 1998), but the suggested process for determining the ecological Reserve (DWAF, 1999a) does not explicitly follow the steps for ecological risk assessment. In broad terms, the suggested process is to define the water quality and quantity required to maintain the ecosystem integrity in accordance with a specific class within homogeneous units (MacKay, 1998). In this chapter, an ecological Reserve determination for water quality is presented within the framework for ERA (Figure 5.1) to assess the applicability of the risk assessment framework to ecological Reserve determinations. Ideally, such an analysis would consider the interrelationships between multiple stressors (water quality variables) as well as their patterns and timing. This assessment is, however, limited to taking site-specific ecosystem characteristics into account and specifying objectives in terms of probability distributions.

5.2. Agree on Objectives

5.2.1. Agree on management goals

The protection philosophy was entrenched in the fundamental principles and objectives for a new water law in SA (DWAF, 1997), with Principles 9 and 10 stating:

> (9) "The quantity, quality and reliability of water required to maintain the ecological functions on which humans depend shall be reserved so that the human use of water does not individually or cumulatively compromise the long term sustainability of aquatic and associated ecosystems."
>
> (10) "The water required to meet the basic human needs referred to in Principle 8 and the needs of the environment shall be identified as "the Reserve" and shall enjoy priority of use by right. The use of water for all other purposes shall be subject to authorisation."

The white paper on water policy (DWAF, 1997) supports the philosophy of water resource protection, stating that:

> "Only that water required to meet basic human needs and maintain environmental sustainability will be

guaranteed as a right. This will be known as the Reserve."

The approach, which was initiated in the principles, has subsequently been enacted (NWA, Act 36 of 1998), with Part 3 of the National Water Act (NWA) stating:

"the ecological Reserve relates to the water required to protect the aquatic ecosystems of the water resource. The Reserve refers to both the quantity and quality of the water in the resource, and will vary depending on the class of the resource."

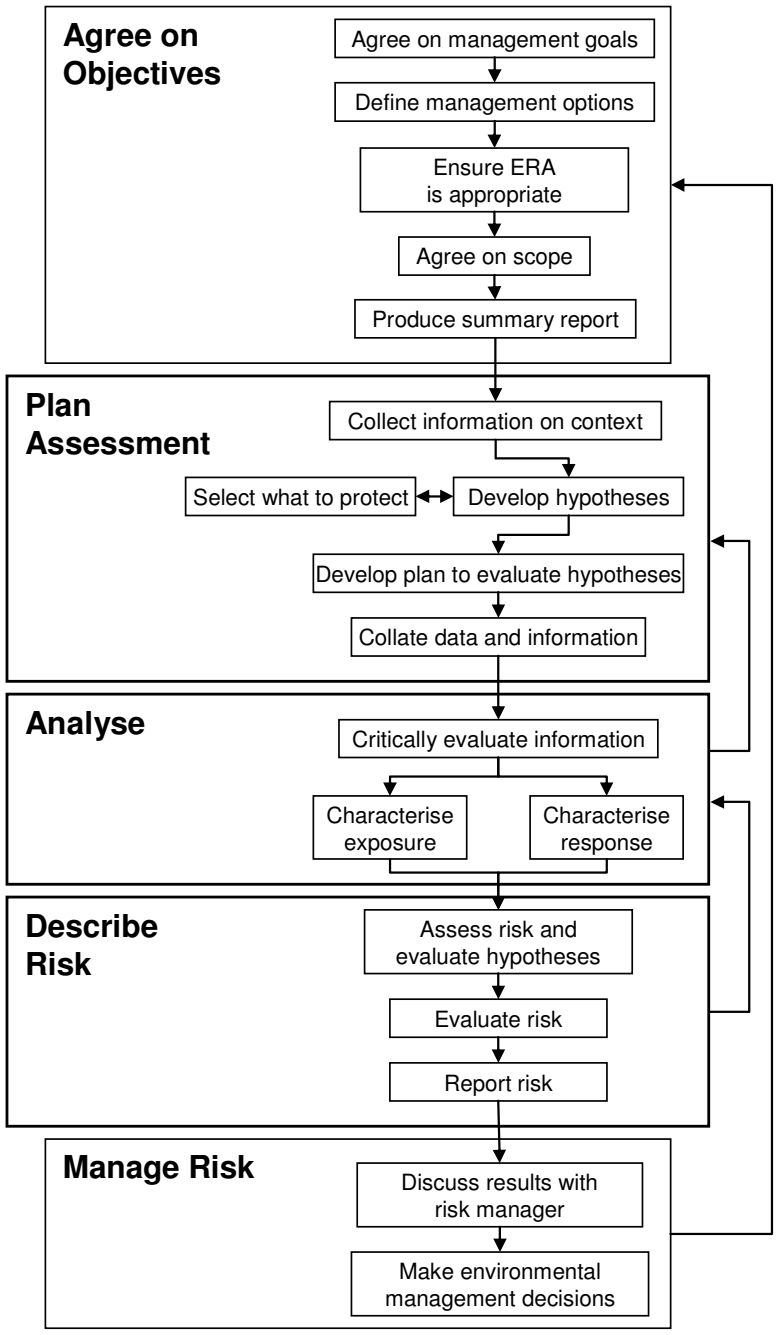


Figure 5.1: Revised process for ERA in South Africa.
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Section 18 of the NWA compels responsible authorities to:

> "…give effect to the Reserve as determined in terms of this Part when exercising any power or performing any duty in terms of this Act"

The ecological Reserve is, however, determined in accordance with a class, which allows a balance to be sought between the need to protect and sustain water resources on the one hand and the need to develop and use them on the other. The ecological Reserve can be described as ecological specifications that provide a specific level of protection to a water resource. The level of protection is related to the goods and services that society derives from the resource, and the potential for the resource to provide such goods and services for future generations.

5.2.2. Define management options

The relationship between risk and water resource classification is the basis for management options. During this study, it became clear that there was not a clear understanding of the relationship between risk, ecological integrity and the provision of goods and services. The author developed a diagram (Figure 5.2), in which classes (A-F) are related to the protection of ecological integrity, with increasing risk of losing ecosystem structure and function being associated with different resource use options. Management objectives can be set along this continuum, with classes E and F having been defined as unacceptable in the DWAF policy (MacKay, 1998). For this study, the limit of acceptable conditions (class D) is defined as habitat conditions and biological integrity deviating significantly from that associated with the ecotype under normal conditions, ecosystem processes (structure and function) being intact and indicator species representing the ecotype still present. The loss of structure and function is in Figure 5.2 does not mean an incremental change, but a system which no longer represent the natural structure (distribution of energy, material and species) and function (flow of energy, material and species). Such change could relate to primary production, feeding patterns, reproduction strategies, diversity, resilience, etc.

The provision of goods and services are linked to the classification system, with an A-class river providing mainly non-consumptive services and having the maximum potential to provide consumptive goods and services. Rivers in a D-class provide a high level of consumptive goods and services, albeit at higher risk of losing ecosystem structure and function. Rivers in classes E and F provide goods at a rate that poses high (unacceptable) risk to ecosystems. For this study, the risks associated to the different classes are based on the

probability that ecosystem structure and function will be lost in a given year. In an A-class, this risk can be equated to one in ten thousand chance of such change, which would typically be realised through long term natural cycles such as climate change that could result in migration or extinction (Figure 1.1). In a D-class, the risk can be equated to a one in a hundred chance that the risk will be realised in a given year (loss of ecosystem structure and function). The impacts that relate to this risk could be natural floods and fire or pathogens, with the typical response being secondary succession or gap-phase replacement (Figure 1.1).

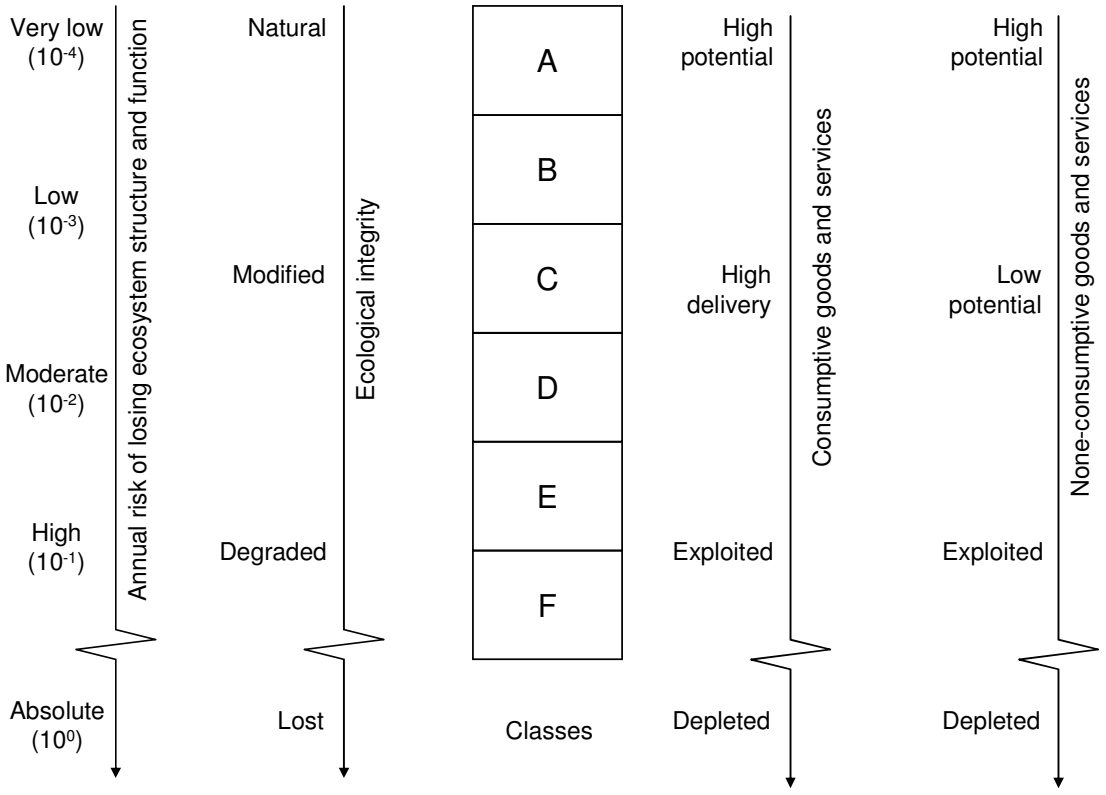

Figure 5.2: The relation between risk and water resource classification.

5.2.3. Ensure ERA is appropriate

Jooste and Claassen (2001a) investigated the application of risk concepts to water resource quality management and concluded that risk may reasonably be used to aid water resource quality management decisions and activities related to, but not necessarily limited to, the

following areas:

- Basis for water quality criteria: The current South African Water Quality Guidelines for Aquatic Ecosystems (DWAF, 1996) were derived from toxicological data and some qualitative assumptions regarding exposure. These criteria are limited because of expected effect differing from substance to substance, co-occurrence of different stressors are not considered, the criteria do not necessarily relate to the same ecological effect and the guidelines provide for limited levels of protection. Setting criteria on a risk basis would induce a measure of transparency into the interpretation of such criteria.
- Site-specific criteria: Applying risk criteria to the site-specific adaptation of criteria supplies a rational basis for incorporating new or locally significant data in a manner that is open to peer review.
- Resource management classification: The provision in the NWA for the classification of water resources can be linked to risk concepts. Management objectives may be expressed in terms of allowable risk. This provides an explicit communality between the receiving water quality/risk objectives and the Reserve as well as effluent criteria and/or standards. More specifically, the management of stressors can be explicitly linked to in-stream objectives.
- Hazard ranking: In some situations, it is neither necessary nor feasible to calculate absolute risks. In the case where different hazards within the same scenario or hazards in different scenarios need to be compared, risk is often a suitable basis for comparison.

5.2.4. Agree and report on the scope

An ecological Reserve determination is to be done as a basis for the evaluation of the licence applications. Scoping meetings and discussions are held, during which the terms of reference for the assessment are formulated as follows:

i. The ecological Reserve should be determined with the highest level of confidence possible, given the time constraints (1 month). The availability of data for this river allowed the assessment to be at the rapid to intermediate level (DWAF, 1999a).
ii. The resource unit for which the ecological Reserve will be determined is defined by quaternary catchment X24H (Figure 5.3).

iii. The following variables for which the ecological Reserve should be determined were identified: Temperature, pH, Dissolved O_2, Cl, TSS, TDS/EC, NH_3 & NO_3, PO_4, Total phosphorous, N:P ratio, Pb, NH_3. The list was based on an assessment of catchment characteristics, current and potential future chemical stressors as well as stakeholder concerns (Table 5.1).

iv. The ecological Reserve should be specified as probability distributions that represent natural variability. The objectives would not merely be stated as single values or "bright lines", but rather represent the distribution of concentrations that should be achieved.

The information in sections 5.2.1 to 5.2.4 was compiled and discussed with the relevant authorities, as a record of decisions.

Table 5.1: Variables selected for the ecological Reserve determination.

System variables		Nutrients	Toxics
Temperature pH Diss. O_2	TSS TDS/EC *	NH_3 PO_4 Total phosphorous N:P ratio (NO_2/NO_3**)	Pb Active chlorine

* Conductivity (mS/m) = TDS (mg/ℓ at 25^{o}C) / 6.5
** Nitrate/Nitrite is represented in the ratio of total inorganic nitrogen (TIN) and total phosphorus (TP)

5.3. Plan Assessment

5.4. Collect information on context

The study area (Figure 5.3) extends from Maroela Weir to the confluence with the Komati River. The Lowveld and Lebombo Uplands ecoregions, (Level I classification, DWAF, 1999b) transects the study area. The Lowveld ecoregion in the study area is comprised of level II regions 5.06 and 5.07, with the Lebombo Uplands representing the 6.01 level II ecoregion. These characteristics of the region (Balance et al., 2001; DWAF 1995c), as summarised in Table 5.2, supported the decision to use one resource unit for the study. This resource unit integrates water quality influences from the biggest part of the Crocodile River catchment.

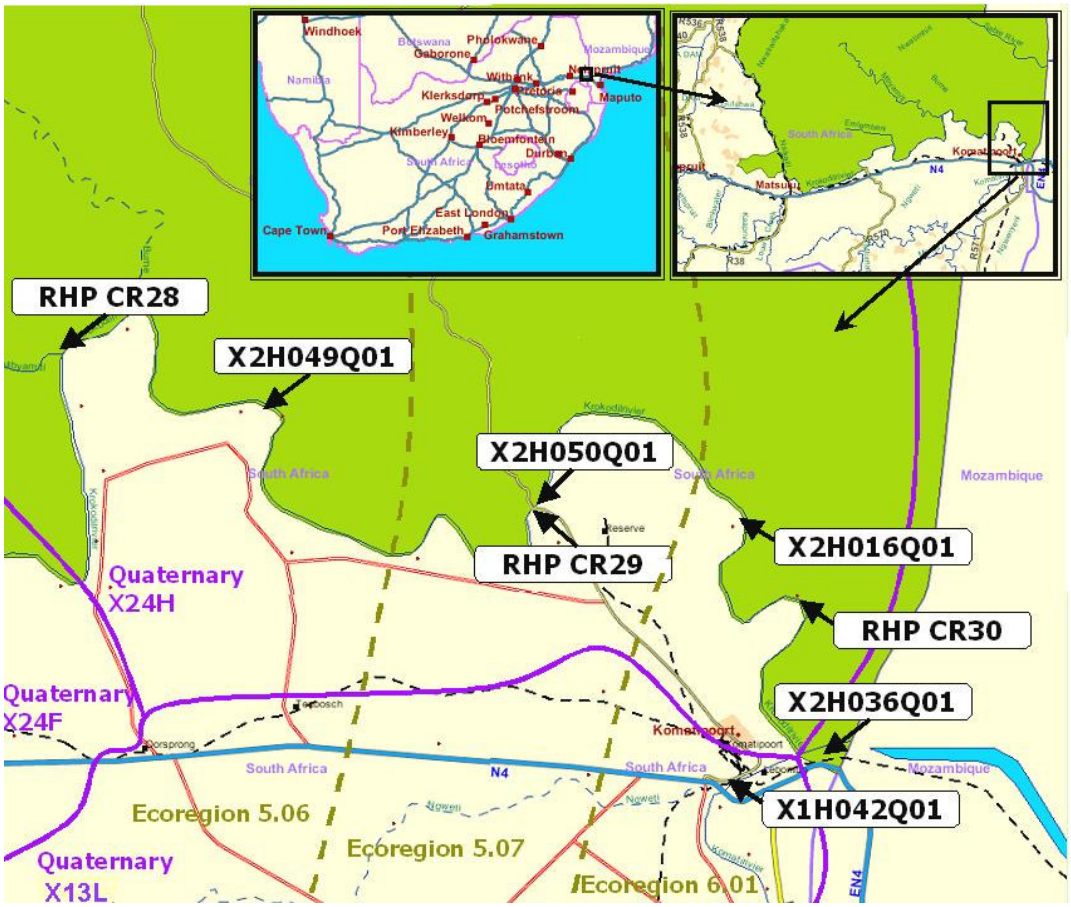

Figure 5.3: Monitoring points along the Crocodile River between Maroela Weir and Komatipoort.
(foldout on page 201)

5.4.1. Develop hypothesis

The determination of the ecological Reserve is a predictive (prospective) assessment. In such a case, the desired ecological response (state) is specified and the stressor levels that would be required to maintain such a state must be determined. Previous applications of the South African ERA framework (Chapter 3) highlighted the difficulties in setting null hypothesis and attempting, through the evaluation of lines of evidence, to assess "the degree to which" the hypothesis can be rejected. This study will use exposure-response relationships to estimate risks related to the desired state. This risk expressed in the context of uncertainty, which relates to the likelihood of underestimating (Type II or β-error) or overestimating risk (Type I

Table 5.2: Physical and climatologic characteristics of the study area.

	Ecoregion 5.06	**Ecoregion 5.07**	**Ecoregion 6.01**
Topography:	Flat moderate relief, typical of lowveld proper.	Moderately undulating plains with a moderate relief	Moderate relief with Lebombo arid maintain bushveld
Precipitation: (mean)	400-800 mm/annum	400-600 mm/annum	400-800 mm/annum
Temperature: (mean annual)	20-22 ^{o}C	≥ 22 ^{o}C	≥ 22 ^{o}C
Altitude: (m.a.m.s.l.)	300-600	200-400	100-300
Soils:	Shallow black, brown or red clayey soils	Shallow calcareous red sandy clay to clay overlay basalt of the Karoo system	Shallow acidic, sandy soils overlay basalt, tuff, breccia and rhyolite.
Veld type:	Sweet lowveld bushveld	Sweet lowveld bushveld	Lebombo arid mountain bushveld
River:	The river is 40-50 m wide and slow flowing. With mostly large sandy pools.	The river is 40-50 m wide and slow flowing. With mostly large sandy pools.	The river is 40-50 m wide and slow flowing. Rocky pools and large sandy pools dominate, with occasional rapids.

or α-error). The implications of the decision are illustrated in Figure 5.4, with the point "e" on the y-axis indicating the desired ecological state (level of response). The appropriate stressor level (level of protection) to attain or maintain this state would be the point "b" on the y-axis. The available data are, however, normally incomplete, which brings about uncertainty in the cause-effect relationship (indicated by the dotted lines along the curve). The risk will be underestimated for conditions in the graph below the solid line. If the power of the analysis (p) is set at 0.05, the stressor level at which acceptable risk will be expected is "c", which is the intersection at "iv". This will lead to a conservative assessment (margin of safety), in favour of protection. The margin of safety is dependent on the level at which α is set (normally 0.05) and the uncertainty associated with the data. The risk will be overestimated for conditions above the solid line, which relates to a stressor level of "a" for the same analysis (through the intersection at "ii"). It is therefore clear that both analyses are statistically sound, but provide very different results. (The above explanation is simplified, since the specification of the stressor level should not just specify a fixed level, but

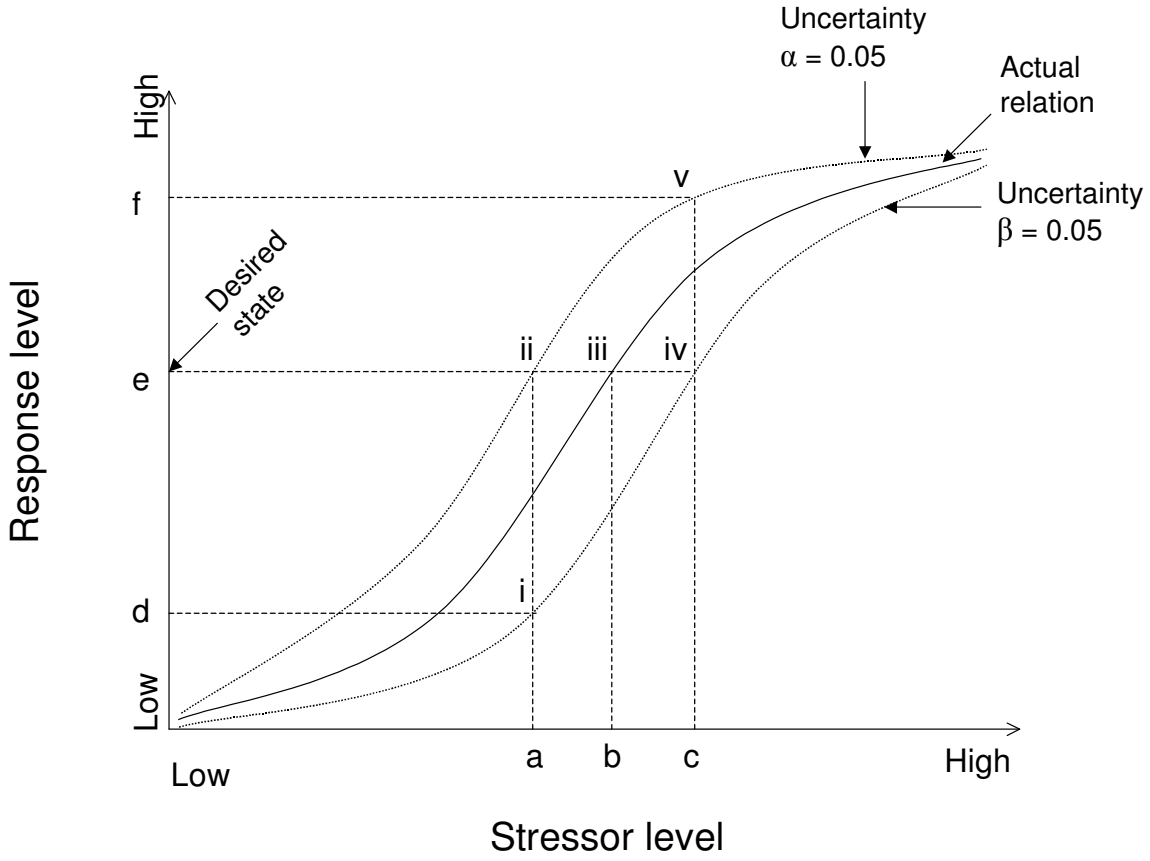

Figure 5.4: A conceptual representation of the confidence in rejecting the null hypothesis as opposed to the confidence in rejecting the alternative hypothesis.

incorporate the frequency and duration of occurrence, as well as spatial patterns.) For the purposes of this study, both perspectives are important, since the underlying objective of the water resource policy is to optimise resource utilization, while ensuring resource protection. As a result, the 5th and 95th percentile values are given, on the basis of frequency-duration curves. The risk hypothesis specified in Chapter 4 refers to the relationship between the sources, stressors, exposure routes, endpoints, responses, measures and ecosystem links and not the evaluation of a null hypothesis. For this assessment, the risk hypothesis can be summarised as follows:

Sources: The study does not relate to a specific source, since the aim of the study is to determine levels of stressor that would provide a specific level of protection.

Stressors:	Temperature, pH, Dissolved oxygen, TSS TDS/EC, NH3, PO4, Total phosphorous, N:P ratio, Pb, Active chlorine
Exposure routes:	Direct exposure of aquatic species
Endpoint:	Integrity of fish populations Diversity and abundance of macro-invertebrates In-stream and riparian habitats
Response:	Chronic and acute response of species used to determine above benchmarks
Measure:	Acute and chronic effect values from South African water quality guidelines (DWAF, 1996) and DWAF benchmark values (DWAF, 1999b), which represent acute and chronic toxicity and function impacts.
Ecosystem links:	Ecological integrity

5.4.2. Select what to protect

As specified in section 5.2.1, the principles and objectives of the NWA state that the long-term sustainability of aquatic and associated ecosystems should not be compromised. The endpoints that are identified as proxies for the objective are the integrity of fish populations, the diversity and abundance of macro-invertebrates, as well as in-stream and riparian habitats.

5.4.3. Plan to evaluate hypothesis

The water quality required to maintain ecosystems associated with the Crocodile River is determined through the applying the ecological Reserve concept. The method for ecological Reserve determination (DWAF, 1999a), identifies the following steps:

1. Delineate geographical boundaries
2a. Determine ecoregional type
2b. Delineate resource units
2c. Select sites
3. Determine reference conditions
4a. Determine present status
4b. Determine importance + sensitivity
5a. Determine Management class
5b. Set management class

6a. Quantify Reserve
6b. Set Resource Quality Objectives (RQO's)
7. Develop monitoring programme
8. Publish notice of RDM

The Crocodile River ecological Reserve determination followed this process with the following modifications:

- Steps 5a and 5b: These are deemed management responsibilities, and this study only provided inputs to such decisions by providing information for classes around the present state. To avoid confusion between the scientific and management responsibilities, the classification in this phase was referred to as categories.
- Step 6a: In quantifying the Reserve, biological and water quality monitoring data were used to supplement dose-response relationships (DWAF, 1996; DWAF, 1998).
- Step 6b: Resource quality objectives should include ecological considerations, human health considerations and resource use considerations (NWA). This study addressed only the first of the requirements; therefore RQOs were not set.
- Step 7: The identification of monitoring was outside of the scope of this study.
- Step 8: An administrative requirement that was not dealt with in this study.

5.4.4. Collect information to support the plan

Water quality and biological assessments were done in the lower Crocodile River catchment (DWAF, 1995c; Heath and Claassen, 1999; NAEBP, 1998). Survey sites and available data are shown in Figure 5.3 and listed in Table 5.3. The data required for determining the water quality component of the ecological Reserve include the following:

- Geological, climatic and ecological information for ecoregion typing
- Hydrology, geomorphology, water quality and ecological information for delineating resource units
- Water quality and ecological information from a reference site to determine reference conditions
- Water quality and ecological information from resource unit sites to determine the present state
- Ecological information to determine importance and sensitivity
- Dose-response information to determine the water quality required to meet the specifications of the ecological Reserve

Table 5.3: The study sites for the ecological Reserve determination.

Section	Water quality [1]	Ecological		Hydrology Modelled [2]
		Desktop [2]	Actual [3]	
Upstream section	-	X24F	-	X24F
Lower Crocodile	X2H049Q01 X2H050Q01 X2H016Q01	X24H	X2CROC-MBYAM (CR28) - 1 X2CROC- CROCB (CR29) - 6 X2CROC-NGONG (CR30) - 1	X24H
Komati River	X1H042Q01 X2H036Q01	X13L	-	-

[1] DWAF (2001) water quality monitoring points

[2] "Desktop" refers to a low confidence study using existing information only, as proposed by DWAF (1999a), which is conducted at the quaternary catchment level

[3] Monitoring stations used by the River Health Programme (Hill *et al.*, 2000)

The ecological parameters established for the determination of the Desktop ecological Reserve were used as a baseline for the study (DWAF, 2000). The following parameters, which were assessed during the study, are listed in Table 5.4:

Present ecological state category (PESC)

The PESC describes the present condition of the resource unit, in relation to the criteria for different classes.

Ecological importance and sensitivity rating (EIS)

Ecological importance relate to aspects such as diversity, uniqueness and scarcity, whereas ecological sensitivity describes the severity of response to stressors.

Default ecological management category (DEMC)

The default rule for DEMC is the PESC, adjusted upward if the EIS is high.

Best achievable ecological management class (Best AEMC)

The Best AEMC is an assessment of what management class can reasonably be achieved in the medium term.

Ecological management category (EMC)

The EMC is the recommended management class, from an ecological point of view. (The final decision on a management class should also include socio-economic considerations).

The view from Kruger National Park (KNP) staff (Deacon, personal communication) is that the Crocodile River is within a National Park and that all rivers in the park have a long-term management goal of "A".

Table 5.4: PES, EIS DEMC and derived EMC used for the assessment (DWAF, 2000).

Quaternary	PESC	EIS	DEMC	Best AEMC	EMC	KNP goal
X24F	B/C	High	B	B	B	A
X24H	C/D	High	B	C	C	A
X13L	C/D	High	B	C	C	-

The geology of the lower Crocodile River (from Kaapmuiden to the confluence with the Komati River) contributes to the water quality in the resource unit. A summary of the geology is provided in Table 5.5.

The reference conditions and the present water quality status, determined in accordance with the method proposed by DWAF (1999b), are presented in Appendix C with a summary of the conditions listed in Tables 5.6 and 5.7. It is notable that recent biological monitoring data (Thirion, 2001) suggest that the ecosystem is in a near natural state, while earlier biological monitoring data (MacMillan 1992; Thirion, 2001) indicate that the ecosystem was in a moderately modified state during the early 1990's.

5.5. Analysis

5.5.1. Critically evaluate information

The scope of the assessment did not allow for seasonal monitoring and analysis on the basis of a new experimental design (study plan). The information and data presented in section 5.3 and Appendix C are, however, based on recent analyses and monitoring of the study area. The data are therefore current and also comply with the requirements of current methods (DWAF, 1999b) and scientific rigour (Figure 3.1).

Table 5.5: Combined lithological units and water quality impact (DWAF, 1995c).

Lithological Units *	Description	Area (%)	Ionic contribution
Q	Surficial deposits, alluvium and scree	1	Al, Fe, Si, Minor K, Ca Mg
Ztk, Ztt, Zu, Zt	Basaltic and peridotic komatiite, tholeiite, chemical sediment, mafic and ultramafic schists interlayered with banded iron formations and ferruginous black, white and grey chert, acid to intermediate volcanic rocks, surpentinized dunite, harzburgzite, arthopyroxenite, websterite, gabbro, anorthosite, dark-green coarse-grained olivine diorite	9	Mg, Ca, Fe, K, Al Minor: Au, As, Mn, Cr, Ni
Zg, Zk	Biotite-trondhjemite gneiss and hornblende-biotite granite	6	Si, Al Na, Ca, K, Fe Minor: Au, As, Cu, Ni
Zn, Znm, Zh, Rm, Md	Grey to white coarse-grained biotite granit: weakly porphyritic to very strong porphyritic, veined by granodiorite, or strongly porphyritic granite with large phenocrysts; patassic gneiss and migmatite with some phenocrysts; strongly porphyroblactic, veined by granodiorite; Dark-green, coarse-grained olivine diorite.	69	K, Si, Fe, Al, Ca, CO_3, Na
Zm, Zf, Zmb, Zj, Zmc, Zfs, Zb, Zfh	Sandstone, grit, conglomorate, shale, sub-greywacke, phyllite, quartzite, jaspillite, trachytic tuff, agglomerate, lava, tuffaceous greywacke, greywacke, shales with interlayers of chert and ferruginous chert, ferruginous shale, basaltic lava, siltstone.	2	Mg, Si, Al, Fe, Ca, K Minor: Au, Ni, Mn
Rs	Granodiorite (Salisbury Kop Pluton)	2	Si, Al, K
Mt	Green to blue-green, medium to fine-grained gabbro, olivine gabbro and quartz gabbro	3	Si, Al, Fe, K
P-*h*, Jd, *h*-t, *h*-r	Undifferentiated below Karoo sequence: cream-coloured, fine-grained massive sandstone; massive dolerite in places; cream coloured fine-grained, massive sandstone, grading to red and white, fine grained argillaceous sandstone to the west edge.	3	Si, Al, Fe
Jl	Green, fine-grained mafic lava, locally porphyritic, amygdaloidal in places, interlayered with rhyolite, especially near the top	5	Si, Al, Fe, K
Jj	Red to light-brown, fine-grained rhyolitic lava, rhyolite and tuff	1	Si, Al, K

* Geological Survey, Barberton 2530, 1:250 000 Lithological Units

Table 5.6: Reference conditions for temperature, pH, DO and TSS.

	5th %tile – median - 95th %tile			
	Summer	Autumn	Winter	Spring
Water temperature (°C)	22 – 26 – 32	21 – 25 – 28	16 – 19 – 22	20 – 23 – 27
pH	6.9 - 7.2 – 7.7	6.8 – 7.1 – 7.4	7.2 – 7.6 – 8.1	7.3 - 7.6 – 7.9
Dissolved oxygen (%)	90 – 100 - 110	80 – 90 - 100	100 – 110 - 120	90 – 100 - 110
TSS (mg/ℓ)	5 – 10 – 67	7 – 13 – 21	1 – 10 – 25	5 – 7 – 10

Note: Summer: Nov-Feb; Autumn: Mar-Apr; Winter: May-Aug; Spring: Sep-Oct

Table 5.7: Reference conditions for nutrients and TDS.

	5th %tile – median - 95th %tile
NH_3 (mg/ℓ)	0.008 - 0.008 - 0.03
TP (mg/ℓ)	0.01 – 0.04 – 0.1
PO_4 (mg/ℓ)	0.005 – 0.015 – 0.04
TIN/TP	20:1 - 15:1 - 10:1
TDS (mg/ℓ)	100 - 250 – 400

5.5.2. Characterise exposure and response

The DEMC for quaternary catchment X24H is C (indicated with light shading in Table 5.8 - 5.14), although the ecological Reserve specifications for all categories are provided for comparative purposes. The present state for each variable is indicated with "Ⓟ". A detailed account of the derivation of ecological Reserve values (Tables 5.8 – 5.14) is presented in Appendix C.

Table 5.8: Ecological Reserve for water temperature*.

	Temperature (°C) : 5th %tile – (median range)- 95th %tile **			
	Summer	Autumn	Winter	Spring
Reference conditions (A)	22-26-32	21-25-28	16-19-22	20-23-27
Largely natural (B)	21-(25-27)-33	20-(24-26)-30	14-(18-20)-23	17-(22-24)-28
Moderately modified (C) Ⓟ	19-(23-29)-34	18-(22-28)-32	12-(17-21)-24	14-(20-26)-30
Largely modified (D)	17-(21-31)-35	16-(20-30)-35	10-(15-23)-26	11-(18-28)-32

Note: Summer: Nov-Feb; Autumn: Mar-Apr; Winter: May-Aug; Spring: Sep-Oct

* Temperatures fluctuations during the diel cycle are incorporated into the ranges. Minimum early morning temperatures are guided by the 5th percentile and late afternoon temperature by the 95th percentile.

** Where a median range is specified, the 5th percentile is relative to the lower median and the 95th percentile relative to the higher median.

Table 5.9: Ecological Reserve for pH*.

	pH units : 5th %tile – (median range) - 95th %tile			
	Summer	Autumn	Winter	Spring
Reference conditions (A)	6.9 - 7.2 – 7.7	6.8 – 7.1 – 7.4	7.2 – 7.6 – 8.1	7.3 - 7.6 – 7.9
Largely natural (B)	6.5-(6.8-7.6)-8.1	6.4-(6.7-7.5)-8.0	6.8-(7.2-8.0)-8.5	6.9-(7.2-8.0)-8.3
Moderately modified (C) Ⓟ	6.1-(6.4-8.0)-8.5	6.0-(6.3-7.9)-8.6	6.4-(6.8-8.4)-8.9	6.5-(6.8-8.4)-8.6
Largely modified (D)	5.7-(6.0-8.4)-8.9	5.6-(5.9-8.3)-9.2	6.0-(6.4-8.8)-9.3	6.1-(6.4-8.8)-9.0

Note: Summer: Nov-Feb; Autumn: Mar-Apr; Winter: May-Aug; Spring: Sep-Oct
* pH fluctuations during the diel cycle are incorporated into the ranges. Minimum early morning pH is guided by the 5th percentile and late afternoon pH by the 95th percentile.

Table 5.10: Ecological Reserve for dissolved oxygen*.

	Dissolved oxygen (% saturation) : 5th %tile – (median range) - 95th %tile			
	Summer	Autumn	Winter	Spring
Reference conditions (A)	90-100-110	80-90-100	100-110-120	90-100-110
Largely natural (B) Ⓟ	80-(90-100)-110	70-(80-90)-100	90-(100-110)-120	80-(90-100)-110
Moderately modified (C)	65-(75-85)-95	55-(65-75)-85	75-(85-95)-105	65-(75-85)-95
Largely modified (D)	50-(60-70)-80	40-(50-60)-70	60-(70-80)-90	50-(60-70)-80

Note: Summer: Nov-Feb; Autumn: Mar-Apr; Winter: May-Aug; Spring: Sep-Oct
* DO fluctuations during the diel cycle are incorporated into the ranges. Minimum early morning temperatures are guided by the 5th percentile and late afternoon temperature by the 95th percentile.

Table 5.11: Ecological Reserve for nutrients.

	Nutrients (mg/ℓ) : 5th %tile – median - 95th %tile			
	NH_3	TP	PO_4	TIN/TP
Reference conditions (A)	0.008 - 0.008 - 0.03	0.01 – 0.04 – 0.1	0.005 – 0.015 – 0.04	20:1 - 15:1 - 10:1
Largely natural (B) Ⓟ	0.016 - 0.016 - 0.05	0.015 – 0.06 – 0.15	0.01 – 0.05 – 0.015	13:1 – 10:1 - 7:1
Moderately modified (C)	0.035 - 0.035 - 0.08	0.02 – 0.08 – 0.2	0.03 – 0.10 – 0.25	9:1 – 7:1 - 5:1
Largely modified (D)	0.08 - 0.08 – 0.16	0.025 – 0.1 – 0.25	0.05 – 0.15 – 0.4	7:1 – 5:1 - 3:1

Table 5.12: Ecological Reserve for TDS.

	TDS (mg/ℓ) : 5th %tile – median - 95th %tile
Reference conditions (A) Ⓟ	100 – 250 – 400
Largely natural (B)	120 – 300 – 480
Moderately modified (C)	150 – 375 – 600
Largely modified (D)	200 – 500 – 800

Table 5.13: Ecological Reserve for TSS.

	TSS (mg/ℓ): 5th %tile – median – 95th %tile			
	Summer	Autumn	Winter	Spring
Reference conditions (A)	5 – 10 – 67	7 – 13 – 21	1 – 10 – 25	5 – 7 – 10
Largely natural (B)	5 – 11 – 73	7 – 14 – 23	1 – 11 – 27	5 – 7 – 10
Moderately modified (C) Ⓟ	6 – 12 – 78	8 – 15 – 25	1 – 12 – 29	6 – 8 – 11
Largely modified (D)	7 – 13 – 83	9 – 16 – 27	1 – 13 – 31	6 – 8 – 12

Note: Summer: Nov-Feb; Autumn: Mar-Apr; Winter: May-Aug; Spring: Sep-Oct

Table 5.14: Ecological Reserve for toxics*.

	Lead (µg/ℓ)	Residual chlorine (µg/ℓ)
Reference conditions (A) Ⓟ	90% < 0.5, 99% < 1.0, 100% < 7.0	90% < 0.2, 99% < 0.35, 100% < 5.0
Largely natural (B)	95% < 1.0, 99% < 7.0	95% < 0.35, 99% < 5.0
Moderately modified (C)	75% < 1.0, 90% < 7.0	75% < 0.35, 90% < 5.0
Largely modified (D)	50% < 1.0, 85% < 7.0	50% < 0.35, 85% < 5.0

* Specified as the % time that the given values should not be exceeded

5.6. Describe Risk

In accordance with the stated risk hypothesis (section 5.3.2), the water quality variables for which the ecological Reserve is determined are the stressors. The risk is therefore expressed as the annual probability of losing ecosystem structure and function as a result of deteriorated water quality (Figure 5.2). The lower Crocodile River receives water from the adjacent aquifer, with the groundwater being of good quality. There is no evidence of the flow being reversed through abstractions. The relationships between flow and water quality variables are investigated in Appendix C (Figure C1; Tables C8, C13 and C29) with seasonal analysis being done where relationships are evident. The upstream resource unit (X24F) is of better quality than X24H, with the EMC being higher. A water quality ecological Reserve in this unit should also be protective of the current unit (X24H). The downstream unit (X13L) is of similar quality to the current unit, and would therefore not be compromised by the ecological Reserve. The proximity of an international border would have implications for relevant water quantity obligations and quality requirements for basic human needs. The confidence in the assessment, based on the availability and characteristics of data and the methods followed, is as follows:

- Temperature High
- pH High
- Dissolved oxygen Low
- Nutrients High for natural, Moderate for largely modified
- TDS Moderate
- TSS Low
- Toxics High

5.7. Manage Risk

5.7.1. Discuss results with risk manager

The details of the analysis were discussed with the relevant authorities (risk managers) and the report was updated to provide a clear description of the procedures and results (Table 5.8 – Table 5.14). Specific attention was given to the use of probability distributions as opposed to the conventional single value criteria.

5.7.2. Make environmental management decisions

The authorities used the results from the assessment as a basis for evaluating licence applications for wastewater discharges that could impact on water quality. The evaluation took account of the ecological Reserve (this study), the basic human needs Reserve and the requirements of other water users to determine the capacity of the resource to provide the required service (allocatable resource).

5.8. Discussion

This specific case study was conducted subsequent to the publication of the South African Guidelines for Ecological Risk Assessment (Claassen et al., 2001b). It therefore does not have as its primary goal the provision of inputs to the development of the document, but rather demonstrate the value of the framework in the context of Reserve determinations.

The flexibility of the case study was limited by regulatory requirements (DWAF, 1999b). The study also posed significant challenges in terms of the study period (one month) and the confidence required (low-moderate). The ERA framework was used to optimise the application of resources available to the study and to present the results in a way that would aid in decision-making. In this regard the emphasis was not so much on the framework, but rather on the philosophical approach. As discussed in section 5.3.2, the assumption is that there will always be some level of uncertainty. The issue is whether this uncertainty should be applied in favour of protection, or in favour of development. The ERA framework provided a means to present both aspects in the final results (section 5.4.2).

The application of the ERA framework shifted the focus from the stressors to the endpoints. Rather than just following a standards-based approach (hazard assessment), specific ecosystem attributes were identified and water quality conditions specified which would maintain the desired state (category). The analysis focussed on determining the stressor levels that would maintain the desired state. In practice, the standards were always used as a baseline, with changes suggested where sufficient evidence was available (Appendix C). This approach provided good value from limited time and resources and showed that the ERA framework could be applied in cases where the study characteristics are governed by regulatory or other requirements and resources and time are limiting.

The case study brought several weaknesses of the Reserve determination method to the fore, some of which related to the approach followed and others to the management context. Of particular importance is that an ERA should describe the likelihood of adverse ecological effects, given exposure to one or more stressors. Ideally, the effects should take account of multiple stressors. This case study viewed each stressor as independent in its occurrence, mode of action and impacts. This assumption brought about uncertainties in the assessment that affect the confidence levels of the results. Although the weakness is apparent, the techniques for such assessments are limited. Whole effluent toxicity approaches (Slabbert *et al.*, 1998) could be applied to assess such effects, with chronic assays being recommended for receiving waters. This study contributed directly to the development of a risk-based approach for water quality management (Jooste and Claassen, 2001b).

While the results comply with the terms of reference (section 5.2.4), the design was not adequate in addressing communication with risk managers. Water resource managers had difficulty in interpreting probability-based results, resulting in significant delays in implementation. It became clear during the assessment that the ecological Reserve determination should ideally be done simultaneously for all resource units within a catchment, as well as for water quality and quantity. The case study was limited to a single resource unit and did not include an assessment of water quantity. Information was therefore not available for processes at the catchment scale, nor could the relationship between water quality and quantity be assessed adequately.

6. Evaluation of the Thesis

6.1. Introduction

The advent of democracy in South Africa brought about radical changes in legislation. While accelerated socio-economic growth became central to the political agenda and to societal needs, such developments have to be sustainable. The drafting of South African guidelines for ERA was born from this need to balance socio-economic development and environmental protection in the South African context. This chapter evaluates the ERA guidelines as well as its application in water resource management.

6.2. South African framework for ERA

The interest in ERA as a potential approach for water resource management in South Africa grew strongly between 1996 and 1998, with the realization for the need of a more structured approach towards the development of ERA guidelines bringing about this thesis (1999-2002). Two processes were considered as a basis for ensuring rigour in the development process. The scientific process, based on falsification, peer review and accumulation of knowledge, was the cornerstone of the process. Secondly, the process for policy development was considered, since ERA is not just a technical process, but also requires alignment with relevant policies. Through sharing experience on implementing ERA elsewhere, a structured phase of consolidation and review brought about many changes from the initial concept (Claassen, 2000). It is clear from this experience that a rigorous plan for the development of processes such as ERA should be established as early as possible, to minimise the amount a rework and maximise the opportunities for testing and evaluating concepts.

6.3. Industrial effluent case-study

The AEL case study presented in Chapter 3 provided a useful application to evaluate the proposed South African framework for ERA. The case study identified several weaknesses in the framework, of which the most critical was the interpretation of the hypothesis. While the framework (Chapter 2) refers to the establishment of a hypothesis based on the relationships between stressor, exposure and the response of the assessment endpoints, the case study was based on the statistical assessment of null hypotheses.

The broad objectives of the AEL study were to assess and quantify the impacts of AEL's operations on the receiving waters, in the context of the regulatory requirements and in support of pro-active management initiatives. The statement and testing of null hypotheses towards meeting these objectives caused difficulties, primarily due to the inappropriate use of hypothesis testing in risk assessment. Specific problems were related to the following:

The hypothesis

The basis of traditional hypothesis testing is to collect evidence and build a case to reject the null hypothesis. To rejecting the hypothesis on the basis of the conventional (but arbitrary) 95% confidence requires a “model” dataset. The required number of data points to achieve this outcome is increased for nonparametric data and data with high variability, both of which are true for water quality in the case study. This requirement dilutes a potential benefit of ERA, which is to provide credible decision support in the context of uncertainty. The failure to reject the null hypothesis also provides no information towards the protection of the ecosystem and is therefore of little use in management decision-making.

Supporting decisions

Hypotheses are statements (theories) of specific conditions, which are then tested. Real world decisions are often in the context of multiple criteria with a multitude of options being possible for each criterion. The case study is no different, and while the case study attempted to consider more options through assessing three different sets of hypotheses (current state, license conditions and expected future state), the results provided little information on cause-

effect relationship for other points along the exposure continuum. Such hypothesis testing approach does not support the expressed national need for accelerated socio-economic growth, in that it does not provide an estimation of risk along the full spectrum of exposure options and therefore does not provide adequate information for decisions to balance protection and development.

Uncertainty

Hypothesis testing takes account of (statistical) uncertainty through a conservative approach, i.e. the hypothesis can only be rejected if the uncertainty is less than the stated confidence requirements. Moreover, since the uncertainty is embedded in the analysis and not reflected in the answer (other than the confidence set for the analysis), the decision-maker has little information as to the extent of uncertainty, especially when the null hypothesis is not rejected.

Suter (1996) stated several issues related to the abuse of hypothesis testing in ecological risk assessment. Practical problems are that it provides less protection for species that are difficult to test or sample, it encourages selection of less-valued endpoints and it offers less protection when more exposure levels and effects are measured. Suter also states that hypothesis testing may lead to poor decision-making, since:

- the “no effect” result cannot be accepted,
- the “no observed effect” response can be misinterpreted,
- it does not support inference through weight of evidence,
- the significance of effects are only addressed at the tested exposure level,
- it is limited to “significant” and “not significant” levels of effect, and
- it confounds effects and uncertainty.

The case study deployed different lines of evidence in testing the stated hypotheses, but did not follow a rigorous process to integrate the lines of evidence and assess risk. This highlights the limitations of hypothesis testing in that the statistical process obscures information on uncertainty, variability and significance to the extent that it is difficult to combine the results from testing a hypothesis on accordance with different lines of evidence.

The evaluation of risk in the case study is inadequate. The findings from testing the hypotheses are summarized, but little is said about the nature, magnitude and probability of effects. The EPA (1998) is more specific in this regard, saying that the evaluation process involves more than just listing the evidence that supports or refutes the risk estimate, but that the risk assessor should carefully examine each factor and evaluate its contribution in the context of the risk assessment.

6.4. South African ERA guidelines

The framework for ERA in South Africa was adapted in accordance with reviewers' feedback (Claassen et al., 2001a) and case study experience (Chapter 3), to produce ERA guidelines for South Africa. The guidelines balanced the need for a detailed manual to conduct ERA's and a framework document that would establish a common approach on which a broad range of environmental assessments could be based. The purpose of the guidelines is to assist risk assessors who have domain-specific knowledge and competence and to assist risk managers in the application of ERA. The case study outlines have been shown to be particularly useful in demonstrating typical applications and engendering a shared understanding. A key comment from users (Claassen, 2002) was that the document does not provide adequate guidance on the specific technical methods that can be deployed to satisfy the requirements of the various steps in the process. It was agreed with regulatory agencies that the document would serve as the overarching framework, with the development of manuals being anticipated for specific applications.

6.5. Ecological Reserve case-study

The aim of the case study presented in Chapter 5 is to define the water quality required to maintain the ecosystem integrity in accordance with a specific class within homogeneous units (ecological Reserve), and to assess the applicability of the ERA approach and guidelines in conducting ecological Reserve assessments. The first challenge to the assessment was to clarify the objectives. While the classes referred to in the Reserve method (DWAF, 1999a) are qualitatively described and further characterized in terms of ecological indicators, the

actual state of the ecosystem in each class is not described adequately. The relationship between risk, ecological integrity, classes and the provision of goods and services in Figure 5.2, presenting the view of the author, goes some way towards clarity, but still leaves room for interpretation. Concepts such as loss of structure and function, degradation and integrity should be better defined.

The case study shows that the use of quotients (comparing exposure values to benchmark values) provides much more information towards decisions than did hypothesis testing. The use of a rigorous process of agreeing on management goals and options allowed feedback to be given to DWAF about weaknesses in the method for ecological Reserve assessments (Jooste and Claassen, 2001). As a consequence, the method is currently being revised to include much clearer definitions of the objectives and classes.

Extensive discussions were held with risk managers (DWAF) in the planning phase, during the execution phase and in discussing the results of the case study. While the characteristics of a risk assessment were central to these discussions, mangers were in the end still reluctant to use results that represent ranges (distributions) and took account of seasonal cycles. Managers were still locked in a paradigm that required scientists to evaluate and interpret evidence and provide a single value as the answer. While this often required scientists to obscure uncertainty and variability it also led to value judgments being made by scientists, rather than managers. Much discussion took place subsequent to the case study and multi-criteria decision-support tools are being developed to assist officials in considering the multiplicity of criteria related to protection and development. A Bayesian approach (Hobbs, 1997) is used to express the expectation that a certain decision will bring about the required outcomes.

6.6. Application of ERA to water resource management

A broad review of water resource assessment and management was established in Chapter 1, specifically with regards to aquatic ecosystem structure and function. Dale & Beyeler (2001) proposed a consolidated view of ecosystem composition, structure and function (Figure 6.1). The emphasis on structure and function in Chapter 1 is in line with the framework proposed

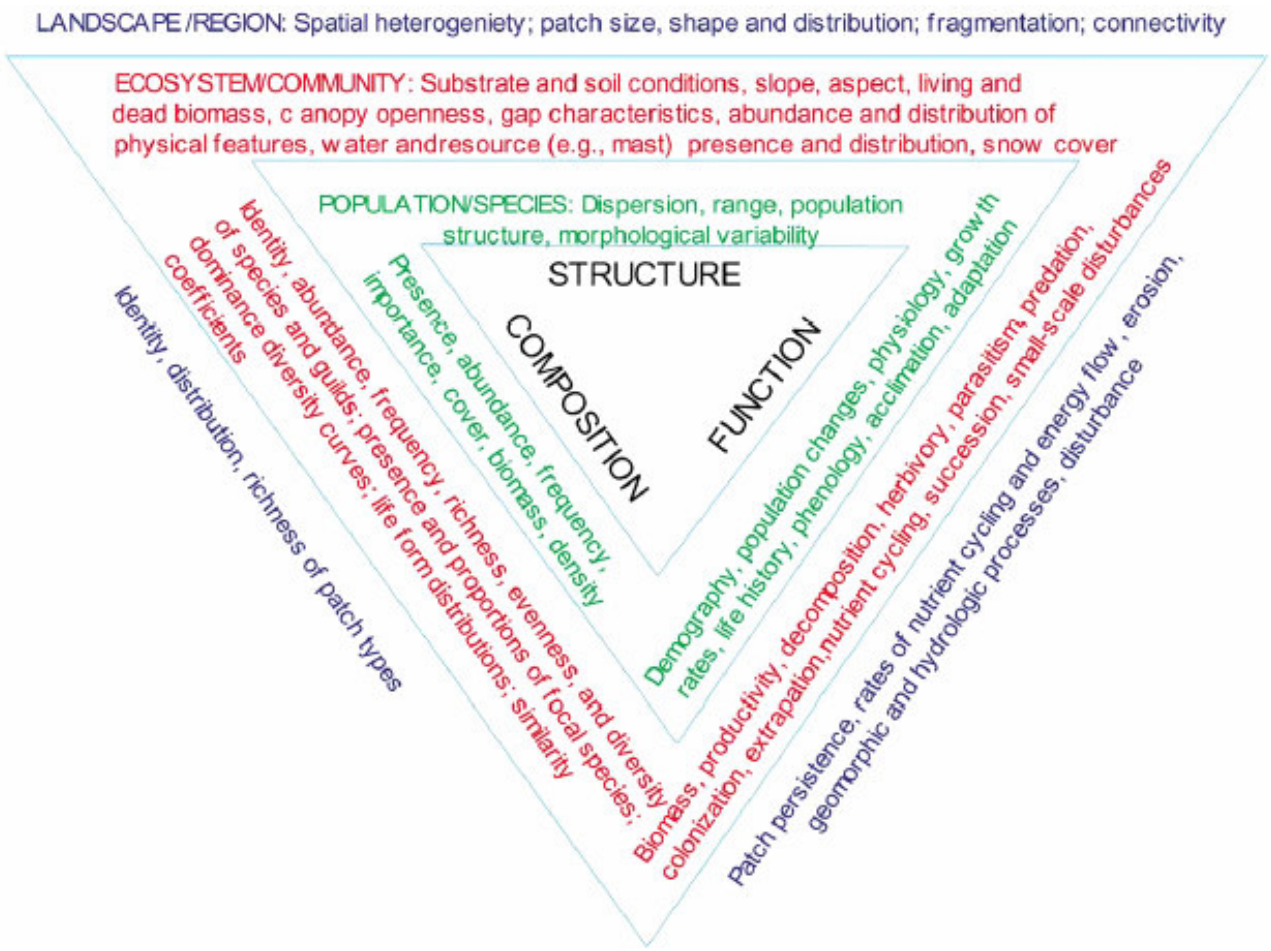

Figure 6.1: A representation of the key characteristics of ecosystem composition, structure and function (Dale & Beyeler, 2001).

by Dale & Beyeler. The case studies in Chapter 3 and Chapter 5 focus on the composition aspect. Many of the current quantitative techniques describe composition, whereas descriptors of ecosystem structure are limited and ecological function only being described qualitatively. Characteristics that are related to composition can be described by discrete presence-absence and abundance metrics. Where structure is described, multivariate drivers lead to more complex relationships, which are more difficult to quantify. The real challenge lies in describing ecosystem function, where stochastic (Abrahamsson & Håkanson, 1998) and chaotic (Upadhyay, 2000) processes integrate structure and composition on the physical-chemical template. At this level, quantitative prediction is based on complex differential equations and fuzzy arithmetic (Özelkan & Duckstein, 2001). An approach that can be suggested is to define composition and structure as essential elements of ecosystem processes, where the latter is defined as the distribution and flow of energy and matter. These

ecosystem processes give rise to functions, which can be related to services in a utilitarian view (Priscoli, 1998) or resilience in a conservation view (Roux et al., 1999). The selection of endpoints in the planning phase of an ERA should thus consider assessment techniques that provide the most appropriate information towards supporting management objectives.

While this thesis focussed on the technical aspects of ERA, there was an implied assumption that it addressed current needs (defined in Chapter 1), and that the technology will therefore be adopted. The experience gained during the development process and subsequent efforts to implement the technology (DEAT, 2002) indicated that this assumption was flawed. It was confirmed that the acceptance of a new technology is not just based on its inherent characteristics, but also a function of political and administrative will (Palmer, 1999), user communities' willingness and ability to adopt it (McLoughlin *et al.,* 2000) and the existence and integration of the technology generation and technology diffusion policies (Hahn and Yu, 1999). Roux (2001) added critical levels of institutional arrangements and financial resources to the list of requirements for effective implementation of environmental technologies. It is therefore necessary to have a thorough understanding of the mechanisms that drive the transition of technologies, from scientific concepts to operational products, as discussed by Rogers (1995). The efforts and skill required to ensure that a technology is adopted should therefore not be underestimated. In recent times (2001/ 2002), regulating agencies in South Africa have increasingly turned to ERA as a solution to the complex problems related to natural resource management (DEAT, 2002; Jooste and Claassen, 2001a). The momentum should be maintained and built upon, through a comprehensive technology diffusion strategy to ensure successful implementation of ERA.

As was suggested in Chapter 3 and Chapter 5, the South African guidelines for ERA provide a practical basis for conducting ecological assessments in the context of water resource management. The current constraint is the willingness and ability of the user community to adopt and deploy the technology. A strong determinant of such adoption will be the extent to which governing bodies support and require ERA's. Although this process has started in the Department of Environmental Affairs and Tourism (DEAT, 2002), there is still a long road ahead. Activities that are being planned include information sessions, workshops and courses, while a publication on risk management (similar to DEAT, 2002) is also being developed. While these activities are necessary to support the implementation process, they are not

sufficient. A comprehensive programme is required to address all levels of governance, the private sector and practitioners. The process and advantages of risk management should form part of this programme. This next phase will benefit from stronger international collaboration, through sharing experiences and contributing to solutions.

7. Glossary of Terms

Acute A single exposure to a toxic substance, which may result in severe biological harm or death. Acute exposures are usually characterized as lasting no longer than a day, as compared to longer, continuing exposure over a period of time (EPA, 1997)

Ammonia A colourless gaseous alkaline compound that is very soluble in water, has a characteristic pungent odour, is lighter than air, and is formed as a result of the decomposition of most nitrogenous organic material; used as a fertilizer and as a chemical intermediate (Parker, 1994)

Chronic Multiple exposures occurring over an extended period of time or over a significant fraction of an animal's or human's lifetime. (EPA, 1997)

Ecological importance and sensitivity Ecological importance relate to aspects such as diversity, uniqueness and scarcity, whereas ecological sensitivity describes the severity of response to stressors.

Ecological management category The EMC is the recommended management class, from an ecological point of view.

Exposure profile The product of characterization of exposure in the analysis phase of ecological risk assessment. The exposure profile summarizes the magnitude and spatial and temporal patterns of exposure for the scenarios described in the conceptual model. (EPA, 1998)

He/His/Him While a person is often referred to in the thesis as being masculine, such a person could equally be feminine. He/his/him should therefore always be read as also including she/hers/her.

Heterotrophic Species that use light or chemical energy to build organic matter

Hypothesis Atentative supposition with regard to an unknown state of affairs, the truth of which is thereupon subject to investigation by any available method, either by logical deduction of consequences that may be checked against what is known, or by direct experimental investigation or discovery of facts not hitherto known and suggested by the hypothesis. (Parker, 1994)

Ecosystem The interacting system of a biological community and its non-living environmental surroundings (EPA, 1997)

Ephemeral A stream channel which carries water only during and immediately after periods of rainfall or snowmelt (Parker, 1994)

Heterotrophic Species that are dependent on organic matter for food (EPA, 1997)

Lethal Concentration Median level concentration, a standard measure of toxicity. It tells how much of a substance is needed to kill half of a group of experimental organisms in a given time

Lentic Of or pertaining to still waters such as lakes, reservoirs, ponds, and bogs (Parker, 1994)

Lotic Of or pertaining to swiftly moving waters (Parker, 1994)

Macrophyte A macroscopic plant, especially one in an aquatic habitat (Parker, 1994)

Microphyte A microscopic plant (Parker, 1994)

Perennial A stream which contains water at all times except during extreme drought (Parker,

1994)

pH An expression of the intensity of the basic or acid condition of a liquid; may range from 0 to 14, where 0 is the most acid and 7 is neutral. Natural waters usually have a pH between 6.5 and 8.5 (EPA, 1997)

Present ecological state category The PESC describes the present condition of the resource unit, in relation to the criteria for different classes.

Probability The probability of an event is the ratio of the number of times it occurs to the large number of trials that take place; the mathematical model of probability is a positive measure, which gives the measure of the space the value 1 (Parker, 1994)

Quotient Result of division sum (Oxford, 2003)

Redox Voltage difference at an inert electrode immersed in a reversible oxidation-reduction system; measurement of the state of oxidation of the system. Also known as oxidation-reduction potential (Parker, 1994)

Reserve means the quantity and quality of water required (a) to satisfy basic human needs by securing a basic water supply, as prescribed under the Water Act, 1997 (Act No. 108 of 1997), for people who are now or who will, in the reasonably near future, be (i) relying upon; (ii) taking water from; or (iii) being supplied from, the relevant water resource; and (b) to protect aquatic ecosystems in order to secure ecologically sustainable development and use of the relevant water resource

Risk A measure of the probability that damage to life, health, property, and/or the environment will occur as a result of a given hazard (EPA, 1997)

Risk assessor An individual or team responsible for conducting the risk assessment

Risk hypothesis The cause-effect relationships between sources, stressors, exposure routes, end points, responses and measures relevant to an ecological risk assessment.

Risk manager An individual, organisation or group responsible for making management decisions which provides the terms of reference for the ecological risk assessment

Uncertainty The estimated amount by which an observed or calculated value may depart from the true value (Parker, 1994)

Variability The quality, state, or degree of being variable or changeable

8. Abbreviations

AD	*Anno Domini*
AEL	African Explosives Limited
AEMC	Achievable ecological management class
AQUIRE	AQUatic toxicity Information REtrieval
BATNEEC	Best available technology not entailing excessive cost
BC	Before Christ
Ca	Calcium
Cl	Chlorine
CMA	Catchment management agency
CO_2	Carbon dioxide
COD	Chemical oxygen demand
DEAT	Department of Environmental Affairs and Tourism (South African)
DEMC	Default ecological management category
DOET&R	Department of the Environmental, Trade and Regions (UK)
DWAF	Department of Water Affairs and Forestry (South African)
EC	Electrical conductivity
EIA	Environmental impact assessment
EIS	Ecological importance and sensitivity rating
EMC	Ecological management category
EPA	Environmental Protection Agency (United States)
ERA	Ecological risk assessment
F	Fluorine
H_2S	Hydrogen sulphide
HAM	Habitat assessment matrix
HCO_3	Hydrocarbonate
HQI	Habitat quality index
K	Potassium
KNP	Kruger National Park
LC_{50}	Lethal Concentration needed to kill 50% of a group of experimental organisms
LoE	Line of evidence
m.a.m.s.l.	Meters above mean sea level
Mg	Magnesium
mg/ℓ	milligram per litre
µg/ℓ	microgram per litre
MPP-EAS	GEF/UNDP/IMO Regional Programme for the Prevention and Management of

	Marine Pollution in the East Asian Seas
Na	Sodium
NH_3	Ammonia
NO_2	Nitrite
NO_3	Nitrate
NWA	National Water Act (South African)
O_2	Oxygen
P	Phosphorus
pH	The 'p' is an operator symbol, which stands for 'negative logarithm'. The 'H' stands for 'Hydrogen'. So pH = -log{H^+}
PES	Present ecological state
Pb	Lead
PO_4	Phosphate
RCC	River continuum concept
RDM	Resource directed measures
RWQO	Receiving water quality objective(s)
S	Sulphur
SA	South Africa
SASS4	South African scoring system – version 4
SDC	Source directed controls
SHE	Safety, health and environment
SiO_2	Silica
SO_4	Sulphate
TDS	Total dissolved salts
TIN	Total inorganic nitrogen (NO_2 + NO_3 + NH_3)
TP	Total Phosphorus
TSS	Total suspended solids
US DoE	United States Department of Energy

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Appendix A: AEL Effluent Discharge Permit

EXEMPTION NUMBER: 1706B

EXEMPTEE: AEL OPERATIONAL SERVICES (PTY) LTD

LOCALITY OF EXEMPTEE'S PREMISES TO WHICH EXEMPTION APPLIES:
MODDERFONTEIN FACTORY

EXEMPTION GRANTED IN TERMS OF SECTION 21(4) OF THE WATER ACT, 1956 (ACT 54 OF 1956) IN RESPECT OF:

(a) THE PURIFICATION OR TREATMENT OF WATER USED FOR INDUSTRIAL PURPOSES, INCLUDING ANY EFFLUENT RESULTING FROM SUCH USE; AND

(b) THE DISPOSAL OF THE PURIFIED OR TREATED WATER, INCLUDING WATER RECOVERED FROM ANY EFFLUENT

By virtue of the powers delegated to me in terms of Government Notice 785 of 22 April 1994, I, Tamsanqa Mthunzi Sokutu, in my capacity as Manager: Scientific Services in the Department of Water Affairs and Forestry, hereby, in terms of section 21(4) of the Water Act, 1956, exempt the abovementioned Exemptee from complying with the provisions of sections 21(1)(a) and (21)(1)(b)(i) of the said Act, relating to the purification or treatment of water used for industrial purposes (which includes water used in any sewerage system or works) and any effluent produced by or resulting from such use and the disposal of the treated or purified effluent, including water recovered from any effluent, to the extent and subject to the conditions specified hereunder.

B. DEFINITIONS

In this Exemption -

"Act" means the Water Act, 1956 (Act 54 of 1956);
"Minister" means the Minister of Water Affairs and Forestry;
"Department" means the Department of Water Affairs and Forestry;
"Director-General" means the Director-General: Water Affairs and Forestry; and
"Regional Director" means the Regional Director: Northern Province (WRM), Department of Water Affairs and Forestry, Private Baa X7420, Hennopsmeer, 0046.

C. CONDITIONS OF EXEMPTION

1. QUANTITY OF EFFLUENT AND METHOD OF DISPOSAL

This Exemption authorizes the disposal of the following:

1.1 A maximum quantity of 2 277 600 (two million two hundred and seventy seven thousand six hundred) cubic metres (m^3) of effluent per annum, based on an average quantity of 250 m^3 per hour at point W5 and 10 m^3 per hour at point W20 and with the quality requirements as specified in condition 2, to be disposed of into the Modderfontein Spruit; and a maximum quantity of 350 400 (three hundred and fifty thousand four hundred) m^3 of effluent per annum, based on a maximum quantity of 960 m^3 per day to be disposed of by spraying onto land. The quality and other requirements as specified in conditions 8 and 9 shall be adhered to.

1.2 Domestic effluent from the Exemptee's premises may only be discharged to an approved sewage system of the local authority.

1.3 The quantity and quality of effluent authorized to be disposed of in terms of this Exemption may not be exceeded without prior authorization by the Minister.

2. QUALITY OF EFFLUENT

2.1 The impact of AEC's contribution to the waste load in the Modderfontein Spruit measured at point W6 shall comply with the standards below:

Variables	Limits/Units
pH	> 5,5 < 8,0
Electrical conductivity (EC)	< 120 mS/m
Nitrate as N	< 6 mg/ℓ
Nitrite as N	< 0,5 mg/ℓ
Ammonia as N	< 1 mg/ℓ
Sulphate as SO_4	< 200 mg/ℓ
Fluoride as F	< 1,5 mg/ℓ
COD	< 50 mg/ℓ

2.2 The effluent shall be discharged to the Modderfontein Spruit at points W5 and W20 and shall at all times comply with the quality requirements specified in the General and Special Standard for Phosphate as prescribed by the Minister in terms of section 2 1 (1)(a) of the Act and published in Government Notice 991 of 18 May 1984, as amended from time to time, except for the following variables which shall at all times comply with the limits specified hereunder:

Variables	Limits/Units
pH	> 5,5 < 8,0
Electrical conductivity (EC)	< 120 mS/m
Nitrate as N	< 12 mg/ℓ
Nitrite as N	< 1 mg/ℓ
Ammonia as N	< 2 mg/ℓ
Sulphate as SO_4	< 200 mg/ℓ
Fluoride as F	< 2 mg/ℓ
COD	< 50 mg/ℓ
Phosphate as PO_4	< 1 mg/ℓ

2.3 Temporary relaxation is granted from conditions 1. 1. I and 2. 1 for the period up to the year 2002 for the following parameters:

W5	From 1/7/1996	From 1/7/1997	From 1/7/1998	From 1/7/1999 to 30/6/2002
Flow (m^3/h)	400	330	290	280
NH_3 as N (mg/ℓ)	73	61	45	35
NO_3 as N (mg/ℓ)	51	43	34	25
Na (mg/ℓ)	130	130	130	60
SO_4 (mg/ℓ)	400	400	400	200
F (mg/ℓ)	12	8	8	6
EC (mS/m)	195	195	195	160
PO_4 as P (mg/ℓ)	2.2	1.4	1.4	1.4

W20	From 1/7/1996	From 1/7/1997	From 1/7/1998	From 117/1999 to 30/6/2002
Flow (m^3/h)	46	46	46	10
NH_3 as N (mg/ℓ)	23	23	11	10
NO_3 as N (mg/ℓ)	120	120	15	10
Na (mg/ℓ)	260	260	104	90
SO_4 (mg/ℓ)	770	770	650	590
F (mg/ℓ)	1.1	1.1	1.1	1.1
EC (mS/m)	310	310	160	150
PO_4 as P (mg/ℓ)	0.9	0.9	0.9	0.9

3. MONITORING

3.1 Modderfontein Spruit

3.1.1 The following variables for water quantity and quality shall be recorded upstream at point WI by a continuous monitoring system:

pH	
Flow	in m^3/hour
Electrical conductivity (EC)	in mS/m
Ammonia as N	in mg/ℓ
Nitrate as N	in mg/ℓ
Fluoride	in mg/ℓ
Phosphate as P	in mg/ℓ

3.1.2 The following variables shall be recorded at point W I by taking a grab sample on a weekly frequency subject to condition 3.8:

Nitrate as N	in mg/ℓ
Sulphate as SO_4	in mg/ℓ
Sodium	in mg/ℓ
Chloride	in mg/ℓ

3.1.3 The following variables for water quantity and quality shall be recorded daily downstream at point W6 by a continuous monitoring system:

pH	
Flow	in m^3/hour
Electrical conductivity (EC)	in mS/m
Ammonia as N	in mg/ℓ
Nitrate as N	in mg/ℓ
Fluoride	in mg/ℓ
Phosphate as P	in mg/ℓ

3.1.4 The following variables shall be recorded at point W6 by taking a grab sample on a weekly frequency subject to condition 3.8:

Nitrate as N	in mg/ℓ
Sulphate as SO_4	in mg/ℓ
Sodium	in mg/ℓ
Chloride	in mg/ℓ

3.1.5 More detailed variables as updated and agreed to annually by the Regional Director shall be recorded at point W6 by taking a grab sample during September and March of each year. (Refer to condition 3.8 for relevance.)

3.2 Effluent discharged into the Modderfontein Spruit

3.2.1 The following variables for water quantity and quality shall be recorded at points W5 and W20 by a continuous monitoring system:

pH	
Flow	in m^3/hour
Electrical conductivity (EC)	in mS/m
Ammonia as N	in mg/ℓ
Nitrate as N	in mg/ℓ

3.2.2 The following variables shall be recorded at points W5 and W20 on a weekly frequency subject to condition 3.8:

Nitrate as N	in mg/ℓ
Sulphate as SO_4	in mg/ℓ
Sodium	in mg/ℓ
Fluoride	in mg/ℓ
Phosphate as P	in mg/ℓ

3.3 Effluent disposed of by spraying on land

3.3.1 The following variables shall be recorded at the abstraction point in the spray pond (Dam M4) on a monthly frequency:

pH	
Electrical conductivity (EC)	in mS/m
Total nitrogen as N	in mg/ℓ
Volume	in m^3/day

3.3.2 The effluent to be disposed of by spraying onto land (refer to conditions 1.1.2 and 9.1) shall be monitored by taking a grab sample on a monthly frequency.

3.3.3 More detailed variables (refer to condition 3.8 for relevance), as updated and agreed to annually by the Regional Director shall be recorded at the abstraction point from Dam M4 by taking a grab sample during September and March of each year.

3.4 Spray area

The following water quality variables shall be monitored quarterly (subject to condition 3.8) at all boreholes as described in SRK report 197104/2 dated September 1994 and any subsequent report:

pH	
Electrical conductivity (EC)	in mS/m
Ammonia as N	in mg/ℓ
Nitrate as N	in mg/ℓ
Sulphate as SO_4	in mg/ℓ
Sodium	in mg/ℓ
Fluoride	in mg/ℓ

3.5 Stormwater

The following variables shall be monitored continuously during a rainy event at points W 1, W5, W6, W20 (refer to conditions 3.1 and 3.2) and any other point necessary to ensure compliance with conditions 2.2 and 7.2 (subject to condition 3.8):

pH	
Electrical conductivity (EC)	in mS/m
Ammonia as N	in mg/ℓ
Nitrate as N	in mg/ℓ

3.6 Continuous monitoring

Continuous monitoring with immediate electronic display at a control room shall be done at each of the following monitoring points:

3.6.1 As from 31 August 1996 at WS, W6, W20 and any other monitoring point deemed necessary to ensure compliance with conditions 2.2 and 7.2 (refer to condition 3.8); and

3.6.2 as from 1 July 1997 at W1.

3.7 Auditing facilities

The following facilities shall be supplied as from 31 August 1996 at point W6 and as from 1 June 2002 at points W5 and W20 for the purpose of continuous auditing by the Regional Director:

3.7.1 Conditions to safeguard the Department's auditing equipment against theft and natural disasters as it would be deemed necessary for electronic equipment;

3.7.2 a power source: and

3.7.3 a direct communication linkage to the Regional Director's office.

3.8 Any variable or frequency of monitoring as may be required from time to time by the Regional Director shall be adhered to.

3.9 Bio-monitoring

A bio-monitoring program on the Modderfontein Spruit shall be instituted during 1997 and shall include but not be limited to the following

3.9.1 Compilation of a sequential database from which the extent and frequency of the future bio-monitoring program can be developed and constantly improved to serve as a reliable site specific bio-monitoring program. This program shall be able to qualify and quantify the biological impact due to the Exemptee's activities on the water environment alone and downstream of the Modderfontein Spruit (refer to condition 14.5);

3.9.2 bio-monitoring points upstream and downstream from the two discharge points (W5 and W20) to compile results according to the SASS 4 method as adjusted for site specific application; and

3.9.3 monthly toxicity tests at the monitoring points as specified in conditions 3.9.2 and 4. 1.

4. MONITORING POINTS

4.1 Monitoring point description forms (Schedule I) accompanied by a map (1:5 000) and a sketch or photograph showing the exact monitoring points shall be provided to the Regional Director within ninety (90) days after this Permit has been issued for the following monitoring points Wl, W5, W6 and W20 for compliance with conditions 3.6 and 7.2:

4.1.1 Point WI shall be the monitoring point upstream in the Modderfontein Spruit and point W6 the downstream monitoring point (refer to condition 2. 1);

4.1.2 points W5 and W20 shall be the monitorina points for final compliance (refer to conditions 2.2 and 2.3) for effluent discharged into the Modderfontein Spruit; and

4.1.3 biological monitoring points (refer to condition 3.9.2).

4.2 Monitoring points shall not be changed without prior notification to and written approval by the Regional Director.

5. METHODS OF ANALYSIS

5.1 Analyses shall be carried out in accordance with methods prescribed by and obtainable from the South African Bureau of Standards (SA-BS), in terms of the Standards Act, Act 3O of 1982, or an accepted method prescribed by the Standard Methods or the EPA or of a comparable accuracy related to the above methods which shall have an accuracy greater than a 95 percentile.

5.2 The method of analysis shall be submitted to the Regional Director for approval as per format in Schedule II within 90 days after the Permit has been issued and shall not be changed without prior notification to and written approval by the Regional Director.

5.3 If SABS methods are not used, the Exemptee shall inform and obtain approval from the Regional Director for the method used.

5.4 Any laboratory used for monitoring or analytical work must participate in inter-laboratory testing.

6. REPORTING

6.1 The information required in terms of conditions 3.1, 3.2, and 3.3 shall be submitted monthly and in terms of conditions 3.4, 3.9, 13, 14.2 and 14.3 annually, to the Regional Director. This information shall be submitted in writing within one month of the close of the period specified, under reference 16/2/7/A2 10/B 16 in the format required in Schedule III or in an electronic format as required by the Regional Director.

7. STORMWATER DISPOSAL

7.1 Stormwater leaving the Exemptee's premises shall not be contaminated to exceed the standard as set in condition 2.2 by any substance, whether such substance is a solid, liquid, vapor or gas or a combination thereof which is used, produced, stored, dumped or spilled on the premises.

7.2 In the case where condition 7.1 cannot be complied with and in areas with a high risk of stormwater contamination, the following precautionary measures should be implemented by January 2002:

7.2.1 Any contaminated stormwater which does not comply with the requirements as stipulated in condition 2.2, shall be contained at the point of origin and the excess diverted to an emergency storage facility

which shall have a minimum freeboard of 0,5 metres above the expected maximum water level which is based on the average monthly rainfall figures for the catchment area concerned, plus the maximum precipitation to be expected over a period of 24 hours with a frequency of once every fifty (50) years, less the gross mean evaporation for the area; and

7.2.2 continuous monitoring shall be done at the main stormwater outfall points during a rainstorm according to condition 3.4 to determine whether the stormwater is uncontaminated (to comply with condition 2.2), in which case the flow can then be diverted away from the emergency storage facility to the Modderfontein Spruit.

7.3 The sewer, effluent and stormwater drains shall be completely separate systems by January 2002.

8 OPERATION OF THE EFFLUENT DAM SYSTEM

8.1 The effluent dam system (Dam M4) shall be operated under appropriate supervision and maintained in such a manner as to ensure that a minimum freeboard of 0,5 metres be maintained above the expected maximum water level, which is based on the average monthly rainfall figures for the catchment area concerned, plus the maximum precipitation to be expected over a period of 24 hours with a frequency of once every 100 years, less the gross mean evaporation for the area.

8.2 Contour walls or furrows shall be provided and maintained around the system to prevent clean stormwater ingress or erosion of the pond walls.

8.3 Actions shall be taken to determine and intercept any of the effluent in the Dam M4 system from entering the Modderfontein Spruit.

8.4 If, in the opinion of the Regional Director, the system fails to meet the requirements of this Exemption or otherwise constitutes a water pollution hazard, the Exemptee shall take such steps as may be deemed necessary by the Regional Director to rectify the situation.

9 SPRAYING OPERATIONS

9.1 A maximum spray volume of 960 m^3 per day shall not be exceeded and the load of nitrogen application shall not exceed 120 kilogram (kg) total nitrogen (as N) per hectare per annum as from January 1997 without prior written approval by the Regional Director (refer to condition 9.4).

The quality shall not exceed the following concentrations:

9.1.1

Variables	Limits/Units
pH	5.5-8.5
Electrical conductivity (EC)	2000 mS/m
Total Nitrogen as N	3000 mg/ℓ
Sulphate as SO_4	5000 mg/ℓ
Sodium	500 mg/ℓ
Fluoride	20 mg/ℓ

9.2 Spraying of effluent shall be practiced in such a manner as to ensure that:

9.2.1 No excess spraying (no waterlogging and pooling) of effluent in any location occurs;

9.2.2 the groundwater pollution plume shall diminish in concentrations as agreed to in condition 10.3; and

9.2.3 no run-off from the spraying area because of wet weather or any other conditions occurs.

9.2.4 The spraying rate of application shall not exceed 13 millimetres per day.

9.3 The spraying system and all auxiliary facilities shall be inspected and maintained in an efficient and functioning order and steps shall be taken to prevent surface and groundwater contamination from the reticulation system.

9.4 The principles as agreed to in the Effluent Spray Management Plan with a complete spray schedule shall be maintained and made available to the Regional Director by January 1997.

10. GROUNDWATER

10.1 A groundwater study shall be undertaken as to determine the source and extent of groundwater pollution and soil contamination in the rest of the area not covered by the SRK report mentioned in condition 3.4, to be completed by January 1998.

10.2 A groundwater monitoring system approved by the Regional Director, shall be installed by January 1998 to monitor possible groundwater pollution in the rest of the area not stated in condition 3.4.

10.3 A groundwater management plan to address all groundwater pollution shall be developed before January 1998, in co-operation with the Regional Director (refer to conditions 3.4 and 9.4).

10.4 The groundwater management plan shall contain a number of actions with targets as agreed to by the Regional Director to address the progressive reduction of all sources of groundwater pollution.

11 SOLIDS DISPOSAL

11.1 Should the method of disposal of waste resulting from operations at the undertaking, used at the time of application, be changed, the Exemptee shall, in order to obtain continued approval of the disposal method, furnish the Regional Director in advance with details of the proposed change.

12 PROTECTING WORKS AGAINST HYDROLOGICAL EVENTS

12.1 Works such as -

12.1.1 containments, ash and slimes dams;

12.1.2 contour walls;

12.1.3 cut-off drains; and

12.1.4 any other deviation or collection structure; shall be so designed and constructed as to ensure a freeboard of at least 0,5 metres above the maximum water level which could be reached as a result of the estimated maximum precipitation that may be expected durina a period of 24 hours with an average frequency of recurrence of one (1) in fifty (50) years.

13 MALFUNCTIONS

13.1 Accurate and up-to-date records shall be kept of all system malfunctions and any incidents which cause or may cause water pollution, or a violation of the standards set out in conditions 2.1 and 2.2. The Regional Director shall immediately be informed of any such incident and copies of the records shall be submitted together with the information required in condition 6.1 as per Schedule II. Such malfunctions and the actions taken shall be tabulated under the following headings with a full explanation of all the contributory circumstances:

13.1.1 Operating errors;

13.1.2 mechanical failures (including design, installation or maintenance);

13.1.3 environmental factors (e.a. flood);

13.1.4 loss of supply services (e.a. power failure);

13.1.5 other causes;

13.1.6 actions taken to prevent water pollution/stormwater contamination; and

13.1.7 actions taken to prevent similar incidents/pollution in the future.

14. GENERAL

14.1 This Exemption shall be taken under revision by 1 June 2002.

14.2 A complete effluent management plan, which also provides for incidents and emergency actions with regard to the water quality shall be implemented by July 1997 and annually updated. What the emergency measures consist of, which alternatives have been considered and the reasons for specific decisions shall all be clearly stated. (The basic principle during any incident is to prevent pollution through containment and not allowing contaminated water to enter the sewerage, stormwater or river systems).

14.3 All employees of the Exemptee participate in the prevention of pollution. The effluent management plan shall include the continuous actions which shall be taken to involve all employees. This can only be achieved by integrated management with regard to the effluent handling system, incidents, as well as making them aware of pollution prevention measures and methods. All activities planned and

completed in this regard shall be reported to the Regional Director on an annual basis.

14.4 If the quality standards specified in conditions 2.1 and 2.2 cannot be complied with by January 2002, the Exemptee. shall initiate, participate and complete a study to determine the impacts (a full impact assessment of the best quality standard achievable by AEL) on the downstream users. The terms of reference of the study shall be submitted to and approved by the Regional Director prior to the study, before January 2000. The study shall include but not be limited to the following impacts:

14.4.1 On stormwater (dust outfall and accidental spillages);

14.4.2 on the river system from the Modderfontein Spruit including the users of water of the Hartbeespoort Dam;

14.4.3 on the Hartbeespoort Dam - loads, concentrations, chlorophyll production; and

14.4.4 stormwater and effluent discharged from Kynoch, Chloorkop.

This study shall be completed before January 2002. The bio-monitorina program needs to be maintained and constantly upgraded and expanded (refer to condition 3.8) to ensure that the information can be used as background as well as to ensure that the quantification of the biological impact is representative.

14.5 The following requirements shall be adhered to concerning the dumping of partially combusted coal ash on Ash Dam 6 (Dam A6) in terms of section 20(1) of the Environment Conservation Act, 1989 (Act 73 of 1989):

14.5.1 By 1 June 2002 Ash Dam A6 shall be designed, constructed (or modified) and operated so that rainwater precipitated thereon and seepacre originating thezefrom are retained therein or contained for purification and/or re-use thereof;

14.5.2 barrier dams and evaporation dams shall be provided where necessary to retain any run-off, including material eroded from the slopes;

14.5.3 the storage capacities of all containment dams shall be sufficient to ensure a free board of at least 0,5 metres above the expected maximum water level, which shall be based on the average monthly rainfall figures for the catchment area concerned, less the gross mean evaporation in that area, plus the maximum precipitation to be expected over a period of 24 hours with a frequency of once in 50 years;

14.5.4 the slopes and the sides shall be constructed (or rehabilitated) in such a manner that little or no erosion occurs; and

14.5.5 the Permit Holder shall submit to the Regional Director for his approval operational and final rehabilitation plans.

14.6 The Exemptee shall immediately inform the Regional Director of any change in ownership, his name, address and/or premises and legal status.

14.7 This Exemption shall not be construed as exempting the Exemptee from compliance with the provisions of the Health Act, 1977 (Act 63 of 1977), or any other applicable act, ordinance, regulation or by-law.

14.8 The medium to long term management objectives shall be that spraying with the "strong effluent stream" must be phased out, that the "weak effluent stream" must be optimally re-used within the Exemptee's industrial complex. Polluted groundwater shall be rehabilitated where deemed necessary by the Minister. A report which will describe how and by when these objectives shall be achieved, shall be submitted to the Director-General by 31 July 1998.

14.9 This Exemption supersedes Exemption 837 B issued on 18 February 1985.

MANAGER: SCIENTIFIC SERVICES
p.p. Minister of Water Affairs and Forestry

Appendix B: Toxicity Testing Method

B1. Acute Daphnid Toxicity Test

Daphnia 24 h or less in age were used for toxicity testing (Slabbert *et al.,* 1998). To obtain the necessary number of young for a test, adult females bearing embryos in their brood pouches were removed from the stock cultures 24 h preceding the initiation of a test and placed in beakers containing moderately hard water and food suspension (trout chow, alfalfa and yeast). Test conditions are summarised in Table 4B1. Test organisms were transferred to a small intermediary holding beaker and from there to the test beakers. A probit computerised statistical programme (EPA, 1991) was applied to calculate the LC_{10} (minimum effect concentration) and LC_{50} (concentration at which 50% of the organisms died).

TABLE B1: *Daphnia* test conditions[1]

Temperature	20±1□C
Light quality	Laboratory illumination
Photoperiod	Approximately 12 h day light
Feeding regime	No feeding
Oxygen concentration	As obtained
pH	As obtained
Size of test beaker	50 mℓ
Volume of test sample	25 mℓ
Number of organisms/beaker	5
Number of replicate beakers	4
Total number of organisms/test	20
Test duration	48 h
Effect measured	Lethality (no movement of body or appendages on gentle prodding)
Interpretation of results	Lethality >10% is an indication of toxicity, provided that control lethality <10%

[1] According to EPA (1985; 1991) procedure

B2. Acute Fish Toxicity Test

One to 2 week old fish were used for toxicity testing, following standard method (Slabbert *et al.,* 1998; EPA, 1991). The test conditions are summarised in Table 4B2. A probit computerised statistical programme (EPA, 1991) was applied to calculate the LC_{50} (concentration at which 50% of the organisms died). A

TABLE B2: *P. reticulata* test conditions[1]

Temperature	23±2°C
Light quality	Laboratory illumination
Photoperiod	Approximately 12 h day light
Feeding regime	No feeding
Oxygen concentration	As obtained
pH	As obtained
Size of test beaker	500 mℓ
Volume of test sample	250 mℓ
Number of organisms/beaker	5
Number of replicate beakers	2
Total number of organisms/test	10
Test duration	96 h
Effect measured	Lethality (no movement of body or appendages on gentle prodding)
Interpretation of results	Lethality >10% is an indication of toxicity, provided that control lethality <10%

[1] According to EPA (1985; 1991) procedure

B3. Algal Growth Test

The unicellular alga, *S. capricornutum* Printz, was used as test organism. The organism was axenically maintained in Erlenmeyer flasks according to standard procedures (EPA, 1991). Culturing was carried out in a constant temperature room at 24±1°C, without shaking, using continuous illumination. Algae were subcultured at weekly intervals to have a constant

supply of logarithmic growth phase cells for toxicity testing. Modified (10%) BG-11 medium was used for culture maintenance and toxicity testing (Slabbert *et al.,* 1998).

The toxicity test was carried out in sterile 24-well tissue culture plates (Slabbert and Hilner, 1990; Slabbert *et al.,* 1998). Test samples (1.8 mℓ) were dispensed in four replicate wells (well volume: 3.5 mℓ). Eight control wells were included per plate. Algal cultures 4 to 6 days old were used for toxicity testing. The algal inoculum was prepared by removing the supernatant medium by means of a sterile pasteur pipette and a vacuum pump. The cells were suspended in fresh culture medium and the cell concentration determined by means of a haemacytometer. Test and control samples were inoculated with 200 000 cells/mℓ (final concentration). The algal suspension was added at a ratio of 1:1 to a 20-times concentrate of the culture medium and used as 200 µℓ volumes for inoculation of test and control samples. The top well of each row of wells received medium only (200 µℓ of a 1:1 dilution of fresh medium and the 20-times concentrated medium). These solutions served as blanks during optical density (OD) determinations. The use of blanks ensured that increases in OD due to precipitation were noted and subtracted from actual growth readings. One plate with standard control water (1 blank and 3 inoculated wells) was used to determine the OD at time 0.

Plates were covered with lids and black insulation tape was applied to the perimeters of the closed plates to avoid a higher growth in the outer wells. Incubation was carried out at 24±1^{o}C for 72 h, using continuous illumination. At the end of the incubation period cells were suspended using a microplate shaker, and growth measured in terms of OD using a microplate reader (450 nm). Results are expressed as percentage inhibition (or stimulation), calculated as follows: 100% - [ODT-OD_0/ODC-OD_0 x 100%], where:

ODC = Average OD of control

ODT = Average OD of test

OD_0 = OD at time 0.

Growth inhibition >20% indicates toxic activity, while stimulation ≤20% is an indication of the presence of nutrients. Linear regression (% effect versus log concentration) was applied to calculate the EC_{20} (minimum effect concentration) and the EC_{50} (concentration causing 50% growth inhibition) .

Appendix C: Analyses for Ecological Reserve determination

(DWAF, 1999b)

Water quality calculations: Temperature

Generic knowledge about the response of ecosystems to temperature

Temperature effects:
- The rate of chemical reactions
- Solubility (including oxygen)
- Physical characteristics of water
- Temporal patterns are behavioural triggers

Generic exposure-response
- Vary from background average by not more than 10% or 2°C whichever is the more conservative. (Target water quality range, DWAF, 1996)
- Deviation from reference median (DWAF, 1999b)
  - 10% or 2°C is natural
  - 12% or 3°C is largely natural
  - 15% or 4°C is moderately modified
  - 20% or 5°C is largely modified

Site-specific knowledge about the response of the ecosystems to the temperature

The historical water temperature at X2H016Q01 is provided in Figure C1. There is no clear trend in the data, although the last few years (associated with low flows) has elevated summer and suppressed winter temperatures. A seasonal analysis of the data is provided in Table C1. The diel variability of temperature is shown in Figure C2, indicating a 6°C differential between daily minimum and maximum temperatures (4h00-20h00). The seasonal variability also presented in Figure C2 shows an 8 – 10°C differential between summer and winter months. Biological monitoring data from 1992/1993 listed in Table C2 shows that invertebrate communities were generally in a moderately modified state, with near natural and largely modified conditions being approached at times. According to the Desktop determination of EISC, the sensitivity of the ecosystem to water quality changes is low (DWAF, 2000).

A conclusion that can be drawn is that the temperature listed in Table C1 is sufficient to maintain the invertebrate community in a moderately modified state. *Tilapia rendalli* can tolerate temperatures from 11 – 37°C (Skelton, 1993), while breeding is arrested when summer temperatures drop below 21°C (Pienaar, 1978).

Table C1: Historical seasonal water temperature at X2H016Q01

	Temperature (5th %tile – median - 95th %tile)			
	Summer	Autumn	Winter	Spring
1980-1992	20-27-32	20-24-30	10-20-24	11-22-27
1991/1992	25-30-34	28-28-29	10-12-22	10-10-10

Note: Summer: Nov-Feb; Autumn: Mar-Apr; Winter: May-Aug; Spring: Sep-Oct

Table C2: Historical SASS scores and temperature

Site	Date	SASS	ASPT	State	°C
CR29*	5/1992	100	4.8	Moderately to largely modified	16.5
CR29*	6/1992	104	4.7	Moderately to largely modified	14.0
CR29*	7/1992	118	5.1	Moderately modified	10.3
CR29*	9/1992	139	5.1	Largely natural to moderately modified	10.2
CR29-	7/1993	111	5.3	Moderately modified	21.6
CR29-	8/1993	118	5.1	Moderately modified	16.8
CR29-	10/1993	96	4.4	Largely modified	22.2
CR29-	6/1994	122	4.9	Moderately modified	17.1
CR29-	9/1994	66	4.4	Largely modified	18.1
CR29-	6/1995	77	4.8	Largely modified	15.8
CR29-	9/1996	78	7.8	Moderately modified	24.0
CR28-	9/1996	133	7.0	Largely natural	28.1
CR30-	9/1996	146	8.1	Natural	23.9

* : MacMillan, 1992
-: Thirion, 2001

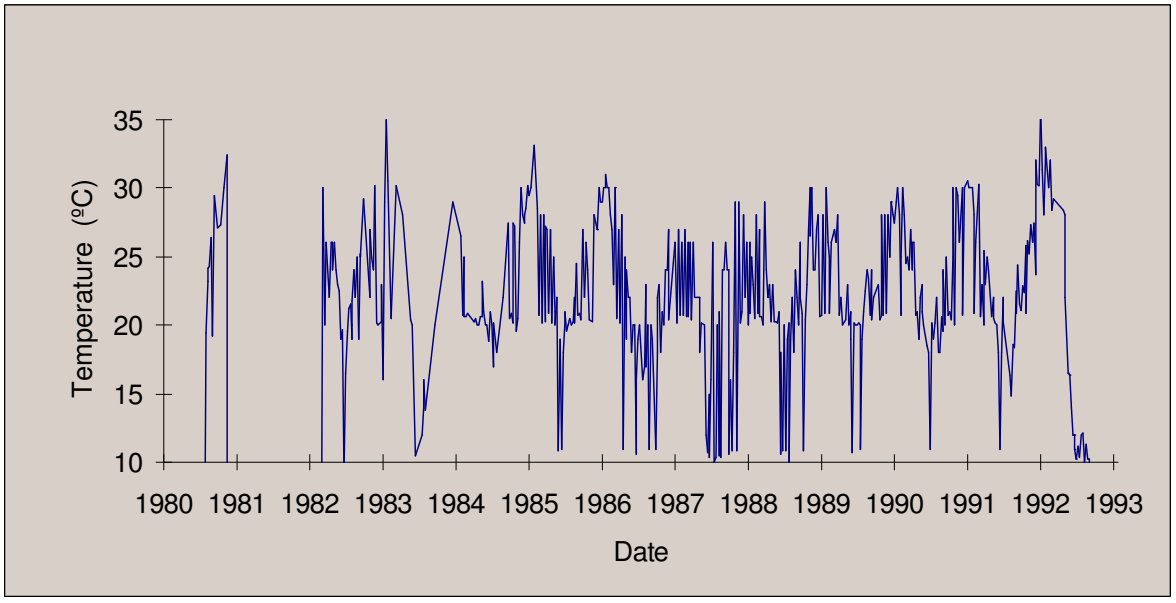

Figure C1: Historical water temperature at X2H016Q01

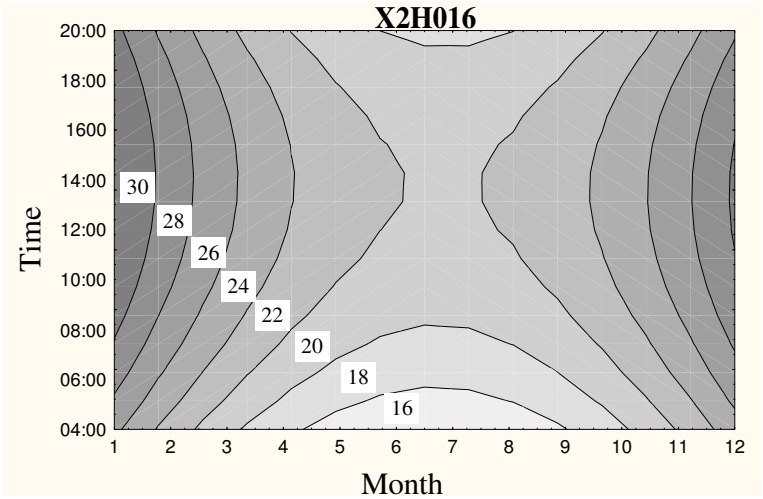

Figure C1: Diel and seasonal trends of water temperature at X2H016Q01 (^{o}C)

Natural levels for temperature in the specific resource unit

The characteristics of ambient temperature at Komatipoort (average of daily minimum and maximum temperatures) are shown in Table C3 (DEAT, 2000).

Table C3: Historical ambient temperature at Komatipoort from 1993 to 2001.

	Temperature (5th %tile – median – 95th %tile)			
	Summer	Autumn	Winter	Spring
Historical ambient temperature	23-26-31	22-25-27	17-19-21	21-23-26

Note: Summer: Nov-Feb; Autumn: Mar-Apr; Winter: May-Aug; Spring: Sep-Oct

Although the median is within 1^{O}C of the median water temperature (Table C1), the range of ambient air temperature is much narrower. The reference conditions for water temperature closely resemble the trend of ambient air temperature. Table C4 represents the expected water temperature under natural conditions. The slightly wider range is based on actual measures during this period (Table C2) and accounts for effects other than ambient temperature on water quality (solar energy, evaporation, source water, riparian cover, turbidity, etc.).

Table C4: Reference conditions for water temperature.

	Temperature (5th %tile – median - 95th %tile)			
	Summer	Autumn	Winter	Spring
Reference conditions (A)	22-26-32	21-25-28	16-19-22	20-23-27

Note: Summer: Nov-Feb; Autumn: Mar-Apr; Winter: May-Aug; Spring: Sep-Oct

Conditions that will result in a largely modified ecosystem

The temperatures specified in Table C1 were sufficient to maintain the ecosystem in the states listed. Given this relationship and what is known generically about the effect of temperature on aquatic ecosystems, the temperature that would maintain a largely modified state is provided in Table C5. The 95th percentile for temperature is limited to 35^{o}C, due to requirements of specific species, physiological requirements (oxygen depletion) and evidence from historical data (Figure B1). The deviation for minimum temperatures during winter and spring is greater than the generic 20%, but is realistic in the context of historical data.

Table C5: Water temperatures for largely modified conditions.

	Temperature (5th %tile – (median range)- 95th %tile)			
	Summer	Autumn	Winter	Spring
Largely modified (D)	17-(21-31)-35	16-(20-30)-35	10-(15-23)-26	11-(18-28)-32

Note: Summer: Nov-Feb; Autumn: Mar-Apr; Winter: May-Aug; Spring: Sep-Oct

Specifications for different levels of protection

Table C6: Ecological Reserve for water temperature*.

	Temperature (5th %tile – (median range)- 95th %tile)			
	Summer	Autumn	Winter	Spring
Reference conditions (A)	22-26-32	21-25-28	16-19-22	20-23-27
Largely natural (B)	21-(25-27)-33	20-(24-26)-30	14-(18-20)-23	17-(22-24)-28
Moderately modified (C)	19-(23-29)-34	18-(22-28)-32	12-(17-21)-24	14-(20-26)-30
Largely modified (D)	17-(21-31)-35	16-(20-30)-35	10-(15-23)-26	11-(18-28)-32

Note: Summer: Nov-Feb; Autumn: Mar-Apr; Winter: May-Aug; Spring: Sep-Oct

* Temperatures fluctuations during the diel cycle are incorporated into the ranges. Minimum early morning temperatures are guided by the 5th percentile and late afternoon temperature by the 95th percentile.

Confidence in the assessment: High

Water quality calculations: pH

Generic knowledge about the response of ecosystems to pH

pH effects:
- The equilibrium of chemical reactions
- Bioavailability of metals and other compounds
- Ionic and osmotic processes

Generic exposure-response
- Vary from background average by not more than 5% or 0.5 of a pH unit whichever is the more conservative. (Target water quality range, DWAF, 1996)
- Deviation from reference median (DWAF, 1999b)
  - 5% or 0.5 of a pH unit is natural
  - 7% or 0.7 of a pH unit is largely natural
  - 10% or 1.0 of a pH unit is moderately modified
  - 12% or 1.2 of a pH unit is largely modified

Site-specific knowledge about the response of the ecosystems to pH

The historical pH of water at X2H016Q01 and an analysis of earliest and most recent pH values are provided in Table C7 and Figure C2. The earliest available data shows clear seasonal trends (Table C8). Biological monitoring data from 1992/1993 listed in Table C9 shows that invertebrate communities were generally in a moderately modified state, with near natural and largely modified conditions being approached at times. This assessment is confirmed by Balance *et al.*, 2001, stating that invertebrate fauna in this section give a varied response, but fish communities show fair (moderately modified) health. According to the Desktop determination of EISC, the sensitivity of the ecosystem to water quality changes is low (DWAF, 2000).

A conclusion that can be drawn is that the pH listed in Table B7 (1996 – 2000) and Table B8 is sufficient to maintain the invertebrate and fish community in a moderately modified state.

Table C7: Earliest and most resent pH values at X2H016Q01.

	pH unit percentiles				
	5th	25th	50th	75th	95th
1970 – single value for February	7.4				
1977 - 1979 (n = 61)	6.9	7.1	7.4	7.6	8.1
1996 – 2000 (n = 285)	7.5	7.8	8.2	8.4	8.5

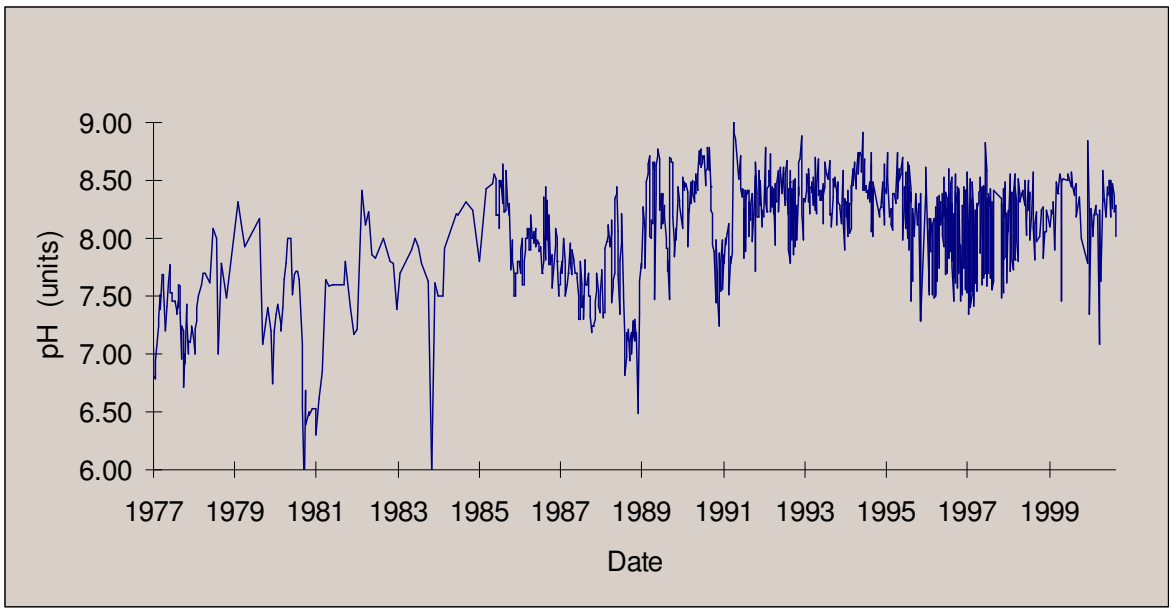

Figure C2: pH at X2H016Q01

Table C8: Seasonal trends for pH (1977-1979 & 1996-2000).

	PH units (5th %tile – median - 95th %tile)			
	Summer	Autumn	Winter	Spring
Earliest data (1977-1979)	6.9 - 7.2 – 7.8	6.8 – 7.1 – 7.3	7.2 – 7.6 – 8.1	7.3 - 7.6 – 7.9
Most recent (1996-2000)	7.5 - 8.1 – 8.5	7.4 – 8.1 – 8.6	7.5 – 8.2 – 8.5	7.6 – 8.3 – 8.6

Note: Summer: Nov-Feb; Autumn: Mar-Apr; Winter: May-Aug; Spring: Sep-Oct

Natural levels for pH in the specific resource unit

Figure C2 clearly shows an increase in pH from 1977 to 2000, a trend that is confirmed in Table C7 (noting that there was a change in the method between 1990 and 1992). The seasonal variability of pH (Table C8) is less apparent in more recent data. The potential impacts from geology, soil and vegetation do not explain this trend. The expected pH under natural conditions (Table C10) is based on the 1977 – 1979 conditions, although industrial and agricultural impacts would have had an impact on these values. The 1977 - 1979 conditions are thus adjusted according to generic knowledge to ensure that the deviation is not more than 0.5 of a pH unit.

Table C9: Historical SASS scores and pH.

Site	Date	SASS	ASPT	State	pH
CR29*	6/1992	104	4.7	Moderately to largely modified	7.8
CR29*	7/1992	118	5.1	Moderately modified	8.6
CR29*	9/1992	139	5.1	Largely natural to moderately modified	8.1
CR29*	10/1992	81	4.5	Moderately to largely modified	8.7
CR29✒	7/1993	111	5.3	Moderately modified	8.4
CR29✒	8/1993	118	5.1	Moderately modified	8.1
CR29✒	10/1993	96	4.4	Largely modified	8.0
CR29✒	6/1994	122	4.9	Moderately modified	8.3
CR29✒	9/1994	66	4.4	Largely modified	8.3
CR29✒	6/1995	77	4.8	Largely modified	8.2
CR29✒	9/1996	78	7.8	Moderately modified	8.5
CR28✒	9/1996	133	7.0	Largely natural	8.6
CR30✒	9/1996	146	8.1	Natural	8.4

* : MacMillan, 1992
✒: Thirion, 2001

Table C10: Reference conditions for pH.

	pH units (5th %tile – median - 95th %tile)			
	Summer	Autumn	Winter	Spring
Reference conditions (A)	6.9 - 7.2 – 7.7	6.8 – 7.1 – 7.4	7.2 – 7.6 – 8.1	7.3 - 7.6 – 7.9

Note: Summer: Nov-Feb; Autumn: Mar-Apr; Winter: May-Aug; Spring: Sep-Oct

Conditions that will result in a largely modified ecosystem

The pH specified in Table C8 was sufficient to maintain the ecosystem in the given states. Given these relationships and what is known generically about the effect of pH on aquatic ecosystems, the pH values for largely modified conditions are provided in Table C11.

Table C11: pH for largely modified conditions.

	pH units (5th %tile – (median range) - 95th %tile)			
	Summer	Autumn	Winter	Spring
Largely modified	5.7-(6.0-8.4)-8.9	5.6-(5.9-8.3)-9.2	6.0-(6.4-8.8)-9.3	6.1-(6.4-8.8)-9.0

Note: Summer: Nov-Feb; Autumn: Mar-Apr; Winter: May-Aug; Spring: Sep-Oct

Specifications for different levels of protection

Table C12: Ecological Reserve for pH*.

	pH units (5^{th} %tile – (median range) - 95^{th} %tile)			
	Summer	Autumn	Winter	Spring
Reference conditions (A)	6.9 - 7.2 – 7.7	6.8 – 7.1 – 7.4	7.2 – 7.6 – 8.1	7.3 - 7.6 – 7.9
Largely natural (B)	6.5-(6.8-7.6)-8.1	6.4-(6.7-7.5)-8.0	6.8-(7.2-8.0)-8.5	6.9-(7.2-8.0)-8.3
Moderately modified (C)	6.1-(6.4-8.0)-8.5	6.0-(6.3-7.9)-8.6	6.4-(6.8-8.4)-8.9	6.5-(6.8-8.4)-8.6
Largely modified (D)	5.7-(6.0-8.4)-8.9	5.6-(5.9-8.3)-9.2	6.0-(6.4-8.8)-9.3	6.1-(6.4-8.8)-9.0

Note: Summer: Nov-Feb; Autumn: Mar-Apr; Winter: May-Aug; Spring: Sep-Oct

* pH fluctuations during the diel cycle are incorporated into the ranges. Minimum early morning pH is guided by the 5^{th} percentile and late afternoon pH by the 95^{th} percentile.

Confidence in the assessment: High

Water quality calculations: Oxygen

Generic knowledge about the response of ecosystems to oxygen

Effects of oxygen:
- Required for respiration in all aerobic organisms
- Affects speciation of metals, sulphur and other compounds

Generic dose-response
- Water quality guidelines (DWAF, 1996)
  - 80-120% of saturation. (Target water quality range)
  - 7-day mean minimum > 60% and 1-day minimum > 40% (Minimum allowable).
- Deviation from reference median (DWAF, 1999b)
  - 80-120% of saturation is natural
  - 80-100% of saturation is largely natural
  - 60-80% of saturation is moderately modified
  - 40-60% of saturation is largely modified
- Super-saturation can cause gas bubble disease in fish and inhibit photosynthesis in green algae.
- Prolonged exposure to DO concentrations less than 50% of saturation can cause significant changes in community composition.

Site-specific knowledge about the response of the ecosystems to oxygen

DO was not measured at X2H016Q01. Limited DO measurements available for X2H050Q01 (DWAF, 2001; Heath & Claassen, 1999; RHP, 2001) are provided in Table C13. Biological monitoring data from 1992/1993 listed in Table C14 shows that invertebrate communities were generally in a moderately modified state, with near natural and largely modified conditions being approached at times. Balance *et al.* (2001) confirms this in stating that invertebrate fauna in this section give a varied response, but fish communities show fair (moderately modified) health. According to the Desktop determination of EISC, the sensitivity of the ecosystem to water quality changes is low (DWAF, 2000).

Table C13: Dissolved oxygen data at X2H050Q01.

	Dissolved oxygen (median)							
	Summer		Autumn		Winter		Spring	
	mg/l (%)	N	mg/l (%)	n	mg/l (%)	n	mg/l (%)	n
1989-1993	6.7 (86)	2	6.2 (78)	1	10.5 (115)	5	7.7 (93)	5

Note: Summer: Nov-Feb; Autumn: Mar-Apr; Winter: May-Aug; Spring: Sep-Oct

Table C14: Historical SASS scores and dissolved oxygen

Site	Date	SASS	ASPT	State	DO (mg/l)
CR29*	6/1992	104	4.7	Moderately to largely modified	7.0
CR29*	9/1992	139	5.1	Largely natural to moderately modified	7.7
CR29*	10/1992	81	4.5	Moderately to largely modified	10.0
CR29✒	7/1993	111	5.3	Moderately modified	11.2
CR29✒	8/1993	118	5.1	Moderately modified	8.9
CR29✒	10/1993	96	4.4	Largely modified	7.9
CR29✒	6/1994	122	4.9	Moderately modified	7.7
CR29✒	6/1995	77	4.8	Largely modified	9.5
CR29✒	9/1996	78	7.8	Moderately modified	7.9
CR28✒	9/1996	133	7.0	Largely natural	8.2
CR30✒	9/1996	146	8.1	Natural	7.3

* : MacMillan, 1992
✒: River Health Programme

Natural levels for DO in the specific resource unit

The seasonal variability of DO (Table C13) illustrates the effect of low flows. The shallower water has a bigger surface to volume ratio and also higher turbulence across rapid and riffle sections. The solubility of oxygen is also higher during winter due to the colder water. The expected DO under natural conditions (Table C15) is based on generic knowledge and adjusted according to measured values.

Table C15: Reference conditions for DO.

	Dissolved oxygen : 5^{th} %tile – (median range) - 95^{th} %tile (% saturation)			
	Summer	Autumn	Winter	Spring
Reference conditions	90-100-110	80-90-100	100-110-120	90-100-110

Note: Summer: Nov-Feb; Autumn: Mar-Apr; Winter: May-Aug; Spring: Sep-Oct

Conditions that will result in a largely modified ecosystem

The DO specified in Table C13 was sufficient to maintain the ecosystem in the given states. Given this relationship and what is known generically about the effect of DO on aquatic ecosystems, the DO values for largely modified conditions are provided in Table C16. (Generic knowledge suggests that a minimum DO of 40%. This value is set as the 5^{th} percentile for autumn, and other values adjusted according to the natural seasonal cycle in Table C15)

Table C16: Dissolved oxygen for largely modified conditions.

	Dissolved oxygen - % saturation (5^{th} %tile – (median range) - 95^{th} %tile)			
	Summer	Autumn	Winter	Spring
Largely modified (D)	50-(60-70)-80	40-(50-60)-70	60-(70-80)-90	50-(60-70)-80

Note: Summer: Nov-Feb; Autumn: Mar-Apr; Winter: May-Aug; Spring: Sep-Oct

Specifications for different levels of protection

Table C17: Ecological Reserve for dissolved oxygen*.

	Dissolved oxygen - % saturation (5^{th} %tile – (median range) - 95^{th} %tile)			
	Summer	Autumn	Winter	Spring
Reference conditions (A)	90-100-110	80-90-100	100-110-120	90-100-110
Largely natural (B)	80-(90-100)-110	70-(80-90)-100	90-(100-110)-120	80-(90-100)-110
Moderately modified (C)	65-(75-85)-95	55-(65-75)-85	75-(85-95)-105	65-(75-85)-95
Largely modified (D)	50-(60-70)-80	40-(50-60)-70	60-(70-80)-90	50-(60-70)-80

Note: Summer: Nov-Feb; Autumn: Mar-Apr; Winter: May-Aug; Spring: Sep-Oct

* DO fluctuations during the diel cycle are incorporated into the ranges. Minimum early morning temperatures are guided by the 5^{th} percentile and late afternoon temperature by the 95^{th} percentile.

Confidence in the assessment: Low (due too little data being available)

Water quality calculations: Nutrients

Generic knowledge about the response of ecosystems to nutrients

Effects of Nutrients:
- Absolute and relative inorganic nitrogen and phosphorus concentrations are key drivers for primary production.

Generic dose-response
- Target water quality range (DWAF, 1996)
  - Total inorganic nitrogen (TIN) and inorganic phosphorus (iP) should not deviate by more than 15% from natural
  - The trophic status of the system should deteriorate
  - Natural TIN and iP cycles should be maintained

	TIN	iP
- Trophic status (DWAF, 1996)		
o Oligotrophic	< 0.5 mg/l	< 5 mg/l
o Mesotrophic	0.5 – 2.5 mg/l	5 – 25 mg/l
o Eutrophic	2.5 – 10 mg/l	25 – 250 mg/l
o Hypertrophic	> 10 mg/l	> 250 mg/l

- Specifications for nutrients (DWAF, 1999b)

Category	NH_3	PO_4/TP	PO_4	TP	TIN:TP (with PO_4 at 0.01-0.5)
A	0-0.007	0-10 %	0-0.01	0.1	> 20:1
B	0.007-0.015	10-20 %	0.01-0-0.05	0.1-0.175	>10:1 & < 20:1
C	0.015-0.03	20-40 %	0.05-0-0.07	0.175-0.25	>5:1 & < 10:1
D	0.03-0.07	40-60 %	0.07-0-0.1	0.167-0.175	< 5:1

Site-specific knowledge about the response of the ecosystems to nutrients

The historical values for nutrients at X2H016Q01 are provided in Figures 4C.3a – 4C.3d.

A comparison of the earliest (1977-1979) and most recent data (1996-2000) is provided in Table C18. The range for nitrate + nitrite values are not significantly different between these periods, although the median was 63% higher in the latter term. The values for ammonium decreased from 1977 to 2000 (60%). The range for ortho-phosphate was narrower during 1996-2000, while the median increased from 0.01 in 1977-1979 to 0.02 in 1996-2000.

Table C19 shows that invertebrate communities at CR30 were generally in a natural to largely natural state from 1996 to 2000. According to the Desktop determination of EISC, the sensitivity of the ecosystem to water quality changes is low (DWAF, 2000). A conclusion that can be drawn is that the nutrients listed in Table C18 are sufficient to maintain the invertebrate community in a near natural state.

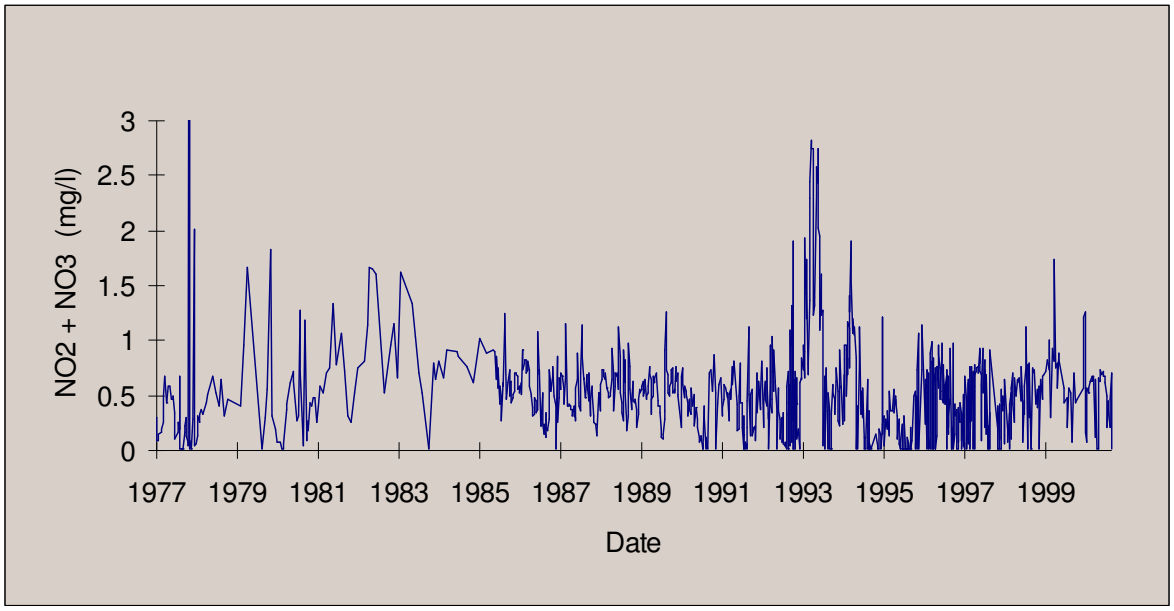

Figure C3a: NO_2 and NO_3 at X2H016Q01

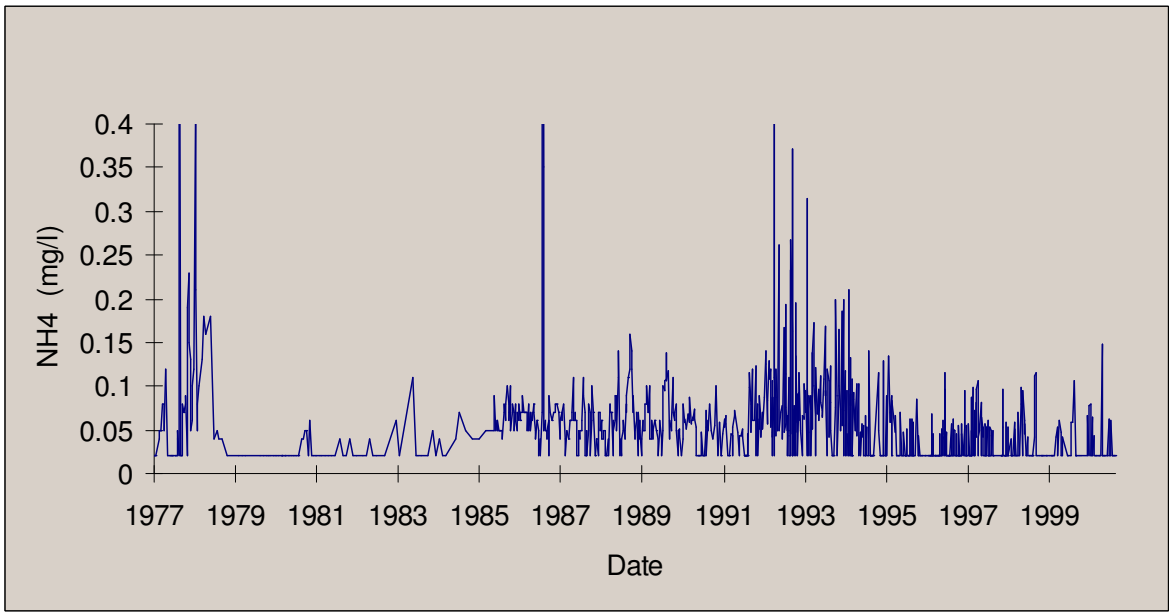

Figure C3b: NH_4 at X2H016Q01

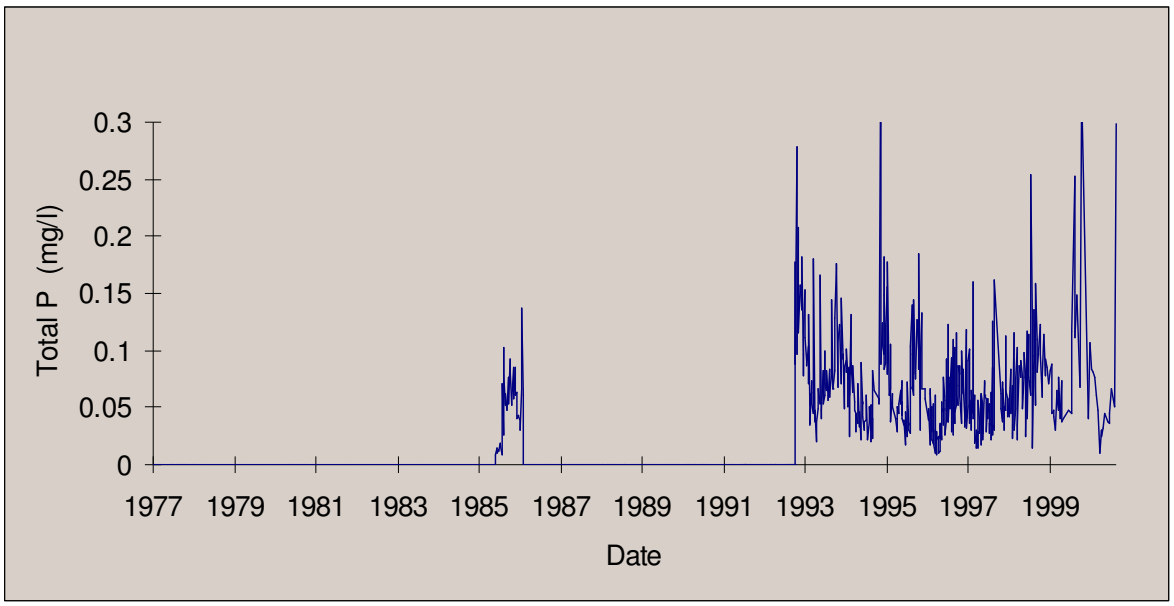

Figure C3c: Total phosphorus at X2H016Q01

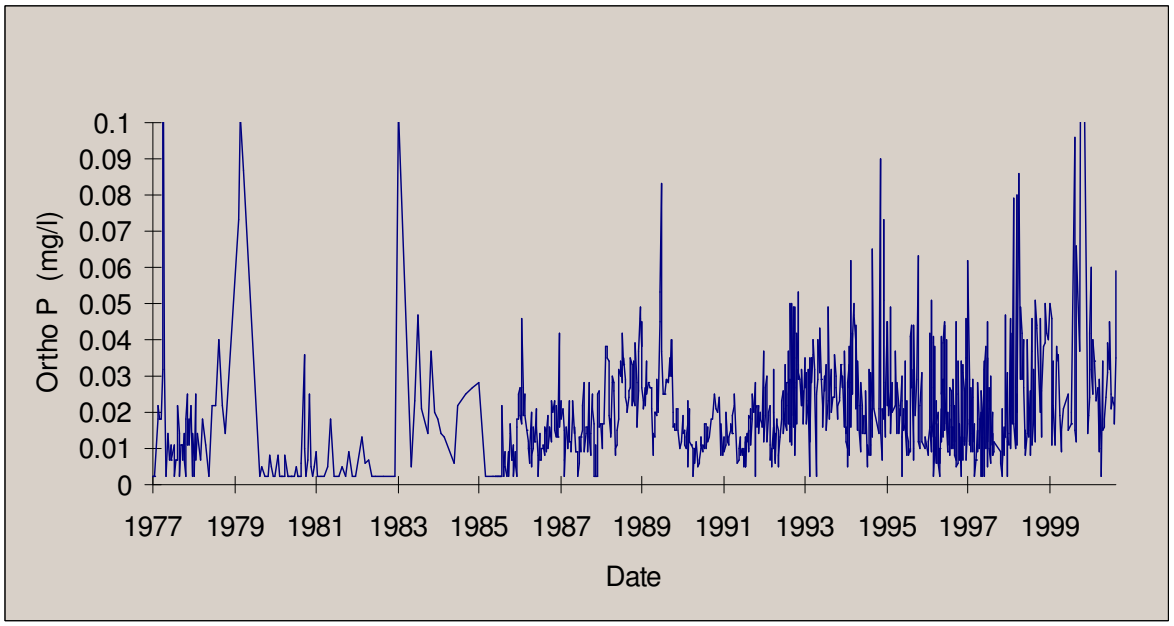

Figure C3d: PO_4 at X2H016Q01

Table C18: Nutrients at X2H016Q01 for the periods 1977 – 1979 and 1996 – 2000.

	Nutrients (5^{th} %tile – median - 95^{th} %tile) mg/l			
	$NO_2 + NO_3$	NH_4	TP	PO_4
1977 - 1979:	0.02 - 0.30 - 0.96	0.02 - 0.05 - 0.21	N/A	0.003 – 0.01 – 0.07
1996 - 2000:	0.02 - 0.49 - 0.93	0.02 - 0.02 - 0.08	0.02 – 0.05 – 0.12	0.006 – 0.02 – 0.05

Table C19: Historical SASS scores and nutrients (mg/l).

Site	Date	SASS	ASPT	State	NO_{2+3}	NH_4	TP	PO_4	TIN:PO_4
CR29*	6/1992	104	4.7	Moderately to largely modified	0.60	0.07	-	0.011	61
CR29*	7/1992	118	5.1	Moderately modified	0.60	0.07	-	0.015	45
CR29*	9/1992	139	5.1	Largely natural to moderately modified	0.20	0.07	-	0.022	12
CR29*	10/1992	81	4.5	Moderately to largely modified	0.10	0.06	-	0.025	6
CR29✒	7/1993	111	5.3	Moderately modified	0.07	0.09	-	0.019	8
CR29✒	8/1993	118	5.1	Moderately modified	0.04	0.05	-	0.007	13
CR29✒	10/1993	96	4.4	Largely modified	0.08	0.08	-	0.022	7
CR29✒	6/1994	122	4.9	Moderately modified	0.04	0.08	-	0.007	17
CR29✒	9/1994	66	4.4	Largely modified	0.11	0.04	-	0.017	9
CR29✒	6/1995	77	4.8	Largely modified	0.07	0.04	-	0.020	6
CR29✒	9/1996	78	7.8	Moderately modified	0.38	0.04	0.05	0.015	28
CR28✒	9/1996	133	7.0	Largely natural	0.49	0.04	0.07	0.019	28
CR30✒	9/1996	146	8.1	Natural	0.69	0.04	0.05	0.016	46
CR30✒	5/1999	148	7.4	Natural	0.59	0.02	0.04	0.016	38
CR30✒	7/1999	159	6.6	Largely natural	0.81	0.03	0.04	0.017	49
CR30✒	9/1999	182	5.9	Natural	0.50	0.02	0.05	0.020	26

monthly median at X2H016
* : MacMillan, 1992
✒: Thirion, 2001

Natural levels for nutrients in the specific resource unit

The values listed in Table C18 shows a TIN:PO_4 ratio of 35:1 for 1977-1979 and a TIN:TP ration of 10.2:1 for 1996-2000. Compared to generic knowledge the 1977-1997 ratio represents a natural state and the 1996-2000 ratio a largely natural state. Recent biological monitoring (Table C19) supports this view, with invertebrate communities being in a natural to largely natural state with TIN:PO_4 ratios between 25:1 and 50:1. Recent TP and PO_4 values exceed those required to maintain a natural system given generic knowledge, but still maintains the system in a near natural state. The reference conditions for TP and PO_4 are thus adjusted from the generic knowledge (Table C20). The TIN:TP ration showed similar deviations from generic rules and are adjusted accordingly.

Table C20: Reference conditions for nutrients.

	Nutrients (5^{th} %tile – median - 95^{th} %tile) mg/l			
	NH_3	TP	PO_4	TIN/TP
Reference conditions (A)	0.008 - 0.008 - 0.03	0.01 – 0.04 – 0.1	0.005 – 0.015 – 0.04	20:1 - 15:1 - 10:1

Conditions that will result in a largely modified ecosystem

The available data for nutrients in Table C19 represents conditions from natural to largely modified. The predictions of conditions that would result in a largely modified system based on the generic relationships are supported by the data in Table C19. The conditions for largely modified conditions are presented in Table C22.

Table C22: Largely modified conditions for nutrients.

	Nutrients (5^{th} %tile – median - 95^{th} %tile) mg/l			
	NH_3	TP	PO_4	TIN/TP
Largely modified (D)	0.08 - 0.08 - 0.16	0.025 – 0.1 – 0.25	0.05 – 0.15 – 0.4	7:1 - 5:1 - 3:1

Specifications for different levels of protection

Table C23: Ecological Reserve for nutrients.

	Nutrients (5^{th} %tile – median - 95^{th} %tile) mg/l			
	NH_3	TP	PO_4	TIN/TP
Reference conditions (A)	0.008 - 0.008 - 0.03	0.01 – 0.04 – 0.1	0.005 – 0.015 – 0.04	20:1 - 15:1 - 10:1
Largely natural (B)	0.016 - 0.016 - 0.05	0.015 – 0.06 – 0.15	0.01 – 0.05 – 0.015	13:1 – 10:1 - 7:1
Moderately modified (C)	0.035 - 0.035 - 0.08	0.02 – 0.08 – 0.2	0.03 – 0.10 – 0.25	9:1 – 7:1 - 5:1
Largely modified (D)	0.08 - 0.08 - 0.16	0.025 – 0.1 – 0.25	0.05 – 0.15 – 0.4	7:1 – 5:1 - 3:1

Confidence in the assessment: High for natural, Moderate for largely modified

Water quality calculations: TDS

Generic knowledge about the response of ecosystems to TDS

Effects of TDS:
- Chronic and acute physiological effects
- Affects buffering capacity and metabolism

Generic dose-response
- Target water quality range (DWAF, 1996)
  - < 15% change from natural, maintain natural cycles

- Specifications for TDS (DWAF, 1999b)
  - Natural (A) 0 - 163 mg/l
  - Largely natural (B) 163 - 228 mg/l
  - Moderately modified (C) 228 - 325 mg/l
  - Largely modified (D) 325 - 520 mg/l

Site-specific knowledge about the response of the ecosystems to TDS

The historical values for TDS at X2H016Q01 are provided in Figure C4.

Table C25 shows that invertebrate communities were generally in a moderately - to largely modified state between 1992 and 1995 and in a natural to largely natural state from 1996 to 2000. According to the Desktop determination of EISC, the sensitivity of the ecosystem to water quality changes is low (DWAF, 2000). It can be concluded that the changes in biotic state may have been affected by TDS, since TDS was significantly different during these periods (Table C24).

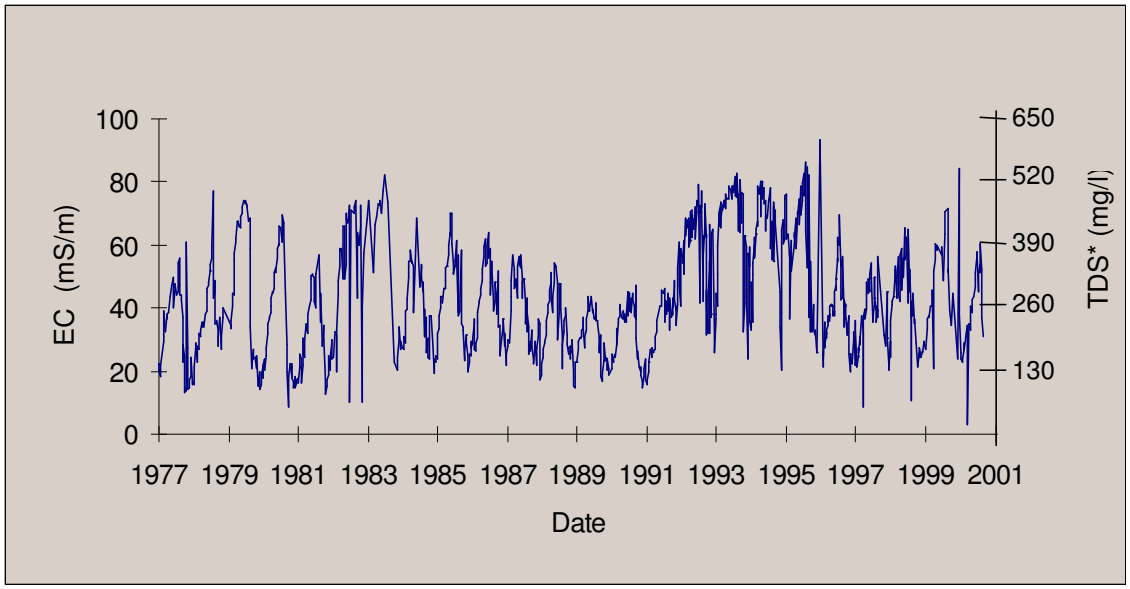

Figure C4: EC at X2H016Q01. (*TDS = EC x 6.5)

Table C24: Historical values for EC at X2H016Q01.

	EC (5th %tile – median - 95th %tile) mS/m
1977-1979	15.8 – 37.5 – 72.1
1992-1995	34.2 – 65.6 – 79.7
1996-2000	22.1 – 39.0 – 60.7

Table C25: Historical SASS scores, EC (mS/m) and TDS (mg/l).

Site	Date	SASS	ASPT	State	EC	TDS#
CR29*	6/1992	104	4.7	Moderately to largely modified	63.7	414
CR29*	7/1992	118	5.1	Moderately modified	69.0	449
CR29*	9/1992	139	5.1	Largely natural to moderately modified	71.5	465
CR29*	10/1992	81	4.5	Moderately to largely modified	71.3	464
CR29-	7/1993	111	5.3	Moderately modified	-	636
CR29-	8/1993	118	5.1	Moderately modified	-	572
CR29-	10/1993	96	4.4	Largely modified	-	480
CR29-	6/1994	122	4.9	Moderately modified	-	491
CR29-	9/1994	66	4.4	Largely modified	-	437
CR29-	6/1995	77	4.8	Largely modified	-	360
CR29-	9/1996	78	7.8	Moderately modified	-	369
CR28-	9/1996	133	7.0	Largely natural	-	366
CR30-	9/1996	146	8.1	Natural	-	404
CR30-	5/1999	148	7.4	Natural	38.8	252
CR30-	7/1999	159	6.6	Largely natural	59.0	384
CR30-	9/1999	182	5.9	Natural	58.3	379

monthly median at X2H016 and TDS = EC x 6.5
* : MacMillan, 1992
-: Thirion, 2001

Natural levels for TDS in the specific resource unit

The 1996-2000 TDS values represent a largely natural to natural state (Table C25). The reference conditions for TDS are thus adjusted from the generic knowledge by specifying the highest TDS values during natural conditions as the 95th percentile and the range according to the earliest data (Table C26).

Table C26: Reference conditions for TDS.

	TDS (5th %tile – median - 95th %tile) mg/l
Reference conditions (A)	100 - 250 - 400

Conditions that will result in a largely modified ecosystem

The available data for TDS in Table C25 represents conditions from natural to largely modified. The predictions of conditions based on the generic relationships are not supported by the data in Table C25, since a TDS value of 636 mg/l was measured in conjunction with a moderately modified system. The conditions for largely modified conditions were adjusted according to the expectations in Table C25 and are presented in Table C27.

Table C27: Largely modified conditions for TDS.

	TDS (5th %tile – median - 95th %tile) mg/l
Largely modified (D)	200 - 500 - 800

Specifications for different levels of protection

Table C28: Ecological Reserve for TDS.

	TDS (5th %tile – median - 95th %tile) mg/l
Reference conditions (A)	100 – 250 – 400
Largely natural (B)	120 – 300 – 480
Moderately modified (C)	150 – 375 – 600
Largely modified (D)	200 – 500 – 800

Confidence in the assessment: Moderate

Water quality calculations: Suspended solids

Generic knowledge about the response of ecosystems to TSS

Effects of TSS:
- Affects water temperature
- Reduces visibility and consequently affects predation
- Physiological effects (such as gill efficiency)

Generic dose-response
- Target water quality range (DWAF, 1996)
  - < 10% change from natural, maintain natural cycles (where background is <100 mg/l)

- Specifications for TSS (DWAF, 1999b)
  - Natural (A) < 10% deviation from natural
  - Largely natural (B) < 15% deviation from natural
  - Moderately modified (C) < 20% deviation from natural
  - Largely modified (D) < 25% deviation from natural

Site-specific knowledge about the response of the ecosystems to the TSS

The historical values for TSS at X2H016Q01 are provided in Figure C5.

Table C30 shows that invertebrate communities were generally in a moderately - to largely modified state between 1992 and 1995. According to the Desktop determination of EISC, the sensitivity of the ecosystem to water quality changes is low (DWAF, 2000). The TDS measured between 1992 and 1995 was thus sufficient to maintain the system at a moderately to largely modified state (Table C29).

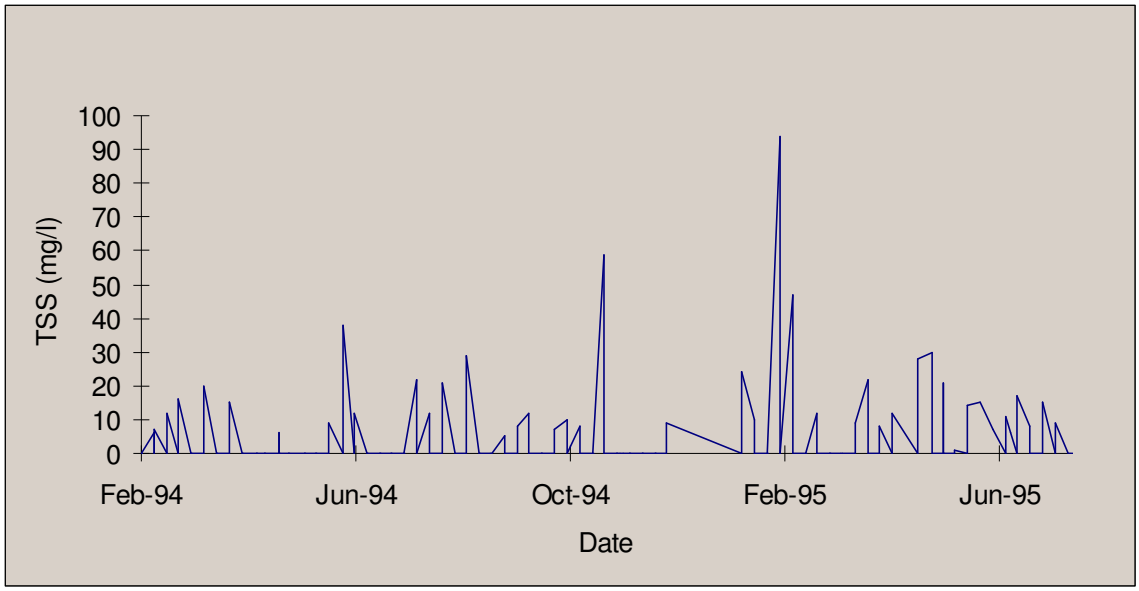

Figure C5: TSS at X2H016Q01.

Table C29: Historical values for TSS at X2H016Q01.

	TSS (mg/l): 5th %tile – median – 95th %tile			
	Summer	Autumn	Winter	Spring
1992-1995	6 – 12 – 80	8 – 15 – 26	1 – 12 – 30	6 – 8 – 11

Note: Summer: Nov-Feb; Autumn: Mar-Apr; Winter: May-Aug; Spring: Sep-Oct

Table C30: Historical SASS scores and TSS (mg/l).

Site	Date	SASS	ASPT	State	TSS
CR29	6/1994	122	4.9	Moderately modified	25
CR29	9/1994	66	4.4	Largely modified	8
CR29	6/1995	77	4.8	Largely modified	8

monthly median at X2H016

: River Health Programme

Natural levels for TSS in the specific resource unit

Suspended solids are increased by agricultural activities in the area. The reference conditions are derived from the measured values by using the generic knowledge (moderate modification is 20% deviation from natural) and presented in Table C31.

Table C31: Reference conditions for TSS.

	TSS (mg/l): 5th %tile – median – 95th %tile			
	Summer	Autumn	Winter	Spring
Reference conditions (A)	5 – 10 – 67	7 – 13 – 21	1 – 10 – 25	5 – 7 – 10

Note: Summer: Nov-Feb; Autumn: Mar-Apr; Winter: May-Aug; Spring: Sep-Oct

Conditions that will result in a largely modified ecosystem

The generic relationships is used to determine the largely modified conditions and are presented in **Table C32**.

Table C32: Largely modified conditions for TSS.

	TSS (mg/l): 5th %tile – median – 95th %tile			
	Summer	Autumn	Winter	Spring
Largely modified (D)	7 – 13 – 83	9 – 16 – 27	1 – 13 – 31	6 – 8 – 12

Note: Summer: Nov-Feb; Autumn: Mar-Apr; Winter: May-Aug; Spring: Sep-Oct

Specifications for different levels of protection

Table C33: Ecological Reserve for TSS.

	TSS (mg/l): 5th %tile – median – 95th %tile			
	Summer	Autumn	Winter	Spring
Reference conditions (A)	5 – 10 – 67	7 – 13 – 21	1 – 10 – 25	5 – 7 – 10
Largely natural (B)	5 – 11 – 73	7 – 14 – 23	1 – 11 – 27	5 – 7 – 10
Moderately modified (C)	6 – 12 – 78	8 – 15 – 25	1 – 12 – 29	6 – 8 – 11
Largely modified (D)	7 – 13 – 83	9 – 16 – 27	1 – 13 – 31	6 – 8 – 12

Note: Summer: Nov-Feb; Autumn: Mar-Apr; Winter: May-Aug; Spring: Sep-Oct

Confidence in the assessment: Low

Water quality calculations: Toxics

Generic knowledge about the response of ecosystems to toxics

Effects of toxics:
- Acute and chronic effects

Generic dose-response

	Pb* (ug/l)	Cl (mg/l)
- Target water quality range (DWAF, 1996)	<0.5	< 0.2
- Chronic effect value (CEV)	1.0	0.35
- Acute effect value (AEV)	7.0	5

* Medium hardness: 60-119 mg/l $CaCO_3$

- Specifications for toxicants (DWAF, 1999b)
  - Natural (A) 90% < TWQR, 99% < CEV, 100% < AEV
  - Largely natural (B) 95% < CEV, 99% < AEV
  - Moderately modified (C) 75% < CEV, 90% < AEV
  - Largely modified (D) 50% < CEV, 85% < AEV

Site-specific knowledge about the response of the ecosystems to toxics

The historical values for lead at CR28, CR29 and CR30 are provided in Table C34. Chlorine concentrations have not been recorded in the study area.

Table C34: Historical values for lead.

	Lead (diss. ug/l)
CR28: Sept 1996	0.02
CR29: Sept 1996	0.02
CR30: Sept 1996	0.02

Natural levels for toxics in the specific resource unit

Geological sources are not expected to contribute significantly to lead (Table 5). The levels reported in Table C34 are expected to be at or above the natural background. This was also the detection limit for the specific analyses, therefore the natural level can be stated as < 0.02 ug/l. Chlorine does not occur naturally in the environment and the reference condition is thus set at 0 ug/l.

Conditions that will result in a largely modified ecosystem

The generic knowledge provides the dose-response relationships. Knowledge about the site does not justify adjustments to the relationships.

Table C35: Largely modified conditions for toxics.

	Lead (ug/l)	Residual chlorine (mg/l)
Largely modified (D)	50% < 1.0, 85% < 7.0	50% < 0.35, 85% < 5.0

Specifications for different levels of protection

Table C36: Ecological Reserve for toxics.

	Dissolved lead (ug/l)	Residual chlorine (mg/l)
Reference conditions (A)	90% < 0.5, 99% < 1.0, 100% < 7.0	90% < 0.2, 99% < 0.35, 100% < 5.0
Largely natural (B)	95% < 1.0, 99% < 7.0	95% < 0.35, 99% < 5.0
Moderately modified (C)	75% < 1.0, 90% < 7.0	75% < 0.35, 90% < 5.0
Largely modified (D)	50% < 1.0, 85% < 7.0	50% < 0.35, 85% < 5.0

Confidence in the assessment: High

Appendix D: Fold out Maps and Figures

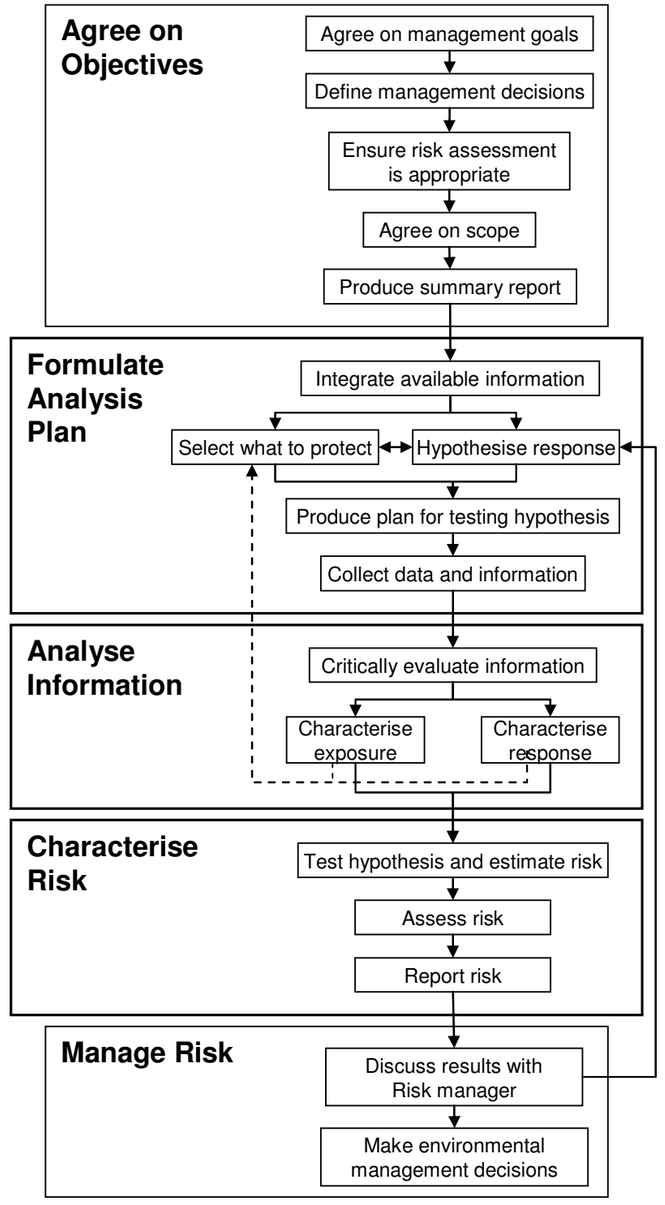

Figure 2.1: Actions in the draft ERA framework for South Africa (adapted from Murray and Claassen, 1999).

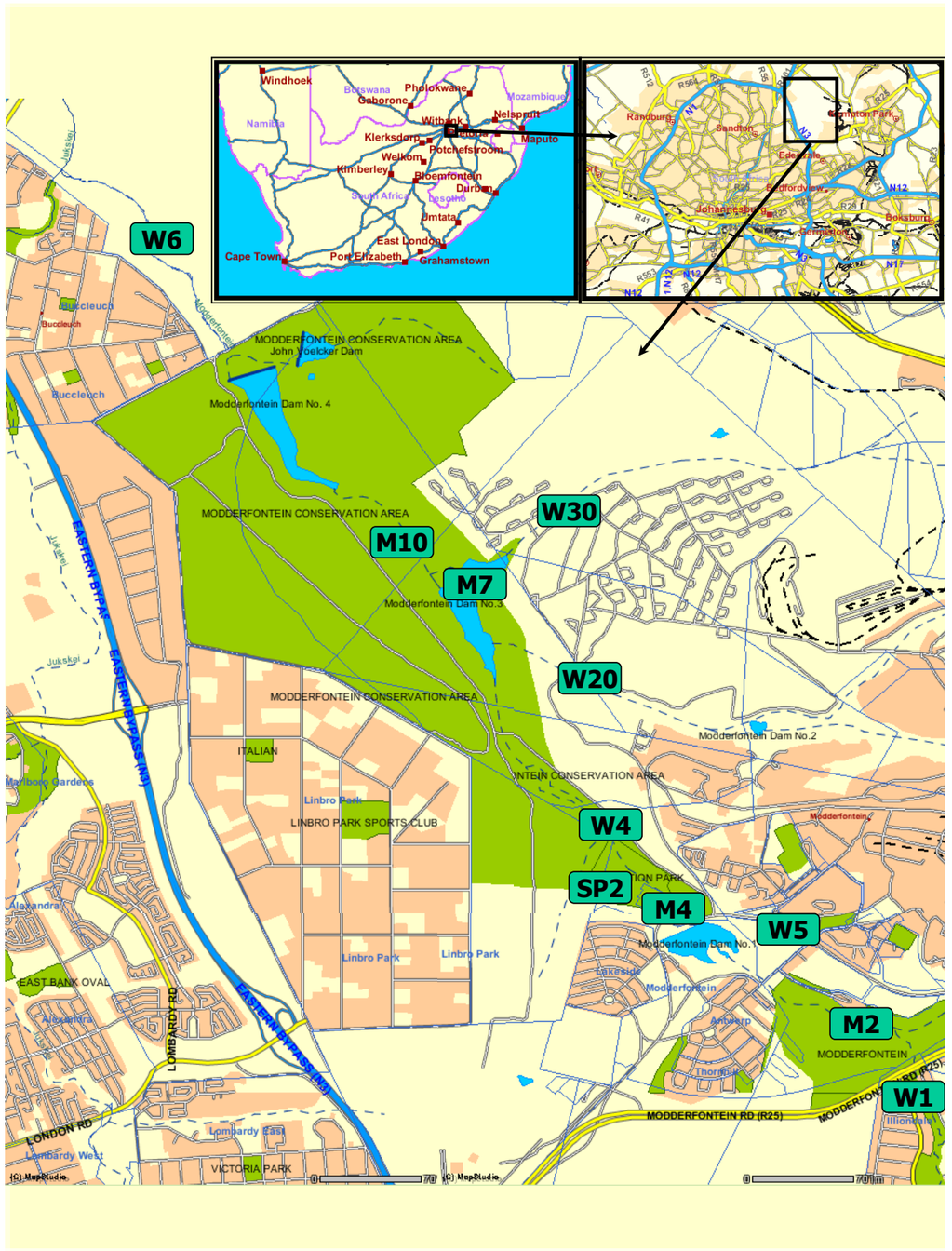

Figure 3.2: Geographic perspective of AEL and monitoring sites.

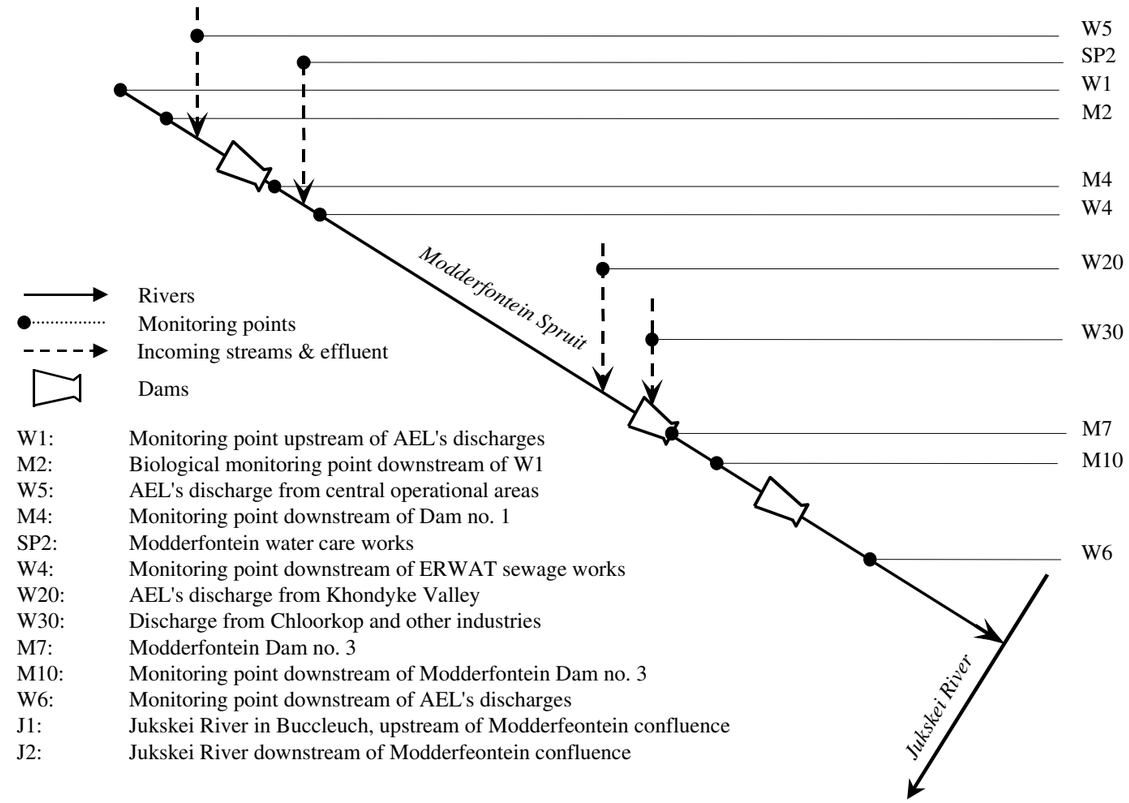

Figure 3.3: Schematic presentation of AEL study area and monitoring sites.

Table 3.2: Hypotheses evaluated in the case study.

		Stressors	
		1. Specified variables at W6	2. Whole effluent
Temporal	A. Current conditions	**1A** "Current values of specified variables do not pose an unacceptable risk to aquatic ecosystems"	**2A** "The current toxicity of effluents do not pose an unacceptable risk to aquatic ecosystems"
	B. Permit values	**1B** "Permitted values of specified variables do not pose an unacceptable risk to aquatic ecosystems"	**2B** "The toxicity of effluents at permitted values do not pose an unacceptable risk to aquatic ecosystems"
	C. Future scenario	**1C** "Likely future values of specified variables do not pose an unacceptable risk to aquatic ecosystems"	**2C** "Likely future toxicity of effluents do not pose an unacceptable risk to aquatic ecosystems"

Specific phrases in the hypotheses have the following meanings:

Specified variables:	Variables regulated by the effluent permit (Appendix A) at W6, W20 and W30. (pH, EC, Nitrate, Nitrite, Ammonia, Sulphate, Fluoride, COD, Phosphate, Sodium and Flow)
Unacceptable risk:	Acute effects in the receiving water or effluent, chronic effects in receiving waters that threaten the sustainability[8] of populations or any stressor that threatens the sustainability[5] of the aquatic ecosystem.
Aquatic ecosystems	Includes all of the aquatic organisms in the Modderfontein Spruit and their interaction with the physical environment, where the flow of energy leads to clearly defined trophic structure, biotic diversity and material cycles.
Whole effluent:	Although the effluent at W20 and W30 are permitted on the basis of water quality parameters, the effluent permit also specifies that toxicological analyses and biological monitoring must be conducted. The hypothesis will be evaluated by taking all available information into account.
Permitted values:	This relates to the license conditions for 1/7/1998 to 30/6/1999, when the study was conducted
Future scenario:	This relates to the permit specifications from 1/7/1999 to 30/6/2002. Here the hypotheses are stated as likely future values, since compliance is not guaranteed – especially given evidence of historical non-compliance.

8 The ability of the populations and ecosystems to sustain production and reproduction

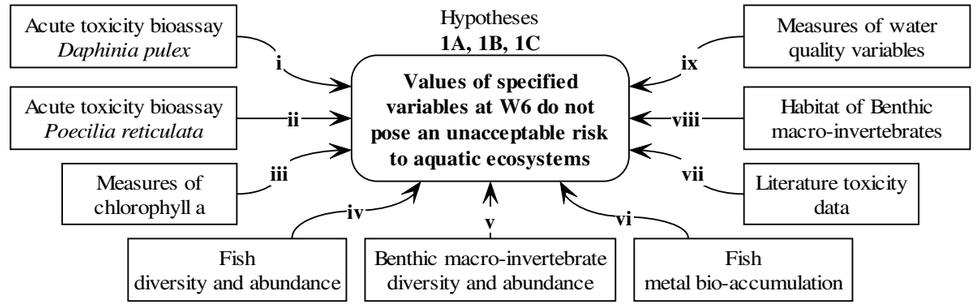

Figure 3.5: Lines of evidence for evaluating risk posed by variables in the Modderfontein Spruit.

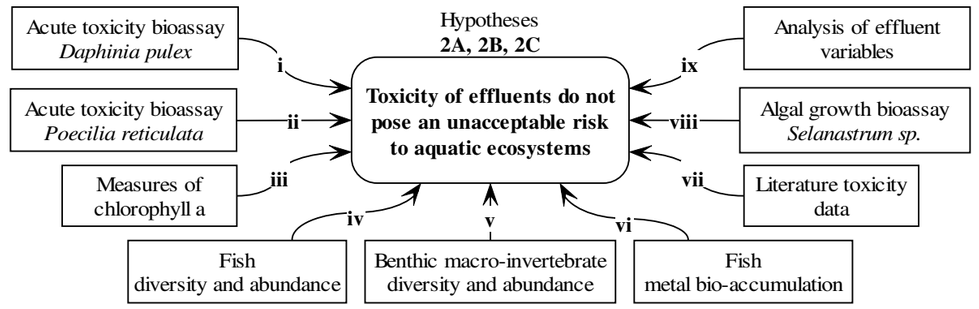

Figure 3.6: Lines of evidence for evaluating risk posed by whole effluent discharge.

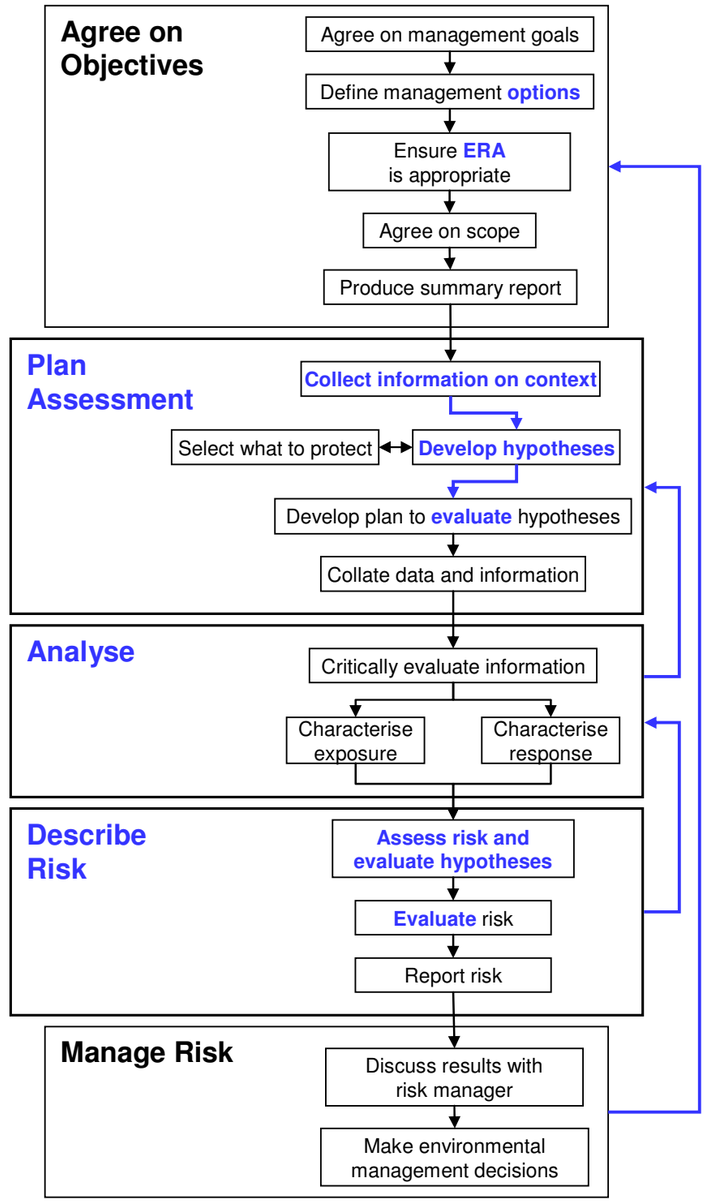

Figure 4.1/5.1: Revised process for ERA in South Africa (revisions indicated in **bold**).

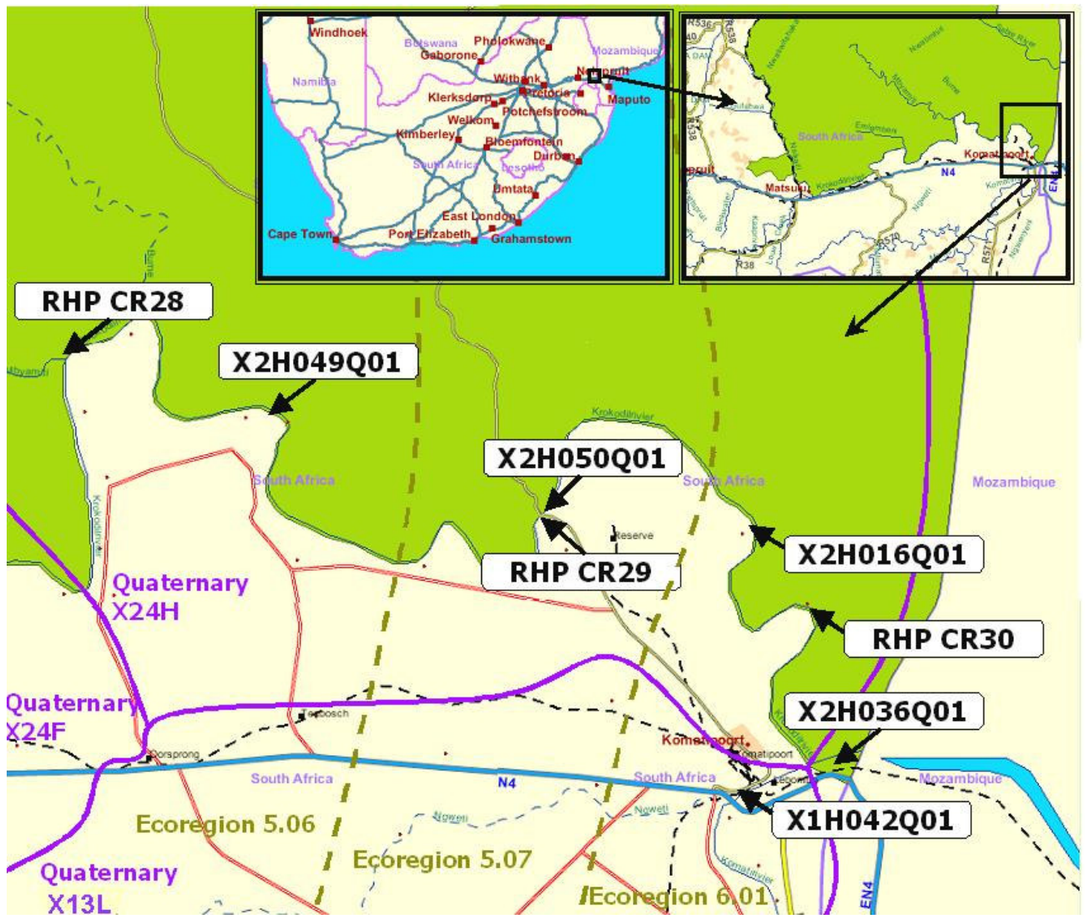

Figure 5.3: Monitoring points along the Crocodile River between Maroela Weir and Komatipoort.