UNIVERSITY OF THE FREE STATE

DETERMINING THE WATER QUALITY ECOLOGICAL RESERVE FOR NON-PERENNIAL RIVERS
A PROTOTYPE ENVIRONMENTAL WATER ASSESSMENT METHODOLOGY

by
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LIST OF ACRONYMS

AEVs	Acute Effect Values
ASPT	Average score per taxon
BBM	Building Block Methodology
BDI	Biological Diatom Index
BOD	Biochemical oxygen demand
CAMS	Catchment Abstraction Management Strategies
CEM	Centre for Environmental Management
CEVs	Chronic Effect Values
Chl -a	*Chlorophyll a*
COD	Chemical oxygen demand
CRUs	Combined Response Units
DO	Dissolved oxygen
DOC	Dissolved organic carbon
DRIFT	Downstream Response to Imposed Flow Transformation
DWA	Department of Water Affairs
DWAF	Department of Water Affairs and Forestry
EC	Ecological class
EC	Electrical conductivity
EF	Environmental flow
EIS	Ecological importance and sensitivity
EWA	Environmental Water Assessment
EWR	Environmental Water Requirement
FRAI	Fish Response Assessment Index
FSR	Flow Stressor Response
HI	Hydrological Index
HRU	Hidrological Resource Unit
IFIM	Instream Flow Incremental Methodology
IGS	Institute for Groundwater Studies
IWQS	Institute for Water Quality Services
IWRM	Integrated Water Resources Management
LIFE	Lotic Invertebrate Index for Flow Evaluation
Malk/TAL	Methylene orange/Total alkalinity
MAR	Mean annual runoff
MIRAI	Macro Invertebrate Response Assessment Index
NWA	National Water Act
NWRS	National Water Resource Strategy
PAI	Physico-Chemical Driver Assessment Index
Palk	Phenolphthalein alkalinity (above pH 8.3)
PES	Present Ecological State
RAM	Resource Assessment and Management

RC	Reference Condition
RDM	Resource Directed Measures
RPU	Runoff Potential Units
RQOs	Resource Quality Objectives
SASS	South African Scoring System
SASS5	South African Scoring System Version 5
SDI	Spring Diatom Increase
SPATSIM	Spatial and Time Series Information Modelling
SPI	Specific Pollution Sensitivity Index
SRP	Soluble reactive phosphates or ortho-phosphate
SS	Suspended Sediments
TDS	Total Dissolved Solids
TEACHA	Tool for the Ecological Aquatic Chemical Habitat Assessment
TIN	Total Inorganic Nitrogen
TN	Total Nitrogen
TOC	Total Organic Carbon
TP	Total Phosphorus
TSS	Total Suspended Solids
TWQRs	Target Water Quality Ranges
WMS	Water Management Systems
WQRU	Water Quality Resource Unit
WRYM	South African Water Resources Yield Model
WR90	Surface water resources of South Africa, 1990
WR2005	Surface water resources of South Africa, 2005

UNITS OF MEASUREMENTS

cm	centimeter
º C	degrees Celsius
º F	degrees Fahrenheit
g/ℓ	gram per liter
m/s	meters per second
µg/ℓ	microgram per liter
µℓ	microliter
µS/cm	microSiemens per centimeter
mS/m	milliSiemens per meter
mamsl	meters above mean sea level
mg/ℓ	milligram per liter
mℓ	milliliter
mm	millimeter
mS/m	milli Siemens per meter
NTU	Nephelometric Turbidity Units

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1. INTRODUCTION, AIM AND THESIS OUTLINE

1.1 Introduction

The adoption of the Constitution of the Republic of South Africa (Act No 108 of 1996) laid the foundations for a democratic and open society in which government is voted for by the voting population of the country. The Constitution also contains a promise by the government to improve the quality of life for all the people in the country. All laws are subject to the Constitution, which promotes equity, protects the rights of access to resources, and seeks to enhance opportunities for the poor and previously marginalised.

The Irrigation and Conservation of Waters Act (1912), and the Water Act (Act No 54 of 1956) made no allowance for the equitable, sustainable use of water resources. It upheld a policy of private water use that was linked closely to land ownership through the concept of riparian water rights (Department of Water Affairs and Forestry (DWAF), 2003a).

This legislation has changed and the whole philosophy of the NWA is now based on the principles of Integrated Water Resources Management (IWRM) (Wentzel, 2008). Access to and use of water were severely limited in the past and special provision had to be made to rectify these imbalances.

The Bill of Rights formed the basis for the development of the White Paper on a National Water Policy for South Africa (April 1997), which in turn was founded on and guided by the Water Law Principles accepted by the South African Cabinet in November 1996. The principle objectives of the National Water Policy are to achieve equity of access to, and sustainable use of, water in support of these aims set out in the NWA (National Water Act (NWA), Act 36 of 1998) (DWAF, 2003a).

The NWA has been acknowledged as “one of the most far-reaching and forward-thinking water acts in the world” (Palmer *et al*, 2000). It is based upon two pillars, one of sustainability and one of equity in line with Agenda 21 and South Africa’s Constitution. The twin pillars support the right in law for the use of water for human and environmental needs (DWAF, 2003a).

Legislation is implemented by defining strategies. Chapter 2 of the NWA requires the Minister of Water Affairs, after consultation, to develop a national water resource strategy (NWRS) to facilitate the proper management of our water resources. The NWRS provides the framework for the protection, use, development, conservation, management and control of water resources for the country as a whole.

Implementation of the NWA requires more than the development of strategies, it also requires the development of methodologies to carry out these management activities to ensure that the legislative requirements of the NWA are met.

1.2 The Reserve

The South African NWA adopted in 1998 specified that water resources are public goods, under state control and subject to obtaining a license for use. The National Government is the custodian of the water resources and it has the responsibility for the equitable allocation and usage of water.

The Act defined the ‘Reserve’. The Reserve is an unallocated portion of water that is not subject to competition with other water uses. It refers to both quality and quantity of water and has two components: the Basic Human Need Reserve and the Ecological Reserve. The Basic Human Need Reserve refers to the amount of water for drinking, food and personal hygiene and the Ecological Reserve refers to the amount of water required to protect aquatic ecosystems. The Minister is responsible for the determination of the Reserve and it can be determined for all or part of a specific water resource.

Palmer *et al*, (2000) described the South African NWA as one of the most advanced water laws in the world by only recognizing two water rights. The two water rights, for aquatic ecosystem protection and for basic human needs, were brought together as the Reserve. All other water users and demands are controlled by licenses and met only after the Reserve is secured.

1.3 Non-perennial Rivers

All, except the largest rivers in the semi-arid west of southern Africa are non-perennial, i.e. the rivers have no flow for at least a part of the year. South African rivers generally tend to have variable flow regimes, depending on rainfall events and time of the year, with the highest variability in intermittent and ephemeral rivers and less variability in the perennial rivers. A major issue in shaping the biotic community structure of ephemeral or non-perennial systems is this hydrological variability. Despite the many non-perennial systems in southern Africa, they remain poorly studied and understood (Botes *et al*, 2003; Seely *et al*, 2002).

Limited scientific data on the ecology and its response to high natural variability of the flow regime can severely hamper efforts to manage and conserve the water of non-perennial rivers (Sheldon *et al*, 2002).

Non-perennial rivers may have different characteristics and may function very differently to perennial rivers and require focused attention in terms of research and management. The hydrological and ecological balance of non-perennial rivers is relatively sensitive to change and can easily lead to degradation of the river system. Degradation can be caused by man through development and use of the river as a water source and as a result of climate change (increased aridity). All such rivers are hydrologically and ecologically sensitive and changes to their hydrological regime can have far-reaching effects on the river flow and the biota that can cause dramatic negative changes (Seely *et al*, 2002). It is, therefore, important that methods are developed to assess the environmental water requirements for non-perennial rivers with acceptable confidence to make sustainable catchment management decisions.

Before any water use licenses (e.g. abstraction permits, discharge permits) may be issued, the South African NWA (Act 36, 1998) requires that the environmental water requirements be determined. The methods that are currently used to determine the environmental water requirements (ecological needs) for South Africa's rivers are based on perennial rivers, but about two-thirds of the rivers in South Africa are non-perennial in nature and this presents a potential problem.

1.4 The Research Project

A research proposal was submitted to the WRC by the author, but was not accepted as it was similar to a proposal by the University of the Free State. The WRC proposed that the two proposals be combined and resubmitted. The following research project was the result of the new, combined proposal.

Research funded by the Water Research Commission was conducted in three phases.

Phase 1

Researchers realised that the current methodologies used for perennial rivers are not necessarily appropriate for non-perennial rivers and with funding from the Water Research Commission (WRC), initiated a research project in 2004. A multidisciplinary team was appointed to evaluate existing methods to determine environmental water requirements, to investigate the differences/similarities between perennial and non-perennial rivers and to obtain a better understanding of the functioning of non-perennial rivers. This culminated in a report "Environmental Water Requirements in Non-perennial Systems" in 2005 (Rossouw *et al*, 2005). This was mainly a desktop study consolidating local and international knowledge on the current methodologies and initiatives on environmental water requirements for non-perennial systems.

Phase 2

The Water Research Commission then allocated more funding for Phase 2 of the research project. This project was a three-year study to establish field-based knowledge of a selected non-perennial system, the Seekoei River (as an example of a non-perennial river) in order to develop a Prototype Environmental Water Assessment Methodology for non-perennial systems. The project, which started in April 2005, was completed in 2009 and was published in 2010 (Seaman, *et al*, 2010.

A non-perennial river, the Seekoei River in the Northern Cape, South Africa, was selected because the system had all the variability and characteristics typical of a non-perennial system as well as one good hydrological record for one site downstream of the study area. After the completion of this initial phase it was concluded that non-perennial rivers are primarily distinguished from perennial rivers by their hydrological regime, which is spatially and temporally much more variable and the existing methods used currently are not appropriate for non-perennial rivers. A prototype methodology was developed that needed to be tested in the next phase.

Phase 3

The testing of the prototype methodology for environmental water assessment in non-perennial rivers was the next phase. This phase involved testing the prototype methodology on rivers with different hydrological flow regimes. The Mokolo River was chosen to test the prototype methodology. It has flow for 72% of the time (Steÿn, 2008). A non-perennial river has flow for less than 80% of the time. This river was chosen because it was a relative data rich system and an Intermediate Reserve has been completed using the perennial rivers methods. That would enable one to compare results.

This thesis focuses on the water quality component of the WRC project. It is important to note that the water quality report was not only focussed on the contribution of the water quality component to the prototype methodology for non-perennial rivers, but also on the understanding of the water quality in non-perennial systems.

The hypothesis for the research was that the current, existing water quality methodology for determining the water quality environmental water requirements, which were developed for perennial rivers, could be used for non-perennial rivers. If not, a new prototype method was to be developed.

The research to test the hypothesis was addressed in three phases (objectives):

- Phase 1 determined what was available in terms of environmental water requirements methodology in the broad context (quality and quantity), both nationally and internationally (Rossouw *et al*, 2005).
- Phase 2 was a more detailed analysis of available methodologies for the different components that were required for determining the environmental water requirements.

  The main requirement of the water quality specialist (water chemistry) in Phase 2 of the project was to provide data on water chemistry data in a form that the rest of the multi-disciplinary team could understand and use, and also to apply existing methods to the data that were available and that were additionally collected from the Seekoei River to determine the water quality environmental water requirements (Seaman *et al*, 2010).

- The primary objective of Phase 3 of the project was to test the prototype methodology, specifically the water quality, and its links to the other components (hydrology, geohydrology, fish, invertebrates, socio-economics) of the river ecosystem, that was developed on different non-perennial systems.

It is important to note that some of the results already published by the WRC were used in the compilation of this thesis. However, only work that Rossouw herself wrote was used, except for the Seekoei and Mokolo Rivers information on the Phytoplankton and Periphytic/Benthic Diatoms, where Ms Vos wrote the text and Rossouw edited and incorporated the information into their water quality draft reports as it is part of the water quality methodology.

1.5 Thesis outline

The thesis consists of eleven chapters. The first chapter is the introduction and aim of the study. The second chapter is the literature review. This is a general overview on the characteristics of non-perennial rivers. The literature review also addresses differences between perennial and non-perennial rivers.

The third chapter covers legislation and policy on the ecological water requirements globally as well as locally.

In Chapter Four existing methodologies to determine the ecological water requiremenst are discussed and in Chapter Five the water quality component of the ecological Reserve is specifically addressed.

Chapter Six consists of the proposed methodology to be applied to the Seekoei River, an example of a non-perennial river. In Chapter Seven the proposed methodology is applied and data on the Seekoei River is presented as a means to better understand a non-perennial river.

Chapter Eight represents the proposed prototype methodology based on the Seekoei River experience.

Chapter Nine is the application of the proposed prototype methodology as applied to the Mokolo River. The conclusions and recommendations are presented in Chapter Ten and References in Chapter Eleven.

2. LITERATURE REVIEW

The first part of the literature study was a general overview on the differences between perennial and non-perennial rivers while the second part was focused on existing national and international methods used in determining the environmental water requirements (quality and quantity). There was a need firstly to get a better understanding of the functioning of non-perennial rivers and secondly to determine which methodologies were available to determine the Ecological Reserve internationally, as well as in South Africa. Once the methodologies were identified through a desktop study one could review and identify the most appropriate methods to be used in this study.

The words of Boulton *et al*, (2000) provide an essential basis for the discussion of the literature that follows: "*Ephemeral and intermittent streams exemplify the extreme of rivers with variable flow regimes, and are globally widespread. The formulation of policies and legislation for non-perennial systems must take into account that intermittent streams and rivers usually occur in regions where the competition for water is high and it is often the environmental needs of the system that are neglected. Regulation to meet demands means that the natural variability in flooding and drying is modified either by removing water from the system and increasing the frequency of drying or by rendering the system permanent for water supply, thus removing the all-important dry phase.*

The severe environmental degradation apparent in many rivers with variable flow regimes worldwide (e.g. the USA, Australia and Namibia) appears to have generated a new and more dynamic approach to managing these rivers. There is a growing recognition that successful management must be based on the natural flow regime, that the dry phase is as significant as flooding, and that this must be incorporated into policies for water resource management. Management of intermittent rivers must be proactive and the natural flow regime must be analysed to assess environmental flow requirements. Each flood must be considered on its own merit. Technology may allow for provision of individual floods but the limitations of planned water releases must be recognised. However, each release constitutes a "large-scale experiment" and, despite problems of replication and long-term effects, we should focus on using these events to aid adaptive management of intermittent river systems. On a policy side, this approach to water resource management must be incorporated into the license agreements of water users, and efforts should be made to educate stakeholders about the value of maintaining the variable flow regimes that underpin the ecology of these rivers."

2.1 Terminology

A large percentage of South Africa's rivers have intermittent or variable flow. Davies *et al* (1993) estimated that more than 44% of our total river length is naturally temporary. Even though there are many non-perennial river systems they are still poorly studied and understood because most research worldwide has been focusssed on perennial river systems (Williams 1988).

Various authors such as Matthews (1988) and Comin and Williams (1994) have attempted to make a distinction between ephemeral, temporary and intermittent streams according to the percentage annual flow, source of flow and periodicity of flow. Other descriptive terms such as non-perennial, seasonal and episodic further confuse the terminology.

As no functional classification for non-perennial rivers were available, Uys and O'Keeffe (1997) produced a descriptive terminology in an attempt to standardize the definitions of the different types of river regimes encountered in South Africa based only on surface water flow.

The aims of the Uys and O'Keeffe paper was "(1) to present a conceptual framework to illustrate the range of temporary river regimes in South Africa, and the influences on them, and, related to this, (2) to propose a systematic terminology for the description of temporary river regimes in the country."

Their terminology defined different river regimes according to the hydrological features of that specific river. They considered the duration and periodicity of flow and no-flow periods, the time of year at which flow recommenced, and the variability and unpredictability in flow regimes within and between five year periods. The proposed terminology could be applied to define the different flow regimes of different rivers in different parts of the country.

The following is a brief description of the Continuum Concept as described by Uys and O'Keeffe (1997).

The Continuum Concept

Conventional river classifications distinguished between different river types using geographical, geological, climatic, or biotic boundaries (Hart and Campbell 1994, cited in Uys and O'Keeffe, 1997). The conceptual framework developed by Uys and O'Keeffe, considered different hydrological flow regimes as the basis for differentiation (Uys and O'Keeffe, 1997).

A range of hydrological regimes from various rivers are represented in the continuum concept. Uys and O'Keeffe (1997) described the gradual change in the flow patterns between points, as marked by the space on the line between points, the fuzzy zone, to describe the transition in flow types between distinctly different hydrological regimes. The continuum concept is illustrated in Figure 1.

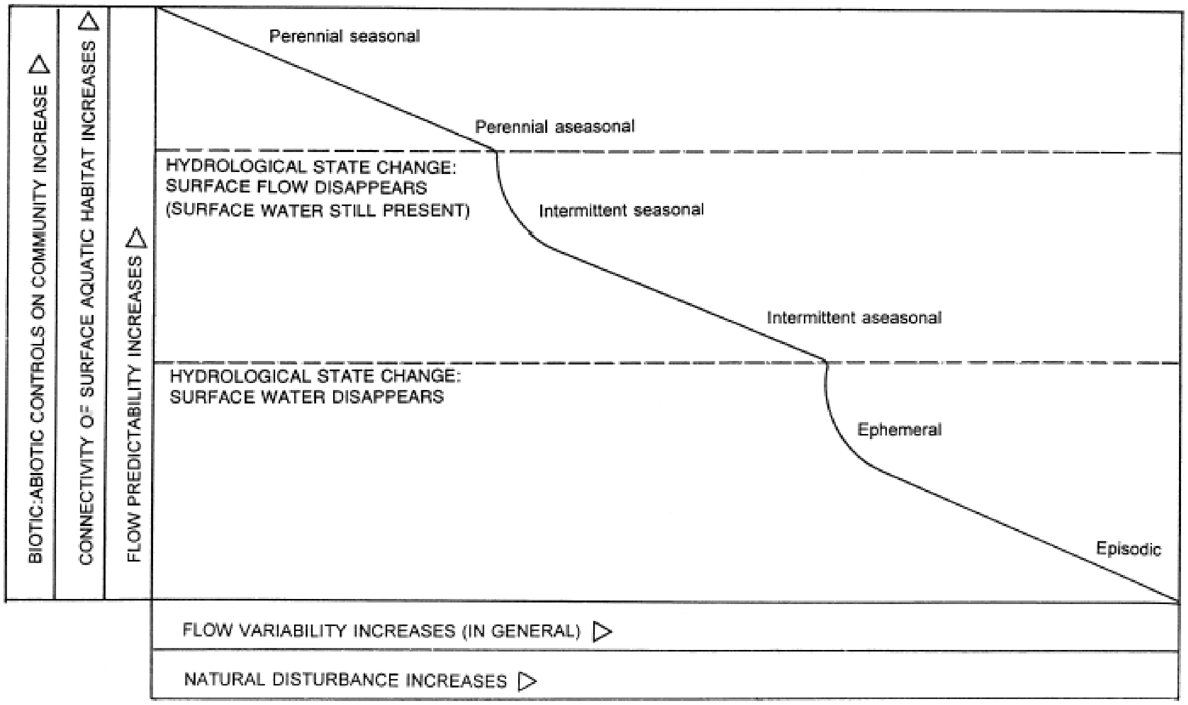


Figure 1: The continuum concept. Two hydrological state changes are shown: one in which surface flow disappears, but not all the surface water is gone), one in which ail the surface water disappears from the channel for long periods (from Uys and O'Keeffe, 1997).

Uys and O'Keeffe (1997) described the *x* and *y* axes of the continuum gradients in the following:

- Flow intermittency which is a general increase towards an episodic state.
- Flow predictability which is a general decrease towards an episodic state.

High variability in flow in non-perennial rivers indicates unpredictable periods of intermittent or flashy flows, whereas the high variability in flow in perennial streams indicates fluctuations in flow under continuous flow conditions. The termination of flow or the disappearance of surface water is very different from the effects of changes in flow volumes on the river ecology. Boulton (1989) comments that loss of water in temporary systems is "probably the most influential environmental parameter affecting the aquatic biota." The coefficient of variation of flows in South Africa range from 0.33 for generally predictable perennial rivers in the Western Cape to 2.58 for generally unpredictable temporary rivers of the northwest, (King *et al*, 1992, cited in Uys and O'Keeffe, 1997). The larger the coefficient of variation of flow, the more non-perennial the rivers will become.

- Community structures of a river ecosystem are formed by the biotic and abiotic components present in a river. As the physical condition or biological component change, so does the community (Peckarsky 1983 and Williams 1987, cited in Uys and O'Keeffe, 1997). Power *et al* (1988) and Poff and Ward (1989) suggested that all the components that influence the community structure influence each other should not be considered in isolation.

The focus points to consider when deciding where a river regime fits along the hydrological continuum are as follows.

1. Does the river stop flowing, and if so, when and for what period within a year (seasonally); how often (e.g. every year) and for what duration in a five year period? Once this information is available the intermittency, predictability, seasonality and variability of flow can be assessed.
2. To further refine the position of the river on the Continuum additional information is required. The duration of persistent surface flow determines the adaptations and resilience of the biota, as well as their resistance to changes.
3. The connectivity of the system must also be specified as this also relates to the biota in the river system. Connectivity describes the connectedness of the flow in surface water.

The main characteristics shared by temporary rivers are intermittency, variability, and unpredictability in flow. Perennial rivers have been classified, both globally and locally, on their seasonal flow patterns and their specific flow characteristics (e.g. Haines *et al,* 1988, Poff and Ward 1989, and Joubert and Hurly 1994, cited in Uys and O'Keeffe, 1997). Non-perennial rivers can also be classified on the basis of their flow regime but also on the extent of their flow variability and unpredictability which in turn is determined largely by the climatic zone through which the river flows.

Uys and O'Keeffe borrowed from the three river classification systems (Haines *et al,* 1988; Poff and Ward, 1989; and Joubert and Hurly, 1994) when they developed their terminology.

The river continuum concept illustrated in Figure 1 described temporary, intermittent, ephemeral and episodic rivers as well as any flow condition between these rivers (Uys and O'Keeffe, 1997). They defined the rivers as follows:

Temporary

Temporary rivers stop flowing and the surface water may disappear along parts of the river channel. This can occur on a yearly basis or in two or more years of a five year period.

Intermittent

An intermittent river may experience several cycles of flow, no flow, and drying in a single year. Intermittent rivers stop flowing and may dry up along parts of their lengths for a variable period. This can occur annually, or for two or more years within a five year period. These rivers can have seasonal flow or flow can be highly variably. Flow will depend on the climate and predictability of rainfall in the area (Uys and O'Keeffe, 1997).

Ephemeral

The river channel disappears for some/all of each year or some years in a five-year period. Ephemeral rivers are dry for longer periods than they have flow. There is flow or floods for short periods in most years. Flow is in response to unpredictable high rainfall events. Typically ephemeral rivers support a series of pools in parts of the river channel.

Episodic

Episodic rivers are highly flashy systems where flow or floods occur only in response to extreme rainfall events. These rivers may never flow in a five-year period, or may flow only once in, for example 25 years.

Uys and O'Keeffe (1997) proposed these definitions in an attempt to encourage consistency in the use of terms in order to improve communication between managers and researchers.

Another generally accepted classification scheme distinguishes four main categories of streams (Boulton *et al*, 2000):

- Ephemeral streams – flow briefly (<1 month) with irregular timing and usually only after unpredictable rain has fallen;
- Intermittent or temporary streams – flow for longer periods (>1 – 3 months), regularly have an annual dry period coinciding with prolonged dry weather;
- Semi-permanent streams – flow most of the year but cease flowing during dry weather (<3 months), drying to pools. During wetter years, flow may continue all year round;
- Permanent streams – perennial flow. May cease to flow during rare extreme droughts.

The latter is much simpler but not as descriptive as the Uys and O'Keeffe (1997) classification.

Other authors have suggested definitions for non-perennial streams:
Seely *et al* (2002) defines an ephemeral/non-perennial river “as one in which water flows sporadically and for short duration, following heavy rain in its catchment area”. Flow is for a short time period, it may flow for a matter of hours or even days, but seldom longer.

Jacobson (1997) defines an ephemeral river as “one in which measurable discharge occurs for less than 10% of the year”.

Climatic and environmental conditions as well as human activities, i.e. dams in catchments, can change a perennial river to a non-perennial river or vice versa over time

A characteristic of ephemeral rivers is that there is usually a significant volume of water stored beneath the river bed channel even if the surface of the river channel is dry for most of the year (Jacobson *et al,* 1995; Seely *et al*, 2002).

Boulton and Suter (1986) defined temporary rivers as rivers in which surface flow stops and may disappear for some period of most years. In arid and semi-arid zones temporary rivers are the dominant river systems.

A different scale than those previously used for river classification (Table 1) was developed and adopted during a workshop from 18 to 22 October 2004 in Bloemfontein at the Centre for Environmental Management for this study, supported by a map (Figure 2), which divided the country into areas of perenniality of rivers (Rossouw *et al*, 2005).

Table 1: Categories of perenniality adapted from Rossouw *et al* (2005) (Seaman *et al*, 2010)

River flow type	**Perennial**	**Non-perennial**		
		Semi-permanent	**Ephemeral**	**Episodic**
Degree of flow persistence	May cease flowing in extreme drought	No flow 1%-25 % of time	No flow 26%-75% of time	No flow at least 76% of time
		Flow for at least 3 months		Flow briefly only after flood
Seasonality	Seasonal or non-seasonal			
		Modder(F.State), Doring (W.Cape), Mogalakwena, Mokolo (Limpopo) flows 72 – 87% of time	Seekoei River (N. Cape) Touws (E Cape) flows 28% of time	Kuiseb (Namibia) Swartdoring and Kys Rivers (N. Cape) flows 12% of time

After extensive discussion, aided by interactive GIS technology, it was decided that the periodicity of inundation of quarters of the year was most appropriate, i.e. inundation for less than one quarter of the year on average was categorised as an episodic river, for more than three quarters of the year on average a semi-permanent river, and the category in between, namely between one quarter of the year and three quarters of the year on average, an ephemeral river. The map of the location of each, divides the country into four main areas, with the perennial rivers mostly in the southwest and east. It divides the rest of the country among the non-perennial rivers, namely the semi-permanent rivers in a narrow band to the interior of the perennial rivers, with their greatest concentration in the south-eastern midlands, the ephemeral rivers covering most of the central and northern areas, and the episodic rivers in the north-western arid areas of Namaqualand and the Kalahari (Rossouw *et al*, 2005).

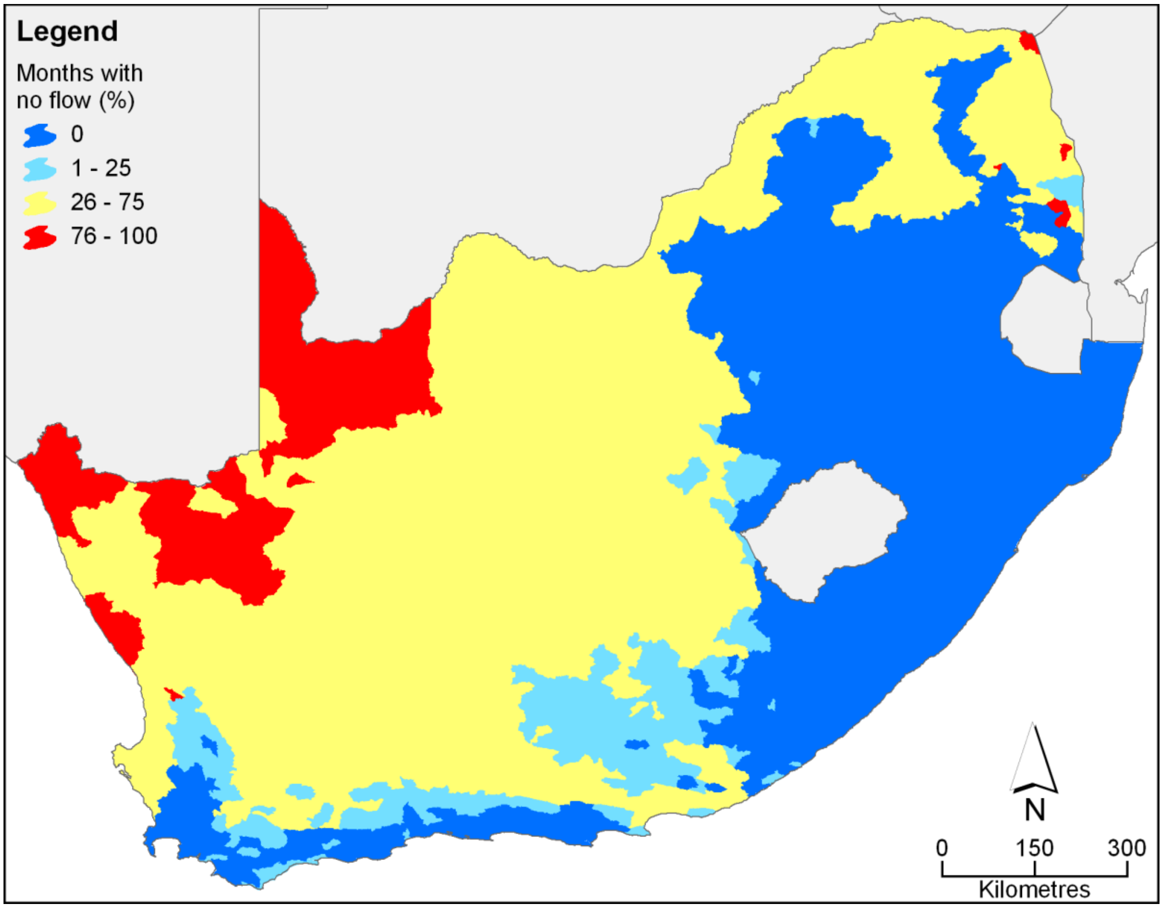


Figure 2: South African quaternary catchments categorized according to relative periods of low flow during each year (Rossouw *et al*, 2005)

2.2 Non-perennial river ecosystems

Non-perennial systems are characterised by high degrees of flow variability and natural disturbances, and low degrees of surface connectivity and flow predictability. This is mainly caused by the temporal and spatial variability in rainfall, the main hydrological variable in an arid climate, as well as high levels of evaporation. Anthropogenic modifications or man-made influences, such as farm dams and weirs, also exacerbate the natural spatial and temporal discontinuity of channel flow (Hughes, 2007).

2.2.1 Location of non-perennial/ephemeral rivers

Non-perennial rivers are located throughout the drylands (arid and semi-arid regions) of the world. These arid and semi-arid areas are found in places with high population densities over many countries, all trying to make a living (Turnbull, 2002). Twenty African countries have more than 90% of their productive agricultural lands in arid and semi-arid areas, making their crops even more susceptible to droughts and floods (Turnbull, 2002). Perennial rivers generally do not cross the drylands of the world, the Nile and Orange Rivers in Africa being two exceptions.

2.2.2 Geographical characteristics

Non-perennial/ephemeral rivers may be perennial in their upper reaches. Many ephemeral/non-perennial rivers are endorheic, (they do not flow into the sea), even in the event of severe flooding. An endorheic river may not have sufficient water in its upper courses, as the ephemeral rivers associated with the mountains of the Sahara for example. The Tsauchab River flowing into Sossus Vlei in Namibia is also endorheic, but it is because of sand dunes blocking its course. Other non-perennial/ephemeral rivers only flow into the sea during high flows (Seely *et al*, 2003).

Key factors determining non-perenniality of rivers are aridity and its associated variable rainfall. Very high rates of evaporation is typical in arid regions, i.e. in the western ephemeral catchments of Namibia, evaporation is more than six times greater than the mean annual rainfall (Jacobson *et al,* 1995). Consequences of high evaporation are a rapid loss of rainwater and runoff from the system. High evaporation losses from surface water such as springs and wetlands, can lead to saline soils, where only salt-tolerant species can survive. High evaporation rates and sediment buildup, also reduces the efficiency of dams in arid and semi-arid regions.

Another factor that is directly correlated to the ephemerality of rivers in drylands is drought. Drought is caused by the variability in rainfall in these arid environments. Droughts increase the pressure on the already limited surface and groundwater resources (Seely *et al*, 2003).

2.2.3 Hydrology of non-perennial/ephemeral rivers

Non-perennial rivers are generally characterised by the erratic occurrence of fully connected channel flow and the lack of base flow. They typically experience irregular flow pulses for a few months or less each year (Hamilton *et al*, 2005). Some non-perennial systems have permanent or semi-permanent pools maintained by either sub-surface input from the surrounding groundwater, sub-surface water movement within the channel itself, channel surface flows that are sufficiently frequent to maintain storage despite evaporation losses. Pools represent potential refugia for biota during no-flow periods and are ecologically very important (Hamilton *et al*, 2005; Sheldon *et al*, 2002).

A river system may not be non-perennial throughout the basin. Even if it is, the type and characteristics may vary within a single river basin depending upon the topographic, geological, vegetation and climate variations as well as land use and water use that occur within the system. It is therefore important to consider the basin as a whole. While this is an advisable approach in all systems, including perennial rivers, it may be more critical in non-perennial river basins (Hughes, 2007).

Knowledge of river ecosystem functioning is based on research on temperate perennial streams. River management and restoration methodologies and water policies and legislation are also based on knowledge of perennial rivers. However, to extrapolate knowledge from perennial rivers directly to intermittent and ephemeral streams can prove to be very inaccurate in simulation the true river conditions.

For example, extremes of flooding and drying (variable flows) largely structure stream assemblages and regulate ecosystem processes in most intermittent streams (Boulton *et al*, 2000). Flooding occurs in both perennial and non-perennial rivers but drying is rare for perennial rivers except during severe drought when the fauna is devastated by desiccation. Drying is more common in the intermittent stream and their biota reflects these conditions (Boulton *et al*, 2000).

Rivers and streams naturally vary in flow although the temporal scale must be specified when the term ”variable” is used. The highest variability in flow regimes usually occur in intermittent and ephemeral rivers, especially those in semi-arid and arid areas. Here, the coefficients of variation of annual flows are, on average, more than 400% greater than those from humid and temperate regions (Davies *et al*, 1994). The higher the hydrological variability the higher the habitat and food web complexity. There are little scientific data to support this hypothesis because data and information about the ecological functioning of the river is often lacking. Such data are a fundamental requirement for managing these types of rivers and to formulate sound management practices.

Historically, water management practices in arid and semi-arid zones have been driven by human demand for water. River regulation and interbasin water transfer are imposed most extensively upon rivers with highly variable flow regimes (including natural intermittency) to sustain human agriculture. The issue is made more complex by a Western human perception that a “healthy” river flows all year round; many of the more ambitious river regulation projects have had technological and intellectual input from experts living in well-watered regions (Boulton *et al*, 2000).

2.2.4 Geohydrology

One of the most important functions of floods in ephemeral rivers is groundwater recharge. Flood water travels down an ephemeral river with water infiltrating into the channel beds. The amount of recharge or infiltration depends on the intensity, volume and duration of a flood. Floods and the recharge of the alluvial aquifers provide a water source for plants, animals and people until the next rain event (Jacobson *et al,* 1995).

The permanent lowering of groundwater tables will have a detrimental effect on ephemeral systems, including the associated riparian vegetation (Seely *et al*, 2003).

Riparian vegetation is present and survives along ephemeral river channels because of the availability of groundwater. Floods, especially irregular, extreme floods, are also critical for aquifer recharge, the morphological reshaping of the channel and the age structure and spatial distribution of riparian trees (Friedman and Lee, 2002). The riparian vegetation is an important resources for people and animals, either wildlife or livestock. The use of groundwater for human consumption is in direct competition with the water needs of the riparian vegetation and should therefore be carefully managed.

2.2.5 Pools

Non-perennial rivers have highly variable flow regimes characterized by low to zero flow at times, and severe flooding at other times. Most non-perennial rivers have river reach stretches that are dry with occasional pools throughout the dry winter or summer months (Bunn *et al*, 2006a). Although the biota in a non-perennial river have adapted to these changing flow-no flow conditions, extreme flow-no flow conditions can wipe out entire groups of biota (Bernardo and Alves, 1999).

If river flow and water levels decrease, biota, such as fish, can migrate to more favourable flow and water level conditions in pools. The pools that retain water become refugia for fish and other biota. The conditions in the pools change and determine the survival of the biota occupying the pools, until recharge and reconnection occur during the following rain period. As soon as connectivity is established between the pools the surviving biota recolonise the river system (Bernardo and Alves, 1999).

One of the most critical hydrological issues that has the potential to impact on the ecological functioning of ephemeral systems is the dynamics of pool storage (Hughes, 2007).
The sustainability of a pool is dependant on a number of factors (Van Tonder *et al*, 2007):

- The pool size;
- The amount of groundwater flowing into the pool (from the channel aquifer below/or upstream of the pool below the water table and the groundwater flux towards the pool from the aquifer adjacent to the pool); and
- Interflow (usually this type of flow is linked to the existence of a perched aquifer, but it could also be intermittent flow along fractures in the unsatutated zone as well as flow on impermeable layer of rock). This type of flow often creates interflow springs.
- Different processes can also feed adjacent pools in the same reach. This is especially the case in areas that are dominated by interflow processes in fractured unsaturated zones and where the density of fractures can be highly variable and dependent upon local geological structure (Hughes, 2007).

The amount of groundwater flow into a pool is a function of the geology, geomorphology, surface slope, slope of the groundwater level of the channel aquifer and the formation aquifer. Geohydrological parameters (transmissivity, storativity, thickness of the aquifer) and the vegetation adjacent to the pool also determine the amount of groundwater that reaches the pool (Van Tonder *et al*, 2007).

Water losses from a pool may be due to the following (Van Tonder *et al*, 2007):

- direct evaporation from the pool surface and evapotranspiration from aquatic plants,
- seepage into the banks to replenish soil moisture lost through riparian vegetation evapotranspiration,
- pools can also recharge groundwater systems,
- movement of water from the pool to the banks/aquifer, adjacent to the pool,
- overflow from the pool (surface flow), and
- pumping water directly from the pools for human use or livestock watering.

The combination of various processes will determine the amount of water stored in pools, their depth and aerial extent, as well as their water quality dynamics (temperature, total dissolved salts, turbidity and nutrients). Both the water quantity and quality are important for the ecological functioning of these pools. These processes will also determine the frequency with which pools are connected within a specific river reach by flowing water and therefore the opportunity for organisms to recolonise parts of the channel system and maintain certain pools as important refugia.

Pool morphology and evaporative loss are the two major components that determine the permanence of pools and the potential to become refugia. The spatial distribution of pools and potential refugia for the aquatic biota is not only determined by the physical template but also by the duration of dry periods and the timing of flow or rainfall events as some pools can persist for a prolonged period without any surface flow connection (Bunn *et al*, 2006a). therefore be carefully managed.

2.2.6 Surface-groundwater interaction

Surface-groundwater interaction is an integral part of the water cycle and is even more important in the non-perennial rivers as opposed to the perennial rivers. Although the focus of this review was on surface water quality, the importance of the influence of the surface-groundwater interaction in determining the surface water quality cannot be ignored.

"*The recognition of the unity of the water cycle as a common resource, the call for Integrated Water Resource Management in the National Water Act (1998) and, most importantly, the increasing impact of legal or illegal groundwater abstractions in the vicinity of rivers on its stream flow (baseflow depletion and induced recharge) all call for a better conceptual understanding and quantitative description of interactions between groundwater and surface water in South Africa*." (Dennis and Witthueser, 2007). These interactions are addressed in the South African Water

Resources Yield Model (WRYM) and the information from this model is used to license groundwater abstraction.

The confidence in the calculations in the WRYM needed to be improved and Dennis and Witthueser completed a literature review to investigate the development of a classification system for South African Rivers that was based on and could describe surface-groundwater interaction (Dennis and Witthueser, 2007).

A number of existing classification schemes were investigated.

- Vegter and Pitman (2003) proposed a classification system for South African Rivers based on the prevailing hydraulic gradient between the aquifer and the stream and the occurrence of a clogging layer (impervious material). The classification scheme addressed important hydraulic features to characterise surface-groundwater interaction, but it falls short on any hydrogeological description of the aquifers.
  They described the hydraulic features as follows:
  1. Piezometric surface were at all times below streambed level (ephemeral streams)
     a. Pervious material between streambed and piezometric surface: Influent stream (for example the lower sections of Kuruman River, Molopo River, Phepane, Kgokgole and other streams in Kuruman and Molopo catchments).
     b. Impervious material between streambed and piezometric surface: Detached stream (steep and rocky streambeds mostly in arid north-western parts of SA).
  2. Piezometric surface slopes towards the stream
     a. Groundwater emerges and reaches the stream at all times, material between piezometric surface and streambed is pervious: Effluent and perennial streams (for example the upper reaches of rivers on the eastern escarpment like the Vaal, Olifants, Tugela, Blyde, Komati Rivers).
     b. Groundwater emerges into the stream at intervals after recharge episodes: Intermittent streams such as streams in the Karoo like Salt River (upper reaches), Kamdeboo, Sundays and Brak Rivers.
     c. Groundwater does not reach the stream due to evapotranspiration: Famished streams as found in the rocky sections of the Limpopo River.
  3. The piezometric level fluctuates alternately above and below stream stage. Stream typically underlain and bordered by alluvial deposits or weathered hard rock, only the interaction between alluvium and stream considered of importance. Alternate in- and effluent conditions (for example stretches of alluvium along the Limpopo River and the Crocodile River near Thabazimbi).

- The Environment Agency (2002) proposed a classification that neglects the prevailing hydraulic gradients and focuses only on the hydraulic characteristics of the aquifer (diffusivity), its spatial extent (regional and/or valley train aquifer) as well as the occurrence of clogging layers.
- An alternative classification scheme was proposed by Rowntree and Wadeson (1998). They proposed a hierarchical geomorphological classification model. They stressed the complexity of river classification due to the heterogeneity of river systems in space and time and proposed that their model be used as a first stage of a classification, which can be applied at different scales.
- Heritage *et al* (2001) proposed a morphological classification for the Sabie River where they identified a continuum of channel types spanning from bedrock-dominated to alluvial dominated channels, with several subdivisions.
- Both geomorphologic classification schemes did not address the surface-groundwater interaction, but the described geomorphologic features like bedrock versus alluvial-influenced channel have a strong influence on surface-groundwater interaction.
- Xu *et al* (2002) based their classification scheme on hydrogeomorphological characterisation (upper catchment areas, middle courses, lower courses and special cases). They used a hydrogeomorphological approach to quantify groundwater discharge to streams in South Africa using groundwater discharge separation from hydrographs. They conceptualised four different types of surface-groundwater interaction (constant losing/gaining streams, intermittent streams, gaining streams with/without storage and interflow dominated streams). Their approach related to the broad geomorphologic types to typical groundwater-surface water interactions (including interflow) but gives no further classification.

Any classification scheme must balance between what is scientifically desirable and what is practically workable. Based on the literature review of surface-groundwater interaction methodologies the following characteristics of rivers emerged as most important for the application of mathematical models (Dennis and Witthueser, 2007):

- Gradient between piezometric surface and river stage (either side).
- Occurrence and characterisation of clogging layers in the riverbed
- Hydrogeological characteristics of the strata along the river stretches
- Regional groundwater gradients.

A simple two tier classification scheme, with a geological classification of the river-aquifer setting followed by a brief hydraulic classification of the interaction is proposed. The approach combines and extends the hydraulic classification by Vegter and Pitman (2003) with geological features similar to the method of the Environment Agency (2002). However, in view of data limitations no classification of the aquifer diffusivity was proposed.

The proposed classification scheme for rivers is scale dependent, but should be applied on the largest scale possible. The two tiered approach allows classifying homogeneous stretches of rivers based on their geological setting before a subdivision based on the prevailing gradients might become necessary. Furthermore the geological classification requires no information of groundwater levels and can be performed by a reconnaissance site visit of a hydrogeologist. Though remote sensing methods can be applied to differentiate rivers flowing in porous media or on bedrocks and sometimes even localised interactions, they will not be able to identify semi-or impervious layers in the river bed. Without any further information available the geological classification alone already narrows down the potential models for the description of surface-groundwater interaction (Dennis and Witthueser, 2007).

The proposed hydraulic classification requires site-specific knowledge of the prevailing gradient and will quite often rely on expert knowledge rather than available data due to the unavailability of boreholes in the vicinity of the river to assess the prevailing gradients. It should therefore be done by an experienced hydrogeologist familiar with the area. Guidance on manifestations and quantification of surface-groundwater interactions can be found in the Groundwater Resource Directed Measures software respectively training manual DWAF (2004a), Parsons (2004), Vegter and Pitman (2003), Xu et al. (2002), Sophocleous (2002) or Winter (1999) (cited in Dennis and Witthueser, 2007).

2.2.7 Environmental characteristics

Non-perennial/ephemeral rivers have always been very important to people and wildlife living in the vicinity of the river, i.e. in Namibia the non-perennial rivers provide linear oases/riparian corridors where people and wildlife can survive in an otherwise arid region (Jacobson *et al*, 1995). In Namibia, ephemeral rivers that flow toward the north and east start in and flow through regions of relatively high rainfall (300-600 mm) per year. Because of the overall higher rainfall, the appearance of the vegetation that lines these river courses are not very different from the surrounding savannas, with both containing many trees and shrubs. In contrast, rivers that flow south toward the Orange River or west toward the coast originate in areas of higher rainfall but flow through very arid areas of 100 mm rainfall or less per year. These rivers and their catchments also provide water for agriculture, tourism and mining as well as for the major urban centres of Windhoek, Walvis Bay and Swakopmund. For Namibia, the westward flowing ephemeral rivers are of significance, not only to people living in the area but to the nation as a whole. This disproportional importance of ephemeral rivers, for people, livestock and wildlife, is not unique to Namibia but is similar to the situation found in other drylands of the world (Seely *et al*, 2003).

Non-perennial/ephemeral rivers not only provide an important water resource to an arid area but is crucial for any vegetation and animals to survive in the region. The vegetation is partly dependent on and influenced by soil characteristics that are affected by the hydrologic flow patterns of ephemeral river flow (Jacobson *et al*, 1995). Silt deposition influences patterns of plant colonization and creating habitats for various organisms. The structure, productivity and spatial distribution of biotic (plant and animal) communities are strongly affected by flow patterns in ephemeral river ecosystems. Altering flow in non-perennial rivers negatively affects the already fragile ecological balance and reduces overall productivity (Jacobson *et al*, 1995).

Flooding is a critical element in the structure and maintenance of ephemeral river ecosystems. Peter Jacobson describes a flood in the Kuiseb River in western Namibia: "*The leading edge of the flood was nearly a meter high and looked more like lava than water as it rolled rapidly down the channel. The water was loaded with sediments and organic material, including seeds, sticks, logs, grasses and animals of various shapes and sizes. The water itself contained high amounts of nutrients and dissolved organic carbon. All of this material was carried downstream and deposited within the desert reach of the Kuiseb River.*" (Jacobson *et al*, 1995).

Floods in ephemeral rivers are usually produced by heavy rainfall events over a short period of time resulting in huge amounts of surface runoff (Jacobson *et al*, 1995). The rate and amount of surface water flow is dependent on the amount and pattern of rainfall in the catchment, and where the flow is measured. Discharge in ephemeral rivers increases, until the combined effect of evaporation and infiltration of rain causes a decrease in water level. Infiltration is the main factor limiting the longitudinal flow of a rainfall event (Jacobson *et al*, 1995). Discharge in ephemeral rivers is highly variable and may be described as a flash flood, a single peak flood or a multiple peak flood. These differences are caused by different rainfall patterns in the catchments. The large variations in floods, coupled with limited data records of past floods, make it difficult to understand and manage ephemeral rivers.

2.2.8 Water quality of non-perennial rivers

Water quality and the appropriate management of the water quality cannot be viewed in isolation, but with a sound understanding of the amount or quantity of water that is available in a catchment as many water quality problems are created because of not sufficient supplies of fresh water (DWAF, 2003b).

The understanding of the flow characteristics of a river it is essential for the analysis and interpretation of its water quality characteristics. The flow regime, and also the water quality of a river, is also related to the characteristics of its catchment through which the river flows, especially the geological, geographical, land use and climatological influences.

The levels of Dissolved Oxygen (DO) in non-impacted running waters are usually close to saturation and thus increases in discharge have little effect. If discharge is reduced sufficiently, due either to natural or anthropogenic causes, pools of standing water may develop. DO levels in such pools may reach critically low levels, particularly during summer months when water temperatures are high (Malan and Day, 2002).

Where shallow pools remain in a channel, diffusion of oxygen from the atmosphere is usually sufficient to maintain concentrations of oxygen above stress levels in temporary water bodies.

Declines in or depletion of dissolved oxygen may have a deleterious or lethal effect on the fauna, and are generally a result of:

- increases in either temperature or salinity (due to lack of flow and evaporation in pools);
- decomposition of benthic organic matter (e.g. leaves, algae, macrophytes);
- algal respiration, which can cause oxygen depletion at night;
- inputs of eutrophic effluents or deoxygenated water from the bottom of a dam.

Increases in dissolved oxygen may result from dense algal growth, which causes surges in oxygen saturation during the day, but oxygen depletion at night, often reaching the lowest oxygen level just before dawn.

When flow resumes in a dry river, a “pulse” of largely unprocessed plant litter is carried downstream, and decomposition of this litter may reduce or deplete oxygen in the water-column.

Runoff washes sediment into the river and resuspends already deposited sediment, increasing the concentration of suspended solids in the water-column. Once the flow decreases, some suspended solids settle out at a rate that depends on the particle size and the hydrodynamics of the river. All the rivers in South Africa, except some in the Natal foothills of the Drakensberg and in the south-western Cape, become highly turbid as a result of the suspended solids, especially during the rainy season (Dallas and Day, 2004). Rivers and streams are normally more turbid than still waters, and many are always markedly turbid such as the Orange River.

The Total Suspended Solids (TSS) concentration is a measure of the amount of material suspended in water. Many of South African reservoirs are highly turbidity because of suspended silt (Dallas and Day, 2004). Wofsy (1983) concluded that suspended sediment concentration above about 50 mg/ℓ prevents significant algal blooms in all but the shallowest streams.

Under low- or zero-flow conditions, slow or zero current, favourable underwater light conditions and (possibly) high water temperatures are conducive to the production of dense mats of filamentous algae, particularly in exposed areas. These mats provide a food source and cover, both of which may be vital for final instar insects attempting to emerge before water temperature drops or conditions become unsatisfactory.

During a pools or dry-channel phase in a temporary river, large amounts of detritus are likely to accumulate in the channel and pools. With time and decomposition of plant matter, nutrient levels are raised. Most nutrients (except ammonia ions) are not toxic to animal life and the major effect of increased nutrient levels is proliferation of fast-growing plants (e.g. algae, waterweeds) and animals, both of which may become pests, alter community structure, and/or cause water quality problems.

Algal growth results in high diurnal dissolved oxygen levels in pools, and significant decreases in oxygen saturation at night. With increased levels of photosynthesis, changes in pH can be dramatic. This may affect the transport of materials across animal membranes.

Deeper pools may also exhibit thermal stratification, whereby distinct layers are formed between the warm surface water in contact with the atmosphere and the cold bottom water. Very little mixing occurs between the water strata and once oxygen is depleted in the lower water column, as a result of respiration by biota, decomposition of organic matter or due to chemical reactions, it is not replenished. Such anoxic conditions can persist until stratification is overturned by mixing of the water layers once again at the end of summer, by wind action, or by the onset of a storm event (Malan and Day, 2002).

Sudden, extreme changes in water temperature may cause conditions that some organisms cannot survive. Water temperature increases, decreases oxygen solubility and may also increase the toxicity of certain chemicals, both which will increased the stress levels of temperature or oxygen sensitive biota. Stream temperatures may increase by 10 to 20 °C as a result of irrigation practices and the return of agricultural drainage (Dallas and Day, 2004).

Water samples for chemical analysis are usually taken only when the river is flowing. Thus, the impact of periods of flow cessation, or of times when the flow regime changes from perennial to seasonal, are usually not recorded. This is an important limitation, since these are the times when water quality changes may be most severe (King *et al*, 2000). During long dry periods however, groundwater accounts for almost all the flow in stream (Malan and Day, 2002). Monitoring of rivers should be planned to include episodic events as seasonally-variable stream flows can cease for large parts of the year. Seasonal rainfall events are also important to monitor as they often produce 'first-flush' loads of nutrients, salts and sediment that can cause rapid changes in concentrations that may not be captured with routine monitoring programs (ANZECC, 2000).

If discharge in a river is reduced, instream concentrations of water quality variables as well as values of physical variables will change. Reductions in surface water volumes, and high evaporation usually result in increased salinity in temporary rivers. The trends of discharge on water quality have been summarised by Malan and Day (2002) and was therefore only considered briefly. Most of the following was extracted from the above document. Responses of stream chemistry to discharge can be extremely complex and site-specific. Thus, predictions of stream chemistry in response to changes in discharge should be made with caution and require verification with field data.

The general effect of an increase in discharge on the concentration of water quality constituents in rivers (modified from Malan and Day, 2002) are summarized below.

Summary of discharge-concentration trends (Malan and Day, 2002):

- Suspended sediments (SS) generally increase with discharge but the rate of increase may level off at high discharges as the substratum becomes limiting. Storms occurring early during the wet season are likely to carry heavier loads of sediments and organic materials compared to storms later on in the season. This is due to limitation in the supply of this material.
- Dissolved minerals derived from the underlying substratum are likely to decrease as discharge increases due to dilution by rainfall and surface run-off containing low solute loads.
- Due to the high degree of mobility in the soil, nitrate is likely to increase during storm events, or during the initial part of the rainy season. Depending on the nutrient status of the soils of the surrounding catchment and the land use activities, such a flushing effect

may be sustained in urban areas, or in regions of intense agricultural activity. In nutrient-poor soils, the flushing effect may be short-lived and followed by rapid assimilation of nitrates by aquatic organisms.

- pH is likely to decrease during storm events, especially in the South Western Cape. This variable is likely to decrease in Cape rivers in autumn but an increase during high flow events is also to be expected in other parts of South Africa although the effect may not be so pronounced.
- Particulate phosphate is likely to increase during spates due to enhanced sediment loads. In the absence of points sources of pollutants, dissolved phosphate (ortho-phosphate) is likely to decrease or remain constant in nutrient poor areas in response to increased discharge. In urban areas, or regions of intense farming activity, however, this trend may well be reversed due to wash-off effects of pollutants or phosphate fertilisers. Dissolved phosphate levels may increase during low flow periods as the proportion of effluent to river water increases.
- The resultant effect of discharge increases on Total Dissolved Salts (TDS) is difficult to predict, reflecting as it does the sum of effects on pH, nitrates, phosphates as well as other chemical constituents. Due to the high rate of evaporation in SA, in non-impacted catchments, TDS is likely to be at a maximum during periods of low flow, and at a minimum during high flow. However, in urban, or polluted, areas, or where surface wash-off of ions is likely to be substantial, such a response may be obscured.

2.2.9 Comparing perennial and intermittent streams

It is useful to address the differences in physical, chemical and biological features between perennial and intermittent streams. Many of the ecological features that typify a stream with a variable flow regime are not predictable by some of the conventional, deterministic models of river ecosystems and require modifications (Boulton *et al*, 2000).

Amplitudes in physical and chemical conditions in ephemeral rivers, particularly in drying pools, far exceed those in permanent streams. As rivers dry, conductivity tends to rise through evaporation. Water temperature also rises (>30°C) and dissolved oxygen saturation falls. In some receding pools, leaf leachate (formed during the decomposition of the leaves) concentration increases and pH may fall to as low as 4,5, further exacerbating conditions for the aquatic biota. These range from intensifying competitive interactions for space and moisture to heavy predation by terrestrial and aquatic invertebrates and vertebrates (Boulton *et al*, 2000).

The numbers of species of water plants, invertebrates and fish are generally lower in intermittent streams compared with nearby permanent streams of the same size and geomorphology. For water plants that are usually submerged or floating, periodic drying poses a serious limitation unless they can produce desiccation-resistant propagules.

Invertebrates that either lack desiccation-tolerant stages or are poor recolonists will be eliminated from intermittent streams when they run dry. Permanent streams will contain both species that are opportunistic and found in nearby intermittent streams as well as long-lived aquatic stages (> 1 year) and limited powers of dispersal. Similarly, most species of riverine fish cannot tolerate drying or the harsh physical and chemical conditions in receding pools, and are restricted to permanent streams. However, some can use intermittent channels for spawning.

The relative magnitude of ecosystem components may differ between intermittent and permanent streams. Subsurface flow in the hyporheic zone of many gravel and sand-bed intermittent streams represent a large proportion of the total discharge, especially when comparing that to the surface flow of perennial rivers. Exchanges of water between the surface and subsurface zones influence ecosystem processes such as algal productivity, respiration, and nutrient cycling. Drying may sever these hydrological linkages, changing a range of ecosystem processes. The usual balance between upwelling (movement of hyporheic water to the surface) and downwelling (surface water infiltrating into the hyporheic zone) tips almost completely towards the latter flux during drying. Microbial respiration continues while sediments remain moist or saturated, consuming available carbon and oxygen, and potentially shifting hyporheic metabolism towards anaerobic processes. This has profound effects on nitrogen transformations, phosphorus availability, and the potential for the hyporheic zone to serve as a refuge for surface dwelling organisms (Boulton *et al*, 2000).

2.2.10 The ecological significance of high flow variability

It may appear that variable flows and intermittency have largely negative effects, adversely affecting water quality during the drying phase and limiting the diversity of water plants, invertebrates and fish. Yet, the significance of the comparison is not that “permanent” is better, but that river systems with high variable flow regimes are different and call for a different approach to their management. Efforts to reduce this flow variability in order to increase biodiversity or to “restore” the river system to one that better fits a Western perception of a “healthy” river may not be the best ecological option (Boulton *et al*, 2000).

Drought is part of the natural cycle experienced by the biota that live in arid and semi-arid regions. Natural low-flow and dry periods are as important for maintaining biodiversity and healthy rivers as natural high flows and floods in other types of rivers. Evolution has created biota that can survive drought conditions and have the resilience to recover after these drought conditions to create healthy aquatic ecosystems in non-perennial rivers (Jones, 2003).

Ecologically, physically and chemically, flow variability determines ecosystem processes and that can lead to habitat patchiness and increased biodiversity (Boulton *et al*, 2000).

2.2.11 Removing variability – impacts of regulation

One of the main aims of human induced flow regulation is to provide a reliable and constant water supply. By definition, this entails preventing intermittency or artificially creating reliable and constant flow downstream of a dam. Water must be harnessed during high flows and released during dry weather, meaning that most flood peaks are dampened or removed completely.

Regulation in arid and semi-arid areas often involves interbasin transfers, thus water storage, and groundwater abstraction. These practices can alter groundwater recharge patterns, leading to the cessation of permanent flow in some areas. Pressure to regulate river flow is greatest in arid and semi-arid areas where human populations are increasing, and the limiting resource is water.

A compromise is sought between maintenance of intermittency as an extreme of the allocation of environmental flows to mimic a natural regime and the demands placed by a thirsty human population enjoying the benefits of irrigation.

The perception that a flowing river is better than a dry one results in water quality standards being relaxed because of the belief that it is better to have sustained, albeit low quality, water than predominantly dry channels. The Selati River (flowing into Kruger National Park) is an example where effluent comprises the main (only) flow during the dry season.

The logic of effluent release is based on two assumptions:

- That ephemeral streams do not support viable aquatic communities, and
- The effluent dependent systems provide “net ecological benefits” such as habitat restoration and increased species diversity by maintaining permanent flow.

There are problems with this logic. In some regions, temporary streams and rivers have quite diverse assemblages and considerable faunal overlap with adjacent perennial sites. Alternatively, temporary streams may support biota that are "temporary stream specialists" or that use these sites for special purposes such as spawning. Further, the poorly diluted or undiluted effluent inevitably has deleterious effects upon the biota of these systems and in the downstream receiving waters, regardless of the tolerance of the organisms to intermittency.

2.2.12 Mismatch between accepted water quality criteria and natural conditions in non-perennial rivers

Historically, water quality criteria have been based on chemical and physical characteristics but increasingly, the use of biological variables is becoming popular because of the perceived advantages of biomonitoring. Furthermore, there is increasing recognition of the potential value of ecosystem measures as indicators of the "health" of a system. However, at certain stages of the flow regime, water quality of intermittent streams naturally deteriorates and the diversity of intolerant biota declines. Unless this is understood, uncritical application to intermittent rivers of water quality criteria and biological indicator species used for assessing the health of permanent rivers will prove misleading.

2.2.13 Environmental flow allocations for non-perennial rivers

Environmental flow allocations are becoming accepted as a valid approach to returning water to over-allocated systems but attention must be paid to the quality (more information on water quality is presented in Chapter 5) as well as quantity of water. Unfortunately, in South Africa there are few scientists experienced in the ecology of non-perennial rivers and their advice may reflect their experience with permanent rivers, potentially with disastrous results.

Specialist knowledge is needed by scientists and river managers to address non-perennial rivers (Boulton *et al*, 2000):

- The importance of the no flow or dry phase (of variable duration and timing) to intermittent rivers;
- The importance of irregularity, gauging the variability on the pre-regulated flow regime (if such data are available and adequate);
- The necessity to assess the first two policies based on the flow regime, not the hydrograph because of the intermittent and variable flow;
- The need for integrated flow management that does not allocate flows based on a few, readily identified water users (e.g. fish, waterbirds) but takes the whole system into account;
- The relationship between water quality and quantity, recognising that cues to the biota may rely on subtle changes in water temperature, etc. and that the water of "artificial

floods" may differ from natural flood-water in important ecological characteristics (e.g. sediment; particulate organics);

- Maintenance of variability of flows to promote and maintain diversity of habitat types over large time (over years) and spatial scales;
- Scientists must recognise that the public perceives intermittency as a "problem", and must structure educational programmes to address this issue.

3. LEGISLATION AND POLICY

Globally, also in South Africa, the historical emphasis of water management strategies has been characterised by maximum development and exploitation of the available resource, largely for the benefit of formal agriculture, industry, mining and other consumers.

Limited water resources and the need for economic growth, in addition to worldwide changes in attitude towards social, institutional and environmental issues, have resulted in a global and local shift in policy regarding the sustainable use of natural resources. This has led to the transformation of legislation dealing with their management.

3.1 Global Initiative

The *Rio Declaration* on *Environment and Development, Agenda 21* and the *Statement of Principles for the Sustainable Management of Forests* were adopted by more than 178 governments at the United Nations Conference on Environment and Development (UNCED) held in Rio de Janeiro, Brazil in 1992. The Rio Declaration proposes a comprehensive plan of action to protect the environment from impacts associated with human activities (DWAF, 2003a).

3.2 National Initiative on Water Resources

A White Paper on a National Water Policy for South Africa (April 1997) was written, and was based on the Water Law Principles as accepted by the South African Cabinet in November 1996. The principle objectives of the National Water Policy (and hence the National Water Act of 1998) are “to achieve equity of access to, and sustainable use of water” (DWAF, 2003a).

In the National Water Policy, the Government is the public trustee of South Africa’s water resources and is commited to carry out its obligations in a way which:

- “guarantees access to sufficient water for basic domestic needs;
- makes sure that the requirements of the environment are met;
- takes into account the interconnected nature of the water cycle – a process on which the sustainability and renewability of the resource depends;
- makes provision for the transfer of water between catchments;
- respects South Africa’s obligations to its neighbours, and
- fulfils its commitment as custodian of the nation’s water.”

The ideals outlined in the Policy were translated into the NWA (Act 36 of 1998). The promulgation of the 1998 National Water Act formalised South Africa's changed approach to the management and utilisation of water resources in South Africa (DWAF, 2003a).

The NWA is based on the principles of Integrated Water Resources Management within the South African context. Access to and use of water were severely limited in the past and special provision had to be made to rectify these imbalances.

The NWA does away with previous concepts and establishes new principles with far reaching effects:

- There is no distinction between public water, private water, normal flow and surplus flow. All water now has the same status.
- The Minister of Water Affairs and Forestry is the public trustee of all the water resources. The Minister has the duty to "*ensure that the water is protected, used, developed, conserved, managed and controlled in a sustainable and equitable manner for the benefit of all persons*" (NWA, 1998).
- The functioning of the water cycle is recognised.
- There are only two rights to water, that for basic human needs and for the water ecology. All other water uses must be authorised and licenced.

IWRM can be viewed as a systematic process for the sustainable development, allocation and monitoring of water resource use within specific social, economic and environmental objectives (Wentzel, 2008).

As specified in Chapter 2 of the NWA the Minister of Water Affairs and Forestry is required to develop a National Water Resource Strategy (NWRS) to plan for the management of the water resources. The NWRS provides the framework for the management of all the water resources for the country as a whole.

Some of the protective measures that are part of the management of the water resources are designated Resource Directed Measures because they are measures designed to be applied to the water resource at catchment level (DWAF, 2003a).

The named Resource Directed Measures are:

- The establishment of the Reserve;
- The classification of the water resource, and

- The setting of Resource Quality Objectives (RQOs).

Subjecting water resources to control in order to be able to manage them sustainably means that the use of water should be administered through the registration and licensing of water uses. Licences for use of a water resource can only be issued once the Reserve has been set.

Other protective measures are designated Source-Directed Controls, because they are intended to control, inter alia, the abstraction of water and the disposal of effluents.

3.3 The Reserve

The Reserve is defined as:

"*The quantity and quality of water required to satisfy the basic human needs, and to protect aquatic ecosystems, in order to secure ecologically sustainable development and use of the relevant water resource*." *(NWA, Act No 36, 1998, Chapter 3, Part 3).*

The Reserve is made up from two distinct parts, namely the basic human needs reserve and the Ecological Reserve. All the essential water requirements including drinking water, water for food preparation, and for personal hygiene should be provided by the basic human needs reserve. Currently this amount is calculated as a minimum of 25 litres per person per day, and is easy to determine (DWAF, 2003a).

The Ecological Reserve describes the quantity, quality and flow variability required to protect and maintain the aquatic ecosystems of the water resource on a sustainable basis.

Compared to the basic human needs reserve the Ecological Reserve is more difficult to determine due to the complexity of the ecosystems and processes involved within the catchment. Detailed studies are required to assess the current status of the resource, and the desired environmental objectives of the resource for the future.

The Ecological Reserve is not intended to protect the aquatic ecosystem at the expense of all development, but to ensure that water resources are afforded a level of protection that will support a sustainable level of development for the future.

The volume and temporal distribution of water needed as the Ecological Reserve will differ from system to system, depending on its sensitivity and ecological importance, and on the priorities for water use within each catchment, i.e human use has higher priority.

The Resource Directed Measures (RDM) Directorate within DWA is tasked with determining the Ecological Reserve for every major water course in the country by:

- classifying each water resource to a Management Class;
- allocating an environmental water allocation appropriate for that Management Class and ecosystem;
- setting Resource Quality Objectives (RQOs) for the water course (i.e. the objectives to be measured in a monitoring programme).

The Resource Quality Objectives refer to the quality of all the aspects of a water resource including:

- the quantity, pattern, timing, water level, and assurance of instream flow;
- the water quality, including the physical, chemical, and the biological characteristics of the water;
- the character and condition of the instream and riparian habitat, and
- the characteristics, condition and distribution of the aquatic and riparian biota

The RQOs are numerical and narrative descriptors of conditions that need to be met in order to achieve the required management scenario.

3.4 The Classification System

One of the major challenges of RDM is to assess, as accurately as possible, how much exploitation a natural water resource can withstand before its ability to ensure sustainable use is reduced.

The classification and RQOs are the means by which RDM seeks to achieve the delicate balance between protection and development. Together they provide the tools to assess the current status, and plan for the desired future condition of the water resources. They are a way of balancing the use and the protection of a water resource.

The Minister is obliged to develop a system that will provide suitable guidelines and procedures to determine the different classes of water resources, and to determine the Reserve.

Until a system for determining different classes of water resources has been prescribed by the Minister (Section12), all resource classes and Reserve determinations are preliminary determinations that can change as more and better information becomes available. These preliminary determinations at least allow the interim implementation of the NWA while at the same time the necessary systems and methodologies are being developed and finalised.

In South Africa, DWAF sets objectives according to different ecological management targets for the Reserve. There are four target classes, A to D (see Table 2). Two additional classes, E (Seriously modified; the Reserve has been seriously decreased and depletion regularly exceeds the amount of water required to maintain ecosystem functioning; the loss of natural habitat, biota and basic ecosystem functions is extensive) and F (Critically modified; the Reserve has been critically decreased and there is never enough water to maintain ecosystem functioning; modifications have reached a critical level and the resource has been modified completely with an almost total loss of natural habitat and biota; in the worst instances the basic ecosystem functions have been destroyed and the changes are irreversable) may describe present ecological status but not targets. Water resources currently in category E or F must have a target class of D or above (DWAF, 1999; O'Keeffe and Uys, 2000).

Table 2: Ecological Management Classes (from DWAF, 1999 and O'Keeffe and Uys, 2000)

Class	Description
A	Negligible modification from natural conditions. Negligible risk to sensitive species. The Reserve has not been decreased and the resource capability has not been exploited.
B	Slight modification from natural conditions. Slight risk to intolerant biota. The Reserve has been decreased to a small extent. A small change in natural habitats and biota may have taken place but the ecosystem functions are essentially unchanged.
C	Moderate modification from natural conditions. Especially intolerant biota may be reduced in number and extent. The Reserve has been decreased to a moderate extent. A change of natural habitat and biota have occurred, but the basic ecosystem functions are still predominantly unchanged.
D	High degree of modification from natural. Intolerant biota unlikely to be present. The Reserve has been decreased to a large extent. Large changes in natural habitat, biota and basic ecosystem functions have occurred.

The desired status of the river must first be set before this objective-based approach can be applied. Once the desired status is known it should be possible to define upper and lower threshold flows from which a change in status will be evident. A number of methods have been developed internationally and within South Africa to define the flows (i.e. the environmental flows) required to maintain a river in whatever class (A to D) as selected as the target management class.

This classification system was the one used historically and was used in the current study as an interim measure while the South African river classification system was finalised. Regulations for the establishment of a water resource classification system have recently been promulgated in Regulation R 810 published in the Government Gazette 33541 of 17 September 2010 (DWA, 2010). The water resource can be classified into one of three classes, Class I to Class III, compared to the four Classes used in the past.

The water resources must be classified into one of the following classes:

- Class I: It is a water resource which is **minimally** used and in which the configuration of the ecological categories of the water resources within a catchment results in an overall condition of that water resource that is **minimally** altered from its pre-development condition.
- Class II: It is a water resource which is **moderately** used and in which the configuration of the ecological categories of the water resources within a catchment results in an overall condition of that water resource that is **moderately** altered from its pre-development condition.
- Class III: It is a water resource which is **heavily** used and in which the configuration of the ecological categories of the water resources within a catchment results in an overall condition of that water resource that is **significantly** altered from its pre-development condition.

The class of a water resource must describe the extent of use of the water resource, the Reserve, the resource quality objectives and the determination of the allocable portion of water resource for use (DWA, 2010).

4 ENVIRONMENTAL FLOW ASSESSMENT: METHODOLOGIES

4.1 Introduction

More than 200 approaches to environmental flow assessments have been reported worldwide, and they are now used in more than 50 countries as a water planning and management tool (Tharme 2003). Four main types of approaches have developed since the mid 1900s, namely the hydrological, hydraulic rating, habitat simulation and holistic methodologies (Tharme, 2003). Other reviewers (Loar *et al*, 1986; Gordon *et al*, 1992; Swales and Harris, 1995; Tharme, 1996; Jowett, 1997; Dunbar *et al*, 1998, Acreman and King 2003, cited in Tharme, 2003) have classified the methodologies slightly differently, but the overall pattern is much the same, and so the classification of Tharme (2003), which is felt to be the most comprehensive to date, is used here. The reader is referred to this document for a full review and bibliography. The four main types are briefly described below, followed by information on new developments since 2003.

4.2 Hydrological methods

These typically desktop approaches were the earliest, simplest and most rapid. They used one or more summary statistics based on a hydrological data set, usually a percentile from the annual flow duration curve, to set what is often called a minimum flow requirenment for the river. Gordon *et al* (1992), Stewardson and Gippel (1997), and Smakhtin (2001) reviewed many of the established hydrological techniques used to determine relevant flow indices, such as the Q_{95} or, ${}_7Q_{10}$. The minimum flow they identified was usually set for the dry season with the purpose of ensuring adequate dilution of pollutants or sufficient habitat for fish. Usually the set flow was assumed rather than known to have ecological relevance, although the most widely used method, the Tennant Method (Tennant 1976), was an exception in that it was based on extensive field observation of fish habitats. Tennant's approach could be used elsewhere in the world, but becomes 'rapid' only after it has been locally calibrated using the same extensive local field observations as done in its country of origin. A major drawback with all of these approaches is their lack of specificity – they do not take into account any features of the river other than its (usually monthly) flow data. The results are broad-brush guides to flows for ecological maintenance that are insensitive to the nature of individual rivers and mostly have little ecological relevance.

A more recent development within this kind of assessments is the Range of Variability approach of Richter *et al* (1997). The natural range of hydrological variation is described using 32 hydrological indices derived from long-term daily flow records. The Indices reflect the magnitude of high and low flows, the timing and frequency of different sized flows; and their duration indexed by moving averages. Inter-annual variability was assessed by calculating each index on an annual basis for each year in the hydrological record. An acceptable range of variation of the indices for maintaining the natural system was then set, for example + or - 1 standard deviation from the mean or between the 25th and 75th percentiles. This method was intended to define interim standards, to be monitored and revised, but a lack of further research has curtailed the use of this method.

4.3 Hydraulic rating methods

Determination of the flows for river maintenance should be guided by field measurements of the river of concern. This principle was recognized since the 1970s and was pioneered by people such as Collings *et al* (1972), as cited in Trihey and Stalnaker (1985). Two separate transect-based methodologies were developed from these principles: hydraulic-ratings (this section) and habitat-ratings (next section).

Loar *et al* (1986) used the term ‘hydraulic rating’ methods (also known as habitat retention methods) for methodologies that used changes in simple hydraulic variables over a range of flows as a surrogate for ecological data on habitat. The variables are usually wetted perimeter, wetted width or depth and are measured at one or more cross-sections at representative sites along the river. The values are plotted against discharge, and break points sought where there is a change in the slope of the curve. The implicit assumption is that when flow falls below such a break point, there will be a sharp change in the quality of habitat and thus repercussions for the aquatic life and ecological integrity of the ecosystem. A major asset of these approaches is the use of river-specific data, which allow precise hydraulic relationships to be described, whilst their main drawback is the common assumption that arbitrarily chosen hydraulic break points have ecological significance. The approach most widely used is the generic Wetted Perimeter Method (Gippel and Stewardson 1998).

4.4 Habitat-simulation methodologies

More complex habitat-rating approaches evolved from the hydraulic-rating methods in the late 1970s and 1980s. These also incorporated ecologically relevant data, often using a quantifiable relationship between the quality of an instream resource, such as fish habitats, and discharge, to guide decisions on environmental flow allocations. The methodologies link the hydraulic relationships of a river with extensive data on the habitat requirements of the biota in the same river. Hydraulic data such as water velocity, water depth and substratum particle size, collected at many cross-sections, are used to compile a description of representative river sites in terms of the hydraulic habitat they provide over a range of flows. The descriptions are then linked to descriptions of hydraulic-habitat requirements of selected biota, using the same variables. The output, usually in the form of graphs, illustrates how much habitat is provided for that species at any flow. These relationships can be used to identify what are perceived to be optimal flows for the species selected. Advantages of these approaches are their strong ecological links, and quantitative outputs that can be used in water negotiations. Early drawbacks included the focus on habitat without recognition of the wider environmental needs of species, on aquatic species whilst ignoring riparian species and on lower flows with no focus on floods. The Instream Flow Incremental Methodology (IFIM) is mostly used as a habitat-simulation methodology (Tharme 2003).

4.5 Holistic approaches

Holistic methodologies developed in South Africa and Australia, as they recognized that all parts of the flow regime is required for ecological functioning and the methodologies soon became recognised as the latest major advance in method development globally today (Tharme, 1996 and Arthington *et al*, 2004). Holistic methodologies emerged in the early 1990s where all parts of the river ecosystem and all parts of the flow regime are addressed. The most advanced methodologies used in developing countries can also address the impacts of changing rivers on all the users of the river resources and can provide economic information on compensation for resources lost, for instance, downstream of newly constructed dams. Holistic approaches are essentially structured data and information management tools that require and use hydrological, hydraulic, sedimentological, geomorphological, chemical, thermal, botanical (aquatic, marginal and riparian plants), zoological (fish, invertebrates, plankton, water birds, other wildlife), and microbiological data to compile an understanding of the functioning of the river ecosystem and develop a consensus prediction of how the ecosystem will change with flow changes. Where subsistence and other users also exist, anthropological, medical, socio-economic and resource economic data can be used to predict the implications for people of the changing river. The methodologies can use any relevant data, knowledge or local wisdom, and incorporate any individual discipline methods to derive the relationships needed for predictions. Their advantages are immense because of their wide scope, because they contribute toward national databases that enhance understanding of the rivers, and because ultimately they allow derivation of their own rapid versions based on past applications. Their main drawback is the cost of large multi-disciplinary teams optimally working over at least one annual hydrological cycle to gather river-specific data.

In the following paragraphs, the three main South African holistic methodologies are introduced, followed by an outline of comparable methods developed in parallel in Australia.

South African methodologies

- ***The Building Block Methodology (BBM)***

Perhaps the best known holistic methodology, the BBM was developed in South Africa in the early 1990s (King and Louw, 1998; King *et al*, 2000). The basis of the BBM is that riverine species are reliant on basic elements or building blocks of the flow regime, including low flows and floods that maintain the sediment dynamics and geomorphological structure of the river. By combining these building blocks an acceptable flow regime for ecosystem maintenance can be constructed. The BBM has a detailed manual for implementation (King *et al*, 2000), and it is the basis of the two next methods now routinely used in South Africa.

- ***Flow-stressor Response (FSR)***

FSR is a semi-holistic method developed in South Africa in 2000 (O'Keeffe and Hughes, 2002) for predicting impacts caused by changes in the low-flow part of the flow regime. It is designed to convert low flow-related ecological stresses to an index that relates to hydrological time series. Using it, hydrological time series are converted to stress time series. For any river site, the stress regime based on a planned future flow regime can be analysed and compared to stresses that would be faced compared to those experienced under the natural flow regime. One assumed advantage of the method is that once the index of stresses has been calibrated for a specific river reach, any flow scenario can be analysed using the same ecological knowledge base. Further methodology developments will entail the inclusion of floods into the method.

- ***Downstream Response to Imposed Flow Transformation (DRIFT)***

DRIFT was also developed in South Africa, and first applied to the Palmiet River in the Western Cape, and in the Lesotho Highlands Water Project (King *et al*, 2003). It is a scenario-based approach that provides a number of scenarios of a future flow regime based on different development scanarios together with predictions of how each of these will change the river condition. It has a strong socio-economic component, which describes the predicted impacts of each scenario of river change on subsistence users of the resources of a river.

DRIFT has four modules:

- **Module 1.** *Biophysical component. S*cientific studies are conducted of all components of the river ecosystem: hydrology, hydraulics, geomorphology, water quality, riparian trees and aquatic and fringing plants, aquatic invertebrates, fish, semi-aquatic mammals, herpetofauna, water bird and microbiota within the time and budget constraints of a specific project. All study results are then linked to flow, with the main objective of being able to predict how any part of the ecosystem will change in response to specified flow changes.
- **Module 2.** *Socio-economic component.* Social studies are carried out at the same time as the biophysical studies and include the identification and costing of all the river resources used by common-property users for subsistence, and the river-related health profiles of these communities and their livestock. All the results of the studies are linked to flow to try and predict how the communities will be affected by specified river changes (results from Module 1).
- **Module 3.** *Scenario-building.* For any future development scenarios and predicted flow regime the client would like to consider, the predicted change in condition of the river ecosystem is described using the database created in Module 1. The predicted impact of each scenario on the common-property subsistence users is also described using the database created in Module 2.
- **Module 4.** *Economics.* The compensation costs of each scenario for common-property users are calculated.
- If there are no common-property subsistence users, modules 2 and 4 can be omitted.
- The DRIFT software SOLVER is a custom-built optimization package that creates the scenarios, and DRIFT CATEGORY (Brown and Joubert, 2003) allocates each scenario to an ecological condition class.

DRIFT is usually used to build flow scenarios, but its database can also be used to set flows for achieving specific ecological objectives. Apart from DRIFT, two other activities can provide valuable additional information to the decision-maker:

- a macro-economic assessment of each scenario can be completed to describe its wider regional or even national implications in terms of industrial and agricultural development, cost of water to urban areas etc.;
- a public participation process can run concurrently with the DRIFT process and can involve a wider body of stakeholders that can voice their level of acceptability of each scenario.

DRIFT has also since been applied to the Breede (Brown and Louw, 2001) and Olifants-Doring (Birkhead *et al*, 2005) Rivers in South Africa.

Because of their multidisciplinary nature, a comprehensive study using the BBM, FSR or DRIFT application could cost up to one million rand for a large river system but, the costs are still probably less than one percent of the cost of a planned water-resource development project.

Australian holistic methodologies

In Australia, the basic BBM concept is reflected in several holistic approaches, such as the Expert Panel Assessment Method (Swales and Harris 1995), the Scientific Panel Assessment Method (Thoms *et al*, 2000), the Flow Restoration Method (Arthington and Zalucki 1998), the Benchmarking Methodology (Brizga *et al,* 2003) and the Flow Events Method (Stewardson and Gippel, 2003).

The Expert Panel Assessment Method was the first of these, designed for use at the reconnaissance and planning phase of a project, and it depended on the professional judgment of a panel of scientific experts. The panel assessed the suitability of flow releases for the maintenance of the river biota and channel morphology, through visual assessment of the flows and in workshop discussions. The Scientific Panel Assessment Method is a more sophisticated version of the Expert Panel Assessment Method and has mainly been applied to highly modified rivers. The Flow Restoration Method is specific to river-restoration projects where flow restoration plays a part, describing the required flows to satisfy a predetermined state. The Benchmarking Methodology assesses how much water can be removed from a river's flow regime, what is the benchmark, before the ecosystem is damaged. It is used at the planning/reconnaissance level, and predicts how a river might change with flow manipulations by comparing it with similar rivers that have undergone varying levels of flow-regime change. The Flow Events Method appears to have similar attributes to the other methods, comparing expected changes in the flow regime to the natural flow regime ecology and the influence of changes in flow on the ecology. to set environmental flows.

Methodologies for other ecosystems

There are also an emerging number of methods that have moved away from the emphasis on the relationship between instream habitat and flow, to investigate different data and information sets that are best suited to other kinds of aquatic ecosystems such as wetlands and lakes or dams (Tharme, 2002). Some documents are available or in preparation for wetlands and lakes (DWAF, 1999), estuaries and the near shore coastal environment (DWAF, 1999), water quality (Tharme, 1996; Malan and Day, 2002), geomorphology and sedimentology (Stewardson and Gippel, 1997), riparian vegetation (Tharme, 1996), wildlife (Tharme, 1996), groundwater-dependent ecosystems (e.g., DWAF, 1999; Parsons, 2004) and social dependence (Pollard, 2002).

Developments from the United Kingdom

A number of new and innovative approaches for assessing environmental flows have evolved from the holistic method development in the 1990s. Two proposed methodologies from the U.K. and two from South Africa are outlined below.

- ***Lotic Invertebrate Index for Flow Evaluation (LIFE)***

LIFE is based on routine macro-invertebrate monitoring data (Extence *et al*, 1999). An index of perceived sensitivity to water velocity was developed by giving all recorded UK taxa a score between 1 and 6. The method works with either species or family level data. The relationship between LIFE score and preceding river flow can be analysed where monitoring sites are close to flow gauging stations. LIFE has a major advantage of being able to use data collected by existing bio-monitoring programmes as long as the sites are close to flow gauging stations. Some disadvantages are:

- Biotic indices are influenced not only by flow but also by other factors such as water quality and the availability of habitat. Caution should be used when biotic indices designed for water-quality monitoring;
- A major limiting factor is the lack of both hydrological and biological data;
- time series of flows and ecological indices may not be independent, and using any statistical analysis should be handled with care.

- ***Catchment Abstraction Management Strategies (CAMS)***

The U.K. Environment Agency has to ensure that the environment is safe and at the same time they have to meet the needs of abstractors. The Agency has developed the CAMS methodology to fulfill their duties and responsibilities (Dyson *et al*, 2003). The CAMS methodology consists of two components, a public consultation with catchment stakeholder groups, and a Resource Assessment and Management (RAM) framework.

The first step in the CAMS methodology is to determine how sensitive a river is to reduced flow patterns. The physical characteristics, fish, macrophytes and macro-invertebrates are used as indicators of sensitivity. Each component is given a RAM score from 1 - 5 (1 being least sensitive to reductions in flow, 5 being the most sensitive).

Once each of the four elements have been scored, the scores are combined to categorise the river into one of five Environmental Weighting Bands, where Band A is the most sensitive (average score of 5) and E is the least sensitive (average score of 1). A flow duration curve for naturalised flows is also produced as part of the RAM framework. The RAM framework then specifies allowable abstractions at different points of the curve for each Weighting Band. Table 3 details the percentage of naturalized 95th percentile flow that can be abstracted for each band.

Table 3: Percentages of naturalized 95th percentile flow that can be abstracted for different environmental weighting bands (Dyson *et al*, 2003)

Environmental weighting band	% of Q_{95} that can be abstracted
A	0 - 5%
B	5 - 10%
C	10 - 15%
D	15 - 25%
E	25 - 30%
Others Special Treatment	

It was found that these percentages are not well supported by hydro-ecological studies and should only be used if nothing else is available. If environmental flows must be defined more accurately, other methods should be used.

4.6 Developments from South Africa

1. The South African Desktop Model

The holistic methods developed in South Africa take several months of work from a multi-disciplinary team to produce scenarios of the effects on the river of flow manipulations. The country's new Water Act determines that any future water-resource developments should be ecologically sustainable with a proportion of the natural flow of the river retained for ecosystem maintenance and functioning. This requirement resulted in the development of a rapid, low-confidence Environmental Flow (EF) assessment process that could be used in planning and reconnaissance level studies. The Desktop Model (Hughes and Hannart, 2003) was developed in 1999-2001 to meet this need, using results from the many EF assessments done within the country. Using the data from the rivers, a relationship was developed between the percentage of Mean Annual Runoff (MAR) defined as the EF for the river and the ecological management class that this would place the river in. Further, for any one management class, a relationship was defined between the percentage of MAR and a Hydrological Index (HI). The HI was derived from two other indices of the long-term flow data records. These were the Base Flow Index, which indicates the proportion of total flow that is base flow, and the Coefficient of Variation (CV), which sums the average CV's for the three driest months and for the three wettest months as an indication of different flow-regime types across the country. Once the relationships had been developed, then for any one ecological management class the HI indicates how much of the MAR needs to be reserved for river maintenance.

The Desktop Model is routinely used in South Africa to define the EF needs for perennial rivers. The Desktop Model is a rapid, low-confidence method, and confidence in its outputs decreases markedly once the HI reaches values of 10 or above. Such values of more than ten tend to be for rivers in more arid areas, thus making the current method unsuitable for non-perennial/ephemeral rivers. Research is needed to investigate if it can be modified for use for arid rivers, or if another rapid, low confidence approach is needed.

2. *Mini-DRIFT*

The scenario-based approach of DRIFT requires the population of a custom-built database with predictive flow-response couplets. This then becomes a rapid and highly flexible tool for creating scenarios but populating the database is time-consuming and requires an understanding of the functioning of a specific river ecosystem and data. It was seen as too complex for immediate use in countries or places with little research and other resources. A trial application of a reduced version of DRIFT was undertaken in Zimbabwe (King *et al*, 2003). The project took a few weeks compared to the months to years of comprehensive EF assessments, but did not produce a populated database and so could not be used for providing predictions of the consequences for any flows scenarios other than the pre-chosen ones. This approach will also need additional research before use on non-perennial rivers.

3. *The Ecological Reserve*

The Ecological Reserve is relatively difficult to determine because of the variability due to a range of Management Classes, different types of ecosystems, and because of limited insights into the different ecosystems and their water needs. Because of this difficulty and the need to move quickly to determine the Reserve nationwide, several levels of Reserve determination have been recognised (Louw and Hughes, 2002).

The levels for Ecological Reserve Determinations

- The levels were initially described in terms of the time it took to carry out an assessment, from Rapid, which might take from eight days at four sites to two months for an Intermediate Reserve at four sites and up to eight months to two years for a Comprehensive Reserve determination. It was originally assumed that the degree of confidence in the results of an assessment would increase in direct proportion to the time and cost involved. In practice, this was not necessarily the case. Any Reserve determination that does not satisfactorily define and describe the biophysical relationships between:
- the hydrological regime,
- channel hydraulics,
- geomorphology,
- water quality, and
- ecological functioning

will return low-confidence information on the link between flow and ecosystem health, no matter how high its cost and how long it took. Rapid, Intermediate and Comprehensive now refer to the method, whilst the terms low, medium or high refer to the level of confidence in the resulting Environmental Flow assessment.

The importance of the confidence level at which the Reserve is determined depends on a number of factors namely the:

- degree to which the catchment is already utilised and changed from natural conditions;
- the ecological sensitivity and importance of the catchment;
- potential impacts of current and future water use.

High-confidence determinations are required for:

- all compulsory licensing;
- large impacts in any catchment such as the construction of a dam in a river;
- important or sensitive catchments.

The South African EF methodologies are the means by which the decision-makers receive information on the likely consequences of the impacts of a water project and reach a decision on the Ecological Reserve for the ecosystem of concern. The RDM requires that the methodologies:

- are legally and scientifically defensible, since they serve as a basis for issuing legally valid water use licences and should be in line with the integrated ecosystem approach to water resource management;
- match administrative requirements;
- provide estimates of the water quantity and quality required to meet the Ecological Reserve, in order to manage the water resources in a sustainable and integrated manner;
- provide a variety of options to meet the projected demand for NWA implementation.

4. Environmental Water Requirements (EWR) for non-perennial systems

South Africa has a wide range of non-perennial aquatic systems, such as rivers, pans and floodplains. A question yet to be seriously addressed is whether these systems are more or less vulnerable than perennial systems. At the moment the general attitude of many seems to suggest that non-perennial systems already receive so little water, in such an unpredictable way, that a little less water should not make that much difference. Others feel that they already exist in such a marginal way that any further stress would have a massive (and largely unknown) effect on them.

Assessing EWRs for non-perennial rivers will be difficult, because they are usually more remote from human settlements than perennial systems and so little data exist for them. In principle, the comprehensive holistic EF methodologies developed in South Africa should be amenable to revision to make provision for non-perennial rivers and, in fact, a number of assessments have been undertaken on non-perennial rivers (DWAF, 1999). The Rapid Desktop Method is not suitable in its present form, not least because average monthly flow values cannot capture the variability in the quantity, quality, timing, and duration of available water, which is so different and so critical in these systems. Minimum low flows or average flow allocations would not be useful to satisfy the environmental water requirements for non-perennial ecosystems (Dyson *et al,* 2003).

The relationship between surface water and groundwater in non-perennial river systems is complex. The slow movement of groundwater means that the impact of the abstraction may continue for many months or even years after abstraction has stopped. An assessment method needs to be developed that combines some aspects of the present methods (for times when the systems have surface water) with some consideration of groundwater and aquifer conditions (for times when there is no surface water). The surface-water component could guide the Ecological Reserve for the wetter months whilst the groundwater component could limit abstractions based on the position of the water table.

5. WATER QUALITY

Water quality is only one aspect in maintaining a healthy ecosystem. Other factors are also important. These include flow regime, habitat quality, sediment quality and the condition of the riparian vegetation, barriers to fish migration, and connections between the river and its catchment and floodplain (Figure 3). Ideally, all these factors should be considered when defining the water resource management program.

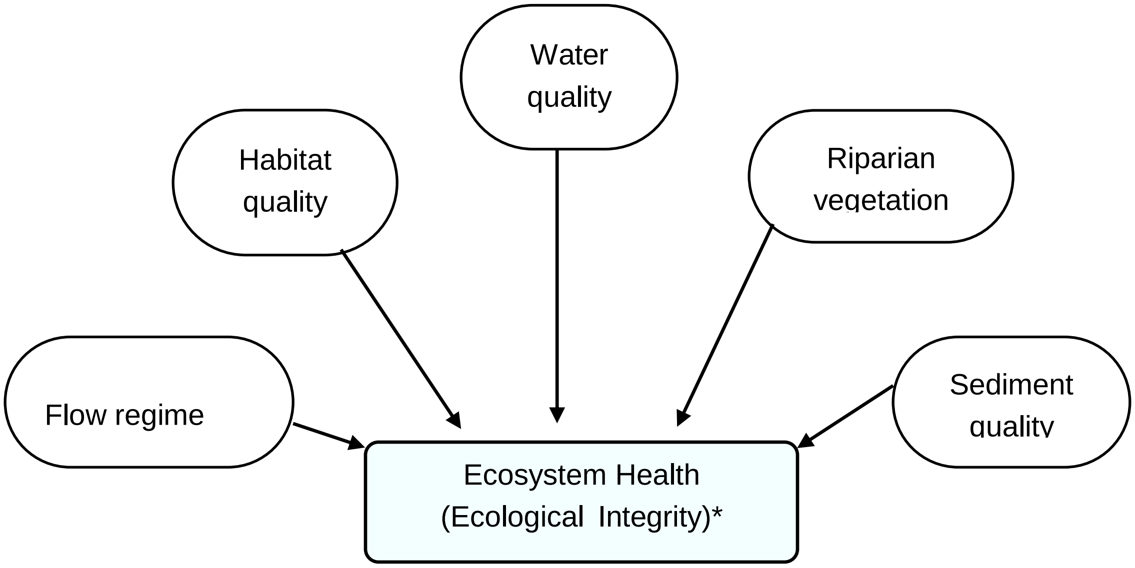


Figure 3: Key factors influencing ecosystem health (modified from Hart, 2002)

***** Ecological integrity, as a measure of the 'health' or 'condition' of an ecosystem, has been defined "as the ability of the aquatic ecosystem to support and maintain key ecological processes and a community of organisms with a species composition, diversity and functional organisation as comparable as possible to that of natural habitats within a region" (DWAF, 1999).

The water chemistry in rivers of South Africa are naturally variable because of differences in geology, soil types, climate, land cover and land use. The water quality of river water differs naturally from region to region, river to river, and longitudinally from the headwaters of a river to its lower reaches (Day *et al*, 1998).

Spatial water quality differences within the same water body depend on the homogeneity of the water body rather than on its size. For example, one sample taken from near the centre of the dam may adequately describe the water quality whereas to determine the water quality in a long, thin reservoir with many bays and inlets will require more samples. Similarly, different pools in a non-perennial river should be sampled rather than trying to take one sample and assuming that it is representative of the entire river.

Non-perennial rivers exhibit far greater amplitudes in both physical and chemical variables than do perennial rivers. As already stated, flow is both unpredictable and highly variable, and flow reductions cause shrinkage or loss of important habitats (e.g. riffles, rapids and marginal vegetation) and affect the size, composition and structure of invertebrate and fish communities. Survival of these communities in non-perennial river environments depends on their ability to adapt to these conditions (Uys, 1996) and on having refugia available.

The variables proposed as significant stressors to invertebrates and fish occupying non-perennial rivers are desiccation, chemical variation (high salinity, variation in ionic proportions, nutrients), high temperatures, low oxygen concentrations, high light intensities, habitat isolation and loss and fluctuating water levels. All these factors are linked to changes in flow and or water levels. Water quality was discussed in more detail in Roos (2005) in general for any river and Rossouw and Vos (2008) specifically for non-perennial rivers.

5.1 Understanding water quality

Aquatic resources worldwide are currently being threatened at an unparalleled rate (DWAF, 1999). South Africa’s available freshwater resources are already almost fully utilised and under stress (DWAF, 1996a). Many water resources are already polluted by industrial effluents, domestic and commercial sewage, acid mine drainage, agricultural runoff and litter (DWAF, 1999). Agriculture, deforestation, and urbanization have resulted in increasing eutrophication of rivers and lakes. Most of South Africa’s rivers have eutrophication problems (DWAF, 1999). The demand for water in South Africa is projected to increase by at least 50 % in the next 30 years (DWAF, 1996a).

The term “water quality” is used to “describe the physical, chemical, biological and aesthetic properties of water”, which determines its fitness for use and its ability to maintain the health of aquatic organisms (DWAF, 1996b). Water quality is an indication of the suitability of water resources to sustain and satisfy various uses or processes. Consequently, water quality can be defined by a range of variables which limit water use.

Water pollution and water quality

Aquatic populations and communities are often impacted by anthropogenic sources of pollution (ANZECC, 2000). The uses of water for human activities also result in the deterioration of water quality and generally limit the further potential use of the water. The results of these impacts include a wide range of changes on the biological integrity of aquatic systems.

Types of physical and chemical stressors

Physical and chemical stressors can be broadly classified into two types (Figure 4) depending on whether they have direct or indirect effects on the ecosystem (ANZECC, 2000).

There are two types of physical and chemical stressors that directly affect aquatic ecosystems. These are stressors that are either directly toxic to biota or that may not be directly toxic, but can still negatively influence the biota in an ecosystem. Direct-effect stressors also create problems, but it is a bit more complicated as both too much and too little of some elements can cause harm to the effective functioning of the biota. For example too high nutrient concentrations result in eutrophication and too low nutrient concentrations inhibit aquatic plant growth.

The major types of pollutants (stressors) and the extent of deterioration in freshwater quality at a global level are summarized in Figure 4.

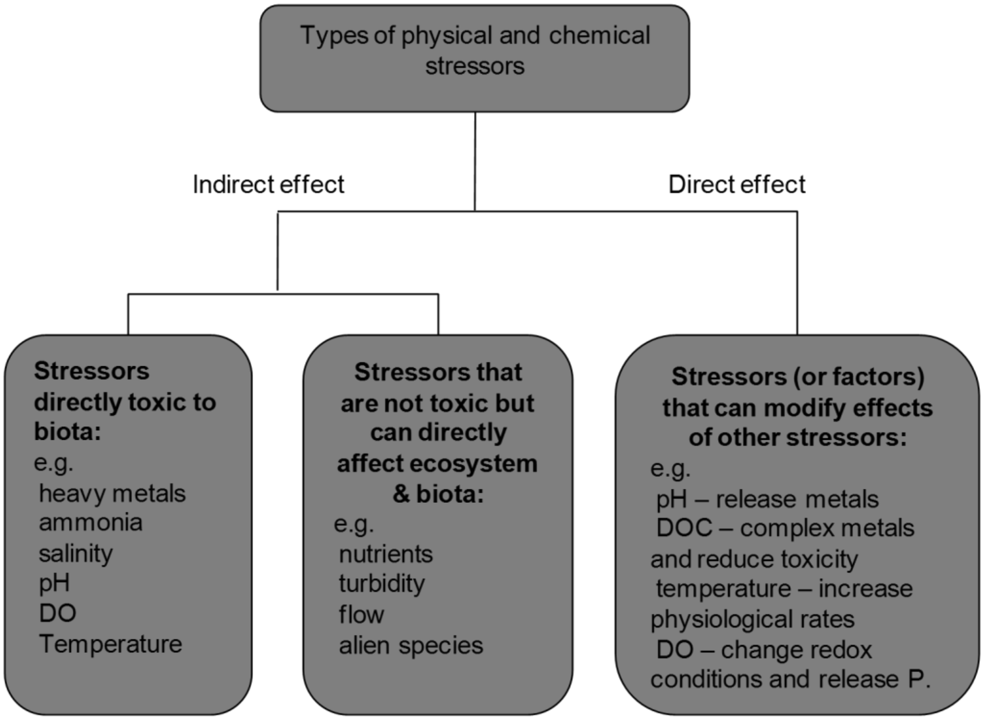


Figure 4: Types of physical and chemical stressors (modified from ANZECC, 2000)

The reason why water resource management has a high priority in South Africa is because of the rapidly increasing water use for basic human needs, development and recreation (DWAF, 1996a). Water use inevitably results in changes in the water quality through the discharge of water containing waste and return flows, and reduces the assimilative capacity of streams.

Water quality and time scales

Water quality can change over time and with location. Time changes water quality within the following parameters (Meybeck *et al*, 1996):

- Minute-to-minute and day-to-day differences as a result of water mixing due to different inputs (rain and wind). These differences can mostly be seen in small water bodies.
- Daily (24-hour) variations because of the natural biological cycles and daylight/darkness cycles.
- Run-off from agricultural land and informal settlements during rainfall events can cause irregular sources of pollution, changing the water quality. The changes in water quality can be measured over days and sometimes even months.
- Seasonal biological and hydrological cycles.
- Year-to-year trends can be caused by changes in land use activities and increased human activities in the catchment.

5.2 Water quality methods used for input to Environmental Water Assessments

The development of the methodology for determining the water quality EWR evolved over a number of years and is described in Chapter 3 in Rossouw and Vos (2008).

It was stated that many tools already existed. All the information on the existing methods for water quality reserve determination was collated in a report by Dr P Sherman (DWAF, 2008a). However, the focus of these tools was on perennial rivers and the existing methodology was tested in the Seekoei River study. It was found that one could use the existing methods when sufficient data were available (Rossouw and Vos, 2008).

In Rossouw and Vos (2008) the one major gap that still existed in the current methodologies available, was linking water quality to flow. As this was also a problem for the perennial rivers it was expected that it would be even more challenging to link flow and water quality in non-perennial rivers.

Environmental water quality guidelines

Water quality guidelines provide an objective means for judging the quality needed to maintain a particular environmental value. The South African guidelines for the protection of aquatic ecosystems (DWAF, 1996b) list recommended target ranges (i.e. target water quality ranges (TWQRs), Acute Effect Values (AEVs) and Chronic Effect Values (CEVs) for specific water quality variables. These can be used to assess the present condition of the system and the extent of its degradation.

The Target Water Quality Range (TWQR) proposed by the Department of Water Affairs and Forestry (DWAF, 1996b) is used to evaluate the water quality for the aquatic ecosystem. TWQR is a management objective, which has been formulated by using quantitative and qualitative criteria. The TWQR is the range of concentrations where no measurable negative impacts are expected on the health of aquatic ecosystems. The TWQR is a protective measure to ensure the continued health of aquatic ecosystems.

The CEV is defined as that concentration of a constituent where up to 5 % of the species in the aquatic community can be chronically affected. If the chronic effects persist or occur frequently, they can lead to the eventual death of species that can lead to the elimination of sensitive species in specific aquatic ecosystems (DWAF, 1996b).

The AEV is defined as that concentration of a constituent where up to 5 % of the species in the aquatic community can experience acute toxic effects, severely impacting on the health of the aquatic ecosystem, even over a short period.

Water quality in a catchment is highly dependent on the degree to which land-use and other physical developments have modified the condition of the land phase of the hydrological cycle. All aspects of the environment are interdependent. Impacts on the environment must be considered in an integrated manner. For example, changes in water temperature may lead to changes in the composition of aquatic communities, because of changes in available oxygen (DWAF, 1996b).

Water quality parameters

Physical and chemical parameters frequently used to describe the water quality Reserve are briefly described below. A more detailed description of the actual steps to be followed and methods to be used to determine the water quality component of the EWR are described in DWAF (2008a).

Dissolved Oxygen

Oxygen is required for all forms of aquatic life. Gaseous oxygen (O_2) from the atmosphere dissolves in the water and is also produced during the photosynthesis processes in aquatic plants and phytoplankton.

Changes or differences in dissolved oxygen (DO) concentrations provide valuable information about the biological and biochemical reactions occurring in waters.

In unpolluted surface waters (low sediment, low organic matter), dissolved oxygen concentrations are usually close to saturation. The Target Water Quality Range (TWQR) for DO is between 80 and 120 % saturation (DWAF, 1996b). Concentrations below 5 mg/ℓ may adversely affect the functioning and survival of biological communities and below 2 mg/ℓ may lead to the death of most fish. Low oxygen concentrations are often an indicator of the water having a high organic content (DWAF, 1996b).

The depletion of oxygen in reservoir bottom waters and the onset of anoxia have an impact on the re-mobilisation of certain constituents bound to the sediment at the bottom of the reservoir. Typically phosphorus is released from the sediments. Sulphates can also be released and causes odour and taste problems.

Assessing the present status for system variables: Dissolved oxygen concentration

- Collect all the dissolved oxygen data for the last three years for the particular water quality reach.
- Convert the dissolved oxygen concentrations into percentage saturation taking account of the water temperature and elevation above mean sea level.
- Calculate the median dissolved oxygen saturation for each month, and assign the monthly water quality assessment category using Table 4.

Table 4: Present status assessment for dissolved oxygen (DWAF, 1999)

Assessment category	Dissolved oxygen concentration (%)
A	80 - 120 % of saturation
B	80 - 100% of saturation
C	60 - 80% of saturation
D	40 - 60% of saturation
E and F	< 40% of saturation

pH

The pH influences many biological and chemical processes in an aquatic ecosystem and is an important water quality variable to use in assessing the water quality of a water body. The pH of most natural waters is between 6.0 and 8.5, although lower values can occur in coloured waters rich in organic matter, such as in the Western Cape, and higher values occur in more eutrophic waters.

Assessing the present status for system variables: pH

- Collect all the pH data for the last three years for the particular water quality reach.
- Calculate the median pH value for each month.
- Assign a water quality assessment category for each month using Table 5.

Table 5: Rapid present status assessment for pH in rivers

Assessment category	Median monthly pH
A	6.5 – 7.5
B	6.0 – 6.5 or 7.5 – 8.0
C	5.5 – 6.0 or 8.0 – 8.5
D	5.0 – 5.5 or 8.5 – 9.0
E and F	<5.0 or >9.0

Total dissolved solids (TDS)

TDS is a measure of all the dissolved materials, organic as well as inorganic, in water. The TDS concentration is generally low in water in contact with granite rock type geology and well-leached soils, less than 30 mg/ℓ TDS. Headwater streams rising in mountainous regions of high precipitation also generally have low TDS concentrations. Most rivers exhibit decreasing TDS concentrations with increasing flow (Malan and Day, 2002; Roos and Pieterse, 1995).

Human activities have severely increased the TDS concentrations of rivers and dams worldwide, especially in arid regions (Dallas and Day, 2004). Not much information is available on the tolerance of biota to increased TDS concentrations. In general, it seems that many species are able to survive and even flourish at relatively high salinities. The recommended TDS concentration guideline for the protection of freshwater aquatic biota is <3 000 mg/ℓ (ANZECC, 2000).

However, there seems to be a ‘critical level’ of salinity between 5 000 – 8 000 mg/ℓ after which most salinity-tolerant freshwater species begin to die (Dallas and Day, 2004).

Assessing the present status for system variables: Total dissolved salts (TDS)

- Collect all the TDS data for the last three years for the particular water quality reach.
- Calculate the median value for each month..
- Assign a water quality assessment category for each month using Table 6.

Table 6: Rapid present status assessment categories for total dissolved salts (TDS) (DWAF, 1999)

Assessment category	Median monthly TDS (mg/ℓ)
A	0 – 163
B	163 – 228
C	228 – 325
D	325 – 520
E and F	> 520

The concentrations in Table 6 cannot be used for rivers with naturally occurring high baseline salinity values. In these cases, Site-specific reference conditions will need to be determined for these high salinity rivers, and the assessment categories must be adjusted accordingly.

Nutrients

One of the most common water quality management challenges is the eutrophication of reservoirs and rivers. Some of the consequences of eutrophication are toxic algal blooms, the excessive growths of aquatic macrophytes, increased occurrences of anoxic conditions, hampering of recreational activities, physical blocking of waterways with macrophytes, species composition and diversity changes and increased treatment costs for potable water.

Nitrogen

Inorganic nutrients provide the chemical constituents on which the entire food web is based. Nutrient cycling implies that nutrients move through different components of a cell, organism, community, or ecosystem and can be cycled and re-cycled by some of these components.

Nitrate (NO_3^{-1}) is the most common form of inorganic nitrogen in reservoirs and rivers and the concentrations are seldom higher than 0.1 mg/ℓ NO_3-N. Effluent discharge from wastewater treatment works and runoff from informal settlements drastically increase the nitrogen concentrations in rivers and reservoirs (Chapman, 1996).

Ammonium (NH_4)

Ammonia is present in small concentrations, less than 0.1 mg/ℓ as nitrogen in unpolluted waters. However, it can be present in higher concentrations in polluted water and can contribute to eutrophication problems (Chapman, 1996). In oligotrophic and mesotrophic lakes, ammonia concentrations in the epilimnion are very low, approximately 0.005 mg/ℓ, during the spring and summer months and any excess is used by phytoplankton (Horne and Goldman, 1994).

Ammonia in water is present primarily as NH_4^+ and the undissociated NH_4OH, the latter being highly toxic to fish. Water temperature and pH are the two factors that determine the proportion and toxicity of un-ionised ammonia in water. High temperatures, high pH and high ammonia concentrations can lead to potential toxic conditions for fish. The target water quality range of un-ionised ammonia is 0.0 – 25 µg/ℓ (DWAF, 1996b).

Assessing the present status for nutrients: Ammonia

- Collect all the ammonium data for the last three years for the particular water quality reach. If the number of data records is less than 60, use a longer period of data. Ideally, the same period of data should be used for both nitrate and phosphate nutrient classification.
- Convert the ammonium values into un-ionised ammonia using information on water temperature and pH (page 24 in the South African Water Quality Guidelines for Aquatic Ecosystems (DWAF, 1996b) describes the methods to convert ammonium data to un-ionised ammonia concentrations).
- Calculate the 90th percentile ammonia value. Where the ammonia concentration is at or near, the analytical detection limit of the DWAF laboratories, the river is allocated a A/B category.
- Assign the water quality assessment category for ammonia using Table 7.

Table 7: Present status assessment for nutrients using the un-ionised ammonia concentration (DWAF, 1999)

General categories for nutrient assessment	Assessment Categories	Ammonia (un-ionised) concentration (expressed as µg NH_3-N/ℓ)
Unimpacted	A	<7
Moderately impacted	B	<15
	C	<30
	D	<70
Highly impacted system	E	<100
	F	>100

Phosphorus compounds

Phosphorus, the same as the nitrates, is an essential nutrient for biota and is part of the nutrient cycle. Algal growth is commonly limited by phosphates and therefore often controls primary productivity in reservoirs and rivers. Effluent discharge from wastewater treatment works and runoff from informal settlements and other human activities can drastically increase the phosphate concentrations in rivers and reservoirs. These elevated concentrations cause eutrophication.

Phosphate (PO_4)

Phosphorus concentrations are generally low, ranging from 5 to 20 µg/ℓ PO_4-P, in unimpacted rivers and reservoirs because it is used by aquatic and algae (Chapman, 1996).

Assessing the present state for nutrients: The ortho-phosphate to total phosphate ratio

- Collect all the ortho-phosphate (SRP) and total phosphorus (TP) data for the last three years for the particular water quality reach.
- The % ortho-phosphate must be calculated for each data set using the following calculation: Ortho-phosphate content = [SRP] / [TP]*100 where [SRP] is the soluble orthophosphate concentration (expressed in mg P/ℓ), and [TP] is the total phosphorus concentration (expressed in mg P/ℓ).
- If the measured orthophosphate concentration is at or near the analytical detection limit of the DWAF laboratories, the river is allocated an A/B assessment category, the same as for the nitrogen component.
- Calculate the median ratio value, and assign the water quality assessment category for orthophosphate using Table 8.

Table 8: Rapid present status assessment of nutrients based on orthophosphate as a percentage of the total phosphorus content (DWAF, 1999)

General category intervals for nutrient assessment	Assessment Category	Percentage orthophosphate content
Oligotrophic	A	< 10 percent
	B	< 20 percent
Mesotrophic	C	< 40 percent
	D	< 60 percent
Eutrophic	E	< 80 percent
	F	> 80 percent

N:P ratios

The N:P ratio is generally high in unpolluted reservoirs and mountainous streams and very low in eutrophic or polluted reservoirs (Downing and McCauley, 1992; Hessen *et al*, 1997). Harris (1986) analysed the TN and TP ratios from 55 lakes and found that the TN:TP ratio varied from over 200 in oligotrophic lakes to less than 15 in the eutrophic lakes. The polluted European and North American rivers also have N:P ratios less than16 (Jarvie *et al*, 1998).

Assessing the present status for nutrients: Nitrogen to Phosphorus ratio

- Collect all the ortho-phosphate (SRP), total phosphorus (TP), ammonium and nitrate data for the last three years for the particular water quality reach. If the number of data records is less than 60, use a longer period of data.
- Calculate the total inorganic nitrogen (TIN) concentration by summing the ammonium and nitrate values for each set of values.
- Calculate the N:P ratio using the TIN and TP values
- Calculate the median N:P ratio, and the median SRP concentration.
- Assign the assessment category using Table 9. Orthophosphate concentrations at or near, the analytical detection limit must be allocated an orthophosphate concentration of <0.01 mg P/ℓ.
- If there is only SRP and no TP data, the SRP values can be used to calculate the N:P ratio, but Table 10 must be used to assign the assessment categories.

Table 9: Rapid present status assessment of nutrients based on the N-P ratio (using TIN and TP) (DWAF, 1999)

		Total inorganic Nitrogen to Total Phosphorus Ratio			
		<5:1	**>5:1 & <10:1**	**>10:1 & <20:1**	**>20:1**
Ortho-phosphate concentration (expressed in mg P/ℓ)	<0.01	C	B	A	A
	<0.05	D	C	B	A
	<0.07	E/F	D	C	B
	<0.10	F	E/F	D	C
	>0.10	F	F	E/F	D/E

Table 10: Rapid present status assessment of nutrients based on the N-P ratio (using only orthophosphate data)

		Total inorganic Nitrogen to Soluble Phosphate Ratio			
		<10:1	**>10:1 & <20:1**	**>20:1 & <30:1**	**>30:1**
Ortho-phosphate concentration (expressed in mg P/ℓ)	<0.01	C	B	A	A
	<0.05	D	C	B	A
	<0.07	E/F	D	C	B
	<0.10	F	E/F	D	C
	>0.10	F	F	E/F	D/E

The development of methods to link environmental-flow and water quality requirements was at an early stage when the DWA methods were developed, and there are critical problems that still need to be addressed such as the development of a reliable tool that enables estimates to be made of concentrations in certain water quality constituents that can be expected under given stream flow conditions. There are many methods to choose from and the choice will depend on the objectives of the study and the financial and manpower resources available.

6. THE PROPOSED METHODOLOGY

South Africa is leading the development of methods to link environmental flows to water quality. This was confirmed by not being able to find references other than South African based studies on water quality and the Ecological Reserve methodology (Schofield *et al*, 2003).

The first step in testing a proposed methodology was to review the current methods that are used to determine the water quality Ecological Reserve and to apply the chosen methods to the Seekoei River.

6.1 Development of methodology to determine the water quality ecological reserve

The water quality reserve is a description of the water quality that is required to maintain the aquatic ecosystem in a predetermined state (DWAF, 2003c). The water quality Reserve determination is generally synchronised with the determination of the water quantity Reserve, with information exchanged happening at various stages during the two processes (DWAF, 2003c).

Ecological Reserve assessments have been required by law since 1998 (National Water Act No 36 of 1998). When the policy was formulated and drafted it was stated that methods already existed to quantify the ecological reserve. This was true for water quantity but not for water quality as it was realised that supplying adequate flows in space and time would not necessary lead to the desired ecosystem health if the water quality was impaired. The National Water Act therefore specifically included water quality criteria within the ecological Reserve (Palmer, 1999; Palmer *et al*, 2004).

Methods were developed for determining the water quality component of the Ecological Reserve. A two-step approach was followed:

- DWAF organised method-development workshops and contracts; and
- DWAF contracted ecological Reserve assessments.

The combined workshop/contract process led to the publication of the first official water quality method in 1999. As ecological Reserve assessments were undertaken, the water quality methods were extended and modified (Palmer *et al*, 2004).

Ecological Reserve assessments for three major rivers contributed to this process (Palmer *et al*, 2004):

- The Crocodile River (Mpumalanga)
- Olifants River (Mpumalanga) and
- Breede River (Western Cape).

Some of the main contributions from the case studies were the following:

Olifants River

- The first methods were developed and applied, including a method that related salt toxicity to resource classes
- The need for a range of skills in a water quality team was identified: Aquatic ecology, aquatic ecotoxicology, water chemistry, and flow/concentration modelling were seen as critical elements.
- Environmental flows are not recommended to solve water quality problems by means of dilution, but rather that water quality consequences of recommended environmental flows be highlighted.

Breede River

- The Breede River study was used to compare the water quality methods within the Downstream Responses to Instream Flow Transformations (DRIFT – King *et al*, 2003, Brown *et al*, 2005) and Building Block Methodology (BBM – King and Louw, 1998, King and Tharme, 1993 and King *et al*, 2000) methods.
- In this study the water quality procedure was better integrated with the quantity based workshop procedure. The data and actions required for the workshop were also listed in Palmer *et al* (2004).
- The main differences between the two methods were the following (Palmer *et al*, 2004):
    - DRIFT: more critical and rigorous use of water quality data
    - DRIFT: tentative “minimum degradation flows” is useful for the water quality team to focus thinking. Water quality consequences can be refined with the information from other specialists.
    - DRIFT: Resource Quality Objectives should be an explicit product of DRIFT (as in BBM) and linked to classes/flow-reduction scenarios.
    - BBM: (In that particular workshop) used water quality more analytically due to recent exposure to the DRIFT method.
    - DRIFT is a more useful approach as water quality consequences are consequences for summer and winter base-flows vs. a single month in summer

    and winter for BBM. The latter may lead to missing peaks outside of the two selected months.
  - BBM gives confidence in prediction per site while DRIFT gives confidence, severity, data source and direction of change for each water quality variable and element of flow reduction.
- The mismatch between daily hydrology data and monthly water quality data remained an issue as the hydrology model presented the results on a daily basis whereas the water quality, if it was a good water quality record, only had data on a monthly basis. This implied that extrapolation of the water quality data will be needed, enhancing inaccuracies.

Crocodile River

The water quality required to maintain ecosystems was determined through the application of the ecological Reserve concept and a modified DWAF (1999) method (Claassen, M in Palmer *et al*, 2004).

The application of the methodologies on the previously mentioned rivers resulted in a five step method being developed compared to the eight steps used in the water quantity component. The five basic steps for the water quality component are the following:

Step 1: Initiation of study and scoping

Step 2: Delineation of Resource Units and preliminary water quality site selection

Step 3: Information collection, site finalization, water quality boundary values, and input to Ecological Resource Class categorization

Step 4: Quantify ecological Reserve Scenarios

Step 5: Ecological consequences of operational scenarios

These steps are described in detail in the Helpfile of SPATSIM (Hughes, 2005) and also in Palmer *et al (*2004 and 2005) and in the Ecostatus Manual by Kleynhans *et al* (2006). This manual has since been updated and a draft copy is available (Kleynhans and Louw, 2007a).

These steps linked up with the water quantity component as illustrated in Figure 5 below (DWAF, 2008a).

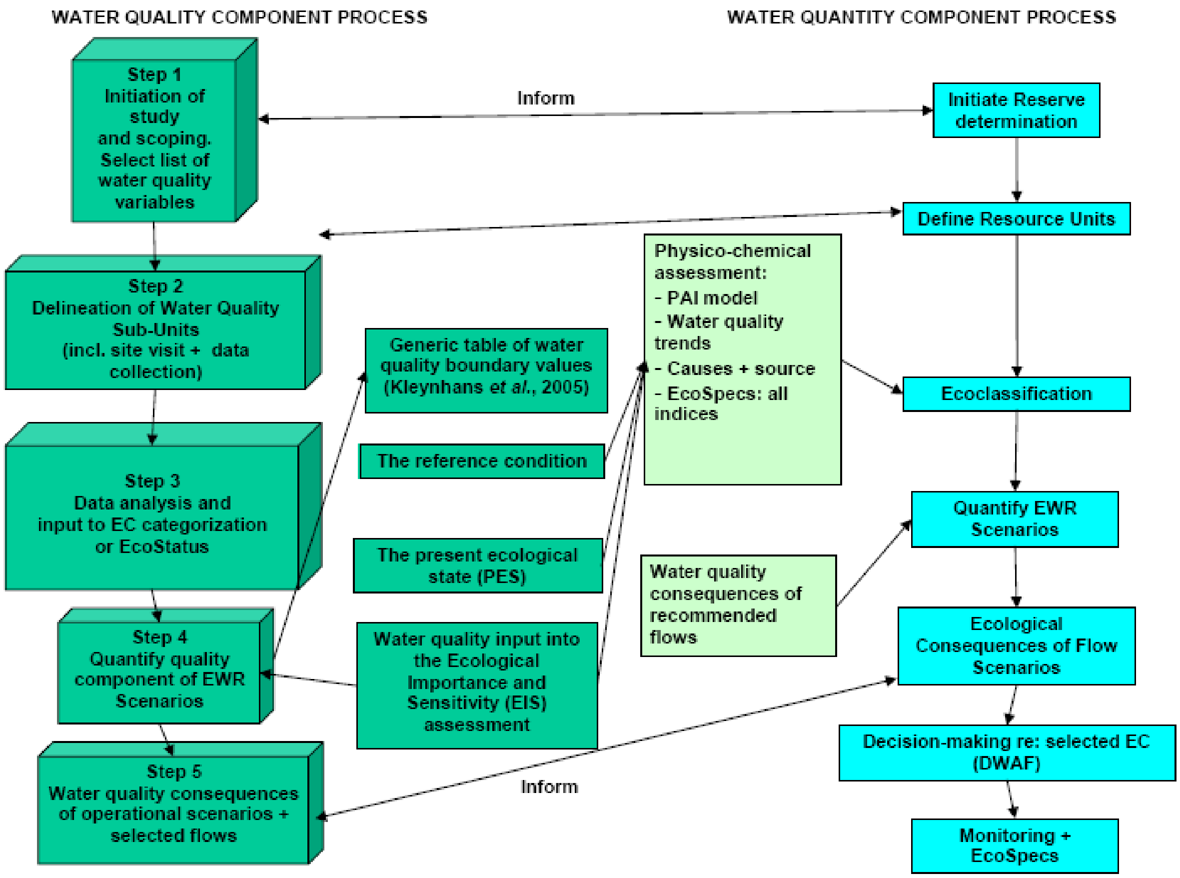


Figure 5: The water quality and quantity reserve determination process (DWAF, 2008a)

6.2 Additional tools

Many tools have been developed in the early to middle 2000 to assist in the determination of the water quality Ecological Reserve. The Physico-Chemical Driver Assessment Index (PAI) as described in the Ecostatus Manual (Kleynhans *et al*, 2006), is an approach and model that can be used to determine the present status of the physical and chemical water quality for a resource unit or a specific site. It can be applied along with the other driver models to undertake a stand-alone assessment or it can be applied as the water quality contribution to a water quality Reserve determination.

One of the requirements of the EcoClassification process is that the ecological consequences of various flow scenarios must be determined. One of the tools currently available is the concentration modelling method (the Q-C model) as proposed by Malan and Day (2003) and also described in Malan *et al* (2003). The Q-C model enables estimates to be made of concentrations in certain water quality constituents that can be expected under given stream flow conditions. It can be used with both the BBM and DRIFT method.

It is a simple approach aimed at providing estimates of predicted water quality rather than precise numerical values.

The method has certain limitations (Malan and Day, 2003):

- Modelling of nutrients is not as successful as that of conservative constituents such as TDS.
- If a poor correlation between measured flow and concentration data and the regression line is obtained (less than 0.6), the predicted concentrations are not likely to be reliable, and the Q-C method should not be used to obtain predictions of water quality.
- Q-C modelling should be used with caution to make predictions of concentration in the case of constituents that are positively correlated with flow.
- This method cannot be used to predict changes in water quality due to different development scenarios impacting on the water quality. Predictions are only valid if the system is operated in the same way as used to derive the flow-concentration relationship.

Another tool that has been developed is SPATSIM, an integrating framework for Ecological Reserve Determination and Implementation (Hughes, 2005). Palmer *et al, (*2004) prepared a chapter on methods for Ecological Reserve assessments within a Decision Support System (DSS). Methods to assess individual water quality variables are also presented in Appendix A of Hughes (2005).

Another tool was developed by Dr S Jooste and links into the SPATSIM DSS. The Tool for the Ecological Aquatic Chemical Habitat Assessment (TEACHA), supports the decision-making in the Reserve process and can also be used in the Ecostatus assessment situation for the physico-chemical assessment index (PAI) as described in the Ecostatus Manual (Kleynhans *et al*, 2006).

TEACHA uses as input water quality data for either a single site (the PES site or resource unit) and (ideally, if available) the water quality data for a reference site/situation. The primary output is a recommended water quality reserve with corresponding ion data to use in resource quality objective setting (Jooste, 2006). The concepts used to derive the benchmarks used in TEACHA are presented in a report by Jooste and Rossouw (2002).

6.3 Limitations of the existing methods

Based on the above it is clear that a number of tools are already available to determine the water quality ecological Reserve. However, the tools and information are currently scattered in a number of publications and the Water Research Commission has currently undertaken a project with the Unilever Centre for Environmental Water Quality in Grahamstown to collate all the information and present it in one Water Quality for the ecological Reserve methodology document (DWAF, 2007 and DWAF, 2008a). However, the focus in the development of these methods has been on perennial rivers and the methodology was tested in the Seekoei River study.

The working hypothesis was that the methods could be applied to non-perennial rivers at least up to Step 3 (information collection, site finalization, water quality boundary values, and input to Ecological Resource Class categorization).

One major gap that still existed in the current methodologies available was linking water quality to flow (Step 4) as the existing method (Q-C model) had a number of limitations and it was expected that even more shortcomings would be found if this was implemented on a non-perennial river.

6.4 A simple water quality model

There are a number of water quantity models on the market that include the water quality component such as the Qual 2E and Ecolab models. However, they are all data and time intensive and require specialist knowledge to run. In trying to link water quality to flow, an easy to use and the ability to use limited water quality data, model is required.

Hughes (2007) presented a “simple” water quality model using the data from the gauging weir at D3H015 (on the Seekoei River), as well as some observations taken by the main project team during field visits in the Seekoei River catchment. The following is a brief summary of his main report.

A simple water quality model was developed that is based on simulating TDS using the runoff component outputs from the rainfall-runoff models and several other parameters to define the water quality signals of these runoff components. The approach was based on a mass balance of the salt load in the pools on a quaternary catchment scale. The basic concept is that some of the TDS load will be taken up in the river bed and banks during the pool drying period and then slowly released during the pool wetting period.

He concluded that the model required further testing and refinement in other semi-arid and arid areas before it can be used as an additional tool.

7. APPLICATION OF THE METHODOLOGY ON THE SEEKOEI RIVER

7.1 Introduction

The existing five step water quality method (Figure 5) was applied to the Seekoei River as part of the Reserve determination. TEACHA, an existing method, was also used. The primary output from TEACHA is a recommended water quality reserve with corresponding ion data to use in resource quality objective setting. As very little water quality data were available the Seekoei River was monitored over an eighteen month period.

Although the study was about methodology evaluation and development it was also to get a better understanding of non-perennial rivers and information on the river ecosystem will be presented in this chapter although it is not required in the methods that was used in determining the ecological water requirement.

According to Avenant (2006) the Seekoei River supported large herds of game that supported Bushmen in the headwaters and valley in historical times.

Agriculture, such as stock farming and crops, was later established along the banks of the Seekoei River and had several implications:

- Large scale destruction of game species due to hunting;
- Introduction of domestic animals;
- Eradication of natural vegetation to plant crops;
- Degradation of Karoo veld;
- Construction of weirs and dams in the river channel.

Erosion is the cause of major environmental changes over the last 60 years in the upper Seekoei River catchment (Holmes, 2001 cited in Avenant, 2006). Flow regulation because of all the weirs and small farm dams have also led to the encroachment of reeds into the river channel (Watson and Barker, 2006).

Flow regulation by the VanderKloof Dam (downstream of the research area), the 49 functioning weirs, the 10 broken weirs, seven dam walls and 22 other earth dams on the Seekoei River has a major impact on the habitat integrity of the river. The reeds that are present for 56% of the river length also have a serious impact on the flow, bed and channel of the river (Watson and Barker, 2006).

7.2 Site selection and description of the different sites

Site selection for the study and sampling sites was initiated with a Macro-reach analysis for the Seekoei River by Dr E Dollar, the geomorphologist, in November 2005. After this a Habitat Integrity Report was written by Mrs M Watson and Dr C Barker in January 2006. Based on a site visit (attended by Dr J Roos (water quality), Dr E Dollar (In-stream geomorphologist), Prof G van Tonder (geohydrology), Mrs M Watson (macro-invertebrates) and Mrs M Avenant (fish)), the above mentioned reports and an aerial survey video taken from a helicopter by Mrs E Schulze from the Free State Department of Tourism, Environment and Economic Affairs, the Selection of sampling sites on the Seekoei River report was produced in February 2006.

The detailed site selection methodology and description of the different sampling sites are presented in the Selection of sampling sites report (Avenant, 2006).

The Seekoei River catchment is situated in the Northern Cape Province and falls into the Upper Orange Water Management Area which is under the jurisdiction of the Free State Regional Office of the Department of Water Affairs.

All the sampling sites of the Seekoei River are situated on the main river channel and not on any of its tributaries. The entire Seekoei catchment falls within the Nama Karoo Level I Ecoregion and thel vegetation type was Shrubland with low Fynbos. The Seekoei River falls in the summer rainfall area where rainfall occurs from October to March where the annual rainfall varies between 300 and 420 mm per annum. Minimum winter temperatures are low, ranging between 0°C and -9°C, with frequent frost occur (Venter et al, 1986, in Avenant, 2006). The evapotranspiration in the Nama Karoo biome is high, especially during the hot summer months (Avenant, 2006).

The Seekoei River drains part of the Upper Karoo, a landscape dominated by flat-lying Karoo Supergroup sediments that have been intruded by innumerable sills and dykes of dolerite. The dolerite sills and rings control the geomorphology and landscape of much of the Karoo basin. The Seekoei River is an example where dolerite plays an important role in the shape of the longitudinal profile (through hydraulic controls, breached/unbreached sills and dykes and knickpoints), influences channel type and the location of pools. The bed of the Seekoei River is often just above bedrock or is often incised into contacts bedrock. The the bed of the Seekoei River is strongly influenced by the relationship between the softer Karoo sediments and the position and breaching of contact bedrock. The Seekoei River channel flows in alluvium for approximately 80% of its length (Dollar, 2005).

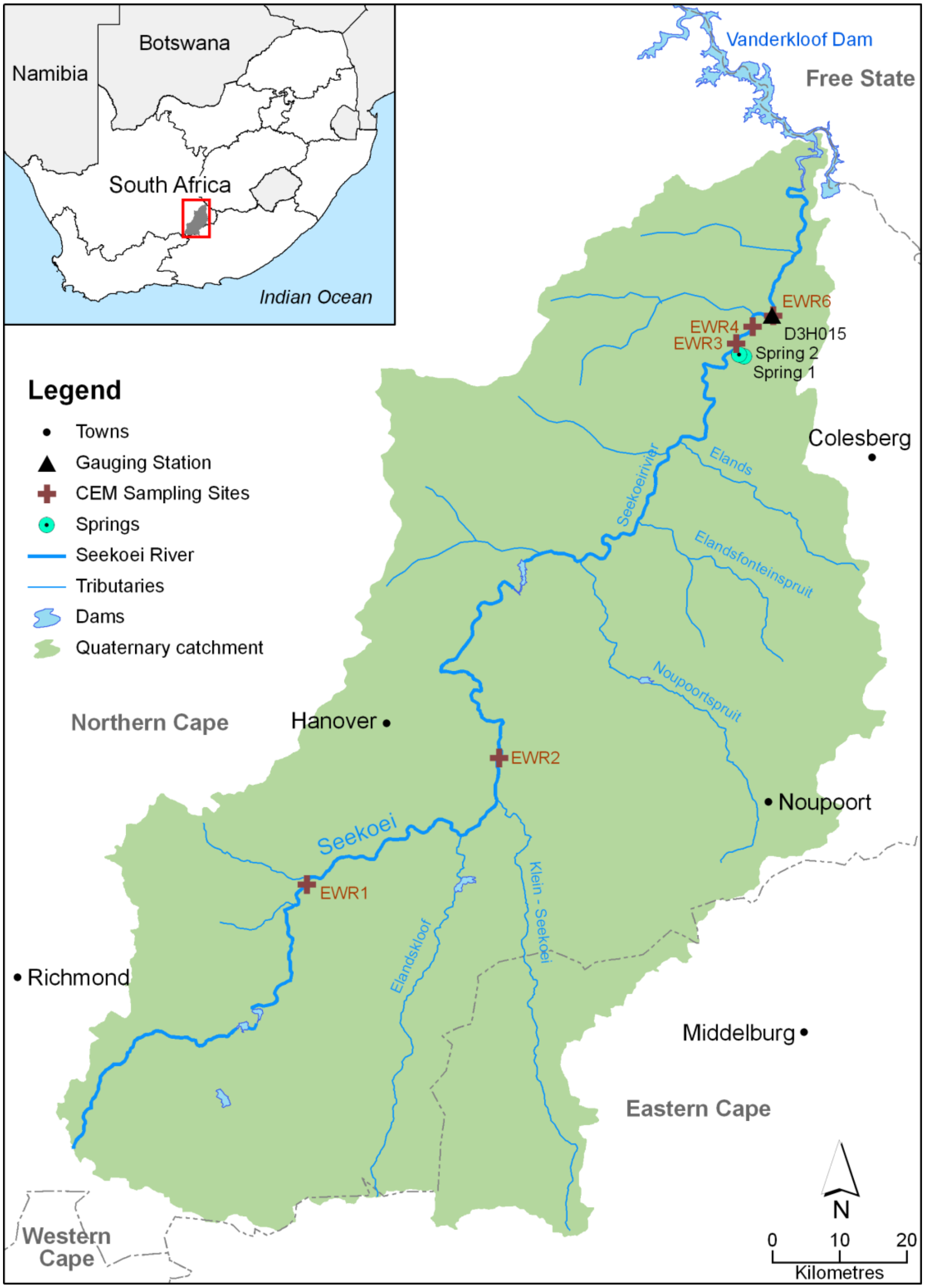


Figure 6: Sampling sites on the Seekoei River (Prepared by F Sokolic, 2011)

The water quality sampling sites correspond to the invertebrate and fish sampling sites as identified in the Selection of sampling sites on the Seekoei River report (Avenant, 2006).

Four sampling sites (Ecological Water Requirement (EWR) sites) were selected and are illustrated in Figure 6. They were the following:

Site 1 – EWR 1

The site was located on the farm, Van Zylskraal, in the Hanover district. The site was seen as representative of the river macro-reach – alluvial, meandering channel with isolated pools (Figure 7 – all the photos used in this chapter were made available by the Centre for Environmental Management (CEM) at the University of the Free State). The site is also relatively natural with few upstream disturbances. There were no formal water abstraction points (Avenant, 2006).

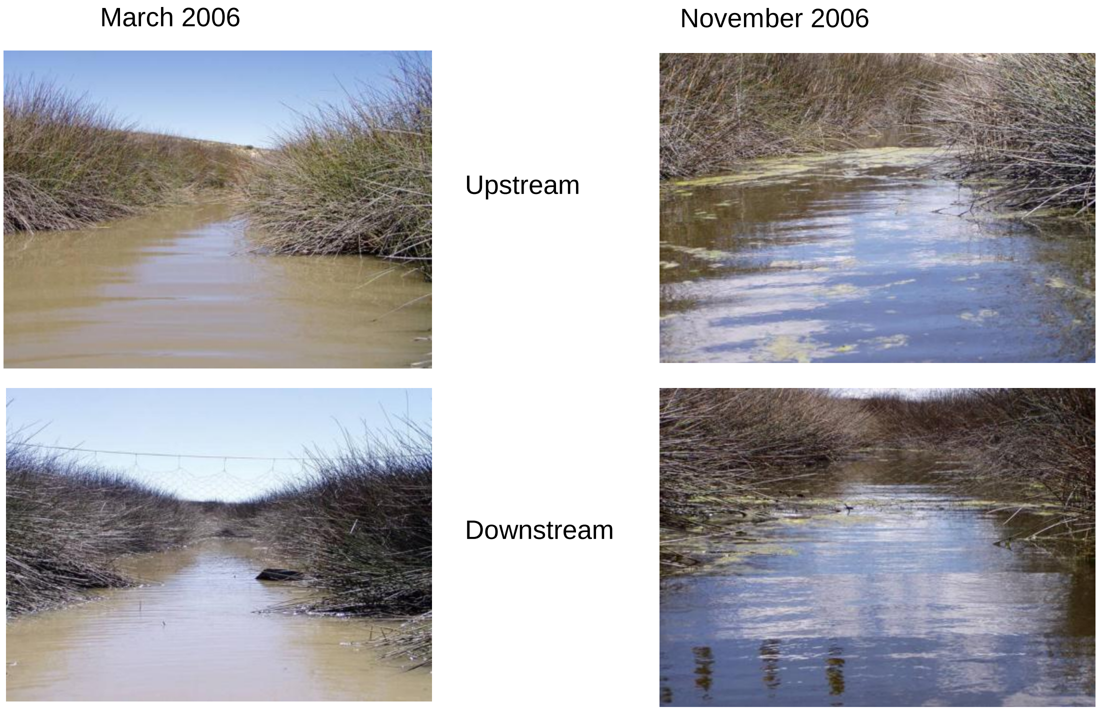
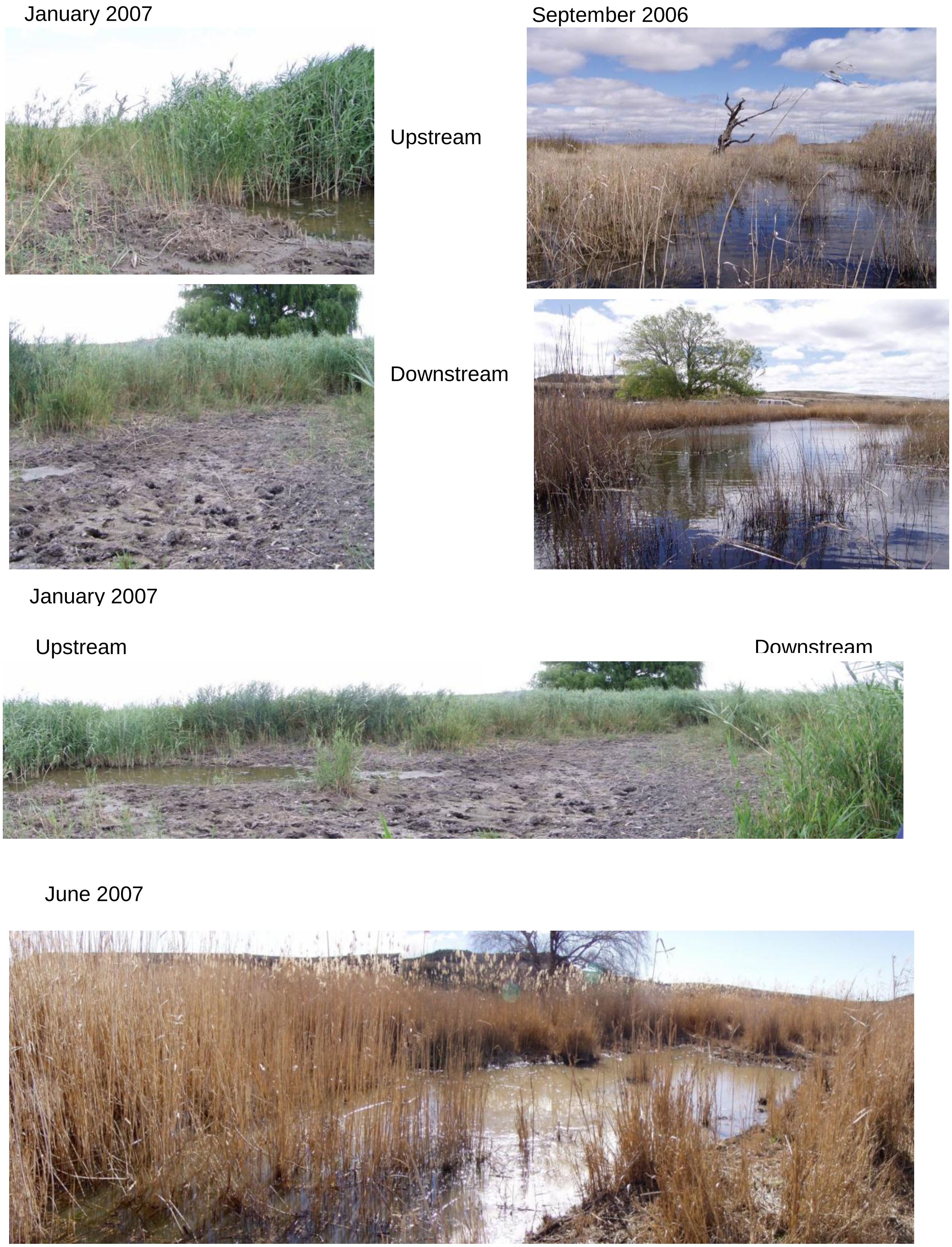


Figure 7: Upstream and downstream photographs for EWR 1 (Photos from CEM, 2006)

Site 2 – EWR 2

The site was situated downstream of the confluence of the Seekoei and the Klein Seekoei Rivers on the farm, Haasfontein, south east of Hanover. The site was seen as representative of the river macro-reach. The pool was relatively natural – formed by a hydraulic control downstream. No formal abstraction sites were evident (Avenant, 2006).

The area was relatively flat with reedbeds surrounding the pool (Figure 8).



January 2007

September 2006

Upstream

Downstream

January 2007

Upstream

Downstream

June 2007

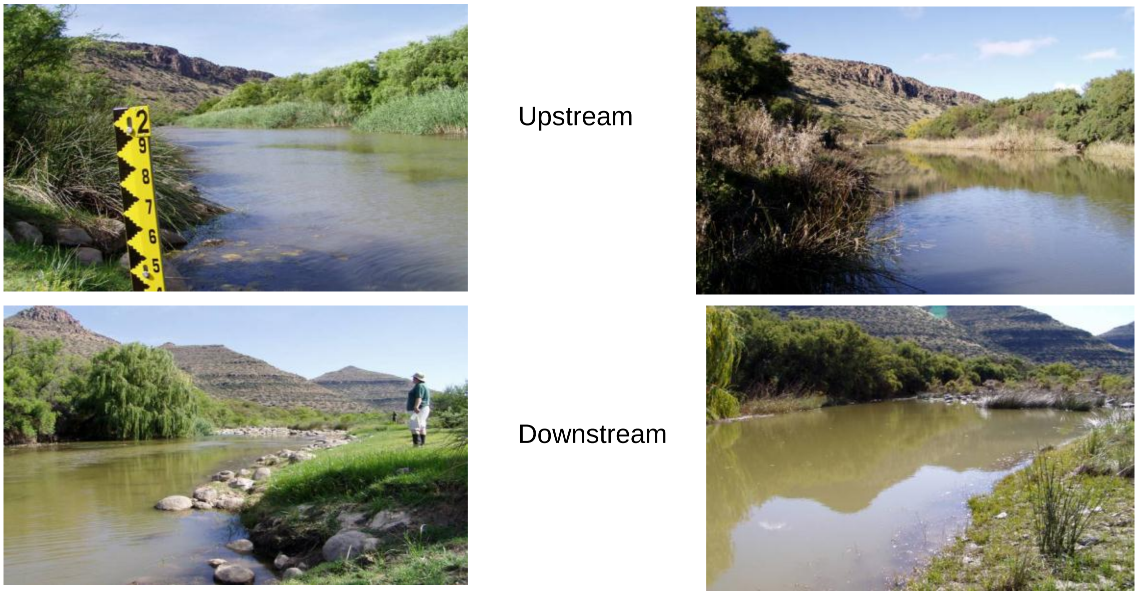
Figure 8: Upstream and downstream photographs for EWR 2 (Photos from CEM, 2007)

Site 3A – EWR 3

Sites 3A and 3B were located on the farm Holfontein, north of Colesberg. The site was situated upstream of gauging station D3H015. This gauging station had a good flow record for the last 25 years. The site was representative of the river reach where the slope of the valley was steeper and the incisions into the bedrock and dolerite created pools and rapids in the river channel (Dollar, 2005) (Figure 9).

January 2007

May 2006



Upstream

Downstream

June 2007

Upstream

Downstream

Pool

January 2007

Rapid

Figure 9: Upstream and downstream photographs for EWR 3 as well as the pool and the rapid (Photos from CEM, 2006, 2007)

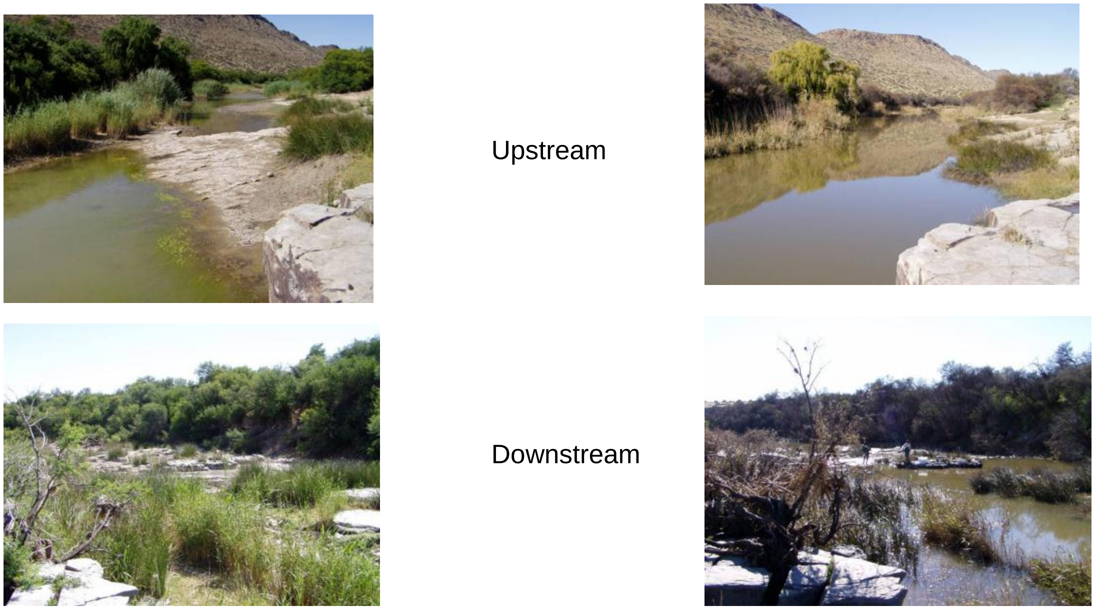
Site 3B – EWR 4

The site was situated upstream of gauging station D3H015. The site was representative of the river reach – bedrock bottom type pool (Figure 10).

Sites 3A and 3B have since been changed to Site 3 for 3A and Site 4 for 3B and the results are presented as data from Site EWR 3 and Site EWR 4.

January 2007

May 2006



Upstream

Downstream

January 2007

Downstream

Upstream

Pool

Rapid

Figure 10: Upstream and downstream photographs for EWR 4 as well as the pool and the rapid (Photos from CEM, 2006, 2007)

Additional sampling sites

Vaalkop Spring 1

Spring 1 is situated in a small (mostly dry), unnamed tributary of the Seekoei River upstream of site EWR 3. This spring is approximately 2.2 km from where the tributary joins the Seekoei River.

The spring surfaced as a result of the baked mudstone layer that forms the bed of the tributary/dry stream. The riparian/surrounding vegetation consists of typical karoo veld, i.e. trees and small shrubs. When the spring surfaces, water grass and filamentous algae can be found in the pools (Figure 11).

August 2006

Upstream

Downstream

Figure 11: Upstream and downstream photographs for Vaalkop Spring 1 (Photos from CEM, 2006)

Vaalkop Spring 2

Spring 2 is situated 900 m downstream of Spring 2 in the same tributary, about 600 m off stream in a smaller tributary.

The spring surfaced as a result of the baked mudstone layer that forms the bed of the tributary/dry stream and is mostly covered by gravel and sand. The riparian vegetation consists of large trees and few small shrubs, while the surrounding vegetation is also karoo type veld. The trees form a canopy over the spring most of the year. The spring mostly flows throughout the year and sustains grass in the streambed downstream from where it surfaced (Figure 12).

The weathered dolerite layer adjacent to the two springs and on top of the baked mudstone layer, forms the perched aquifer that is the water source of the two springs.

August 2006

Figure 12: Photographs for Vaalkop Spring 2 (Photos from CEM, 2006)

D3H015 – Q01 DWA Gauging Station – EWR 6

The upper part of the Seekoei River catchment is steep with flood-out type channels, resulting in surface water becoming dispersed and disappearing very quickly on the flat plain immediately downstream. EWR sites 1 and 2 were situated in this area. The lower reaches of the river, where sites EWR 3 and 4 were located, is situated in a gorge extending approximately 8 km. Although this area covers a small area of the total catchment, most of the flow recorded (Figure 13) at the measuring weir (D3H15-Q01 at De Eerste Poort), is generated here, and has a major influence on the flow regime (Hughes, 2007).

Prolonged flow (after events) occurs only in the lower part of the catchment and is attributed to unsaturated zone drainage from the high topography area in the vicinity of the gorge. There are also a number of springs that feed into the river upstream of EWR 3.

However, field visits indicated that these flow characteristics do not extend very far upstream of the gauging station (Figure 14) and that while there is flow in the channels of the lower part of the catchment, the upstream channels do not experience flow. This observation was consistent with the low topographic gradients in the upper parts of the catchment (Hughes, 2007).

The only DWAF gauging station with water quality data within the catchment is on the Seekoei River at De Eerste Poort (D3H15-Q01). The data from this site is the only historical water quality data available for the study area. The full data period is from 1980 to 2006.

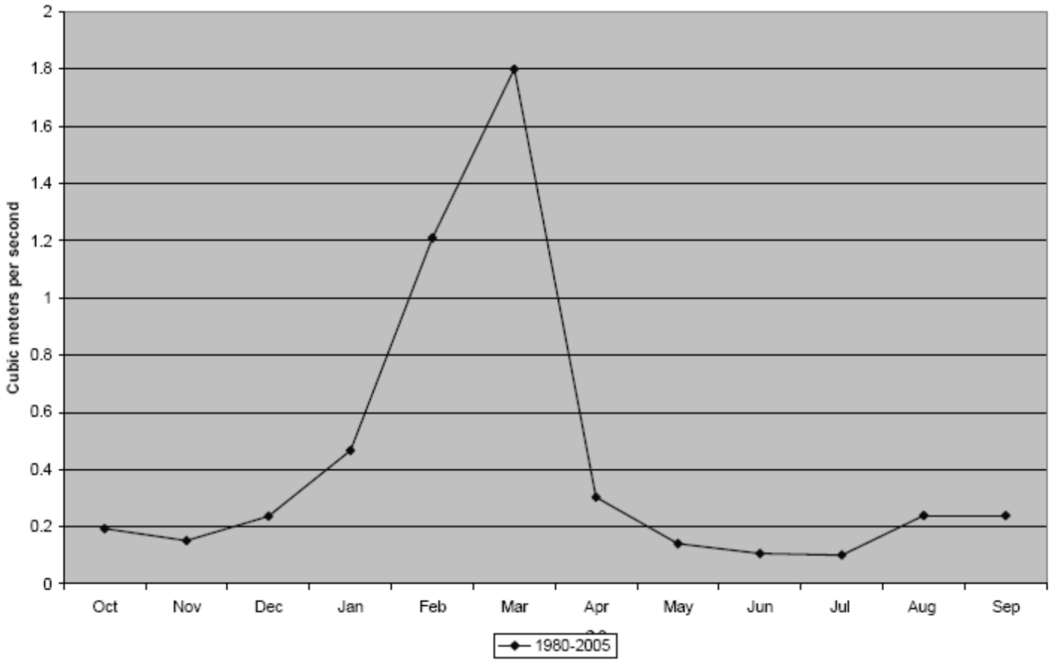


Figure 13: Mean monthly stream discharge at Gauging station D3H015 (DWAF, 2005)

January 2007

August 2006

Upstream

Downstream

June 2007

Figure 14: Upstream and downstream photographs for D3H015 – Q01 DWA Gauging Station – EWR 6 (Photos from CEM, 2006, 2007)

One of the most critical issues that has the potential to impact on ecological functioning in non-perennial rivers systems, is the dynamics of pool storage. Pools in the Seekoei River occur mostly upstream of hydraulic controls: In the upper part of the catchment the controls tend to be sedimentary features, and in the lower parts dolerite intrusions. Under drying conditions, the dynamics of the pool storage in the lower part of the catchment seemingly depended upon the balance between spring discharge and pool evaporation, which will differ between seasons. In the upper parts of the catchment, where there was little evidence of spring flow, it is possible that small contributions to pools are made through connections with the groundwater, but these are expected to be relatively small due to the low hydraulic gradients. Most of the pools in the upper part of the catchment were therefore expected to dry out relatively rapidly, depending on the evaporative demand (Avenant *et al*, 2007).

7.3 Data requirements

Data can be divided into three components: physical, chemical and biological measurements for both surface and groundwater sampling. The data requirements set out below also link up with the water quality data requirements of the invertebrates, fish and riparian vegetation specialists.

A broad based-approach was followed in that more, rather than fewer samples and constituents were measured as a starting point. The aim was to investigate the Seekoei River, to develop an understanding of the functioning of a non-perennial river. A broad based approach was also followed to determine the critical minimum chemical and physical parameters, that would be required to reach a scientifically defendable result in future environmental water quality assessment of non-perennial rivers.

7.4 Field sampling procedure

Water quality samples were collected according to standard practices at the EWR sites over a period of 18 months from November 2005 to June 2007. Samples were taken every two to three months depending on the availability of the team and the budget.

In situ measurements were made at each sampling site and subsurface water samples (1.5 – 2 litres) were collected from the shore and brought to the laboratory at CEM for further physical and chemical analysis. Samples were kept in dark containers on ice during transportation and stored in a refrigerator (≤ 5 – 0°C) until the analyses could be done in the laboratory.

The procedures followed at each sampling site were:

- The sampling point was located using a handheld GPS (Garmin:eTrex Vista Personal Navigator GPS).
- The water quality observations and samples were taken before the fish or invertebrate sampling commenced as both these activities create disturbances in the water which influences the water quality measurements.
- The sampling bottles were marked with the date and sampling location.
- The following information was recorded on the field data sheets:
    - Name of the site and sampling point, the date, the time, the time of sampling, and the names of the samplers.
    - Sampling point coordinates from the GPS reading and altitude.
    - Water and weather condition observations at the site (for example cloudy or sunny, windy, water colour, sediment and algae, aquatic and other (reeds) plants or odours)
    - Any other factors or conditions that may potentially influence the sample results.
- The water temperature (°C), conductivity (µS/cm), total dissolved salts (mg/ℓ), concentration of dissolved oxygen (mg/ℓ) and percentage of saturation (O_2%) were measured with a YSI Model 85 oxygen, conductivity, salinity, temperature meter. These were done *in situ* from the shore. Conductivity and TDS serves as an indicator of the amount of dissolved salts in the water.
    - The YSI Model 85 instrument was calibrated as per the manufacturer’s instructions (once per day).
    - The probe was lowered into the water to just below the water surface, allowed to acclimate and the readings were taken and recorded on the field data sheet.
- The above procedure was repeated for the pH and redox measurements *in situ* with a Euteck Instruments CyberScan pH 110 meter (pH/mV/°C/°F with RS232).
- A number of surface water samples were then collected.
- All the samples were then stored in a cooler box with ice for transport to the laboratory. Once in the laboratory, the samples were stored in a refrigerator (≤5 – 0°C) until the analyses could be done.
- A marked 500 mℓ sampling bottle was lowered into the water to just below the water surface for the chemical analysis of the sample.
    - The water that was used for chlorophyll-*a* analyses was filtered on site directly after taking the sample and the filter paper stored in foil on ice until the laboratory was reached. Subsurface water to be used for algal composition assemblage (phytoplankton) identification was preserved using formaldehyde (2%) in 100 mℓ bottles.

- Diatom samples were collected according to the method described in Taylor *et al* (2005) and Taylor *et al* (2007) and preserved with 90% alcohol in 100 mℓ bottles.
- Samples collected for turbidity measurements were taken back to the laboratory.
- All the sampling equipment was then cleaned and rinsed with distilled water and stowed for transport to the next sampling site.
- The flow (m/s) was measured in the river by using an OTT Z30 Counter attached to an OTT Small Current Meter C2, by placing the propeller 4/10's from the bottom of the water column depth

7.5 Laboratory sample analysis

All the water quality samples collected for both chemical and biological analysis were analysed using existing standard methods.

Chemical analysis

Dissolved reactive ortho-phosphate (PO_4-P) was determined using 100 mℓ GF/C water, already filtered in the field, together with the Stannous Chloride Method as described in *Standard Methods* (2005). Ammonium molybdate reacts with stannous chloride, whereby molybdophosphoric acid is formed and reduced by stannous chloride to intensely coloured molybdenum blue. Absorbency was read at 690 nm by using a VIS-7220 spectrophotometer, after which the unknown concentrations were determined by plotting them against a standard curve of known concentrations for each of the analysis.

The Institute for Groundwater Studies (IGS) at the University of the Free State analysed the following constituents using an Inductively Coupled Plasma (ICP) Spectrometer: Calcium (Ca^{2+}), Magnesium (Mg^{2+}), Sodium (Na^{1+}), Potassium (K^{1+}), Phenolphthalein alkalinity (Palk), Total alkalinity (Methylene orange - Malk), Chloride (Cl^{1-}), Nitrate-nitrogen (NO_3-N), Phosphate (PO_4^{3-}), Sulphate (SO_4^{2-}), and Ammonium-nitrogen (NH_4-N). All the above constituents that were measured were used to calculate the total dissolved salts (TDS), NO_3-N plus NH_4-N were used to calculate the dissolved inorganic nitrogen (DIN) and PO_4-P was used as dissolved inorganic phosphorus (DIP).

The following constituents were also measured by the Institute for Groundwater Studies at the University of the Free State using an ICP Spectrometer: Silica (Si), Fluoride (F^{1-}), Aluminium (Al), Arsenic (As), Boron (B), Copper (Cu), Cadmium (Cd), Iron (Fe), Manganese (Mn), Lead (Pb), Zinc (Zn), Total Organic Carbon (TOC), Dissolved Organic Carbon (DOC). The Chemical Oxygen

Demand (COD) and Biochemical Oxygen Demand (BOD) were also determined and the Total Phosphates (TP) and Total Nitrogen (TN) calculated.

Turbidity

Turbidity was determined with an Aqua Lytic Turbidimeter AL 1000 and was expressed as Nephelometric Turbidity Units (NTU). It is a measurement of the light scatter caused by particulates in a water sample such as suspended organic, inorganic and biological material. Secchi depth was measured using a Secchi-disc from the shore.

Determination of Chlorophyll-a concentration

Chlorophyll-*a* is used as an index of trophic status and is based on the fact that it is normally the most abundant and important pigment in phytoplankton cells. Therefore, measurements provide a convenient estimation of the algal biomass (Walmsley, 1984). Chlorophyll-*a* in the Seekoei River was measured using a modified method described by Sartory and Grobbelaar (1984) and Stevenson and Bahls (1999), and involved filtering a known volume of water through a GF/C filter paper, after which the filter paper was suspended over night (<12h) in 10 mℓ 95% ethanol to extract the chlorophyll from the algal cells. After filtration in the field, the filter paper was placed in foil and in the fridge to keep it from light. The filter paper was placed in alcohol in the laboratory. The absorbency was measured at 665nm and 750nm. After adding 100 µl of 0.3 N HCl, the absorbency was again measured after 2 minutes using a VIS-7220 spectrophotometer.

Collecting Diatoms

Diatoms were sampled according to methods as described by Taylor *et al* (2005). At site EWR 1 diatoms were collected from sedges, at site EWR 2 from reeds, and at sites EWR 3 and 4 from stones in current (cobble) by scrubbing the substrate clean and preserving the material collected in a 100 mℓ bottle with 10 mℓ 95% ethanol. Diatom identification was done for the March and September 2006 samples by Dr J Taylor at the North West University Campus, Potchefstroom.

Algal species composition

An inverted Zeiss Light Microscope was used to identify the dominant algal genera after fixation with formaldehyde (final concentration of 2%) and the sample was then placed in a sedimentation chamber for at least 24 hours. The number of a specific algal genera was determined in a known volume of water, counting the individuals (cells, filament and colonies) occurring in 20 blocks of known dimensions. The result was multiplied by a constant to obtain the total counts. Algal genera were determined as a percentage of the total community.

Bacterial analysis

The bacterial counts for Total coliforms and *E. coli* were done by the Institute for Groundwater Studies at the University of the Free State using the IDEXX Colilert Method.

7.6 Results and discussion

In this section both historical data as well as the data collected over the eighteen month study period (November 2005 to June 2007) was discussed and where appropriate water quality reserve methods (DWAF, 2008a) were applied using all the water quality data that were available.

Historical data

The analysis of the historical data were dealt with in two sections. The first section presents a water quality situation assessment of the Seekoei River at the DWA D3H015-Q01 gauging station using water quality data collected at that point. The second section presents the application of the TEACHA model (as discussed in Section 6.2) to determine a Rapid Ecological Water Quality Reserve also using the data from the D3H015-Q01 gauging station.

7.6.1 Water quality situation assessment at D3H015-Q01

The water quality data for gauging station D3H015-Q01 are available from DWAF: Resource Quality Services and were retrieved from their Water Management Systems (WMS) data storage facility for the whole record period (1981 to 2006).

Salinity

Long-term Changes – there appears to be a small decreasing trend in the TDS/EC (Figure 15). The data set also indicate a large variability from year to year, i.e less than 200 mg/ℓ in 1991 to almost 600 mg/ℓ in 1992 to more than 1800 mg/ℓ in 1993. During the drier years such as in the 1992/1993 season the TDS can increase dramatically as the weir dries up at the gauging station.

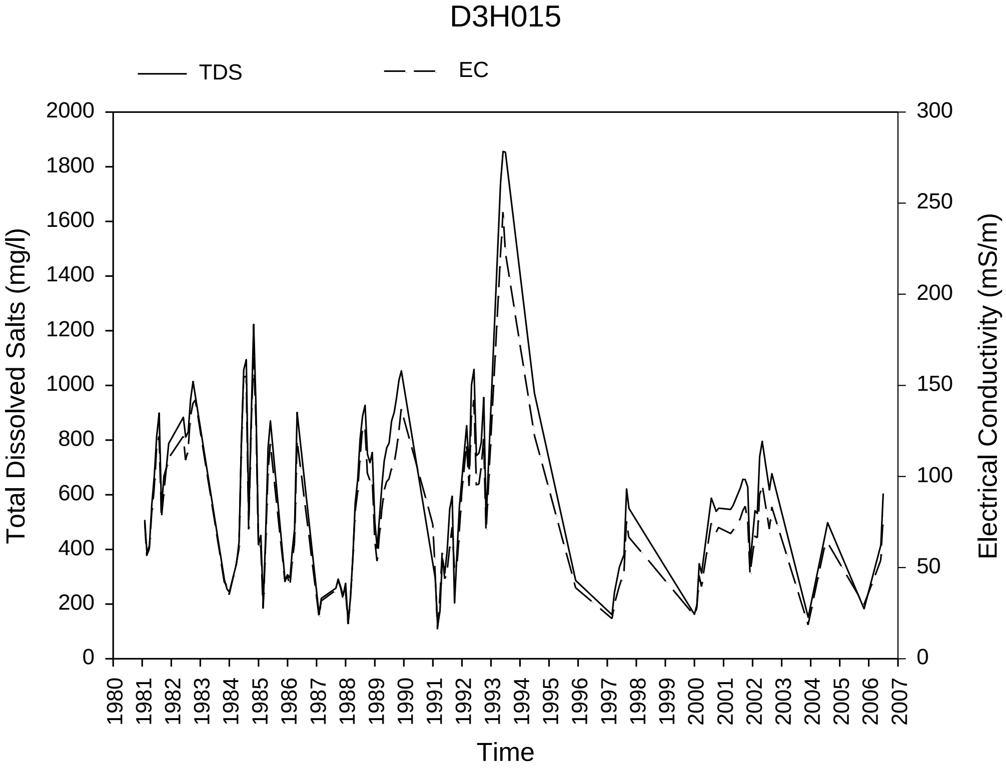


Figure 15: Long-term TDS trends at Gauging Station D3H015 (Seaman *et al*, 2010)

Sodium and chloride are the dominant ions, with sulphate, magnesium and calsium also present in considerable amounts, as can be seen from the following two graphs (Figures 16 and 17).

The box-and-whisker plot used (Figure 16) is a method of presenting statistical characteristics of a data set. The minimum and maximum, as well as the 25th, 50th and 75th percentile values are determined. The 25th percentile, for example, implies that 25 percent of all the observations were lower than that value. In the box- and-whisker plot, the lower and upper sides of the box represents the 25th and 75th percentile values, indicating that 50% of all the observations fell within that range. The 50th percentile, also called the median, indicates average conditions and falls somewhere within the box. The whiskers extend from the box to the minimum and the maximum values. The dotted lines represent the mean values and the dots above the whiskers are outliers.

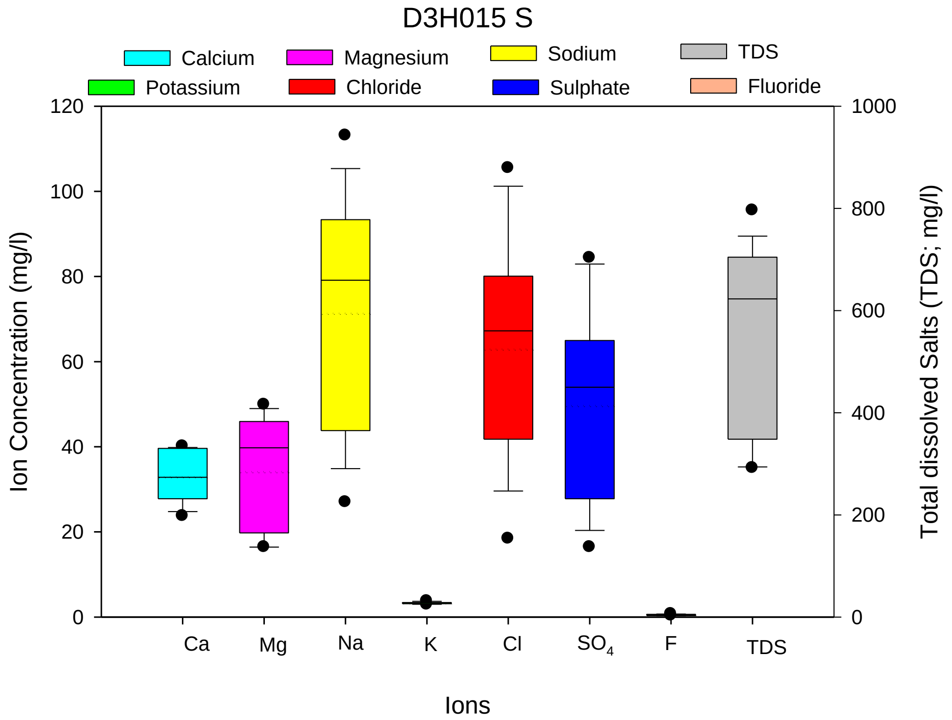


Figure 16: Box-and-whisker plot illustrating the dominant ion concentrations from 1980 to 2007 at Gauging Station D3H015 (Seaman *et al*, 2010)

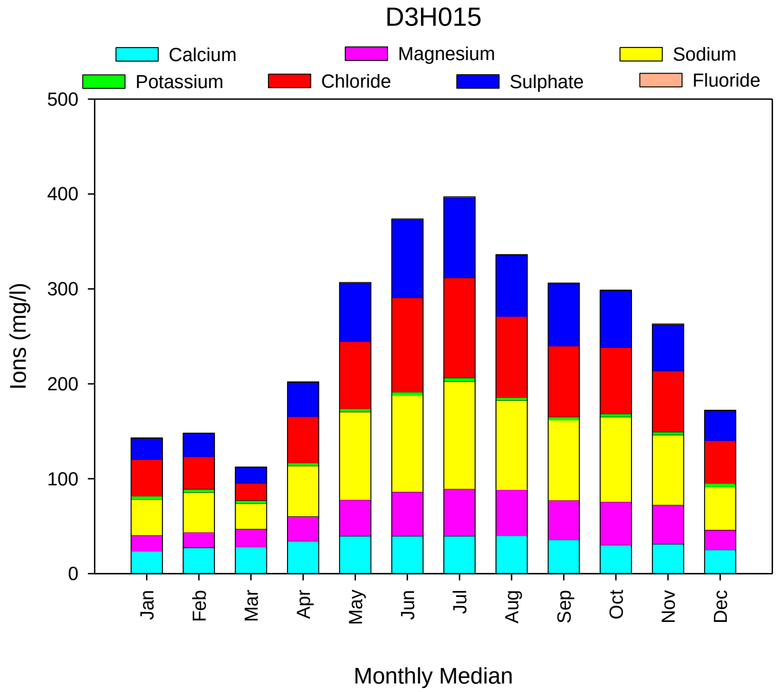


Figure 17: Vertical bar graph illustrating the seasonal ion concentration pattern from 1980 to 2007 at Gauging Station D3H015 (Seaman *et al*, 2010)

Seasonal changes – a strong seasonal trend is evident in TDS/EC with elevated TDS concentrations occurring during the drier winter months. This can be seen from the seasonal graph above (Figure 17) and the graph below (Figure 18).

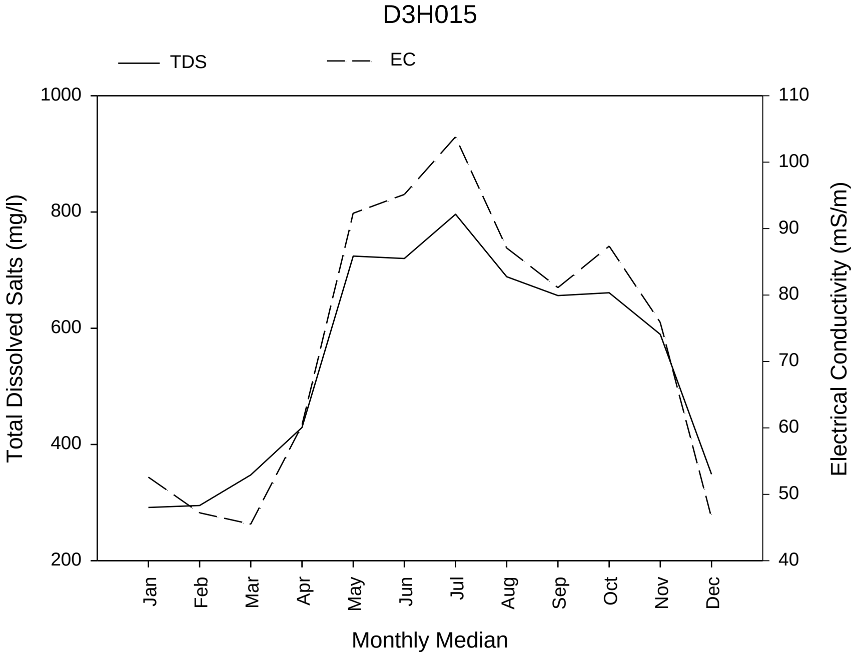


Figure 18: Seasonal distribution of long term median monthly TDS/EC values (Seaman *et al*, 2010)

There were no routine measurements available for temperature, dissolved oxygen, total suspended solids or toxic substances. These measurements are not critical for the basic EWR assessment, but could be crucial in catchments where pollution from mining, industrial, agricultural or domestic is expected.

Nutrient status

Long-term Changes – there does not appear to be a definite trend in the Dissolved inorganic nitrogen (DIN) or phosphate (DIP) (Figure 19).

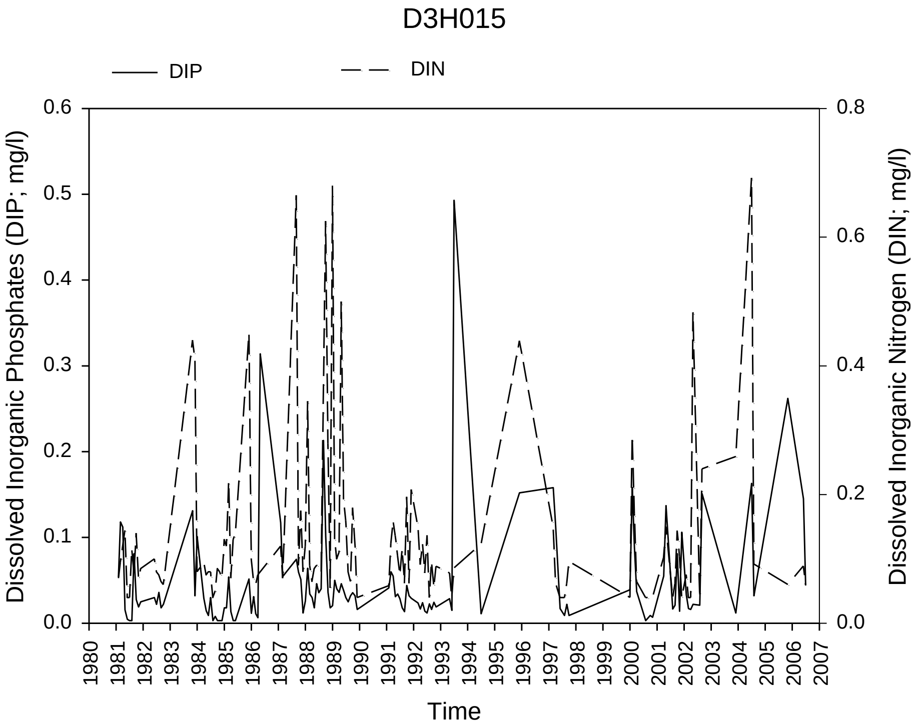


Figure 19: DIP and DIN concentrations over time (Seaman *et al*, 2010)

Seasonal changes – a seasonal trend is evident. The DIP decreases over the winter months whereas the DIN shows an increase and then a decrease before increasing again during the warmer summer months (Figure 20). The decrease in the DIP values can be explained by the fact that the phosphates have been used by the algae during the summer months and have not been replenished by rain. Caution must be used when evaluating the seasonal trends, especially with the DIN.

The DIN data were collected infrequently during the months of May (11 times out of the 26 year record, and only once to twice for that month compared to two to four samples taken for the other months). One would normally expect the DIP and DIN values to follow the same increasing and decreasing pattern, which is not indicated in Figure 20.

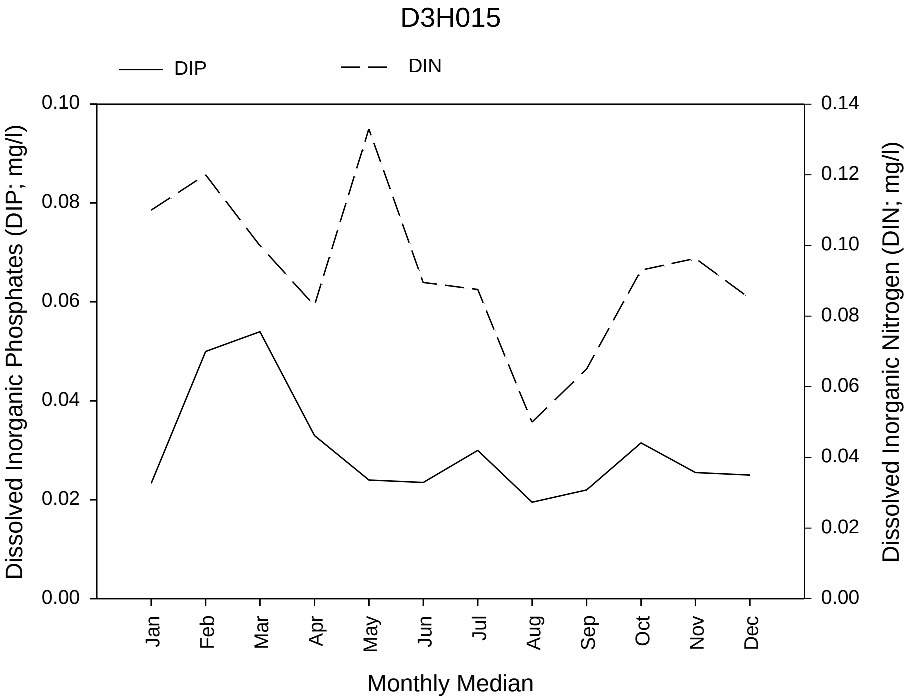


Figure 20: Seasonal trends for median monthly DIP and DIN (Seaman *et al*, 2010)

7.6.2 Rapid Ecological Water Quality Reserve

The data from the water quality gauging station (D3H015-Q01) were used to determine a Rapid Ecological Water Quality Reserve using the TEACHA 1.32 model developed by Dr Jooste. The results are presented in Appendix 1.

A summary of the results is presented below. The format of the results is the same as that presented to the Director-General of DWAF for approval of the Ecological Water Quality Reserve.

D3H015-Q01
General Chemistry – major inorganic salts

Parameter	Ecological Reserve[1]	Basic Human Needs Reserve	Water Quality Reserve[2]
$MgSO_4$ (mg/ℓ)	< 221	N/A	< 221
Na_2SO_4 (mg/ℓ)	< 41	N/A	< 41
$MgCl_2$ (mg/ℓ)	< 92	N/A	< 92
$CaCl_2$ (mg/ℓ)	< 88	N/A	< 88
NaCl (mg/ℓ)	< 615	N/A	< 615
$CaSO_4$ (mg/ℓ)	< 351	N/A	< 351

[1] - 95th percentile compliance. [2] - DWAF 2002

Nutrients

Parameter	Ecological Reserve[1]	Basic Human Needs Reserve	Water Quality Reserve
Phosphate (PO_4-P (mg/ℓ):	< 0.07	N/A	< 0.07
Total Inorganic Nitrogen (TIN) (mg N/ℓ)	< 0.23	N/A	< 0.23

[1] - 95th percentile compliance

Physical water quality

Parameter	Ecological Reserve	Basic Human Needs Reserve[2]	Water Quality Reserve
pH (range) **5th percentile** **95th percentile**	 > 5.6 < 9.2	5 – 9.5	 > 5.6 < 9.2
Dissolved Oxygen (mg/ℓ)	> 6.0	N/A	> 6.0

[2] - Water Research Commission (1998)

Toxic substances and complex mixtures

Parameter	Ecological Reserve	Basic Human Needs Reserve[2]	Water Quality Reserve[3]
Ammonia (mg NH_3-N/ℓ)[1]	< 0.007	N/A	< 0.007
Toxicity	Natural – 100% species protection extrapolated from 95% CEV	<TWQR	Natural – 100% species protection extrapolated from 95% CEV

where: TWQR is the Target Water Quality Range

CEV – Chronic Effect Value

[1] - 95th percentile

[2] - DWAF (1996a)

[3] - DWAF (1996b)

NOTE: Where there were differences in the water quality values for the present ecological status and basic human needs, the lower or more protective value was selected for the water quality Reserve.

Only the data from the gauging station could be used to determine the Rapid Ecological Water Quality Reserve for the Seekoei River as the EWR sites 1 to 4 did not have sufficient or any long term data to use with the TEACHA model. However, the results from this reserve were not appropriate for the whole Seekoei River as the following section will indicate.

Present day data

In this section the water quality situation of the Seekoei River, based on the present day data that were collected over the 18 month research period, were assessed. Some information on the impact of the water quality on the invertebrates and the fish will also be discussed.

7.6.3 Water quality situation assessment at EWR sites 1, 2, 3, 4 and 6

The raw data for all the sampling sites as well as all the graphs are available from the author. The study period was from November 2005 to June 2007.

Physical water quality

Water Temperature

The water temperature typically followed a winter low, summer high temperature profile at all the EWR sites as can be seen in Figure 21. A summary of the water temperatures at all the EWR sites are presented in Table 11.

Table 11: Summary of the water temperatures at the different EWR sites

Temperature in °C	EWR 1	EWR 2	EWR 3	EWR 4	EWR 6	Spring 1	Spring 2
Median	12.30	17.70	18.50	18.80	16.60	18.20	20.60
Minimum	4.60	7.10	7.50	5.20	10.80	9.00	18.30
Maximum	26.00	29.10	26.00	27.20	32.80	33.60	22.60
10% Conf	5.10	7.90	7.70	6.73	12.06	12.10	18.72
90% Conf	24.02	27.66	25.10	24.86	29.93	28.15	22.54

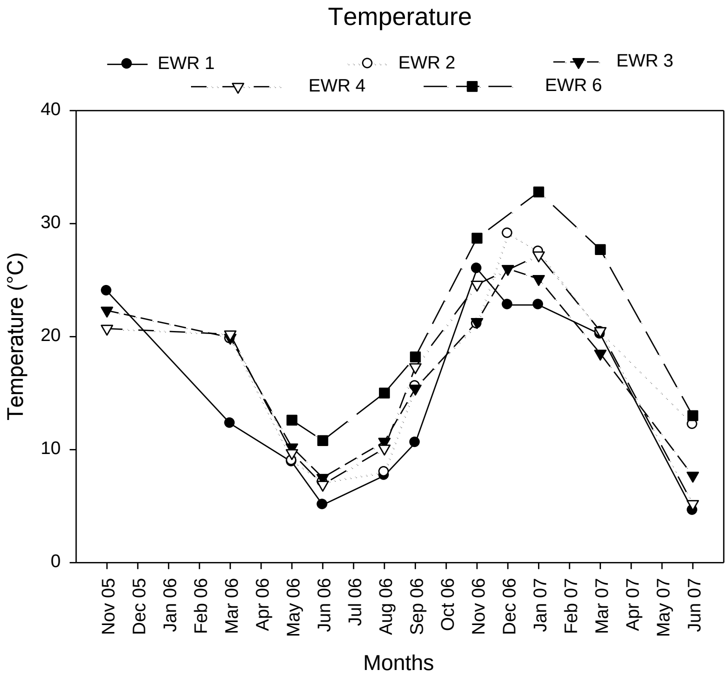


Figure 21: Water temperature over time at the different EWR sites (Seaman *et al*, 2010)

Dissolved Oxygen

The dissolved oxygen concentrations (Table 12) were generally higher during the colder winter months, except at Spring 2 where the dissolved oxygen concentrations were always low. One would assume that the point of sampling at the spring is very close to where it emerges into the surface water from below and has not yet been oxygenated.

Table 12: Summary of the dissolved oxygen at the different EWR sites

Diss oxygen in mg/ℓ	EWR 1	EWR 2	EWR 3	EWR 4	EWR 6	Spring 1	Spring 2
Median	7.65	6.71	6.06	7.32	8.30	9.71	2.01
Minimum	2.91	1.22	3.44	4.14	7.28	6.33	1.72
Maximum	11.25	11.35	9.38	9.40	11.88	15.60	6.03
5% Conf	3.93	1.61	3.48	4.19	7.51	6.80	1.73
95% Conf	1.55	2.47	1.41	1.40	1.22	3.35	1.43

Turbidity

The turbidity was generally low as can be seen from Table 13 and light limitation has a low probability of being a limiting factor for algal growth.

Table 13: Summary of the turbidity at the different EWR sites

Turbidity in NTU	EWR 1	EWR 2	EWR 3	EWR 4	EWR 6
Median	17.30	9.70	6.15	15.65	5.30
Minimum	1.42	3.40	3.60	4.50	2.50
Maximum	152.00	28.00	122.00	39.00	20.20
5% Conf	1.77	4.12	4.32	5.00	2.50
95% Conf	32.25	7.50	25.94	9.19	5.54

pH

The pH had a neutral to alkaline profile at all the EWR sites as can be seen from Figure 22 and Table 14. The alkalinity is the result of the geology of the area. The pH at EWR Site 2 is slightly lower that at the other EWR sites and is the result of the local geology. The higher pH values during the summer months are the result of the increased algal growth, releasing more oxygen into the water and increasing the pH values. February and March are generally your higher rainfall periods and algae are “washed”out of the system, lowering the oxygen in the water and decreasing the pH values. During the winter months algal growth is limited mainly by the colder temperatures.

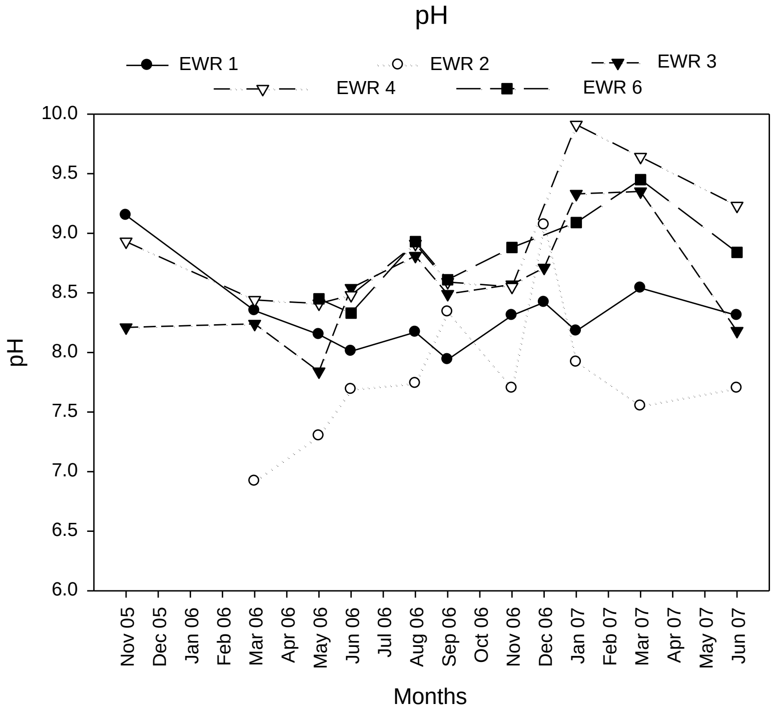


Figure 22: The pH distribution over time at the different EWR sites (Seaman *et al*, 2010)

Table 14: Summary of the pH at the different EWR sites

pH	EWR 1	EWR 2	EWR 3	EWR 4	EWR 6	Spring 1	Spring 2
Minimum	7.94	6.92	7.84	8.41	8.33	7.34	6.83
Maximum	9.15	9.07	9.35	9.91	9.45	8.30	7.08
5% Conf	7.98	7.09	8.01	8.42	8.37	7.37	6.84
95%Conf	0.22	0.42	0.31	0.38	0.30	0.36	0.09

General Chemistry – major inorganic salts

The total dissolved salts (TDS) were measured at each EWR site and the ionic composition was determined in the laboratory. Table 15 below indicates that EWR 1 had a much higher TDS concentration than any of the other sites. EWR 2 had the lowest concentration, whereas EWR 3, 4 and 6 had very similar concentrations, as was expected. The springs also have different TDS concentrations from the EWR sites.

Table 15: Summary of the TDS concentrations at the different EWR sites

TDS in mg/ℓ	EWR 1	EWR 2	EWR 3	EWR 4	EWR 6	Spring 1*	Spring 2*
Median	1968	365	741	675	746	466	456
Minimum	968	206	307	366	311	455	453
Maximum	2582	671	865	1103	2450	477	458
5% Conf	1203	224	345	367	401	132	456
95%Conf	327	125	141	166	612	31	454

* Only two samples were collected

Comparing the ionic composition at the different sites it was found that different ions dominated at the different sites. At EWR 1 sodium, chloride and sulphates dominated. EWR 2 was different from the others in that calcium, sodium and then chloride and magnesium were the dominant ions. EWR 3 to 6 were mostly sodium and chloride dominant with some sulphates and magnesium forming part of the TDS at site EWR 3 and some sulphates at EWR 6. The two springs were calcium, magnesium and sulphate dominant. This indicated that the local geology and sources of water to the EWR sites determined the chemical footprint of a particular site.

The pool depths at the EWR sites also played an important role in the TDS concentrations. The pool depth was more or less constant over the study period at EWR 1. However, the TDS concentration varied from a minimum of 968 mg/ℓ in March 2006 to a maximum of 2582 mg/ℓ in June 2006 even though the water level was constant. This may imply that the pool is groundwater fed, but that not sufficient “fresh” water enters the pool as surface flow to dilute the high TDS concentrations. It was assumed that the high TDS occurred naturally due to the local geology. White crysteline deposits were found around the pool where salts have precipitated. This can be a natural occurance as salt-affected soils of primary origin result from the long-term influence of natural processes accumulating salts in a particular region (Bailey *et al*, 2006).

The rapid increase in TDS during the base flow recession period suggests an additional mechanism apart from the spring flow and surface runoff. This, according to Hughes (2007), may be related to the storage of salts within the pools and adjacent soils that is absorbed during pool drying and gradually released after the pools have been re-filled.

At EWR 2 to 6 the TDS concentrations increased as the water level dropped due to evaporation and evapo-transpiration.

Similar results were found in a study at Cooper Creek in Australia (Hamilton *et al*, 2005). Evaporation controlled the water levels in the pools between flows. The TDS concentration increased as the water levels dropped. However, they also found that there were distinct differences in the ionic composition between the different pools and cautioned that one needs to investigate the water source inputs into the different pools in order to understand a non-perennial system. Additionally they stated that the geology, morphology and channel and riparian-zone features should also be considered when investigating pools in a non-perennial system.

Groundwater water quality

A number of boreholes were drilled at each of the EWR sites (Sites 1 to 4). At least three boreholes were drilled in a triangular pattern along each of the four pools. The purpose was to determine the direction of groundwater flow and to develop an understanding of the interaction between the groundwater, surface water and springs. The results were presented in Van Tonder *et al* (2007). The only water quality measured was the electrical conductivity (Table 16). The EC measurements were not taken at the same time or same place (for the pools) as the surface EC measurements. Because of this, the values for surface and groundwater EC cannot be compared directly. However at EWR 1 it was clear that the pool EC was much higher than that of the boreholes, whereas at EWR 2 to 4 the pool and borehole water EC values were mostly similar.

Table 16: Borehole and pool EC measurements in mS/m at the different EWR sites

Borehole number at each EWR Site	2006	March 2007	October 2007
EWR 1			
BH1	197	160	137
BH3	61	109	86
BH4	90	Dry	Dry
BH5	161	126	110
Pool	420		
EWR 2			
BH1	95	82	78
BH2	100	86	97
BH3	48	46	56
BH4	48	43	38
Pool	36		
EWR 3			
BH1	82	78	128
BH2	99	92	95
BH3	81	85	86
Pool	90		
EWR 4			
BH1	87	76	77
BH2	85	51	82
BH3	80	78	86
BH4	86	52	77
Pool	86		

In the case of a non-perennial river, the two most important mechanisms for pool sustainability and maintenance is the number and flow rate of springs upstream of pools and/or the groundwater flux towards pools in the channel aquifer (Van Tonder *et al*, 2007). Although the groundwater-surface water interaction was not part of the existing perennial river methodologies it became clear that in non-perennial rivers this can be a critical component in understanding the water quality in the river and pools.

A conceptual model for interflow and groundwater springs were developed by Van Tonder *et al* (2007) and is presented in Figure 23.

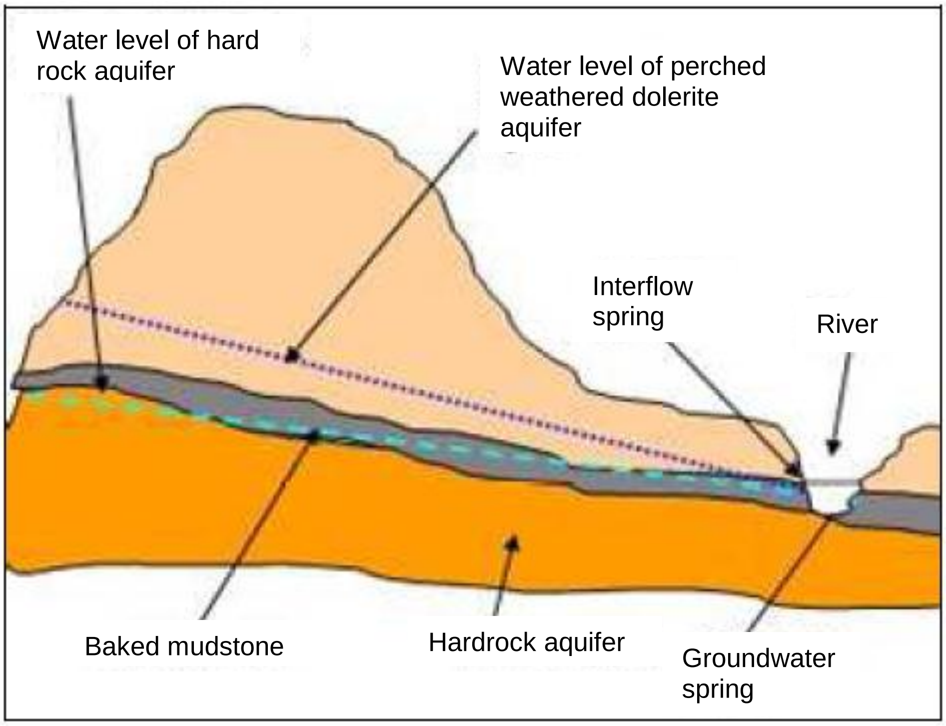


Figure 23: A conceptual model for interflow and groundwater springs (Van Tonder *et al*, 2007)

Interflow is “the water that infiltrates the soil surface and moves laterally through the upper soil horizons until it is intercepted by a channel, or until it returns to the surface downslope of its point of infiltration”. Wet weather seeps and springs are the result of interflow. Interflow usually occurs in the headwater (upper catchment) part of steams, while groundwater baseflow occurs in the middle and lower parts of the catchment (Rossouw *et al*, 2005).

In the Seekoei River the flux towards the pool from the hard rock aquifer adjacent to pools is usually very low and most of this flow will be used by riparian vegetation (Van Tonder *et al*, 2007). The pool/river water quality will not be influenced by this flux.

Nutrients

Nutrients will be discussed in more detail under phytoplankton. The tables below present the concentration ranges for DIP (Table 17) and DIN (Table 18) during the sampling period.

Table 17: Concentration ranges for DIP at the different EWR sites

DIP in mg/ℓ	EWR 1	EWR 2	EWR 3	EWR 4	EWR 6	Spring 1*	Spring 2*
Median	0.065	0.094	0.047	0.013	0.042	0.105	0.100
Min	0.029	0.028	0.001	0.001	0.001	0.100	0.100
Max	0.360	1.430	0.130	0.150	0.160	0.110	0.100
5% Conf	0.070	0.438	0.032	0.034	0.051	0.060	0.000
95%Conf	0.035	0.034	0.001	0.001	0.005	0.101	0.100

Table 18: Concentration ranges for DIN at the different EWR sites

DIN in mg/ℓ	EWR 1	EWR 2	EWR 3	EWR 4	EWR 6	Spring 1*	Spring 2*
Median	0.202	0.224	0.161	0.166	0.191	1.394	1.992
Min	0.053	0.078	0.056	0.053	0.049	0.714	1.973
Max	4.629	0.311	0.703	0.265	0.948	2.073	2.409
5% Conf	1.007	0.063	0.134	0.045	0.242	8.177	0.611
95%Conf	0.060	0.080	0.055	0.058	0.051	0.782	1.975

* Only two samples were taken

Phytoplankton

More detailed discussions on the phytoplankton and periphytic/benthic diatoms are presented in Rossouw and Vos, 2008. The phytoplankton analysis (Table 19) measured as Chlorophyl-a was used as an indicator of the ability of the Seekoei River to sustain algal growth. The concentrations that were measured indicated that the values were high enough to sustain algal growth. The Chlorophyl-a values also indicated that there were sufficient alga available to sustain invertebrate populations. The concentrations were, however, low enough not to pose a threat of developing into nuisance algal populations (Rossouw and Vos, 2008).

Table 19: Chlorophyll-a concentrations at the different EWR sites

Chl-a in µg/ℓ	EWR 1	EWR 2	EWR 3	EWR 4	EWR 6
Median	24.00	23.64	6.81	7.17	12.63
Min	5.02	3.58	1.00	1.00	1.00
Max	150.47	47.29	153.33	44.42	42.99
5% Conf	7.27	4.16	1.00	1.00	1.00
95% Conf	31.47	12.62	33.20	12.15	12.89

The discussion below briefly reviews the water quality factors that influence algal abundance.

Shading from a dense riparian canopy often limits the primary production in forest streams, but in arid-zone streams and rivers light is seldom considered a limiting factor as riparian vegetation is mostly sparse (Bunn *et al*, 2006b). For the Karoo-type vegetation that grows in the Seekoei River catchment, light was not considered a limiting factor as a result of riparian vegetation and as the water turbidity was low at all the sites, light has a low probability of being a limiting factor for algal growth as is illustrated in Table 20 below. The turbidity at EWR 4 was higher than at the other sites, except EWR 1, and as a result more phosphates were bound in the sediment particles than at the other EWR sites. This resulted in lower phosphate concentrations in the water and a much higher DIN:DIP ratio at EWR 4. This was based on limited data and caution must be exercised in interpreting the results.

Table 20: Turbidity units and nutrients at the different EWR sites

	Sites				
Parameter (Median)	EWR 1	EWR 2	EWR 3	EWR 4	EWR 6
Turbidity (NTU)	17.300	9.700	6.150	15.650	5.300
DIN (mg/ℓ)	0.200	0.220	0.160	0.170	0.190
DIP (mg/ℓ)	0.065	0.094	0.047	0.013	0.042
DIN:DIP	3.200	2.750	3.050	31.070	5.200

Another limiting factor for algal growth is temperature, and for the Seekoei River it was observed that the concentration of the total algal assemblage (algal assemblage data can be viewed in Appendix 4 in Rossouw and Vos, 2008,) decreased as the water temperature decreased.

The algal assemblage (at all the sites was dominated mainly by the Chlorophytes (green algae) and the Bacillariophytes (diatoms). A Spring Diatom Increase (SDI) occurred at all the sites (September to November 2006) as diatom growth was limited in winter by water temperature (Pritchard and Bradt, 1984). In the summer months the green algae numbers increased as conditions, such as higher light and temperature conditions, started to favour them over the other algal groups (Rossouw and Vos, 2008).

At all the sites the algal species diversity was higher during the warmer months. At site EWR 2 the algal species diversity remained the same during the colder months, probably because it was a smaller, shallower pool compared to the other sites and experienced higher temperatures in the winter (warmed more quickly) that supported algal growth (Rossouw and Vos, 2008).

The third and probably the most important limiting factor are nutrients, i.e. nitrogen (N) and phosphorus (P), and silica for diatoms (Horne and Goldman, 1994). In the samples taken from the Seekoei River it was found that for most of the sampling periods, N was probably the limiting factor (N:P ratio <10; Horne and Goldman, 1994). P was the limiting factor at all the sites during November 2007 when the water level at all the sites was low and there was no flow at sites EWR 3 and EWR 4 during August 2006 and January 2007. It can thus roughly be concluded that P was limiting during dryer cycles (Rossouw and Vos, 2008).

During late winter to late spring 2006, *Nostoc* sp. was found on the rapid (stones in current) below the pool at site EWR 3 and *Calothrix* sp. was found attached to aquatic grass on a few occasions in the pools of sites EWR 3 and 4 (Rossouw and Vos, 2008). This corroborates N as the limiting factor as both species are known to be able to fix N_2 gas from the atmosphere (Horne and Goldman, 1994).

The gradual increase in the nutrient (DIN and DIP) concentrations, through the winter supported the “SDI” as well as the increase in total algal concentration from late spring to January 2007, as light and temperature (warm summer waters) had probably no limiting effect on the algal growth (Rossouw ans Vos, 2008).

The data collected however, were insufficient to predict future phytoplankton scenarios. Phytoplankton is sensitive to physico-chemical changes and only further studies will show whether the trends evident in the data were strictly seasonal or unique to the system (Rossouw and Vos, 2008).

Periphytic/ Benthic Diatoms

Benthic algae (periphyton or phytobenthos) are primary producers that most successfully exploit streams as habitat, as they attach themselves to substrates. In unshaded streams in temperate regions, these organisms stabilise substrata and are considered the main source of energy for organisms in higher trophic levels (Stevenson and Bahls, 1999 and Biggs, 1996 in Rossouw and Vos, 2008).

Common members of benthic algae are pennate diatoms, filamentous green, and blue-green algae (Horne and Goldman, 1994). Because diatoms have silica frustules they are not easy to digest which makes them better competitors than for instance green-algae (Rossouw and Vos, 2008).

As benthic diatoms are attached to a substrate they are readily affected by any biological, physical or chemical disturbances that occur in the stream while they are developing (Stevenson and Bahls, 1999 in Rossouw and Vos, 2008). Benthic diatom growth is not only influenced by light, temperature, the availability of nutrients and grazing, but also by the availability of substrates and flow/current velocity (Vis *et al*, 1998 and Biggs, 1988 in Rossouw and Vos, 2008). Studies have found that diatom assemblage in slow currents (0.15 m/s) has a three times higher density than those in fast currents (0.4 m/s) (Asaeda and Hong Son, 2000 in Rossouw and Vos, 2008).

The diatoms (epiphytic) at site EWR1 were dominated by *Nitzschia frustulum* (52 %) during March 2006 and by *Epithemia adnata* (23 %) and *Tabularia fasciculata* (20 %) during September 2006. The site scored SPI 8.7 (Specific Pollution sensitivity Index) and BDI 7.3 (Biological Diatom Index) during March 2006, which rates the water quality at the site as moderate. SPI and BDI are indicators used by Dr Taylor in the analysis of the diatoms (Taylor *et al,* 2005 and Taylor *et al,* 2007). During September 2006 the SPI scored 11.2 and BDI 4.7, which also indicated moderate water quality for the site. Since the site has a naturally high TDS concentration the dominant species are very tolerant toward high electrolyte content (electrolyte-rich to brackish), and thus scored a low SPI (Rossouw and Vos, 2008).

The diatoms (epiphytic) at EWR 2 were dominated by *Nitzschia archibaldii* during both March 2006 (59 %) and September 2006 (23 %). The SPI (13.3 & 9.4) and BDI (15.0 & 10.3) indicated good quality water for March 2006 and moderate water quality for September 2006 (Rossouw and Vos, 2008).

At EWR 3 there was an indication of poor water quality (SPI 7.1 & BDI 6.5) during March 2006 as *Nitzschia frustulum* (46 %; electrolyte-rich to brackish) were dominant. During September 2006 the index score changed to moderate water quality (SPI 13.4 & BDI 7.4) as *Nitzschia frustulum* was replaced by *Epithemia sorex* (60 %; elevated electrolyte content) as the dominant species (epilithic diatoms) (Rossouw and Vos, 2008).

Site EWR 4 scored the lowest for water quality with SPI 6.0 and BDI 5.6 during March 2006 (poor quality) and SPI 9.2 and BDI 6.0 (moderate quality) during September 2006. The diatom (epilithic) sp. *Nitzschia frustulum* (electrolyte-rich to brackish) was dominant during both March and September 2006 (92 % & 61 %) (Rossouw and Vos, 2008).

Site EWR 2 was the only one of the sites where the SPI score decreased from March 2006 to September 2006. Considering all the parameters, one of the influences responsible for the decrease in SPI score could be the decrease in water depth at site EWR 2, while the water depth and flow increased at the other sites (Rossouw and Vos, 2008).

The list of diatom species and the index scores can be obtained from the author.

Macroinvertebrates

Macroinvertebrates and fish are briefly highlighted to complete the discussion of the river ecosystem.

Results indicate that there was a significant difference between macroinvertebrate communities at sites EWR 1 and 3 ($r=0.765$, $p<0.1$) and less significant differences between sites EWR1 and 4 and between sites EWR 2 and 3 (Watson, 2007).

The macroinvertebrate community at the four sites in the Seekoei River could be distinguished into three groups namely:

Group 1: Macroinvertebrates present at sites EWR 3 and 4 when flow was present
Simuliidae (17.13%)
Gyrinidae (11.83%)
Corixidae (10.31%)

Simuliidae prefer high flow, are very sensitive to low oxygen levels and are opportunistic colonists. Gyrinidae and Corixidae can occur in lotic and lentic water and are both facultative taxa.

Group 2: Macroinvertebrates present at sites EWR 1 and 2 in pools
Chironomidae (18.04%)
Notonectidae (16.3%)
Corixidae (15.29%)
These are all resident and facultative taxa.

Group 3: Macroinvertebrates present at sites EWR 2, 3 and 4 when there was no flow. Site EWR 2 started drying out from January 2007 and fluctuated from June (fuller) to October 2007 (drier).
Corixidae (11.42%)
Pleidae (7.64%)
Chironomidae (6.57%)

Dytiscidae (7.34%)
All these taxa are facultative and resident taxa and prefer quieter water.

Association of macroinvertebrate presence and abiotic factors:

Abiotic data were superimposed on the Multidimentional Scaling ordination of macroinvertebrate abundance data in total biotopes at all four sites. All variables namely temperature, % oxygen, conductivity, turbidity, TDS, pH, DIP (Dissolved Inorganic Phosphorus), DIN (dissolved inorganic nitrogen), chl-a (Chlorophyll a), width, depth, maximum velocity (current speed), minimum velocity, average velocity, composition of substratum types (separate for silt, sand, cobbles etc.) and combined percentage stones present (sum of cobbles, pebbles, boulders, bedrock and gravel) were tested. Only maximum velocity (current speed), percentage organic material, silt and stones present showed any relationship with macroinvertebrates present in total biotopes (Watson, 2007).

Other results from work done in Australia also suggest that the hydrology and connectivity in non-perennial rivers with highly variable flow regimes have a complex influence on biotic communities when these water resource are developed. Water abstraction or weirs/dams reduces the magnitude, frequency and duration of flows, thus potentially reducing the frequency and duration of the connectivity between pools. The impact of the reduced connectivity on the biota can have negative repercussions for all the river ecosystem processes. These impacts are likely to be more severe in non-perennial rivers, because in their natural state they are likely to have a variable and intermediate level of connectivity, which will promote macroinvertebrate diversity (Sheldon *et al*, 2002).

Fish

The fish community of the Seekoei River is well-adapted to the harsh environmental conditions prevailing in the Orange River system such as flash floods and droughts. Five indigenous fish species, *Barbus anoplus*, *Labeobarbus aeneus*, *Labeo capensis*, *L. umbratus* and *Clarias gariepinus*, have been recorded for the river. All of these are considered to be moderately tolerant to tolerant to modifications in water quality (Kleynhans, 2003 in Seaman *et al*, 2010).

EWR 1

Only one fish species, *Barbus anoplus*, was found at EWR1. *Barbus anoplus* is a widespread species in South Africa - usually occurring within the 16ºC isoline. It is a hardy species often found in waters prone to a wide salinity range (De Bie, 1985). The species is known to successfully colonize shallow, unstable rivers and is able to survive the hard conditions associated with receding water levels and high silt loads (Cambray, 1983).

EWR 2

Four indigenous fish species, *Barbus anoplus*, *Labeo umbratus*, *L. capensis* and *Clarias gariepinus*, and one exotic, *Cyprinus carpio*, have been recorded at EWR 2. All of the recorded species are tolerant generalists and well-adapted to the harsh conditions in the Orange River system.

EWR 3 and EWR 4

EWR 3 and 4 are both situated in the lower section of the Seekoei River and host similar fish communities. With the exception of one exotic species, *Micropterus salmoides* which was introduced in a pool just upstream from site EWR 4, the same seven species are found at both sites. All of these are moderately tolerant to tolerant to water quality changes.

Differences between sites

EWR 1 was set apart from the other sites in that only one species was present in that river reach. Considering the habitat available at the site, the low frequency of connectivity between isolated pools in the river reach, and the position of the site in the catchment this is believed to reflect natural conditions.

The highest variability in the fish species composition was recorded at EWR 2. Available habitat at EWR 2 consisted mostly of a shallow pool that dried up twice during the study period. Species composition and abundance usually remain more constant in deep complex pools than in shallow simple habitats. The variability in the fish community at this site is believed to be as a result of the large fluctuations in water depth.

The slightly higher fish species richness and abundances found in the lower section of the Seekoei River (sites EWR 3 and 4) are possibly related to the following: the availability of complex habitats which include deep complex pools, shallow vegetated pools, rapids, runs, and riffles; higher base flow due to the contribution of water from interflow springs; the higher frequency of connectivity between pools; and proximity to the Orange River main stem (Avenant, 2007).

Toxic substances and complex mixtures

A number of other chemical constituents besides the ions for the TDS calculations were measured. They were silica, fluoride, aluminium, arsenic, boron, copper, cadmium, iron, manganese, lead and zinc. Other constituents such as total phosphates, total nitrates, chemical oxygen demand, biologic oxygen demand, total organic content and the dissolved organic content were also measured. These constituents are not normally measured for Reserve determinations but were measured in this study as it was also a research project aimed at understanding the functioning of a non-perennial system.

Most of the constituents measured and compared to the ideal water quality guideline for aquatic ecosystems (DWAF, 1999) were outside the ideal concentration range. However, this was due to the geology of the area and not due to pollution, as the area was mostly undeveloped as described in Section 7.1.

General comments on water quality and flow relationships

There were water quality and flow data at D3H015-Q01 from 1980 to 2006. Hughes (2007) made some observations using the TDS data from the gauging station and the surface and spring data collected by the project team:

- "*The initial groundwater investigation report suggests that the groundwater spring flow that sustains pools during periods of zero flow has a TDS of approximately 400 mg/ℓ.*
- *The observed runoff at D3H015 has TDS values ranging from less than 100 to over 1500 mg/ℓ.*
- *The highest TDS values occur after prolonged periods of base flow or at the start of flow events that have very low flows.*
- *Several assumptions can be made about flow processes based on the previous bullet point.*
    - *If the start of an event has very low flows, most of the runoff at D3H015 will be displaced pool water that has very high TDS values due to the concentrating effects of evaporation.*
    - *If the start of an event has quite high flows the TDS will be more a reflection of surface runoff water quality, which appears to have low (±100 mg/ℓ) TDS values.*
    - *The quite rapid increase in TDS during the base flow recession period suggests an additional mechanism apart from the spring flow and surface runoff already identified. This may be related to the storage of salts within the pools and*

adjacent soils which is incremented during pool drying and gradually released after pools have been re-filled.

- *Relatively simple mass balance modelling of the system using assumed pool storage volumes, evaporation rates and TDS values for different water sources could provide a possible method for simulating the general trends of pool water quality under different flow conditions.*"

7.6.4 Ecological Water Quality Reserve determination

After all the specialists completed their technical reports a workshop was held in Bloemfontein in October 2007. The inputs of all the specialists were required to apply the existing methodology to the Seekoei River and to propose changes where the methodology failed.

It was concluded that the existing water quality methodology could be used without any changes as there was one long term data record that could be used to apply TEACHA and after collecting water quality data over eighteen months, the water quality status of the Seekoei River could be determined. There was also sufficient water quality information to give reasonable input into the invertebrate and fish water quality requirements. However, determining reference conditions (before any development in the catchment) was regarded as not feasible as there were no historical water quality data available for most of the catchment. A present day water quality status was inferred based on the present water quality data, the condition of the catchment and current and past land-use activities.

The fish and invertebrate methodologies were the two components of the existing methodology that posed the greatest challenges, but these will not be discussed here as the focus was on the water quality methodology.

Six major challenges were identified from the Seekoei River study when determining an EWA for non-perennial rivers (Seaman *et al*, 2010). They were the following:

- Establishing reference conditions, mainly due to a lack of present day and historical data. This is also one of the early stages in the current perennial river EWA methodology
- Hydrological modelling is the basis of the existing methodology. The starting point is a description of the Present Day flow and if possible the natural flow regime at key points along the river. These flow conditions are the drivers of the river's nature and the biophysical regime responds to the flow. The final hydrological output of a flow assessment is a description of flows needed to attain or maintain a range of possible future biophysical regimes that would be the result of different development or

management scenarios. To model the movement of water through the system, non-perennial river modellers face several challenges of which the lack of sufficient and reliable rainfall and runoff data are the main obstacles.

- Understanding pools is crucial as pools are one of the main characteristics of non-perennial rivers and are important refugia for fish and invertebrates as well as a source of water for wildlife, cattle and humans in an arid landscape. The unpredictability of the location, persistence and water quality makes management of pools challenging and is linked to the connectivity and surface water/groundwater interactions.
- Connectivity, or the lack of connectivity, between pools is one of the most important attributes of non-perennial rivers. Although it occurs intermittently, it allows transport of sediments and nutrients along the system and stimulates the movement of fish and invertebrates and also dilutes poor water quality in the pools. Connectivity is linked to the hydrological modelling and cannot be simulated with accuracy.
- Surface water/groundwater interactions affect the occurrence of flow, the existence and persistence of the pools, and the amount of water stored in the alluvial material beneath and adjacent to the river channel (Hughes, 2005). Both surface hydrology and geohydrology need to be modeled to provide meaningful insights into the hydrological functioning of non-perennial systems.
- Extrapolation of ecosystem attributes along the length of a non-perennial river must be carefully considered because of the variability from one pool to the next. Generalisations cannot be made with any confidence even at very coarse resolutions unless data are available to substantiate the results.

The only groundwater input to the study was that described in Section 7.6.3 under the “Groundwater water quality” heading. In future non-perennial river ecological Reserve studies the groundwater-surface water interaction should be one of the issues that need to be addressed.

The Seekoei River study presented a unique opportunity in getting a better understanding of how a non-perennial river functions and also created an opportunity to test and change the existing EWA methodology. In accordance with the study’s overarching aim, a prototype methodology for determining the EWR for non-perennial rivers was developed even though the team did not end up with EWR values at the different EWR sites.

A prototype methodology to determine the Ecological Reserve was developed from input from all the specialists and a report was written (Seaman *et al*, 2010). The prototype methodology is discussed in the next chapter (Chapter 8) and the application to the methodology on the Mokolo River will be discussed in the following chapter (Chapter 9).

8. THE PROTOTYPE ECOLOGICAL RESERVE METHODOLOGY

It is important to note that the thesis was focussed on the contribution of the water quality component to the prototype methodology for non-perennial rivers. To gather the information required, existing standard methods to determine the water quality component of the Ecological Reserve were used. These methods are the same as the ones used for perennial rivers and are described in DWAF (2008a) and as described and applied in the previous chapter.

The method that will be described below is the one proposed in Seaman *et al* (2010). The prototype methodology comprises 11 phases and 28 activities (Figure 24) and will be briefly described below. Although this report focusses on water quality, it is important to note that it should be done jointly with the water quantity component.

Phase 1: Initiate EWA study

Activity 1: Define the river in terms of perenniality

At the earliest stage of an Environmental Water Assessment (EWA) a decision has to be made on whether or not to follow the approach used for perennial rivers. If the river is perennial then the standard EWA approach for perennial rivers should be used (Seaman *et al*, 2010). If the river is non-perennial, then this EWA approach for non-perennial rivers should be used, followed by Steps 6 to 8 in Seaman *et al (*2010).

If the river has adequate coverage of gauging weirs, then obtain the relevant flow data from DWA. Parts of river systems can be non-perennial whilst other parts are perennial, and the data collected should be relevant to the sections of river to be assessed. These will provide the degree of non-perenniality of the system.

If the river has inadequate or no gauging data, then two possible approaches are suggested by Hughes (2008). "*Either use some of the existing, standard modelling approaches and attempt to infer some of the finer scale processes from the information generated by the model. Or use more detailed modelling approaches and extrapolate from limited observed data to provide necessary inputs*." WR90 or the updated WR2005 database could provide important information but the data

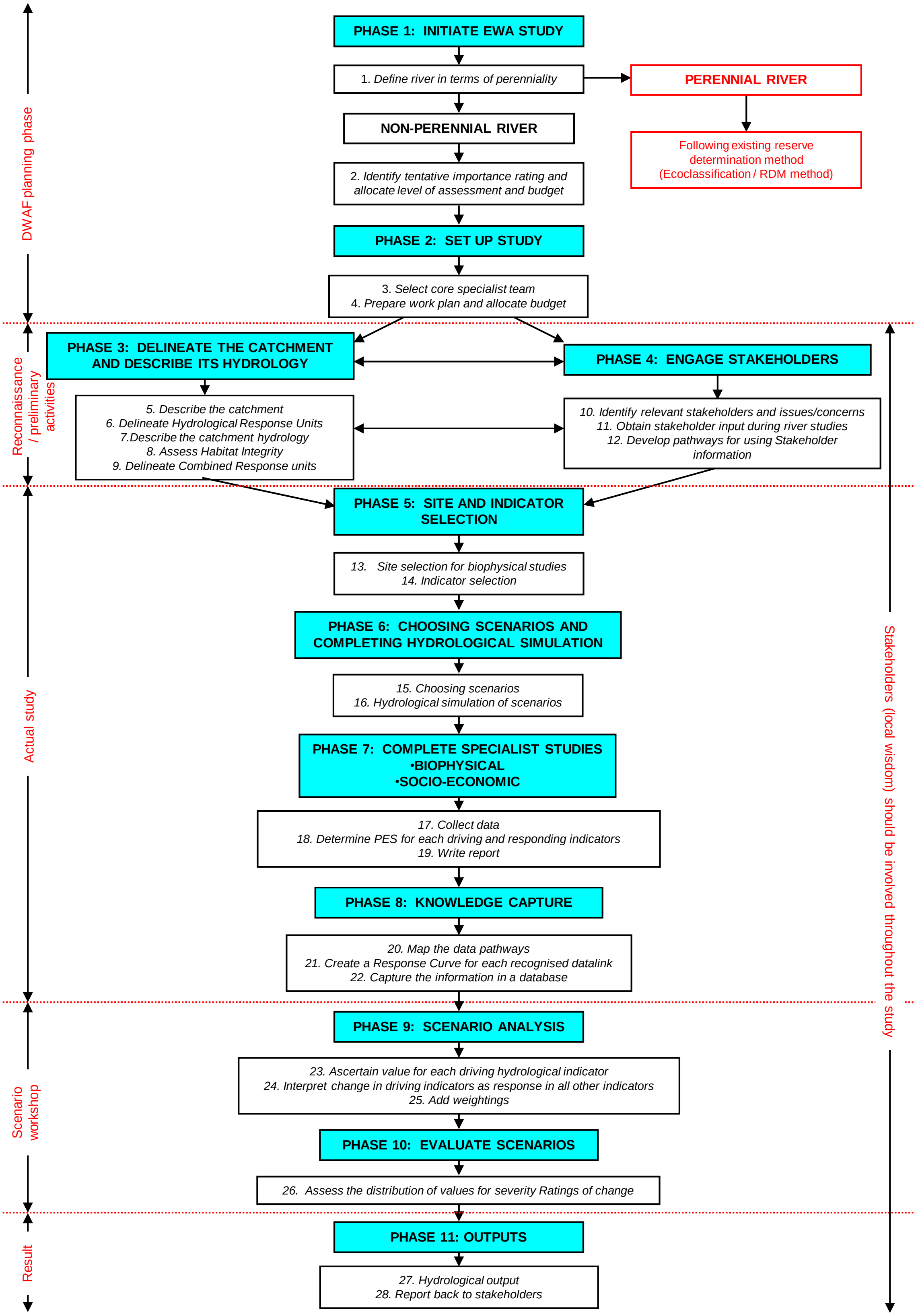


Figure 24: The 11-phase process proposed for EWAs for non-perennial rivers (Seaman *et al*, 2010)

should be checked against any available information for a specific site or part of the relevant catchment (Hughes, 2008).

It is necessary to know the degree of non-perenniality because different types of rivers may require different multidisciplinary teams for EWAs.

Activity 1 was finalised during a workshop on the 6th August 2008 in Bloemfontein, where the Mokolo River was chosen.

There were a number of reasons for choosing the Mokolo River:

- The wet season was in line with the project planning – to do field work in the rainy season to get the wet season data.
- It was a data rich system. There are historical data and recent reports available on the system.
- Most importantly, there would be water in the system to support field data collection, compared to the Touws that will be highly seasonal and the Swart-Dorings that will be episodic. These two additional rivers were chosen because their flow patterns were very different from the Mokolo and each river had at least one discharge data record at a gauging station that could be used in the study. There were other rivers in the same flow ranges but without discharge data records (Steÿn, 2008).

Activity 2: Identify tentative importance rating and allocate level of EWA and budget

Importance rating: The true ecological importance and sensitivity (EIS) of a river system must be determined after specialist studies, and this is especially true for non-perennial rivers because they act as vital refugia for fish. As this was a research study a comprehensive EWA assessment was followed and tested on the Mokolo River.

Phase 2: Set up study

Activity 3: Select core specialist team

Select a core study team that represents key disciplines: For non-perennial systems this will likely consist of a project leader, a hydrologist, a geohydrologist, a geomorphologist /geographer/GIS specialist, a socio-economist, a river ecologist (fish and invertebrates) and water quality specialist. All should have local knowledge of the river system, because these are usually data-poor systems and heavy reliance will be made on the specialists' intuitive understanding of them. A team was selected consisting of the above key disciplines

Activity 4: Prepare workplan and allocate budget

A budget and workplan should be prepared and approved and, in consultation with DWA, the range of scenarios to be considered should be agreed.

The scenarios were a team decision.

Phase 3: Delineate the catchment and describe its hydrology

In non-perennial rivers, where data are limited and extrapolation to unstudied reaches is uncertain, new approaches may be of use to help describe and understand the system. One key characteristic of this prototype EWA methodology is an intensive use of catchment data to help understand the nature of the river. This is linked with hydrological analyses and habitat integrity assessment to produce a division of the catchment into Combined Response Units (CRUs) that are relatively homogeneous in terms of natural features and land use. The CRUs are similar to the Integrated Units of Analysis produced by DWAF's Water Resource Classification System (Dollar *et al*, 2007), and the Reserve Assessment Units (RAUs) of Kleynhans and Louw (2007b).

Water quality resource unit delineation

Water quality resource units are areas that are expected to have a homogenous water quality.

There are many factors that influence the surface water quality. The geology and climate of a region, the land use activities such as agriculture, towns and their associated infrastructure and effluents, informal settlements, game farming etc., groundcover and the groundwater contribution to the surface water. When delineating water quality resource units all the above factors need to be taken into account, starting with the geology of the region.

Similar geological areas are expected to have similar background water quality. All other activities and features further influence the water quality.

For the Mokolo River the water quality resources units were delineated using the following components:

- GIS maps: Geology, land cover, EcoRegional (Level 1) classification, topography and rainfall, land use and quaternary catchments. These maps were overlain and areas that were expected to have similar water quality were grouped together.
- Once the water quality resource units were delineated, using the GIS maps, they were compared to the results from the Intermediate Reserve Determination for the Mokolo River System (Water for Africa and Clean Stream Biological Services, 2008). The results were similar.

Five water quality resources units (WQRU) were identified to be used as a component in determining the CRU's, based mainly on the activities in and around the mainstream of the Mokolo River (Figure 25):

1. The Grootspruit, Sandspruit and Sand Rivers. This WQRU was in a similar geological area and there was a natural ridge that separated this unit from the next as the river had to flow through a poort. This unit represented the upper portion of the Mokolo River and the whole unit fell within one Level 1 Ecoregion (Bushveld Basin).
2. The WQRU stretched from where the river exits the poort up the inflow of the Mokolo Dam. The dam influences the water quality in the downstream part of the river. Upstream and downstream of the dam was seen as sepertate WQRU, even though the geology was very similar.
3. The WQRU downstream of the Mokolo Dam stretched up to just after the confluence of the Sandloop with the Mokolo River.
4. The fourth WQRU was from the confluence of the Sandloop with the Mokolo River to where the geology changes to Karoo and Basement formations.
5. The last WQRU was from that break in the geology up to the Mokolo and Limpopo confluence. The lower river does not usually flow close to its confluence with the Limpopo River.

Although five WQRUs were chosen, it was understood that the last unit seldom has flow in the river as the water disappears into the alluvial floodplain. In terms of possible water quality sampling sites only the first four units were chosen.

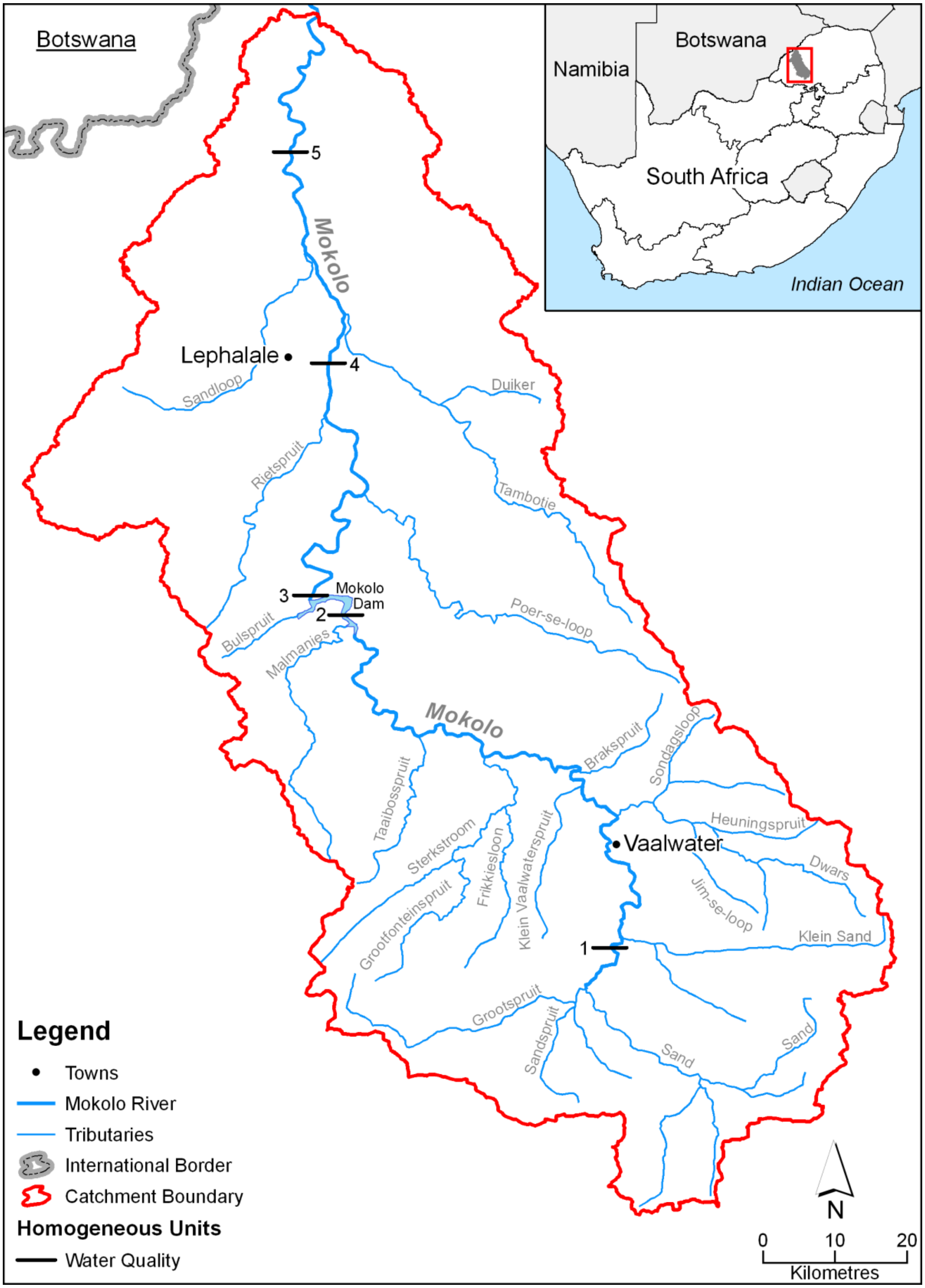


Figure 25: The Water Quality Resource Units for the Mokolo River (Prepared by F Sokolic, 2011)

WQRU1: On the Mokolo River just before it flows through the poort
WQRU2: On the Mokolo River using the EWR1a and EWR2 sites of the Intermediate Reserve study
WQRU3: On the Mokolo River using the EWR4 site of the Intermediate Reserve study
WQRU4: On the Mokolo River close to Lephalale, formerly Ellisras, and the Mokolo Sandloop confluence.

The minimum number of constituents that should be measured are Electrical Conductivity in mS/m, temperature in °C, dissolved oxygen (mg/ℓ and % saturation), pH, nutrients (nitrates and phosphates) and turbidity as well as periphyton. More constituents were measured from the samples collected during the field investigation.

Other constituents that could be measured that would be beneficial to the understanding of the system are diatoms, bacteriological measurements, i.e. *E. coli* and salts.

The following was required for the water quality assessment: the sites that would be sampled, existing groundwater and surface water quality data for both the main stem as well as the tributaries of the Mokolo River, a site visit and an inventory of all the land use activities and land coverage of the Mokolo River catchment.

The Combined Response Units (CRUs) then guided the selection of sites for the EWA by combining the WQRU with the other identified response units (fish, riparian vegetation, invertebrates, surface and groundwater response units).

This activity was completed during a workshop held on 17th and 18th March 2010 in Bloemfontein.

Activity 5: Describe the catchment

The catchment should be described in as much detail as possible with appropriate maps (geology, rainfall, land cover, topography, vegetation etc.) included to assist the specialists in collecting data (relevant to the particular catchment area) on their specialist fields and to identify development activities that of impact on the catchment. This would then also assist the GIS specialist (and/or Catchment geomorphologist) in determining the Combined Response Units and the team in identifying specific scenarios.

Data from various sources were consulted and the GIS specialist presented maps, representing the available data that were used in determining the CRUs during the March 2010 workshop. Each individual specialist had to delineate the CRUs appropriate for his/her specialist field. This was then overlaid and combined CRUs were then determined. The CRUs for the different fields were generally very close to one another.

Activity 6: Delineate Runoff Potential Units (RPUs)

A Runoff Potential Unit (RPU) is similar to a Hidrological Resource Unit (HRU) (Figure 24) but additional layers such as catchment, slope, infiltration rate, vegetation cover, rainfall intensity and flow accumulation, are also included in the determination.

The catchment geomorphologist required information from the whole catchment, and not just instream areas, in river delineation and determining the location of sampling and monitoring sites. Description of the RPUs were also used by the hydrologist to assist in the description and modelling of the catchment hydrology.

Activity 7: Describe the catchment hydrology

It is very important to consider the basin as a whole and identify the flow variations that are likely to occur before setting up a hydrological model. Non-perennial systems will have specific characteristics that depend on the climate, geology, topography, soils and vegetation, combined with highly interdependent impacts. One of the most important components of any hydrological study of semi-arid regions is therefore the development of a conceptual idea of the main processes that occur within the specific catchments (Hughes, 2008).

This component was completed and reported on by the hydrologist (Dennis, 2010a).

Activity 8: Assess the Habitat Integrity

Kleynhans *et al* (2008) state that the "*Assessment of habitat integrity is based on an interpretation of the deviation from the reference condition. Specification of the reference condition follows an impact-based approach where the intensity and extent of anthropogenic changes are used to interpret the impact on the habitat integrity of the system. To accomplish this, information on abiotic changes that can potentially influence river habitat integrity are obtained from surveys or available data sources. These changes are all related and interpreted in terms of modification of* *the drivers of the system: hydrology, geomorphology and physico-chemical conditions and how these changes would impact on the natural riverine habitats*."

Habitat integrity was assessed using either an aerial survey, ground site survey or a desktop approach using available maps, aerial photos, satellite images and GOOGLE Earth images depending on the budget allocated.

The outcome of an habitat integrity assessment is a geo-referenced database, as well as maps with information on the location of structures in river, roads, bridges, alien vegetation, vegetation removal, dry or irrigated lands, erosion, industries, mines and towns.

The habitat integrity database and maps, in conjunction with land cover and land use data, can now be used as an overlay with the RPUs which were identified in Activity 6.

Activity 9: Delineate Combined Response Units (CRUs)

The Combined Response Units (CRUs) could then be delineated by superimposing the RPUs with information from the Hydrological Models and Habitat Integrity Assessment.

CRUs identified were response units that are relatively homogenous in geomorphological characteristics, hydrology, anthropogenic impacts and habitat types.

Phase 4: Engage stakeholders

The scenarios developed reflected the major river ecological issues and concerns of the relevant major groupings of stakeholders. Involving the stakeholders early in the process not only helps identify the major issues, but also provides invaluable input on the past and present usage and flow patterns of the river where data were few. This is particularly important for non-perennial rivers as there may be very little other information on the river or its users.

Activity 10: Identify stakeholders and their issues/concerns

Identify the major stakeholder groups through public announcements and meetings. Identify the major issues and concerns of the various stakeholder groups regarding the river, and its importance in their lives.

Activity 11: Obtain stakeholder input during river studies, on the nature of the river and its users

The field visits by the EWA team provide a unique opportunity to interact with the landowners and other locals on the nature and history of the river.

Valuable water quality information can be obtained from the landowners during this activity.

Activity 12: Develop pathways for the stakeholder information to be included in later phases of the EWA.

The third stakeholder activity mentioned above is the ‘continual engagement with stakeholders and feedback on final outcomes’ throughout the EWA process.

Phase 5: Site and indicator selection

Once the assessment had begun, the Response Units identified and the stakeholder consultations begun, the team then proceeded with two key activities that had to be completed before any field work could begin.

Activity 13: Site selection for biophysical studies

The number of sites along the river for data gathering was dictated primarily by the time and financial budget.

With the Response Units chosen, a desktop analysis tentatively identified a potential study site within each unit. This analysis employed maps, satellite imagery, aerial photographs and any other appropriate information that have already been collected, and considered such criteria as:

- accessibility, both in terms of roads, and landowner’s permission
- proximity to a gauging weir
- the degree to which the site would represent the Response Unit
- availability of scientific or social use of the river data
- a point for which hydrological modelling can be done.

All the above were taken into account during the workshop held on 17th and 18th March 2010 in Bloemfontein.

The final choice of site locations were done on site at the river, and should ideally be done at times of low flow when the general geomorphological nature of the river bed can be seen. This was done during the field visit to the Mokolo River catchment from 26th to 30th April 2010. However, the river was in flood and a small inflatable boat was used to gather as much information as was possible. There was only to be one opportunity for a site visit, therefore the team did all they could to gather as much information on the river as possible, even under flood conditions.

Activity 14: Indicator selection

Indicators are attributes of the system that can be used in scenarios to describe change. Future development scenarios are used to indicate possible changes in the Ecological Status of a river given specific development options. In water-allocation studies, including the Ecological Reserve studies, they should be variables that can be expected to respond to changes in flow or water levels. They should cover the main physical, chemical, biological and social aspects of the river ecosystem, including issues of interest or concern to stakeholders to the extent possible.

For non-perennial rivers, it is suggested that the list of indicators should be short and, with experience gained and more information becoming available, possibly generic for all such rivers.

The guiding criterion for selecting indicators was that they should be amenable to some level of prediction of how they would change with catchment developments. Flowing water and pools were separated as they had different indicators. In perennial rivers it is assumed that there will be flow in the river for most of the time. In non-perennial rivers it is assumed that there will be no flow for some periods. Because of the expected no flow conditions, isolated pools become more important and need to be addressed differently from flowing water.

The indicators that would impact on water quality in the Mokolo River were the following for **flowing water**:

- Percentage contribution of groundwater to surface water
- Total annual volume of surface flow (Mean Annual Runoff)
- Number of floods per year that cover the Flood Zone1 (Lower Dynamic vegetation zone) (Figure 26 is an example of how the different flood zones are demarcated)
- Number of floods per year that cover the Flood Zone2 (Lower Bank vegetation zone)
- Number of floods per year that cover the Flood Zone3 (Upper Bank vegetation zone)

The water quality constituents that were measured were electrical conductivity in mS/m (or TDS in mg/ℓ), pH in pH units, nutrients (nitrates and phosphates in mg/ℓ) and algae in cells per mℓ.

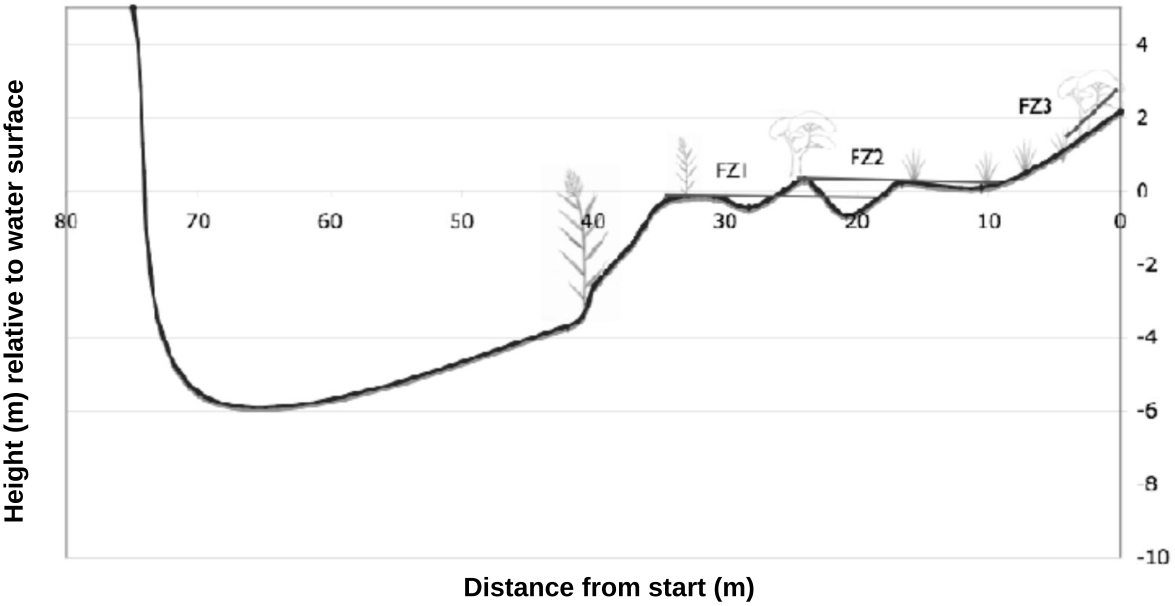


Figure 26: Flood Zones 1 to 3 (Rowntree, 2010)

The indicators that will impact on water quality in the Mokolo River are the following for **isolated pools:**

- Length of time (as a percentage of total flow) per year with no surface flow
- Contribution of channel subsurface flow to isolated pools

The above two indicators are not commonly known and is part of the challenge to be able to predict water quality in pools as groundwater can be a major contributor to the pools, especially during the dry season.

The water quality constituents that need to be measured are the same as for flowing water and are electrical conductivity in mS/m (or TDS in mg/ℓ), pH in pH units, nutrients (nitrates and phosphates in mg/ℓ) and algae as Chlorophyll-a. These water quality constituents also satisfy the requirements of the fish and invertebrate specialists.

Note: The above constituents are those that are required as part of the water quality input into the prototype methodology. However, should the water quality reserve for a particular site be required on an intermediate or comprehensive water quality reserve level, inorganic salt data are required. The ionic data is required to run TEACHA which generates aggregate salts (DWAF, 2008a).

Electrical conductivity data can be used as a surrogate for inorganic salts, but it needs to be justified and aggregate salts can not be calculated.

Other constituents that were required for the Prototype Methodology were nutrients, pH, temperature, dissolved oxygen, turbidity or water clarity, toxic substances and response variables such as fish and invertebrates.

Phase 6: Choosing scenarios and hydrological simulation

Once a scenario is developed, the scenario begins with the simulation of the flow regime that would pertain under that proposed development, followed by the predicted physical, chemical and biological responses of the river ecosystem. Positive and negative social, resource-economic and macro-economic impacts are also the predicted.

This activity is a team effort once the hydrological simulations are available. The development of the hydrological simulations was one of the critical steps in the Prototype Methodology and was also time consuming, resulting in delays of the follow-up activities of the Prototype Methodology.

Activity 15: Choosing scenarios

Where data (water quality, invertebrates, fish, hydrology, geohydrology, geomorphological etc.) are few – the most common situation in many South African catchments – it is best to choose fewer rather than more scenarios as there might not be sufficient knowledge to make predictions that distinguish between many similar scenarios. A prioritised list of four to six scenarios is a useful starting point, with those chosen being as dissimilar as possible in terms of the likely future changes within the catchment. The final choice of scenarios should be made in consultation with DWA and after stakeholder consultation. Input from the hydrologist is important as the scenarios chosen must be amenable to hydrological modelling and potentially be able to demonstrate quite different future flow regimes.

Activity 16: Hydrological simulation

Hughes (2008) provided a detailed description of the approach for simulating the hydrology of non-perennial rivers. In terms of the Indicators listed in Activity 14, the outputs of the hydrological simulation should include, per selected hydrological modelling site, information on:

- connectivity
- general indication of the flooding regime likely to influence channel morphology

- sediment delivery.

However, using his perennial river hydrological model for the non-perennial rivers created a lot of uncertainty and very low confidence in the results from the model and alternative models needs to be investigated.

Phase 7: Complete the specialist biophysical and socio-economic studies

Scenarios and indicators chosen in Phase 5 and 6 guided the specialists in the type of data required to predict changes in the river. Appointed specialists collected data at each chosen EWA site, determined the Present Ecological State (PES) in terms of their particular discipline and wrote a specialist report.

Activity 17: Collect data

The specialists needed to be able to develop an understanding of the relationship 1) between flow/water level changes (drivers) and each indicator, or 2), between indicators, so that flow/water level changes can be transformed into changes in the value of indicators.

Water quality data were collected and analysed from each EWA site using methods described in DWAF (2008a). Most water quality methods available were developed for use in perennial rivers and either have to be adapted using expert judgement or results have to be interpreted keeping the differences between perennial and non-perennial rivers in mind.

Activity 18: Determine Present Ecological State (PES) for each driving and responding indicators

The PES is used in the scenario evaluation to determine the change at the EWA site from the present to the new state expected under a particular scenario.

The PES for each of the driving indicators (Connectivity and Floods) and responding indicators (Fish, Macro-invertebrates and Riparian vegetation) have to be determined before the scenario workshop. Most of the non-perennial rivers have little to no historical data and it is virtually impossible to determine a reference (natural) condition with any confidence. Most of the current methods used to determine PES rely strongly if not completely on a comparison of observed data and reference data. As the reference condition cannot usually be defined for a non-perennial river, there is no high confidence PES method for such rivers and specialists therefore need to use expert judgement supported by field data and historical records (if available) to provide a

PES category . Explanations and motivation for the PES category decided on has to be included by each specialist. The generic ecological categories for PES are provided in Table 21.

Table 21: Generic ecological categories for PES (modified from Kleynhans, 1996 and Kleynhans, 1999) as cited in Seaman *et al* (2010).

ECOLOGICAL CATEGORY	DESCRIPTION SCORE	(% OF TOTAL)*
A	Unmodified, natural	90-100
B	Largely natural with few modifications. A small change in natural habitats and biota may have taken place but the ecosystem functions are essentially unchanged.	80-89
C	Moderately modified. Loss and change of natural habitat and biota have occurred, but the basic ecosystem functions are still predominantly unchanged.	60-79
D	Largely modified. A large loss of natural habitat, biota and basic ecosystem functions has occurred.	40-59
E	Seriously modified. The loss of natural habitat, biota and basic ecosystem functions is extensive.	20-39
F	Critically / Extremely modified. Modifications have reached a critical level and the system has been modified completely with an almost complete loss of natural habitat and biota. In the worst instances the basic ecosystem functions have been destroyed and the changes are irreversible.	0-19

* % of the deviation of the biophysical components from the natural reference condition (Kleynhans and Louw, 2007b)

The PES of the driving indicators and the responding indicators together with causes, consequences and trajectories of change are then evaluated using the following guidelines and a combined PES category is determined for each EWA site.

The driving indicators are examined and if one of these is in a lower category than the responding indicators then the causes, sources and trajectories of change are re-examined. If the responding indicators (Fish, Macro-invertebrates and Riparian vegetation) are likely to mimic the critical (lowest PES category) driving indicator then the combined PES category will usually be the same category as the critical driving indicator. If not then the PES category may be set in the same category as the critical responding indicator (Louw and Hughes, 2002).

This combined PES category is then used in the scenario evaluation to indicate the change at the EWA site from the present to the state expected under that particular scenario.

There is an abundance of data for the middle reaches of the Mokolo River and the methods used for perennial rivers were applied in determining the PES category. The PES results are described in the following chapter, Chapter 9. An intermediate Reserve study was already undertaken and many of the sites chosen in this study correspond to sites in the Intermediate Reserve study (DWAF, 2008b).

A field visit to the Mokolo River was completed in April/May 2010 and only one set of data were produced. The DWA historical data from the hydrological gauging stations as well as data presented in the Intermediate water quality report was also used to determine the PES category. The upper and lower reaches of the Mokolo River did not have historical water quality data and expert opinion was used to determine the PES category for water quality (see Chapter 9).

Activity 19: Write reports

Specialists need to complete reports.

Phase 8: Knowledge capture

Once the specialist reports have been completed, the knowledge is captured for use in the construction of scenarios. One of the procedures capturing specialist knowledge involved creating Response Curves of all major identified relationships at all the EWA sites, between for example:

- a river's flow regime and its ecological condition (e.g. the relationship between floods and a fish guild) for each of the EWA sites
- ecological condition and social welfare (e.g. the relationship between water quality and human health (quantified as incidence of disease))
- ecological condition and resource economics (e.g. the relationship between riparian vegetation use and household income used for construction materials (not quantified, only qualitative).

These Response Curves tease out the individual driving and responding parts of the ecosystem for any particular flow change or water depth change, allowing each specialist to concentrate on their own part of the ecosystem model without being pushed to anticipate how other parts might be behaving.

The Response Curves are constructed by the EWA team.

Activity 20: Map the data pathways

The physical and chemical water quality specialists construct flow diagrams that show the links that exist between the three hydrological drivers (connectivity, floods, sediment delivery) and their indicators (pools, channel and riparian aquifer recharge and water quality) (see Activity 14), explaining the importance and nature of the link. For pools, for instance, all three hydrological drivers could be seen as potentially affecting pool size/number and so they will show as three links feeding into "Pools". If any of the three physical/chemical indicators strongly influence each other, then this link is also shown. Pool size and number, for instance, might affect aquifer recharge.

Once the hydrological, physical and chemical links have been satisfactorily captured then the biologists repeat the process with their indicators, showing any direct links from any of the hydrological, water quality and geomorphological parameters to any of theirs. Finally, the sociologists repeat the exercise, showing the hydrological, physical, chemical and biological indicators linked to each of their indicators.

The final result is a diagram of how information flows through the team as they make their assessments and predictions. In effect, this is the layout of the 'ecosystem model' as understood by the specialist team.

A Response Curve is then constructed for each link, describing the conceptual relationship to the best of the specialist's ability. One example would be to capture our understanding of how "Pools" change with changes in "Connectivity". Each Response Curve describes the relationship on the assumption that only those two indicators are changing, with the rest of the ecosystem remaining unchanged.

Activity 21: Create a Response Curve for each recognised data link

The Response Curves have a common format, whether they are for physical, ecological or social links. Each Response Curve starts with the Present Day condition as the zero value for the indicator. This is known for the independent variable, either from the hydrological modelling exercise or from a previous response curve identified in the information-flow diagram, and is depicted as Zero for the dependent variable.

The shape of the Response Curve is then completed, using the Severity Ratings 1 to 5 as guides (Table 22). Severity Ratings are used as it is usually impossible to quantify the predicted change in true quantitative terms. They:

- give semi-quantification to predictions where true quantification is impossible;
- standardise the unit of prediction for all indicators.

Table 22: Severity Ratings of Change (King and Brown, 2006 cited in Seaman *et al*, 2010).

Severity Rating	Severity of change	Equivalent loss (% decrease in abundance/ area/concentration/number)	Equivalent gain (% increase in abundance/ area/concentration/number)
0	None	no change	no change
1	Negligible	0-20% loss	1-25% gain
2	Low	21-40% loss	26-67% gain
3	Moderate	41-60% loss	68-250% gain
4	High	61-80% loss	251-500% gain
5	Very high	81-100% loss	501% gain to ∞

Each Response Curve created should be accompanied by:

- an explanation of the shape of the curve
- details of the information source and level of confidence in its shape.

The Response Curves of two indicators may differ from site to site and have different explanations at each site, and so it is important that they are site specific. Fewer rather than more indicators should be chosen, because the more indicators, the more data pathways and Response Curves, and thus the more complex the model being built. However, as many as required should be chosen, irrespective of the complexity.

The minimum water quality indicators that were chosen for the Mokolo River were the following:

- Conductivity
- pH
- Nitrates
- Phosphates
- Algae/ Chlorophyll a
- Microbiological pollution. *E. Coli*, cholera, etc.
- Toxics: Site specific pollution, including pesticides.

Response curves for each of these indicators are drawn for each of the following hydrological indicators:

When the river is flowing:

- Total annual volume of surface flow (MAR);
- Percentage contribution of groundwater to surface flow dry season;
- Percentage contribution of groundwater to surface flow wet season;
- Number of floods per year that cover Flood Zone 1 (Lower Dynamic veg zone);
- Number of floods per year that cover Flood Zone 2 (Lower Bank veg zone);
- Number of floods per year that enter Flood Zone 3 (Upper Bank veg zone);
- Length of time per year with surface flow i.e. flow in main channel; and Specified pollution

When there are isolated pools:

- Length of time per year with no surface flow;
- Channel subsurface flow (5 day minimum in dry season); and Specified pollution.

The above data should be generated by the hydrological model that is being used.

Activity 22: Capture the information in database

The information on the shape of each Response Curve is captured electronically, using Excel or other suitable software. An example of a reponse curve is presented below in Figure 27.

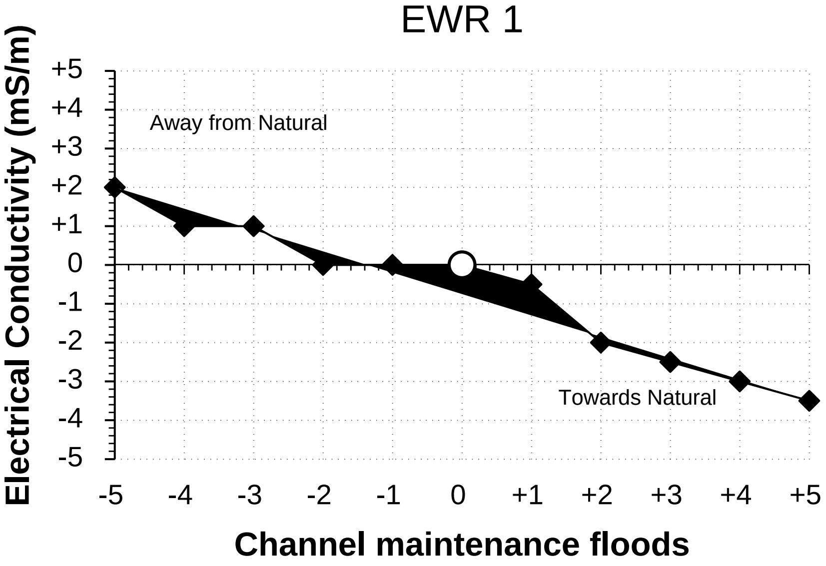


Figure 27: An example of a response curve

The circle in the middle (0,0) represents the present day condition at a specific site, i.e. EWR 1. The x-axis represents a range of possible changes in flow categories and in this example, channel maintenance floods. The y-axis represents the response of the indicator, electrical conductivity in this example, in terms of abundance, integrity or concentrations. The positive sign represents an increase and the negative sign a decrease from present day condition. This example illustrates that an increase in channel maintenance floods would result in a decrease in Electrical Conductivity while a decrease in channel maintenance floods would result in an increase in Electrical Conductivity.

Phase 9: Scenario analysis

Activity 23: Ascertain value for each driving hydrological indicator

Scenario analysis begins with an interpretation of the outputs of the hydrological analysis for each of the driving indicators (i.e. hydrology, geomorphology and water quality). For example, an 80% increase in Connectivity predicted with the hydrological model could transform into a Severity Rating of +3 (Table 23).

Table 23: Hypothetical predictions of change in the three driving variables for three scenarios,

Driving indicator	Severity Ratings			
	Present Day	Scenario 1	Scenario 2	Scenario 3
Connectivity	0	+3	+1	-1
Floods	0	+3	+2	-1
Sediment delivery	0	0	+2	-2

Hypothetically Scenario 1 could be the building of a new dam, Scenario 2 could be an increase in agricultural activities and Scenario 3 could be the removal of some weirs.

Activity 24: Interpret change in driving indicators as response in all other indicators

These severity rating values become the driving values in linked Response Curves. For instance, on a Response Curve showing the relationship between Connectivity and Pools, a +3 value for Connectivity could read off from a response curve as a, say, +2.5 value for Pools, negative (–) in other words, Pools would increase in abundance/size by 26-67% under this scenario. The severity rating values for all indicators are systematically ascertained in this way, using the data-flow pathways identified in Activity 20.

Activity 25: Add weightings

Where more than one indicator feeds into another, their combined influence on the receiving indicator has to be judged through the use of a weighting system. For example, the relative influences of the three hydrological driver indicators feeding into "Riparian vegetation cover", response indicator, have to be weighted to produce one statement (weighted sum) on the resulting outcome for riparian vegetation cover, so that this single statement can be used by any subsequent indicator, such as "status of indigenous fish community" response indicator.

The specialists initially use expert knowledge to decide on a weight for each driver of a receiving indicator. They then calculate the weighted allocation per driver as a proportion of 1. Each weighted allocation is multiplied by its value from the relevant Response Curve. Finally, the resulting severity rating values are combined, usually as an average, to provide a final value for how the receiving indicator is predicted to change under that scenario. This severity rating value can then in turn become a driving value for a receiving indicator further along the sequence.

The final set of predictions for any scenario can be summarised in tabular, graphic or text form.

Phase 10: Evaluate the scenario in terms of ecological condition

The severity rating values emanating from a table of responses can be used to provide a preliminary estimate of the overall shift in ecological condition of the ecosystem.

Activity 26: Assess the distribution of values for Severity Ratings of Change

Guidelines from the DRIFT method **(**Brown and Joubert, 2003) can be used as a starting point to assess the severity ratings of change.

- If at least 85% of the indicators have a predicted Rating of Change (Response curve value) of 1 or 0 and none has a value of more than 2, then the system under that scenario would probably remain in the present ecological category.
- If at least 85% of the indicators have a predicted Rating of Change (Response curve value) of 2 or less, and none is more than 3, then the system changes one category from the present ecological category.

- If at least 85% of the indicators have a predicted Rating of Change (Response curve value) of 3 or less, and none is more than 4, then the system changes two categories from the present ecological category.
- If at least 85% of indicators have a predicted Rating of Change (Response curve values) of 4 or less, then the system changes three categories from the present condition, i.e if the system was a category A, it changes to a category D.

The additional information housed within each Response Curve shows if the shifts in ecological condition (i.e. the Ratings) are toward or away from natural. Similar 'Toward' and 'Away' values cancel each other out. The majority of the remaining values are then accepted as the direction of change toward or away from natural.

Phase 11: Outputs

The two main recipients of the scenario outputs are DWA, which will eventually make any decision regarding management of the river system, and the stakeholders, who should make input into this decision in terms of the level of acceptability of each scenario.

Activity 27: Hydrological output

The most useful output for DWA is a table of flows (expressed as volumes or mean monthly flows) for each month of the year and for several levels of assurance.

The table of flows, the EWR, would probably consist mostly of no-flow periods. These no-flow periods are essential in the functioning of non-perennial rivers but the period of flow is also very important as this is where the connectivity of the river is established.

Activity 28: Report back to stakeholders

The assessed scenarios should now be presented to the stakeholders. The stakeholders then have the opportunity to reject or accept each scenario and to express their opinions.

9. THE PROTOTYPE METHODOLOGY APPLIED TO THE MOKOLO RIVER

9.1 Background information on the five selected EWA sites

The Mokolo River study area falls within the Limpopo Water Management Area forming part of the Limpopo Province in the northern part of South Africa. The Mokolo River catchment covers an area of 8 387km^2, starting in the Waterberg Mountains in the upper reaches of the Sand River down to the confluence of the Mokolo River with the Limpopo River. The area consists of quaternary catchments A42A to A42J. Figure 28 illustrates the quaternary catchments in the Mokolo catchment. The main water user (87%), especially in the upper catchment, is agriculture. Tobacco, maize, sunflowers, vegetables and fruit are the main crops, with industry, coal mining (there are major concerns about the growth in coal mining in this area and the increased water demands as a result of the increased mining activities), power generation and domestic water supply using the remaining 13% of the present water use (DWAF, December 2008b). The two main towns located in the study area include Lephalale (Ellisras) and Vaalwater (Dennis, 2010a).

The topography varies depending on the the geological formations present. The northern part of the study area is characterised as relatively flat with elevations ranging between 600 and 700 metres above mean sea level. The hills are associated with the Bushveld Igneous Complex. The central and southern parts of the area are underlain by rocks of the Karoo Supergroup and Waterberg Formation (Dennis, 2010a).

The Mokolo River originates in a flattish, open area with numerous koppies and flows through a steep gorge towards the town of Vaalwater from where the river flows through a relatively flat area until it enters the Mokolo Dam. The Mokolo Dam is the only large dam in the study area and was constructed to provide water to the power station and coal mines located near Lephalale. From there, it flows through another gorge before entering the Limpopo Plains, near the confluence with the Rietspruit. The river then flows through a flat sandy area, until it reaches the Limpopo River (RHP, 2006).

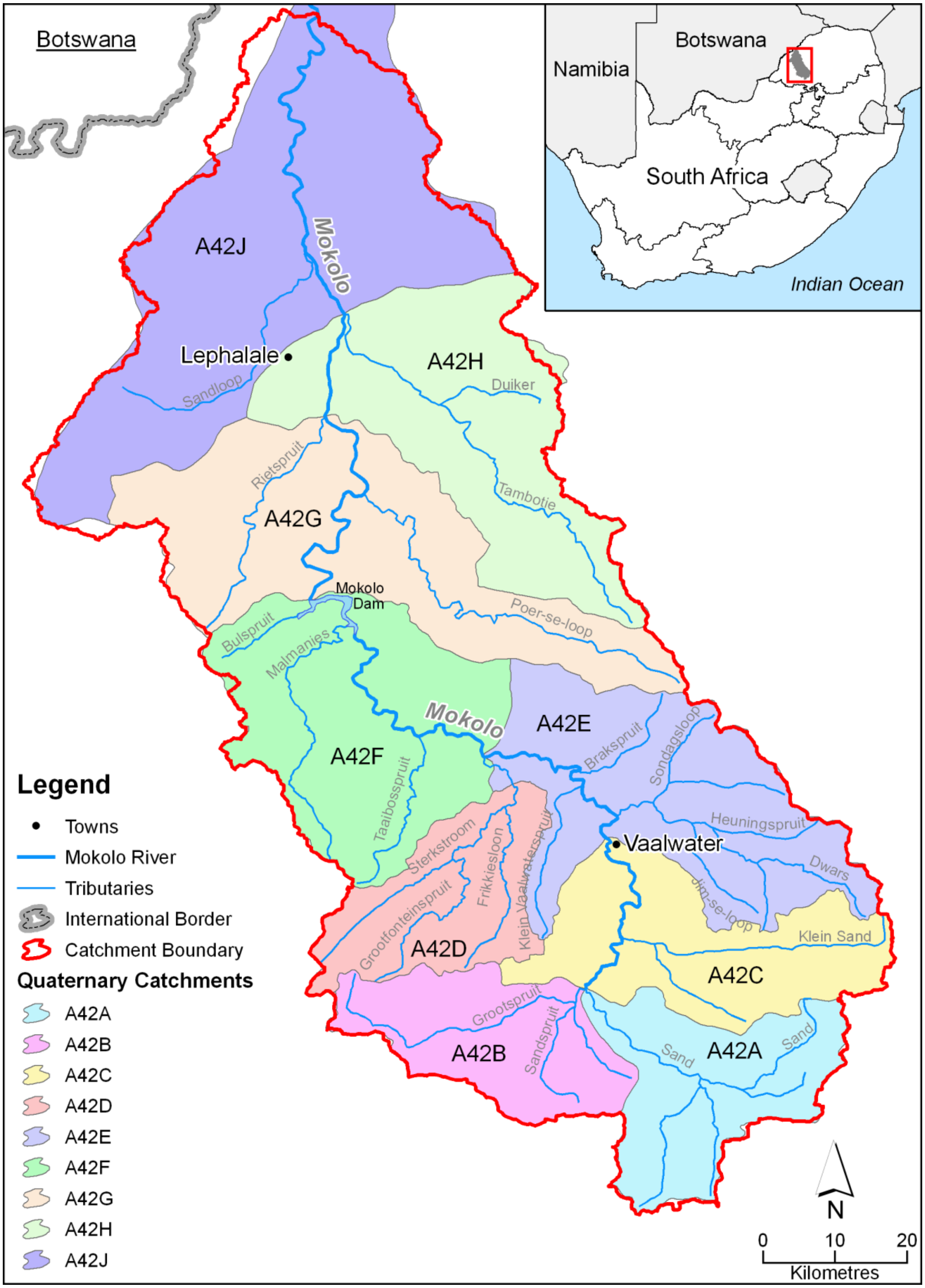


Figure 28: Quaternary catchments of the Mokolo River (Prepared by F Sokolic, 2011)

The five EWA sites are shown in Figure 29, along with all the other monitoring stations, the Intermediate Reserve EWR sites, as well as the DWA gauging stations.

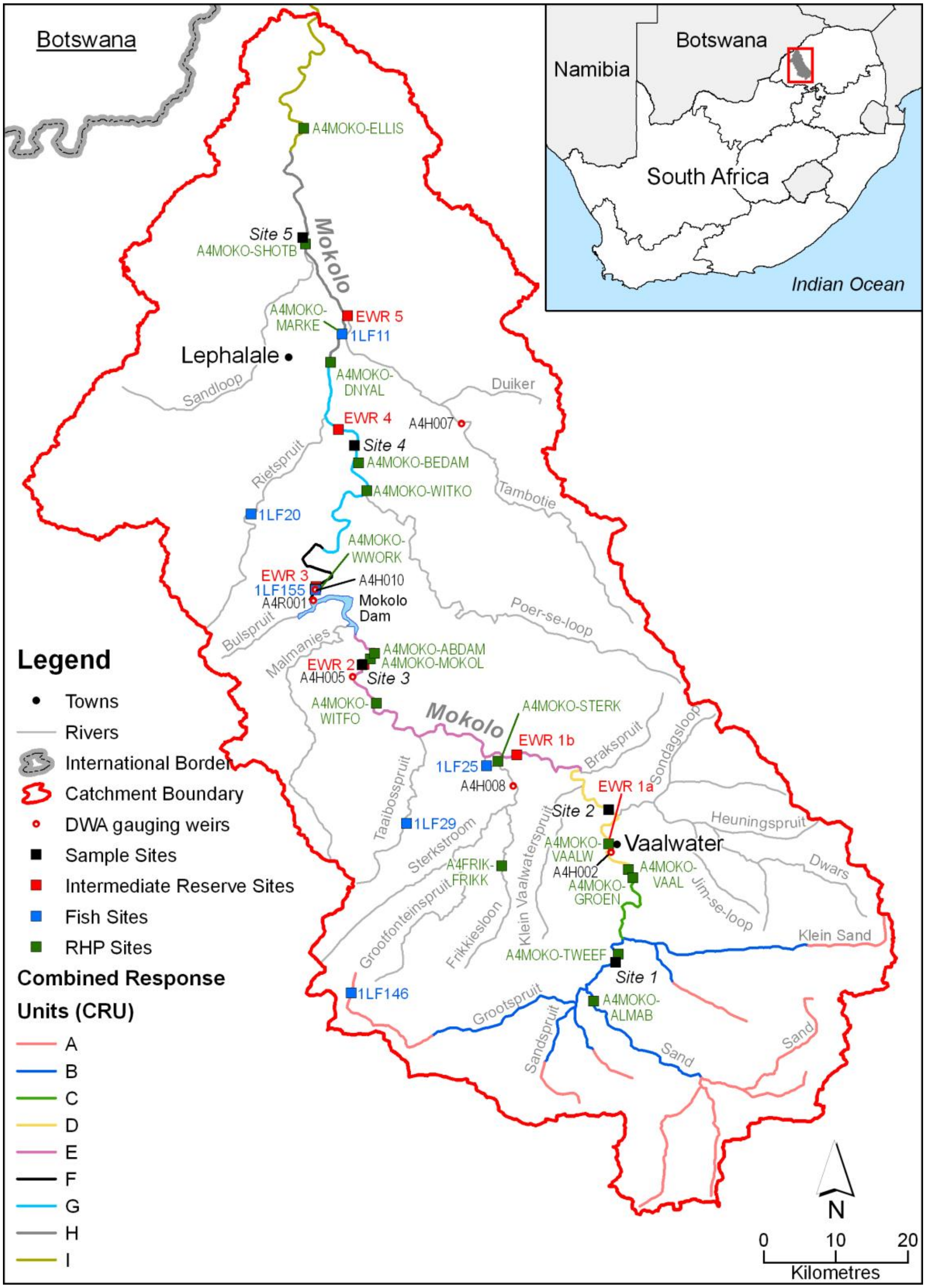


Figure 29: The EWA sites, referred to as Site 1 to 5, as well as all other monitoring sites in the Mokolo catchment (Prepared by F Sokolic, 2011)

A site description based on Watson (2010) follows for each of the EWA sampling sites. All the sites are in the Limpopo Water Management Area and are on the main stem of the Mokolo River.

EWA Site 1

EWA Site 1 is situated upstream of RHP site A4MOKO-TWEEF (Figure 29) on the farm "Mooiwater Landgoed" in subcatchment A42C (Figure 28). The Hydrological Index is 3.178 (Hughes and Hannart, 2003), indicating low flow variability and that this part of the Mokolo River is perennial. The site is situated in the Lower foothill sections of the Sand, Sandspruit, Klein-Sand and Grootspruit tributaries up to its confluence with the Mokolo River.

The geology of the area is characterised by the Waterberg Group of which the Aasvoëlkop Formation consisting mostly of siltstone, mudstone and shale frequently spotted with cavities and interbedded fine grained sandstone at the base is prevalent (SACS, 1980).

EWA Site 1 falls within the Western Bankenveld Ecoregion with the Central sandy bushveld being the dominant vegetation type. The plant groups are associated with the soil types in the region. The tall, deciduous *Terminalia sericea* and *Burkea africana* woodland are tipically found on deep sandy soils, with the low, broadleaved *Combretum* woodland found on shallow rocky or gravelly soils and species of *Acacia, Ziziphus* and *Euclea* are found on flats and lower slopes on eutrophic and less sandy soils (Mucina and Rutherford, 2005).

The main impact on the river is farming and small dams which lead to an increase in zero flow periods and the loss of longitudinal connectivity (DWAF, 2008b).

The site was flooded at the time of sampling (April 2010) and the distinction between substrate and habitat types was difficult. Marginal vegetation (reeds) was present along the main channel (Figure 30). Submerged vegetation (terrestrial grasses) was present in Floodplain Zone 2 (FPZ2).

Downstream

Upstream

Figure 30: Upstream and downstream photographs for EWA 1 (Photos by CEM, 2010)

EWA Site 2

EWA Site 2 is situated downstream of RHP site A4MOKO-VAALW and downstream of the town of Vaalwater (Figure 29) on the farm "Leeuwdrift" in subcatchment A42E (Figure 28). The Hydrological Index is 6.47 (Hughes and Hannart, 2003), indicating low flow variability and that this part of the Mokolo River is also perennial. The site is situated in the Lower foothill section from the start of Macroreach D (24.332S, 28.1249E) to upstream of Mokolo Dam. Mostly high, with some medium to low runoff is expected for this river reach.

The geology of the area is characterised by the Waterberg Group of which the Vaalwater Formation lithology, consisting mainly of alternating fine grained feldspathic and partly micaceous sandstone, arkose, micaceous siltstone and shale of various colours on top with a whitish, light reddish or yellowish fine to medium grained sandstone at the base, is dominant (SACS, 1980).

EWA Site 2 falls within the Waterberg Ecoregion with the Central sandy bushveld being the dominant vegetation type, the same as at EWA Site 1. Some areas in the valleys are dominated by *A. tortilis* and a grass-dominated herbaceous layer is present on dystrophic soils (Mucina and Rutherford*,* 2005), the same as was found at EWA Site 1.

The main impact on the river is farming and small dams which lead to an increase in zero flow periods and the loss of longitudinal connectivity (DWAF, 2008b).

The site was flooded at time of sampling (April 2010) and distinction between substrate and habitat types was difficult. Marginal vegetation (reeds) in current was present along main channel (Figure 31). Submerged vegetation (terrestrial grasses) was present in Floodplain Zone 2 (FPZ2).

Upstream

Downstream

Figure 31: Upstream and downstream photographs for EWA 2 (Photos by CEM, 2010)

EWA Site 3

EWA Site 3 is situated upstream of RHP site A4MOKO-MOKOL and Intermediate Reserve Site EWR2 on a nature reserve (Figure 29) on the farm “Laurel 159” in subcatchment A42F (Figure 28). The Hydrological Index is 22.385 (Hughes and Hannart, 2003), indicating higher low flow variability than upstream sites. The Mokolo River is still a perennial river at this site.

The geology of the area is characterised by the Waterberg Group. The EWA site is situated on the divide between the Cleremont and Mogalakwena Formations consisting of sandstone and grit. The Cleremont lithology consists mainly of very coarse, white sandstone on top with fine-grained, purple, micaceous sandstone at the base, The Mogalakwena Formation lithology consists of a conformable, disconformable base with light to dark purple-brown, coarse grained sandstone and grit with at least three zones of conglomerate, boulder conglomerate, sandstone with pebbles and grit on top (SACS, 1980).

EWA Site 3 falls within the Waterberg Ecoregion with the Western and Central sandy bushveld being the dominant vegetation type. *Acacia erubescens* dominates the flat areas while *Combretum apiculatum* is found on the shallow soils. *Terminalia sericea* is found on deep sands (Mucina and Rutherford*,* 2005). The vegetation is very similar to that of EWA Sites 1 and 2.

The main impact on the river is farming and small dams which lead to an increase in zero flow periods and the loss of longitudinal connectivity (DWAF, 2008b). The riparian vegetation integrity is good and is probably due to game farming in this section of the river.

Site was flooded at time of sampling (April 2010) and distinction between substrate and habitat types was difficult (Figures 32). Marginal vegetation grass and reeds in and out of current was present in backwater area in FPZ2. Submerged vegetation (terrestrial grasses) was also present in Floodplain Zone 2 (FPZ2).

Upstream

Downstream

Figure 32: Upstream and downstream photographs for EWA 3 (Photos by CEM, 2010)

EWA Site 4

EWA Site 4 is situated upstream of the Intermediate Reserve Site EWR4 (Figure 29) on the farm “Vygeboomspoort” in subcatchment A42G (Figure 28). The Hydrological Index is 22.177 (Hughes and Hannart, 2003), indicating slightly lower flow variability than the upstream site. The Mokolo River is still a perennial river at this site. The site is situated in the Lowland River section from end of Macroreach F (23.9184S, 27.7334E) to just downstream of the Rietspruit confluence. High to medium runoff is mostly expected.

The geology of the area is characterised by the Waterberg Group. The Mogalakwena Formation, as in EWA Site 3, is the dominant geological formation at this site (SACS, 1980).

EWA Site 4 also falls within the Waterberg Ecoregion but with the Waterberg Mountain Bushveld vegetation dominant. A grass layer is present and vegetation on the mountains is *Faurea saligna-Protea caffra* bushveld through to broadleaved deciduous bushveld on the rocky mid- and foot slopes of the area. *Burkea africana-Terminalia sericea* savannah is mostly present in the lower valleys and on deeper sands in the plateau (Mucina and Rutherford*,* 2006).

The Mokolo Dam has a major influence on the downstream Mokolo area. However, large areas are not influenced by the Mokolo Dam and this in turn influences connectivity and length of zero flow periods, lack of floods and unseasonal releases from the dam (DWAF, 2008b).

Site was flooded at time of sampling (April 2010) and distinction between substrate and habitat types was difficult. Marginal vegetation grass and reeds in and out of current was present in backwater area in FPZ2. Submerged vegetation (terrestrial grasses) was also present in Floodplain Zone 2 (FPZ2) (Figures 33).

Upstream

Downstream

Figure 33: Upstream and downstream photographs for EWA 4 (Photos by B van der Waal, 2010)

EWA Site 5

EWA Site 5 is situated downstream of Intermediate Reserve Site EWR5 and A4MOKO-SHOTB (Figure 29) on the farm “Die End/Ons Hoop” in subcatchment A42J (Figure 28). The Hydrological Index is 47.41 (Hughes and Hannart, 2003), indicating much higher flow variability than upstream sites. The site is situated in the Lowland River section from just downstream of the confluence with the Rietspruit River to the confluence with the Limpopo River. Low runoff is mostly expected.

The geology of the area is characterised by the Karoo Group. The Clarens Formation consisting of intercalated argillaceous and arenaceous rocks (Busari, 2008) such as sandstone and siltstone is the dominant formation.

EWA Site 5 falls within the Limpopo Plains Ecoregion. The dominant vegetation type is the Limpopo Sweet Bushveld. The vegetation consists of short open woodland and where the natural vegetation has been disturbed, *Acacia erubescens, A. mellifera* and *Dicrostachys cinerea* dominate (Mucina and Rutherford*,* 2006).

The Mokolo Dam has a major influence on the downstream Mokolo area. The dam changes the flooding regime and connectivity in the floodplain and it also influences the riparian zone (DWAF, 2008b).

The Site was flooded at time of sampling (April 2010) and a distinction between substrate and habitat types was difficult (Figure 34). Marginal vegetation grass and reeds in and out of current was present in flooded area in FPZ2.

View of sampling area

Sampling site

Figure 34: Photographs for EWA 5 (Photos by CEM, 2010)

9.2 Data collected from 26 to 30 April 2010

Water quality data were collected at the five EWA sites during a site visit from 26 to 30 April 2010. All the sites were flooded at the time of sampling. The physical-chemical water quality data of the five sites are presented in Table 24.

Table 24: Results of physical and chemical analyses in the five EWA Mokolo River sampling sites

	Site name				
Variables	**EWA1**	**EWA2**	**EWA 3**	**EWA 4**	**EWA 5**
pH	7.01	6.81	6.69	6.70	6.65
Electrical Conductivity mS/m	8.37	6.75	4.96	4.92	4.94
Temperature ºC	15.70	16.80	19.00	21.60	21.80
Dissolved Oxygen mg/ℓ	3.88	7.80	7.73	6.20	5.11
Oxygen percentage	39.60	80.60	83.20	70.00	60.00
Redox mv.	-18.10	-11.80	-3.20	2.40	5.20
Turbidity NTU	26.00	27.00	16.20	9.80	8.00
Secchi disc depth cm	32	35	40	77	70
Ca mg/ℓ	4.435	3.326	2.334	2.279	1.769
Mg mg/ℓ	2.527	2.225	1.493	1.383	1.096
Na mg/ℓ	11.222	9.620	7.501	6.621	7.147
K mg/ℓ	3.949	2.815	1.741	1.608	1.453
Cl mg/ℓ	11.890	9.993	7.007	6.108	7.366
NO_3-N mg/ℓ	0.207	0.208	0.211	0.192	0.158
PO_4 µg/ℓ	108.68	25.31	80.89	100.00	73.95
SO_4 mg/ℓ	3.886	3.696	3.047	3.420	2.614
NH4(N) mg/ℓ	0.151	0.103	0.105	0.101	0.091
DIP mg/ℓ	0.109	0.025	0.081	0.001	0.074
DIN mg/ℓ	0.358	0.311	0.316	0.293	0.249
TDS mg/ℓ	63.78	52.91	38.32	35.11	34.97
EC/TDS conversion factor	7.62	7.84	7.73	7.14	7.08

The algal results are presented in Table 25.

Table 25: Algal assemblage and Chlorophyll-a concentrations for the Mokolo River EWA 1 to 5 sites during April 2010 sampling period

Sites	**1**		**2**		**3**		**4**		**5**	
Genera:	cells/mℓ	%	cells/mℓ	%	cells/mℓ	%	cells/mℓ	%	cells/mℓ	%
CYANOPHYCEAE	***147***	**11**	***147***	**6**	***147***	**25**	***0***	**0**	***74***	**13**
Anabaena (F)									74	13
Oscillatoria (F)	147	11	147	6	147	25				
BACILLARIOPHYCEAE	***587***	**44**	***1,917***	**77**	***293***	**50**	***369***	**45**	***74***	**13**
Cocconeis									74	13
Cyclotella							74	9		
Gyrosigma	147	11								
Melosira (F)							74	9		
Navicula	147	11								
Nitzschia	293	22	293	12	293	50	147	18		
Pennate diatoms (other)			1,477	59			74	9		
Synedra			147	6						
CHLOROPHYCEAE	***441***	**33**	***293***	**12**	***147***	**25**	***369***	**45**	***296***	**50**
Ankistrodesmus							74	9	74	13
Chlamydomonas	147	11	293	12	147	25	74	9	74	13
Chlorella	147	11					74	9		
Chlorococcum									74	13
Monoraphidium	147	11								
Oocystis (col.)							147	18		
Scenedesmus (col.)									74	13
EUGLENOPHYCEAE	***147***	**11**	***147***	**6**	***0***	**0**	***74***	**9**	***148***	**25**
Euglena			147	6			74	9	74	13
Trachelomonas	147	11							74	13
Total:	**1,322**	**100**	**2,504**	**100**	**587**	**100**	**812**	**100**	**592**	**100**

Chlorophyll-*a* (μg/ℓ)	5	<1	<1	<1	<1

(F= filamentous; col. = colonies)

In evaluating the results of the phytoplankton assemblage and chlorophyll-*a* concentration as was already stated, it must be taken into account that the river was in flood at the time of sampling and lower values were expected. The water quality in terms of electrical conductivity (or total dissolved salts) was good. This was also confirmed in the Intermediate Reserve document (DWAF, 2008b). The slightly higher EC value at EWA 1 compared to the other EWA sites could be attributed to more irrigation land use than in the downstream areas. The nutrients were also slightly higher and this could be due to fertiliser being used on the irrigated lands.

The algal assemblages were analysed by T Vos and the results for the Mokolo River (Table 25) shows EWA 1 to 3 were dominated by the Bacillariophyceae (diatoms), EWA 4 had a co-dominancy of Bacillariophyceae and Chlorophyceae (green algae), whereas EWA 5 was dominated by the Chlorophyceae.

EWA 1 had a total of 1 322 cells/mℓ that was dominated by the diatom genus *Nitzschia* (293 cells/mℓ), and a chlorophyll-*a* concentration of 5 µg/ℓ (PES = A/B; natural). EWA 2 had a total of 2 504 cells/mℓ and was dominated by Bacillariophyceae genera with a chl-*a* concentration of <1 µg/ℓ (PES = A; natural). EWA 3 was dominated by the diatom genus *Nitzschia* (293 cells/mℓ) in a total assemblage of 587 cells/mℓ. The chl-*a* concentration was <1 µg/ℓ (PES = A; natural). EWA 4 (812 cells/mℓ) was equally dominated by the diatoms and green algae, with the diatom genus *Nitzschia* and green algal genus *Oocystis* dominant (147 cells/mℓ each). The chl-*a* concentration was <1 µg/ℓ (PES = A; natural). EWA 5 was the only site to be dominated by the Chlorophyceae. No genus dominated the sample of 592 cells/mℓ. A chl-*a* concentration of <1 µg/ℓ was measured (PES = A; natural)

All the samples had very low algal concentrations and fell into the natural PES class.

Diatom results are presented in Tables 26 and 27 and also indicate a natural PES class.

Table 26: Diatom results for the April 2010 sampling

Site	**Count**	**No. species**	**SPI**	**Genus Index**	**%PTV[1]**
1	56	22	10.3	14.6	8.9
3	56	23	15.3	15.5	1.8
4	50	22	15.9	15.2	4.0
5	76	19	13.7	13.2	6.6
Interpretation of index scores					
Index score	**Class**				
>17	high quality				
13 to 17	good quality				
9 to 13	moderate quality				
5 to 9	poor quality				
<5	bad quality	[1] - percentage pollution tolerant valves			

Table 27: Diatom taxa for the April 2010 sampling

Taxon	Site (relative abundance)			
	1	**3**	**4**	**5**
Achnanthidium exiguum (Grunow) Czarnecki	0	0	4	0
Achnanthidium minutissimum (Kützing) Czarnecki	2	**13**	2	0
Amphora copulata (Kützing) Schoeman and Archibald	0	2	0	0
Aulacoseira granulata (Ehrenberg) Simonsen	2	0	0	0
Cyclotella meneghiniana Kützing	0	0	0	1
Cymbella turgidula Grunow	0	4	0	0
Diploneis subovalis Cleve	2	0	0	0
Discostella stelligera (Cleve and Grunow) Van Heurck	0	0	4	0
Encyonema minutum (Hilse in Rabh.) D.G. Mann	2	2	2	0
Encyonema neogracile Krammer	0	0	**26**	**18**
Eolimna minima (Grunow) Lange-Bertalot	0	0	0	4
Eunotia flexuosa (Brébisson)Kützing	0	0	0	1
Eunotia mesiana Cholnoky	0	0	2	0
Eunotia rhomboidea Hustedt	0	0	0	1
Eunotia sp.	0	4	2	7
Eunotia zasuminensis (Cabejszekowna) Körner	**45**	**20**	2	0
Fallacia pygmaea (Kützing) Stickle and Mann	2	0	0	0
Fragilaria biceps (Kützing) Lange-Bertalot	0	2	0	8
Fragilaria capucina Desmazieres	4	0	0	1
Fragilaria sp.	0	2	6	1
Fragilaria ulna var. *acus* (Kützing) Lange-Bertalot	4	4	0	5
Frustulia crassinervia (Brébisson) Lange-Bertalot and Krammer	2	0	2	**11**
Gomphonema clavatum Ehrenberg	0	0	2	0
Gomphonema gracile Ehrenberg	0	0	8	4
Gomphonema parvulum (Kützing) Kützing	5	0	2	3
Gomphonema pumilum (Grunow) Reichardt and Lange-Bertalot	2	2	0	0
Gomphonema sp.	4	7	8	1
Gyrosigma attenuatum (Kützing) Rabenhorst	2	4	0	0
Hantzschia amphioxys (Ehrenberg) Grunow	4	0	0	0
Kobayasia subtilissima (Cleve) Lange-Bertalot	0	2	0	0
Luticola mutica (Kützing) D.G. Mann	2	0	0	0
Navicula arvensis var. *maior* Lange-Bertalot	0	0	0	3
Navicula cryptocephala Kützing	0	5	0	0
Navicula feuerbornii Hustedt	0	4	2	0
Navicula lepidula Grunow	0	0	2	0
Navicula notha Wallace	2	0	8	**11**
Navicula rostellata Kützing	4	0	0	0
Navicula sp.	0	0	0	1

Navicula zanoni Hustedt	0	4	2	0
Nitzschia acidoclinata Lange-Bertalot	0	0	0	1
Nitzschia frustulum (Kützing) Grunow	0	2	2	0
Nitzschia sp.	5	4	6	**17**
Nitzschia terrestris (Petersen) Hustedt	4	0	0	0
Pinnularia sp.	2	2	2	0
Rhopalodia gibba (Ehrenberg) Müller	0	2	0	0
Sellaphora pupula (Kützing) Mereschkowksy	2	0	0	0
Staurosira construens Ehrenberg	0	9	0	0
Staurosirella pinnata (Ehrenberg) Williams and Round	2	4	4	0
Stenopterobia delicatissima (Lewis) Brébisson	0	2	0	0

9.3 EWA surface water analysis

The format as presented in DWAF, 2008b (Appendix D: Physico-chemical Variables) was followed in presenting the determination of the Present Ecological State (PES).

The EWA sampling sites selected correspond with some of the EWR sites in DWAF (2008b) and the results presented in that report were used and not recalculated. A combination of present day (collected data) and historical data were used to determine the EWA at each EWA site.

The following sites were used:
EWR 1A was similar to EWA Site 2, EWR 2 was similar to EWA Site 3 and EWR 4 was similar to EWA Site 4 (DWAF, 2008b). Where additional data (temperature, oxygen and turbidity) were available these were added to the tables. It is important to note that the additional data generated were from a once off sampling event at the end of April 2010.

EWA Site 1 and Site 5 had very little water quality data but the same data presentation format, as was used for the other sites with more data, was used to describe the PES of these two sites. However the confidence in the data at these two sites was much lower than that of the other three sites due to the limited data record. EWA Site 5 was expected to be very similar to EWA Site 4, as the geology and landuse was similar, and EWA Site 4 data were used at EWA Site 5.

EWA Site 1

Data Evaluation

Data availability	Conf
No DWA monitoring data were available for either reference condition or PES. Limited phytoplankton, periphyton and diatoms were available (n = 1). Limited temperature, dissolved oxygen (DO) or turbidity data were available (n=1). No metal data were available. Electrical conductivity (EC) was used instead of aggregated salts as TEACHA could not be used.	1

Reference Conditions

Reference conditions	Conf
No DWA or any other monitoring data were available.	0

Present Ecological State

The water quality table, which is completed as part of the assessment and assigns the EcoStatus rating for water quality, is shown below as Table 28.

Table 28: Water quality for EWA Site 1

RIVER	Mokolo River	**Water Quality Monitoring Points**	
		RC	None
EWA SITE	1	**PES**	Data (n=1) measured during the site visit
Confidence assessment	Confidence in the assessment is very low, as little data are available.		
Water Quality Constituents		**Value**	**Category (Rating) / Comment**
Inorganic salts (mg/ℓ)	$MgSO_4$	-	TEACHA could not be used and EC used as surrogate
	Na_2SO_4	-	
	$MgCl_2$	-	
	$CaCl_2$	-	
	NaCl	-	
	$CaSO_4$	-	
Nutrients (mg/ℓ)	SRP	0.109	D (2.5) : Benchmark category was used
	TIN	0.358	B (1): Benchmark category was used

RIVER	Mokolo River	**Water Quality Monitoring Points**	
		RC	None
EWA SITE	1	**PES**	Data (n=1) measured during the site visit
Confidence assessment	Confidence in the assessment is very low, as little data are available.		

Water Quality Constituents		**Value**	**Category (Rating) / Comment**
Physical Variables	pH (5th and 95th percentiles)	7.01	A (0): Benchmark category was used
	Temperature	15.70	Very little data, but few impacts expected. Catchment not pristine, so A/B (0.5) – qualitative assessment only. Low oxygen can not be explained
	Dissolved oxygen	3.88	
	Turbidity (NTU)	26	Very little data, but loads should have increased due to agricultural activities C (2) – qualitative assessment only
	Electrical conductivity (mS/m)	8.37	A (0): Water quality generally good
Response variables	Chl-a: periphyton	-	-
	Chl-a: phytoplankton	5	A (0): Benchmark category was used
	Biotic community composition: macroinvertebrate (ASPT) score	SASS: 245 ASPT: 6.4	A (0) Data obtained from Invertebrate specialist
	Fish	65.2%	C (2)- Data obtained from fish specialist
	Diatoms	SPI: 10.3	C (2) - based on one sample during flood conditions in 2010
Toxics (mg/ℓ)	Fluoride	-	-
	Ammonia	0.151	E/F (5)
OVERALL SITE CLASSIFICATION		**B/C**	

The above B/C classification is not based on any calculations although values used in the PAI model were inserted. As only one sample for the site was available, and based on the EC and current land use activities it was the specialist opinion that the water quality has changed from reference conditions to a present ecological state to a B/C.

PES Trend

One cannot comment on the trend as only one sample was taken at each EWA site and for EWA Site 1 no other historical or present day data were available. However, it is known that irrigation farming is an important land use in the EWA 1 region. If irrigation increases, there may be an increase in EC due to irrigation return flows being discharged to the river. If irrigation stays the same as that of the present conditions, there should be no increase or decrease in EC and if there is a decrease in irrigation activities there may be a decrease in EC values.

EWA Site 2

The EWR 1A results from the Intermediate Reserve for the Mokolo River (DWAF, 2008b) was used at EWA Site 2. Where only one sample was collected during the Intermediate Reserve study, the results from the 2010 sampling were included in Table 29, but not used in the calculations as they made such a small contribution, did not change the PES and were not part of the long-term data records used in calculating the RC and PES.

Data Evaluation

Data availability	Conf
DWAF monitoring data were available for reference condition and PES. Limited phytoplankton, periphyton and diatoms were available (n = 1). Limited temperature, dissolved oxygen (DO) or turbidity data were available from 2010 sampling(n = 1). Little metal data were available. Electrical conductivity (EC) was used instead of aggregated salts as TEACHA could not be used.	3

Reference Conditions

Reference conditions	Conf
DWAF monitoring data were available. Water quality station A4H002Q01 was used to set reference conditions with n = 68, and data available from 1977 – 1979.	3

Water Quality Constituents		**Value: RC**
Inorganic salts (mg/ℓ)	No data available.	
Nutrients (mg/ℓ)	Soluble Reactive Phosphate (SRP)	0.011
	Total Inorganic Nitrogen (TIN)	0.080
Physical Variables	pH (5th and 95th percentiles)	6.68 and 7.70
	Electrical conductivity (mS/m)	12.28
Toxics (mg/ℓ)	Fluoride	0.10
	Ammonia	-

Present Ecological State

The water quality table, which was completed as part of the assessment and assigns the EcoStatus rating for water quality, is shown below as Table 29.

Table 29: Water quality for EWA Site 2

RIVER	Mokolo River	**Water Quality Monitoring Points**	
		RC	A4H002Q01, ’77-’79, n = 68
EWR SITE	2 (1A)	**PES**	A4H002Q01, ’02-’07 (with 1 point in 2007), n = 48 (but 37 for F and SO_4)
Confidence assessment	Confidence in the assessment is **moderate**, due to limited DO, temp., turbidity or toxics data, although the gauging weir is close to the EWA site.		
Water Quality Constituents		**Value**	**Category (Rating) / Comment**
Inorganic salts (mg/ℓ)	$MgSO_4$	-	TEACHA could not be used and EC used as surrogate
	Na_2SO_4	-	
	$MgCl_2$	-	
	$CaCl_2$	-	
	NaCl	-	
	$CaSO_4$	-	
Nutrients (mg/ℓ)	SRP	0.0165	B (1): Benchmark category was recalibrated
	TIN	0.123	A (0)
Physical Variables	pH (5th and 95th percentiles)	6.92 - 7.83	A (0)
	Temperature	16.80	Limited data (n=1), but few

RIVER	Mokolo River	**Water Quality Monitoring Points**	
		RC	A4H002Q01, ’77-’79, n = 68
EWR SITE	2 (1A)	**PES**	A4H002Q01, ’02-’07 (with 1 point in 2007), n = 48 (but 37 for F and SO_4)
Confidence assessment	Confidence in the assessment is **moderate**, due to limited DO, temp., turbidity or toxics data, although the gauging weir is close to the EWA site.		
Water Quality Constituents		**Value**	**Category (Rating) / Comment**
	Dissolved oxygen	7.80	impacts expected. Catchment not pristine, so A/B (0.5) – qualitative assessment only
	Turbidity (NTU)	27	Limited data, river in flood – higher turbidity expected. B (1) – qualitative assessment only
	Electrical conductivity (mS/m)	12.05	A (0)
Response variables	Chl-a: periphyton	EWR 1A: 21.58	C/D (2.5) (n=1)
	Chl-a: phytoplankton	< 1	A (0) Limited data (n=1)
	Biotic community composition: macroinvertebrate (ASPT) score	SASS: 127 ASPT: 5.3	C (62.3)
	Fish	70.3	C - largely flow-related
	Diatoms	EWR 1A: SPI = 17.3 and 16.8	A/B (0.5) (n = 2)
Toxics (mg/ℓ)	Fluoride	0.18	A (0)
	Ammonia	0.001	A (0)
OVERALL SITE CLASSIFICATION (from PAI)		**B/C (80.0)**	

PES Trend

PES	Trend	Trend PES	Time	Reasons	Conf
B/C	Stable	B/C		Present day flows follow the same pattern as natural flows, although zero flows are now sometimes experienced.	3

EWA Site 3

The EWR 2 results from the Intermediate Reserve for the Mokolo River (DWAF, 2008b) were used at EWA Site 3. Where one sample was collected during the Intermediate Reserve study, the results from the 2010 sampling were included in Table 30, but not used in the calculations as they made such a small contribution, did not change the PES and were not part of the long-term data records used in calculating the RC and PES.

Data Evaluation

Data availability	Conf
DWAF monitoring data were available for reference condition and PES. Limited phytoplankton, periphyton and diatoms were available (n = 1). Limited temperature, DO or turbidity data were available(n = 1). Little metal data were available. Electrical conductivity (EC) was used instead of aggregated salts as TEACHA could not be used.	2.5

Reference Conditions

Reference conditions	Conf
DWAF monitoring data were available. Water quality station A4H005Q01was used to set reference conditions with n = 85, and data available from 1977 – 1980.	3

Water Quality Constituents		Value: RC
Inorganic salts (mg/ℓ)	No data available.	
Nutrients (mg/ℓ)	SRP	0.011
	TIN	0.06
Physical Variables	pH (5th and 95th percentiles)	6.00 and 7.25
	Electrical conductivity (mS/m)	9.09
Toxics (mg/ℓ)	Fluoride	0.19
	Ammonia	-

Present Ecological State

The water quality table, which was completed as part of the assessment and assigns the EcoStatus rating for water quality, is shown below as Table 30.

Table 30: Water quality for EWA Site 3

RIVER	Mokolo River	**Water Quality Monitoring Points**	
		RC	A4H005Q01, ’77 - ’80, n = 85 (but 163 for EC)
EWA SITE	3	**PES**	A4H005Q01, ’98 - ’01, n = 39 (but 47 for TIN)
Confidence assessment	Confidence in the assessment is **low.** Little DO, temp., turbidity (n=1) or toxics data are available, and although the gauging weir is close to the EWR site, present state data is only available up until 2001.		
Water Quality Constituents		**Value**	**Category (Rating) / Comment**
Inorganic salts (mg/ℓ)	$MgSO_4$	-	TEACHA could not be used and EC used as surrogate
	Na_2SO_4	-	
	$MgCl_2$	-	
	$CaCl_2$	-	
	NaCl	-	
	$CaSO_4$	-	
Nutrients (mg/ℓ)	SRP	0.0059	A (0): Benchmark category was recalibrated – RC data very variable
	TIN	0.02	A (0). RC data very variable
Physical Variables	pH (5th and 95th percentiles)	7.46 - 7.87	A (0): Benchmark category recalibrated for lower A category
	Temperature	19	Limited data (n=1), but few impacts expected. Some temperature and DO fluctuations may occur at low flows - B (1) – qualitative assessment only
	Dissolved oxygen	7.73	
	Turbidity (NTU)	16.20	Limited data, but loads not expected to be high. A/B (0.5) – qualitative assessment only
	Electrical conductivity (mS/m)	9.4	A (0)
Response variables	Chl-a: periphyton	EWR 2: 25.54 WQ site 4: 18.68	D (3) (n=1). C (2) (n=1)
	Chl-a: phytoplankton	<1	A (0) (n=1)

RIVER	Mokolo River	**Water Quality Monitoring Points**	
		RC	A4H005Q01, '77 - '80, n = 85 (but 163 for EC)
EWA SITE	3	**PES**	A4H005Q01, '98 - '01, n = 39 (but 47 for TIN)
Confidence assessment	Confidence in the assessment is **low.** Little DO, temp., turbidity (n=1) or toxics data are available, and although the gauging weir is close to the EWR site, present state data is only available up until 2001.		
Water Quality Constituents		**Value**	**Category (Rating) / Comment**
	Biotic community composition: macroinvertebrate (ASPT) score	Jan '08: SASS – 82; ASPT - 5.1 March '08: SASS - 126 ; ASPT - 6.6	C
	Fish	65.1	C
	Diatoms	EWR 2: SPI=16.1 WQ site 4: 18.8	B (1) (n=2) A (0) (n=1)
Toxics (mg/ℓ)	Fluoride	0.15	A (0)
	Ammonia	0.002	A (0)
OVERALL SITE CLASSIFICATION (from PAI)		**B (84.2)**	

Note that the diatom and chlorophyll-a results for the Sterkstroom River (WQ site 4) were used for this site as this is an important tributary in this river reach. Sterkstroom water quality data were assessed, and indicate an A category (DWAF, 2008b).

PES Trend

PES	Trend	Trend PES	Time	Reasons	Conf
B	Stable	B		Present day flows follow the same pattern as natural flows, although zero flows are now experienced.	3

EWA Site 4

The EWR 4 results from the Intermediate Reserve for the Mokolo River (DWAF, 2008b) were used at EWA Site 4. Where one sample was collected, the results from the 2010 sampling were included, but not used in the calculations as they made such a small contribution, did not change the PES and were not part of the long-term data records used in calculating the RC and PES.

Data Evaluation

Data availability	Conf
Data from A4H007Q01 were used for RC (on Tambotie River) and A4H010Q01 for PES. Data from A4H010Q01 were used for EWR 3 and 4, with modifications to the PAI table – particularly based on on-site indicators and the influence of Poer-se-loop tributary joining the Mokolo River between the two sites. Present state data only until 1996 and RC data sourced from A4H007Q01 on the Tambotie River (same EcoRegion level II). Limited temperature, DO or turbidity data were available (n=1). Little metal data were available. Electrical conductivity (EC) was used instead of aggregated salts as TEACHA could not be used.	2

Reference Conditions

Reference conditions	Conf
DWAF monitoring data were available. Water quality station A4H007Q01was used to set reference conditions with n = 82, and data available from 1977 – 1980.	3

Water Quality Constituents		Value: RC
Inorganic salts (mg/ℓ)	No data available.	
Nutrients (mg/ℓ)	SRP	0.007
	TIN	0.065
Physical Variables	pH (5th and 95th percentiles)	5.14 and 6.70
	Electrical conductivity (mS/m)	15 and 24
Toxics (mg/ℓ)	Fluoride	6.77
	Ammonia	0.160

Present Ecological State

The water quality table, which was completed as part of the assessment and assigns the EcoStatus rating for water quality, is shown below as Table 31.

Table 31: Water quality for EWA Site 4

RIVER	Mokolo River	**Water Quality Monitoring Points**	
		RC	A4H007Q01, ’77 - ’80, n = 82
EWA SITE	4	**PES**	A4H010Q01, ’92-’96, n = 27 (but 19 for temp. and 6 for NH_3)

Confidence assessment	Confidence in the assessment is **low** as little DO, temp., turbidity (n=1) or toxics data are available. Data from A4H010Q01 were used for EWR 3 and 4, with modifications to the PAI table – particularly based on on-site indicators and the influence of Poer-se-loop tributary joining the Mokolo River between the two sites. Present state data only until 1996 and RC data sourced from A4H007Q01 on the Tambotie River (same EcoRegion level II).

Water Quality Constituents		**Value**	**Category (Rating) / Comment**
Inorganic salts (mg/ℓ)	$MgSO_4$	-	TEACHA could not be used and EC used as surrogate
	Na_2SO_4	-	
	$MgCl_2$	-	
	$CaCl_2$	-	
	NaCl	-	
	$CaSO_4$	-	
Nutrients (mg/ℓ)	SRP	0.015	A (0): Benchmark category was recalibrated – Data very variable
	TIN	0.067	A (0). Data very variable
Physical Variables	pH (5th and 95th percentiles)	7.2 - 7.76	B (1): RC data 5.14 (5th percentile) and 6.7 (95th percentile) – reliability?
	Temperature	21.6	Limited data, but no impacts expected. Small temperature and DO fluctuations may occur - B (1) – qualitative assessment only
	Dissolved oxygen	6.20	
	Turbidity (NTU)	9.80	Limited data, but loads not expected to be too high and river generally clear. A (0) – qualitative assessment only
	Electrical conductivity (mS/m)	10.87	A (0)
Response variable	Chl-a: periphyton	-	-
	Chl-a: phytoplankton	<1	A (0)
	Biotic community composition: macroinvertebrate (ASPT) score	SASS: 126 ASPT: 4.8	C
	Fish	63.73	C

RIVER	Mokolo River	**Water Quality Monitoring Points**	
		RC	A4H007Q01, ’77 - ’80, n = 82
EWA SITE	4	**PES**	A4H010Q01, ’92-’96, n = 27 (but 19 for temp. and 6 for NH_3)
Confidence assessment	Confidence in the assessment is **low** as little DO, temp., turbidity (n=1) or toxics data are available. Data from A4H010Q01 were used for EWR 3 and 4, with modifications to the PAI table – particularly based on on-site indicators and the influence of Poer-se-loop tributary joining the Mokolo River between the two sites. Present state data only until 1996 and RC data sourced from A4H007Q01 on the Tambotie River (same EcoRegion level II).		
Water Quality Constituents		**Value**	**Category (Rating) / Comment**
	Diatoms	Sept ’07: SPI=17.8 March ’08: SPI=17.4	A (0) (n=2)
Toxics (mg/ℓ)	Fluoride	0.278	A (0)
	Ammonia	0.001	A (0)
OVERALL SITE CLASSIFICATION (from PAI)		**B (86.8)**	

PES Trend

PES	Trend	Trend PES	Time	Reasons	Conf
B	Stable	B		Consistent variability over time dependent on dam operations probably still impacting this site.	2

EWA Site 5

Data from EWA Site 4 were extrapolated to EWA Site 5 as very little (n=1) data are available for this site. However, the confidence was low as it was already low at EWA Site 4.

Data Evaluation

Data availability	**Conf**
No DWA monitoring data were available for either reference condition or PES. Limited phytoplankton, periphyton and diatom data were available (n = 1). Limited temperature, dissolved oxygen (DO) or turbidity data were available (n=1). No metal data were available. Electrical conductivity (EC) was used instead of aggregated salts as TEACHA could not be used.	1

Reference Conditions

Reference conditions	**Conf**
No DWA or any other monitoring data were available.	0

Present Ecological State

The water quality table, which was completed as part of the assessment and assigns the EcoStatus rating for water quality, is shown below as Table 32.

The B/C classification below is not based on any calculations although values used in the PAI model (DWAF, 2008a) were inserted. As only one sample for the site was available, and based on the EC and current land use activities it was the specialist opinion that the water quality has changed from reference conditions to a present ecological state to a B/C.

PES Trend

One cannot comment on the trend as only one sample was taken at each EWA site and for EWA Site 5 no other historical or present day data were available. However, if one extrapolates from EWA Site 4, no definite trend is expected but that will depend on the way in which the dam is operated.

Table 32: Water quality for EWA Site 5

RIVER	Mokolo River	**Water Quality Monitoring Points**	
		RC	None
EWA SITE	5	**PES**	Data (n=1) measured during the site visit
Confidence assessment	Confidence in the assessment is very low, as little data are available.		
Water Quality Constituents		**Value**	**Category (Rating) / Comment**
Inorganic salts (mg/ℓ)	$MgSO_4$	-	TEACHA could not be used and EC used as surrogate
	Na_2SO_4	-	
	$MgCl_2$	-	
	$CaCl_2$	-	
	NaCl	-	
	$CaSO_4$	-	
Nutrients (mg/ℓ)	SRP	0. 074	D (2.5) : Benchmark category was used
	TIN	0.249	B (1): Benchmark category was used
Physical Variables	pH (5th and 95th percentiles)	6.65	A (0): Benchmark category was used
	Temperature	21.80	Very little data, but few impacts expected. Catchment not pristine, so A/B (0.5) – qualitative assessment only. Lower oxygen due to organic material in the water.
	Dissolved oxygen	5.11	
	Turbidity (NTU)	8	Very little data, but loads probably higher due to flood conditions B (1) – qualitative assessment only
	Electrical conductivity (mS/m)	8.37	A (0): Water quality generally good
Response variables	Chl-a: periphyton	-	-
	Chl-a: phytoplankton	<1	A (0): Benchmark category was used
	Biotic community composition: macroinvertebrate (ASPT) score	SASS: 144 ASPT: 4.7	A (0) Data obtained from Invertebrate specialist
	Fish	62.9%	C (2)- Data obtained from fish specialist

RIVER	Mokolo River	**Water Quality Monitoring Points**	
		RC	None
EWA SITE	5	**PES**	Data (n=1) measured during the site visit
Confidence assessment	Confidence in the assessment is very low, as little data are available.		
Water Quality Constituents		**Value**	**Category (Rating) / Comment**
	Diatoms	SPI=13.7	B (1) (n=1)
Toxics (mg/ℓ)	Fluoride	-	-
	Ammonia	0.091	C/D (2.5)
OVERALL SITE CLASSIFICATION		**B/C**	

9.4 Groundwater quality

The following information on the groundwater contribution and quality was extracted from Dennis (2010b).

The intermittent Mokolo River, an example of a non-perennial river system, has a defined river channel with river flow at least for a couple of months each year. Flow is affected by rainfall-runoff events, groundwater contribution, or a combination of both. During wet years the river can be perennial. Groundwater can potentially play an important role in sustaining and maintaining aquatic ecosystems during drier periods. Pools are sustained by interactions between surface and sub-surface waters. Water may also be flowing along the river in underground channel aquifers, replenishing pools. Groundwater flow both within the alluvium and within the country rock adjacent to the river must be considered in characterising the groundwater contribution to the ecological reserve.

Dennis (2010b) provides a more detailed description of the groundwater flow and groundwater to surface water interaction.

The Internal Strategic Perspective for the Limpopo Water Management Area (WMA) was published in 2004 (DWAF, 2004b). The main issues relating to groundwater quality as described by Dennis (2010b) are:

- Although groundwater resources are mostly relatively deep (50-100 m is quite typical) this water resource is sensitive to surface activities that pollute. Groundwater is available and widely used. The amount of groundwater that can be used varies and is dependent on the hydrogeological characteristics of the underlying aquifer.

- Groundwater contributes to base flow via subsurface seepage and springs. The Waterberg and Soutspansberg Ranges are important areas for groundwater recharge and drainage baseflow.
- Groundwater quality is affected by:
  - o Pollution from urban areas and informal settlements surrounding urban and mining areas
  - o Contamination of groundwater as a result of high concentration of pit latrines in many rural villages. These pit latrines are often responsible for the longer-term pollution of underlying aquifers.
  - o Impact of mining and industrial activities.
  - o Diffuse pollution as a result of agricultural activities such as the leaching of fertilisers into the soils.

Groundwater quality in the Mokolo area is generally naturally “poor” due to the coal and gas fields. The groundwater could still be used for industrial or irrigation purposes, but is not suitable for domestic use (DWAF, 2004b).

The following water quality data are presented in Table 33 (from Dennis 2010b): The data were collected during the field visit in April/May 2010.

Table 33: Groundwater quality data

Sampling area	Sampling depth	EC in mS/m	pH	Use of groundwater
EWA 1	12m	10 to 20	5 to 6	Irrigation
EWA 2	4m	20 to 30	5.6 to 6.8	Irrigation
EWA 3	4m	10 to 20	5 to 6	Game farming
EWA 4	4m	10 to 20	5 to 6	Game farming and irrigation
EWA 5	+10m	TDS: 200 mg/ℓ	-	Game farming

Groundwater has an important contribution to make towards sustaining aquatic ecosystems. However, the volume of groundwater is less important than its ability to sustain surface water habitats during dry periods or prolonged periods of drought.

The groundwater contribution to the surface water of the Mokolo River has not been determined and is currently one of the challenges that the modellers face. The groundwater, having higher TDS concentrations than the surface water, can have a significant impact on the surface water quality if the groundwater contribution is significant.

One should be cautious in interpreting once-off sampling data or patchy historical data. The confidence in the data used for the EWA sites were low in many instances as a result of either very little data to no data or patchy historical data. This underlines the importance of systematic monitoring over time, as sampling once is not sufficient to draw credible conclusions.

10. SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

The NWA has been acknowledged as “one of the most far-reaching and forward-thinking water acts in the world” (Palmer *et al*, 2000). It is based upon two pillars, one of sustainability and one of equity in line with Agenda 21 and South Africa’s Constitution. The twin pillars support the right in law for the use of water for human and environmental needs (DWAF, 2003a).

The NWA is implemented through the National Water Resource Strategy. The NWRS provides the framework for the protection, use, development, conservation, management and control of water resources in the country.

Some of the protective measures are designated Resource Directed Measures because they are measures designed to be applied to the water resource as an integrated system, i.e. at catchment level (DWAF, 2003a). One of the RDM is the establishment of the Reserve.

Subjecting water resources to control in order to be able to manage them sustainably means that the use of water must be administered through the registration and licensing of water uses. Licences for use of a water resource can only be issued once the Reserve (basic human needs reserve and the Ecological Reserve) has been set.

The Ecological Reserve includes the quantity, quality and variable flow requirements needed to protect the aquatic ecosystems of a water resource.

To implement the NWA methodologies need to be developed to carry out these management activities. The development of the Ecological Reserve methodologies were based on perennial rivers, but as most of the rivers, except the largest rivers, in the semi-arid west of southern Africa are non-perennial, concern was raised about the viability of using the same methodologies on these highly variable rivers. Despite the many non-perennial systems in southern Africa, they remain poorly studied and understood.

The hypothesis for the research was that the current, existing water quality methodology for determining the water quality component of the Ecological Reserve, which was developed for perennial rivers, could be used for non-perennial rivers.

In the first phase of the study (covered in Chapters 2 to 5) the differences and similarities between perennial and non-perennial rivers were investigated to obtain a better understanding of the functioning of non-perennial rivers and to consolidate the available information on local and international knowledge on the current methodologies and initiatives on environmental water requirements for non-perennial systems.

It became clear that there are many methods currently available worldwide and the holistic approach, developed in South Africa and Australia, seemed the most popular approach to obtain a better understanding of the functioning of a river. A holistic approach also addresses all parts of the river ecosystem and all parts of the flow regime. The three holistic approaches from South Africa are the Building Block Methodology, Flow-stressor Response and Downstream Response to Imposed Flow Transformation. Within each of these methodologies there are different modules to address different aspects of the Ecological Reserve determination requirements. For the Downstream Response to Imposed Flow Transformation methodology there are the Biophysical, Socio-economic, Scenario-building and the Economics modules. Within each of these modules there are subdivisions and each of these sub-divisions require its own methodology to determine the specific variable. For instance in the Biophysical module FRAI is used to determine the fish component, MIRAI is used for the Invertebrates and PAI is used to determine the water quality.

All three are holistic approaches and are supported by the Department of Water Affairs as valid methodologies to determine the Ecological Reserve. The challenge in applying the methodologies to the non-perennial rivers becomes clear once one tries to apply the methodologies to the specific variables.

In the second phase the existing prescribed DWAF methodology, developed for perennial rivers, was applied to the Seekoei River, an example of a non-perennial river, in order to develop a Prototype Environmental Water Assessment Methodology to determine the Ecological Reserve for non-perennial systems.

The method described and approved by the then Department of Water Affairs and Forestry was applied to the Seekoei River, an example of a typical non-perennial river.

The water quality component consisted of a five step process and ran concurrently with the eight step water quantity process.

The water quality component:
Step 1: Initiation of study and scoping
Step 2: Delineation of Resource Units and preliminary water quality site selection
Step 3: Information collection, site finalization, water quality boundary values, and input to Ecological Resource Class categorization using the Physical Assessment Index (PAI)

Step 4: Quantify ecological Reserve Scenarios
Step 5: Ecological consequences of operational scenarios.

For each of these steps the standard methods , i.e. the Physical Assessment Index, that are available were used and could be applied to the Seekoei River for the water quality component of the Reserve.

The determination of the reference condition was problematic at all the EWR sites where only present day water quality data were available. No historical water quality data were available in the upper part of the Seekoei River catchment. The reference condition is required to determine the present day Ecological category at an EWR site.

The reference conditions were determined by using expert knowledge, local (farmers) knowledge, current and prior land use activities, current state of the land and land cover, geology and channel morphology. It was a qualitative assessment, but the results were confirmed by comparing the reference condition results with those derived by the fish, invertebrate and riparian vegetation experts using similar components, but also including available habitat, substrate types for the fish and the invertebrates, water quality and aquatic plant presence.

An additional tool, The Ecological Aquatic Chemical Habitat Assessment (TEACHA), could also be used as the one gauging station had a sufficiently long term water quality data record. TEACHA uses as input water quality data for either a single site (the PES site) and (ideally, if available) the water quality data for a reference site (the earlier data from the same site was used for the reference condition component). The primary output is a recommended water quality reserve with corresponding ion data to use in resource quality objective setting.

After the completion of the first two phases it was concluded that non-perennial rivers are primarily distinguished from perennial rivers by their hydrological regime, which is spatially and temporally much more variable and the existing methods used currently are not appropriate for non-perennial rivers.

The water quality component of the existing methodology could be used without modification as is for the Reserve determination. However, the fish, invertebrate and riparian vegetation components of the existing methodology had severe limitations and an alternative methodology was needed.

Six limitations were identified from the Seekoei River study (Seaman *et al*, 2010). They were the following:

- Establishment of reference conditions.
- Suitable hydrological modelling.
- Understanding pools.
- Connectivity between pools.
- Surface water/groundwater interactions.
- Extrapolation of data .

A prototype methodology was developed with these limitations in mind and the prototype methodology needed to be tested in the next phase. This phase involved testing the prototype methodology on the Mokolo River.

Once again the existing methodology could be used without modification as is for the water quality component of the Reserve determination.

The results obtained from SASS5 and MIRAI (invertebrate methods) in non-perennial rivers often reflect the natural decline in condition associated with hydrological fluctuations and not necessarily the level of pollution or degradation present. The tolerant generalist species (low scoring SASS taxa associated with pollution and degraded sites in other systems) are present during the drying period in non-perennial rivers resulting in a poor class when the Macro-Invertebrate Response Assessment Index class is determined. A method, which could distinguish between natural and anthropogenic degradation, is needed (Watson, 2010).

The questions, which need to be answered in the various sections (flow, habitat and water quality), as part of the Macro-Invertebrate Response Assessment Index model are not always relevant as they are mostly geared to flowing habitat (diverse habitat, diverse flow types and high water quality). As few flow/habitat/water quality sensitive families/species are present in non-perennial rivers the questions posed are difficult to answer and the result is usually a low PES in a non-perennial river even though the site is relatively pristine. The method also does not appear to be sensitive enough to reflect small changes in the integrity of the site in a non-perennial river. This was also found in studies on intermittent rivers in the United States where other metrics developed were mostly for use in perennial rivers, which have high total taxa and presence of sensitive species (Davis *et al*, 2003, cited in Watson, 2010).

The suitability of the Fish Response Assessment Index model for use on the non-perennial Seekoei River was evaluated in Avenant (2010). The results indicated that the existing fish indices are not ideally suited for these rivers with their naturally low species richness and hardy, generalist fish communities. Other difficulties with the use of a score-based method include prediction of the expected species, calculation of a frequency of occurrence rating, selection of the right sampling times for comparative purposes, loss of habitats and sampling points under different flow conditions, and problems experienced when using accumulated data to try to correct for a situation of having too few sampling points. A more generalised approach was proposed for non-perennial systems. This could include a number of community characteristics, such as abundance, species richness, species diversity and evenness, recruitment, fish health and the presence/absence of exotic species (Avenant, 2010).

The proposed prototype methodology is a eleven phase process and was described in Chapter 8.

The water quality component did not change from the Seekoei River application as the basic steps were the same. The standard methods were applied to the Mokolo River.

The Mokolo River results could be viewed with more confidence than that of the Seekoei River. The Mokolo River system was data rich (especially in the middle reaches of the river) compared to the Seekoei River (one gauging station with historical and present day data in the lower river reach) or many other non-perennial rivers, such as the Swartdorings River where no historical or present day water quality data are available. The more data that are available the better the information that can be extracted and the higher the confidence in the results.

It is expected that there will always be less data available for the non-perennial rivers compared to the perennial rivers. A method, such as the spreadsheet developed for the determination of a Rapid Ecological Reserve Determination for Wetlands (Rountree and Malan, 2011), need to be developed to use catchment information as a guideline on the changes that have occurred from the reference condition to the present day.

The amount of data can also influence the predictive ability, i.e. if historical and present day data are available, more confidence can be attributed to the prediction of future water quality conditions under different future development scenarios. However, the prediction of future water quality conditions in the non-perennial rivers will also have a greater inaccuracy than those of the perennial rivers even with equal amounts of data because of the variability and unpredictability of the hydrological regime.

Another reason for a higher confidence in the results from the Mokolo River study is the fact that the Mokolo River flows for at least 72% of the time (except for the lower reach of the river upstream of the confluence with the Limpopo River) compared to the Seekoei River that flows for 45% of the time in the lower reaches and less than 10% of the time in the upper reaches.

The higher flow in the Mokolo River ensures that there is a good chance that there will be water in the river to do field work such as the collection of water quality samples, fish netting and invertebrate collection, compared to the Seekoei River where even some of the pools dry out completely and no water quality samples could be collected.

When comparing the DWA Proposed methodology (Eight step method) applied to the Seekoei River and the Prototype Methodology (Eleven phase method) as applied to the Mokolo River there were several similarities for the water quality input into both methodologies:

- Both required an understanding of the catchment to be able to identify the water quality constituent that will be important for that specific river.
- Both required water quality data, both historical and present day data – more data are better and improve the confidence in the output.
- Standard water quality methods could be applied to both methodologies (as described in the text and DWAF, 2008a).
- Both require input into a model where response curves were drawn based on different future catchment development scenarios.

The ability to predict, with greater confidence than is currently the case, the future water quality conditions under different future development scenarios could be improved upon. A simple water quality model was developed by Hughes (2007) that is based on simulating TDS using the runoff component outputs from the rainfall-runoff models and several other parameters to define the water quality signals of these runoff components. The water quality model is dependent upon the simulated hydrology and the pool storage parameters. If either of these is in error, the results will be affected accordingly. The model requires further testing and refinement in other semi-arid areas before it can be considered for more general use as the simulated values were far different from the actual measured values in the pools of the Seekoei River.

The concentration modelling (Q-C) method was another method developed to predict water quality in a flow-concentration relationship. This method developed by Malan and Day (2003) also had a number of limitations and was not used for this study as the results obtained would not have been reliable and using the existing response curve method as input into the Reserve determination models gave satisfactory results at a level that was sufficient for the purpose of this study.

The current methodologies (both the Proposed and Prototype methodologies) were equally usable to determine the water quality component of the Ecological Reserve for non-perennial rivers as the same basic methods were used to determine the water quality component of the Reserve.

The lack of water quality data remains the single most challenging aspect of determining the water quality status of a river, perennial and non-perennial, especially the lack of historical data. The only way to compensate for a lack of data is to use expert knowledge, local knowledge and catchment information (land use, potential pollution sources, soil types, land cover and geology).

A quantitative method to determine the PES of the water quality by using the landuse and other catchment information, such as the spreadsheet developed for the determination of a Rapid Ecological Reserve Determination for Wetlands (Rountree and Malan, 2011), need to be developed. The catchment information could be used as a guideline on the changes that have occurred from the reference condition to the present day.

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APPENDIX 1

Water Quality Reserve Document using the TEACHA model method

Rapid Ecological Water Quality Reserve for the Seekoei River in D3

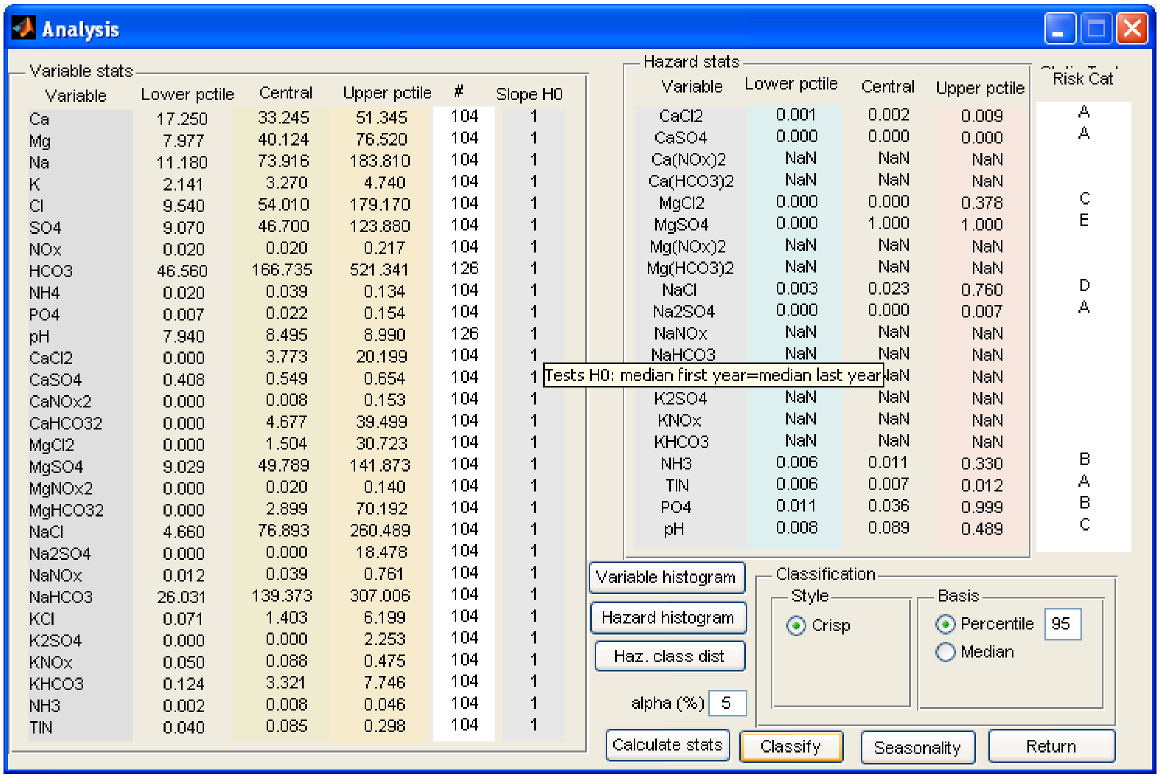
	Reference State	**Present state**	**Comments**
Station name	D3H015Q01 SEEKOEI RIVER AT DE EERSTE POORT	D3H015Q01 SEEKOEI RIVER AT DE EERSTE POORT	
Full data period	1981 - 1985	1991 - 2006	
Total number of records used	113	128	
Trend significance			All variables analysed show a slope in the data.
*****Known point sources of pollution upstream	None	None	
*Other Land-uses	All agriculture	All agriculture	
*EISC**		Moderate	
*PESC**		Class C	
Other, specify			Software used for analysis: MATLAB 7.0.4 (Teacha1-31)
Confidence			Reserve determination – medium confidence

**EISC: Ecological Importance ans Sensitivity Class

**PESC: Present Ecological State Class

NOTE: This reserve is recommended under the following constraints:-

1. Use of the best available scientific knowledge and method (software) which is undergoing refinement
2. Based on available data



Variable stats

Variable	Lower pctile	Central	Upper pctile	#	Slope H0
Ca	17.250	33.245	51.345	104	1
Mg	7.977	40.124	76.520	104	1
Na	11.180	73.916	183.810	104	1
K	2.141	3.270	4.740	104	1
Cl	9.540	54.010	179.170	104	1
SO4	9.070	46.700	123.880	104	1
NOx	0.020	0.020	0.217	104	1
HCO3	46.560	166.735	521.341	126	1
NH4	0.020	0.039	0.134	104	1
PO4	0.007	0.022	0.154	104	1
pH	7.940	8.495	8.990	126	1
CaCl2	0.000	3.773	20.199	104	1
CaSO4	0.408	0.549	0.654	104	1
CaNOx2	0.000	0.008	0.153	104	1
CaHCO32	0.000	4.677	39.499	104	1
MgCl2	0.000	1.504	30.723	104	1
MgSO4	9.029	49.789	141.873	104	1
MgNOx2	0.000	0.020	0.140	104	1
MgHCO32	0.000	2.899	70.192	104	1
NaCl	4.660	76.893	260.489	104	1
Na2SO4	0.000	0.000	18.478	104	1
NaNOx	0.012	0.039	0.761	104	1
NaHCO3	26.031	139.373	307.006	104	1
KCl	0.071	1.403	6.199	104	1
K2SO4	0.000	0.000	2.253	104	1
KNOx	0.050	0.088	0.475	104	1
KHCO3	0.124	3.321	7.746	104	1
NH3	0.002	0.008	0.046	104	1
TIN	0.040	0.085	0.298	104	1

Tests H0: median first year=median last year

Hazard stats

Variable	Lower pctile	Central	Upper pctile	Risk Cat
CaCl2	0.001	0.002	0.009	A
CaSO4	0.000	0.000	0.000	A
Ca(NOx)2	NaN	NaN	NaN	
Ca(HCO3)2	NaN	NaN	NaN	
MgCl2	0.000	0.000	0.378	C
MgSO4	0.000	1.000	1.000	E
Mg(NOx)2	NaN	NaN	NaN	
Mg(HCO3)2	NaN	NaN	NaN	
NaCl	0.003	0.023	0.760	D
Na2SO4	0.000	0.000	0.007	A
NaNOx	NaN	NaN	NaN	
NaHCO3	NaN	NaN	NaN	
		NaN	NaN	
K2SO4	NaN	NaN	NaN	
KNOx	NaN	NaN	NaN	
KHCO3	NaN	NaN	NaN	
NH3	0.006	0.011	0.330	B
TIN	0.006	0.007	0.012	A
PO4	0.011	0.036	0.999	B
pH	0.008	0.089	0.489	C

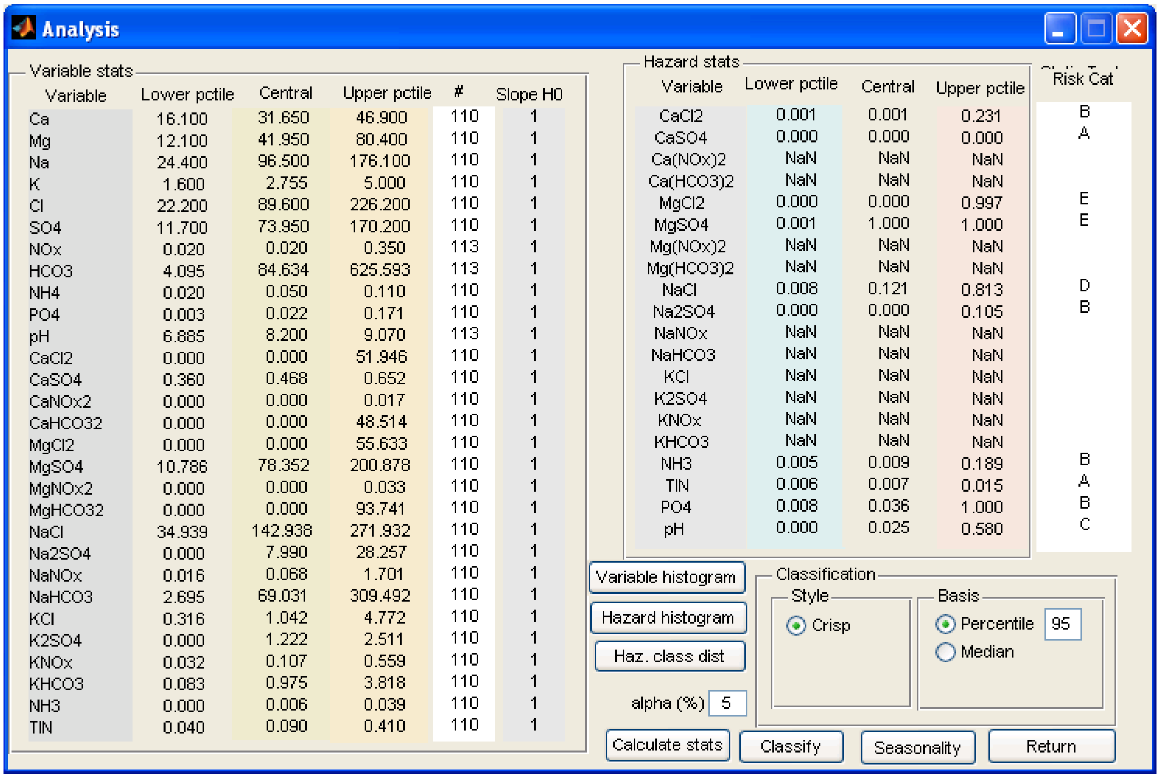
alpha (%) 5

Classification

Style: ● Crisp

Basis: ● Percentile 95 ○ Median

Table 1: Analysis and classification of variables for the Present State



Variable stats

Variable	Lower pctile	Central	Upper pctile	#	Slope H0
Ca	16.100	31.650	46.900	110	1
Mg	12.100	41.950	80.400	110	1
Na	24.400	96.500	176.100	110	1
K	1.600	2.755	5.000	110	1
Cl	22.200	89.600	226.200	110	1
SO4	11.700	73.950	170.200	110	1
NOx	0.020	0.020	0.350	113	1
HCO3	4.095	84.634	625.593	113	1
NH4	0.020	0.050	0.110	110	1
PO4	0.003	0.022	0.171	110	1
pH	6.885	8.200	9.070	113	1
CaCl2	0.000	0.000	51.946	110	1
CaSO4	0.360	0.468	0.652	110	1
CaNOx2	0.000	0.000	0.017	110	1
CaHCO32	0.000	0.000	48.514	110	1
MgCl2	0.000	0.000	55.633	110	1
MgSO4	10.786	78.352	200.878	110	1
MgNOx2	0.000	0.000	0.033	110	1
MgHCO32	0.000	0.000	93.741	110	1
NaCl	34.939	142.938	271.932	110	1
Na2SO4	0.000	7.990	28.257	110	1
NaNOx	0.016	0.068	1.701	110	1
NaHCO3	2.695	69.031	309.492	110	1
KCl	0.316	1.042	4.772	110	1
K2SO4	0.000	1.222	2.511	110	1
KNOx	0.032	0.107	0.559	110	1
KHCO3	0.083	0.975	3.818	110	1
NH3	0.000	0.006	0.039	110	1
TIN	0.040	0.090	0.410	110	1

Hazard stats

Variable	Lower pctile	Central	Upper pctile	Risk Cat
CaCl2	0.001	0.001	0.231	B
CaSO4	0.000	0.000	0.000	A
Ca(NOx)2	NaN	NaN	NaN	
Ca(HCO3)2	NaN	NaN	NaN	
MgCl2	0.000	0.000	0.997	E
MgSO4	0.001	1.000	1.000	E
Mg(NOx)2	NaN	NaN	NaN	
Mg(HCO3)2	NaN	NaN	NaN	
NaCl	0.008	0.121	0.813	D
Na2SO4	0.000	0.000	0.105	B
NaNOx	NaN	NaN	NaN	
NaHCO3	NaN	NaN	NaN	
KCl	NaN	NaN	NaN	
K2SO4	NaN	NaN	NaN	
KNOx	NaN	NaN	NaN	
KHCO3	NaN	NaN	NaN	
NH3	0.005	0.009	0.189	B
TIN	0.006	0.007	0.015	A
PO4	0.008	0.036	1.000	B
pH	0.000	0.025	0.580	C

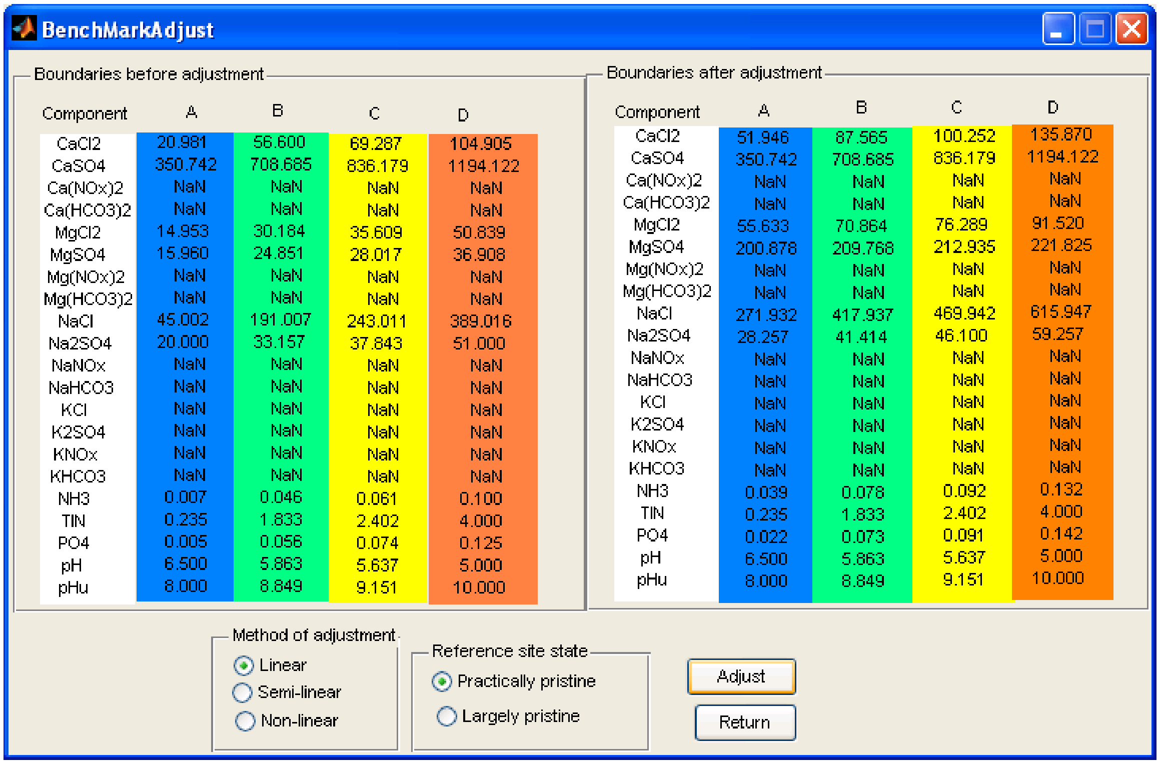
alpha (%) 5

Classification

Style: ● Crisp

Basis: ● Percentile 95 ○ Median

Table 2: Analysis and classification of variables for the Reference Site



Boundaries before adjustment

Component	A	B	C	D
CaCl2	20.981	56.600	69.287	104.905
CaSO4	350.742	708.685	836.179	1194.122
Ca(NOx)2	NaN	NaN	NaN	NaN
Ca(HCO3)2	NaN	NaN	NaN	NaN
MgCl2	14.953	30.184	35.609	50.839
MgSO4	15.960	24.851	28.017	36.908
Mg(NOx)2	NaN	NaN	NaN	NaN
Mg(HCO3)2	NaN	NaN	NaN	NaN
NaCl	45.002	191.007	243.011	389.016
Na2SO4	20.000	33.157	37.843	51.000
NaNOx	NaN	NaN	NaN	NaN
NaHCO3	NaN	NaN	NaN	NaN
KCl	NaN	NaN	NaN	NaN
K2SO4	NaN	NaN	NaN	NaN
KNOx	NaN	NaN	NaN	NaN
KHCO3	NaN	NaN	NaN	NaN
NH3	0.007	0.046	0.061	0.100
TIN	0.235	1.833	2.402	4.000
PO4	0.005	0.056	0.074	0.125
pH	6.500	5.863	5.637	5.000
pHu	8.000	8.849	9.151	10.000

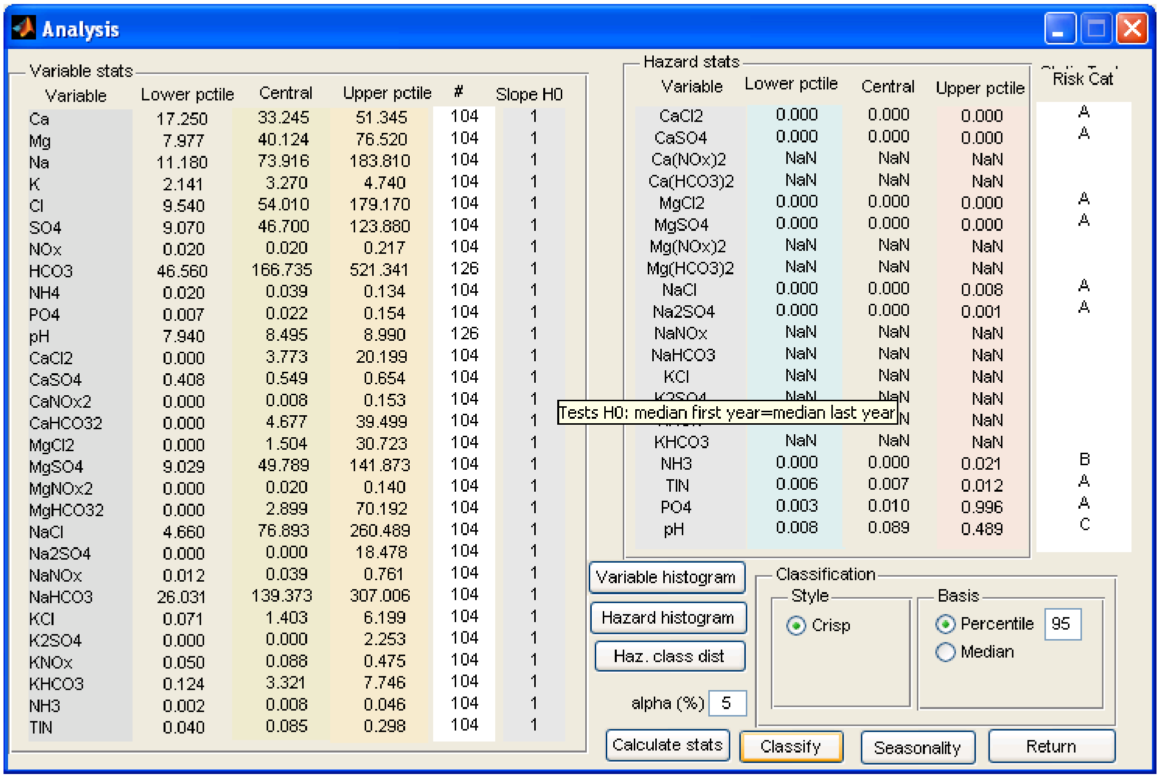
Boundaries after adjustment

Component	A	B	C	D
CaCl2	51.946	87.565	100.252	135.870
CaSO4	350.742	708.685	836.179	1194.122
Ca(NOx)2	NaN	NaN	NaN	NaN
Ca(HCO3)2	NaN	NaN	NaN	NaN
MgCl2	55.633	70.864	76.289	91.520
MgSO4	200.878	209.768	212.935	221.825
Mg(NOx)2	NaN	NaN	NaN	NaN
Mg(HCO3)2	NaN	NaN	NaN	NaN
NaCl	271.932	417.937	469.942	615.947
Na2SO4	28.257	41.414	46.100	59.257
NaNOx	NaN	NaN	NaN	NaN
NaHCO3	NaN	NaN	NaN	NaN
KCl	NaN	NaN	NaN	NaN
K2SO4	NaN	NaN	NaN	NaN
KNOx	NaN	NaN	NaN	NaN
KHCO3	NaN	NaN	NaN	NaN
NH3	0.039	0.078	0.092	0.132
TIN	0.235	1.833	2.402	4.000
PO4	0.022	0.073	0.091	0.142
pH	6.500	5.863	5.637	5.000
pHu	8.000	8.849	9.151	10.000

Method of adjustment
- ● Linear
- ○ Semi-linear
- ○ Non-linear

Reference site state
- ● Practically pristine
- ○ Largely pristine

Table 3: Boundaries for classification – before and after adjustment



Variable stats

Variable	Lower pctile	Central	Upper pctile	#	Slope H0
Ca	17.250	33.245	51.345	104	1
Mg	7.977	40.124	76.520	104	1
Na	11.180	73.916	183.810	104	1
K	2.141	3.270	4.740	104	1
Cl	9.540	54.010	179.170	104	1
SO4	9.070	46.700	123.880	104	1
NOx	0.020	0.020	0.217	104	1
HCO3	46.560	166.735	521.341	126	1
NH4	0.020	0.039	0.134	104	1
PO4	0.007	0.022	0.154	104	1
pH	7.940	8.495	8.990	126	1
CaCl2	0.000	3.773	20.199	104	1
CaSO4	0.408	0.549	0.654	104	1
CaNOx2	0.000	0.008	0.153	104	1
CaHCO32	0.000	4.677	39.499	104	1
MgCl2	0.000	1.504	30.723	104	1
MgSO4	9.029	49.789	141.873	104	1
MgNOx2	0.000	0.020	0.140	104	1
MgHCO32	0.000	2.899	70.192	104	1
NaCl	4.660	76.893	260.489	104	1
Na2SO4	0.000	0.000	18.478	104	1
NaNOx	0.012	0.039	0.761	104	1
NaHCO3	26.031	139.373	307.006	104	1
KCl	0.071	1.403	6.199	104	1
K2SO4	0.000	0.000	2.253	104	1
KNOx	0.050	0.088	0.475	104	1
KHCO3	0.124	3.321	7.746	104	1
NH3	0.002	0.008	0.046	104	1
TIN	0.040	0.085	0.298	104	1

Tests H0: median first year=median last year

Hazard stats

Variable	Lower pctile	Central	Upper pctile	Risk Cat
CaCl2	0.000	0.000	0.000	A
CaSO4	0.000	0.000	0.000	A
Ca(NOx)2	NaN	NaN	NaN	
Ca(HCO3)2	NaN	NaN	NaN	
MgCl2	0.000	0.000	0.000	A
MgSO4	0.000	0.000	0.000	A
Mg(NOx)2	NaN	NaN	NaN	
Mg(HCO3)2	NaN	NaN	NaN	
NaCl	0.000	0.000	0.008	A
Na2SO4	0.000	0.000	0.001	A
NaNOx	NaN	NaN	NaN	
NaHCO3	NaN	NaN	NaN	
KCl	NaN	NaN	NaN	
K2SO4	NaN	NaN	NaN	
[illegible]	[illegible]	[illegible]	NaN	
KHCO3	NaN	NaN	NaN	
NH3	0.000	0.000	0.021	B
TIN	0.006	0.007	0.012	A
PO4	0.003	0.010	0.996	A
pH	0.008	0.089	0.489	C

Classification

Style
- ● Crisp

Basis
- ● Percentile 95
- ○ Median

alpha (%) 5

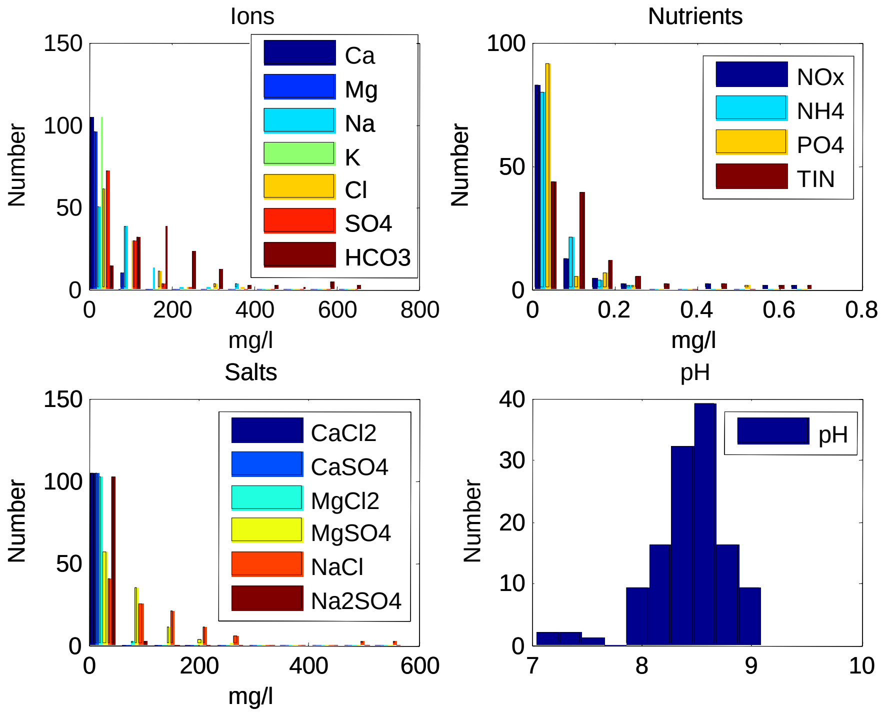


Figure 1: Variable histogram for the Present State

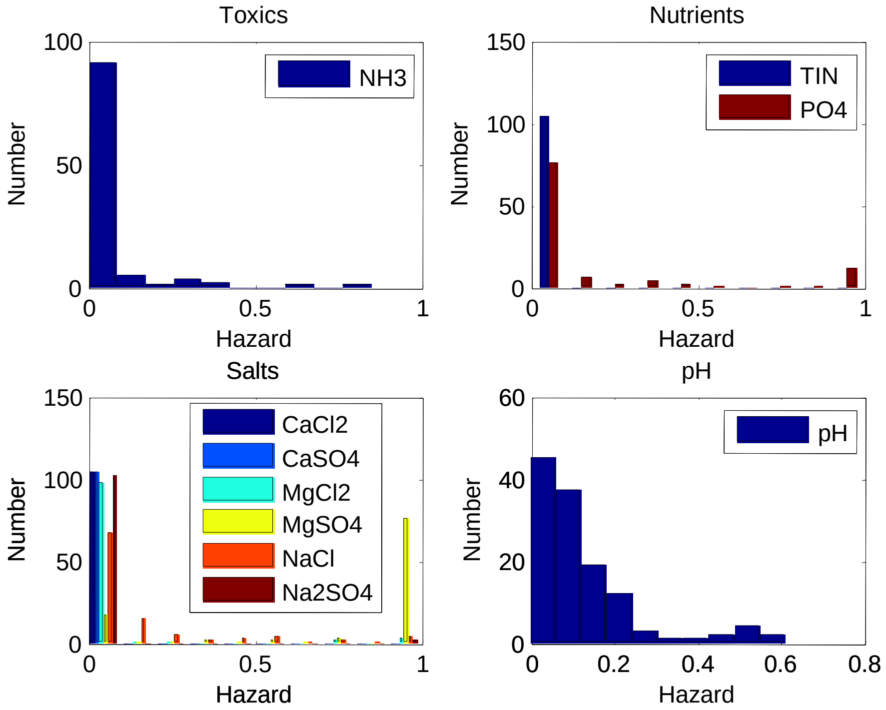


Figure 2: Hazard histogram for the Present State

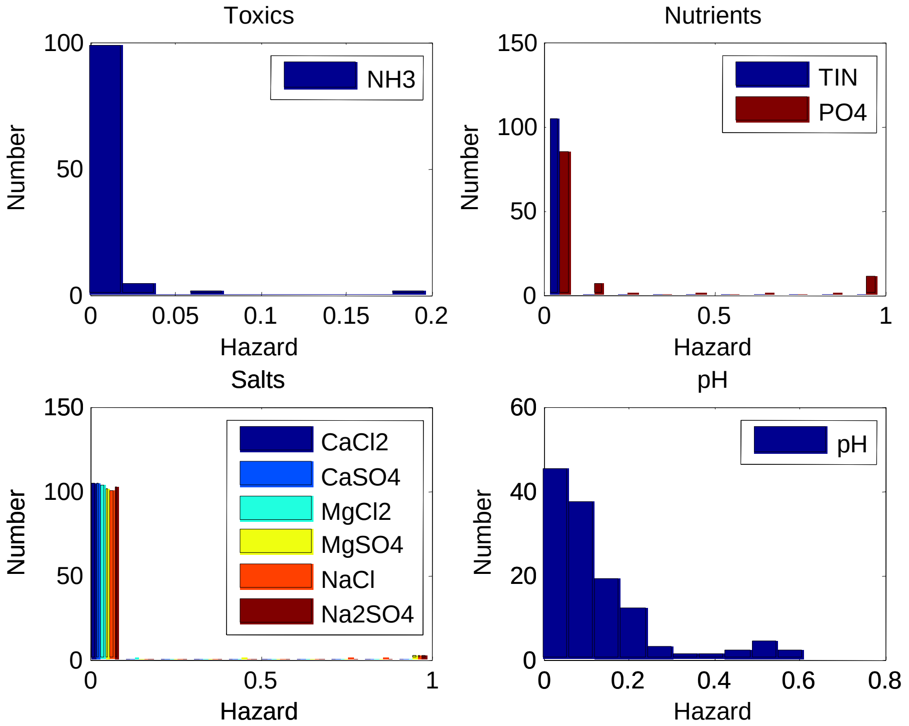


Figure 3: Hazard histogram for the Present State - Adjusted

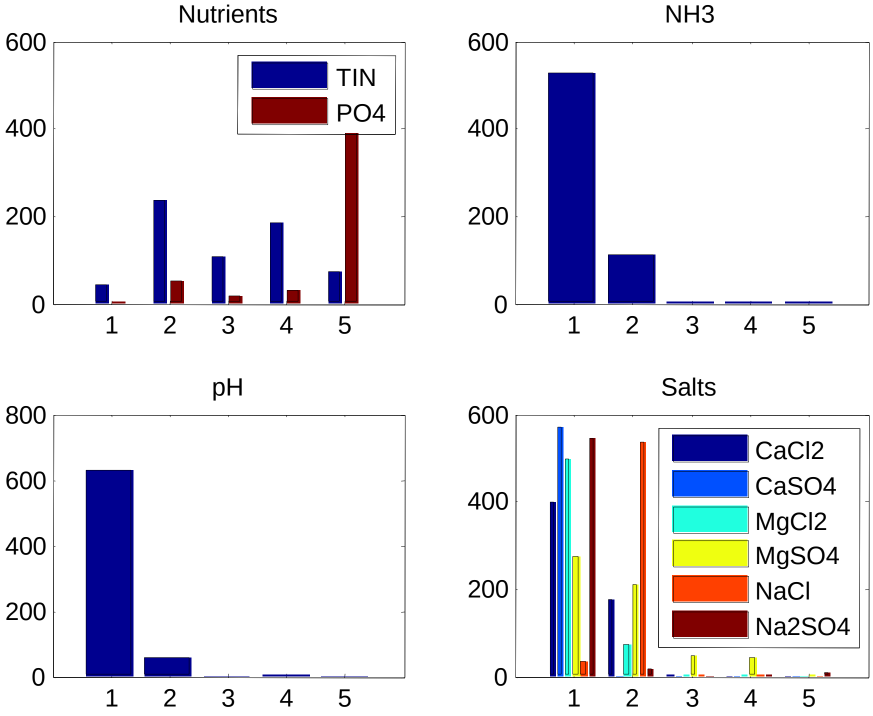


Figure 4: Hazard Distribution Class for the Present State

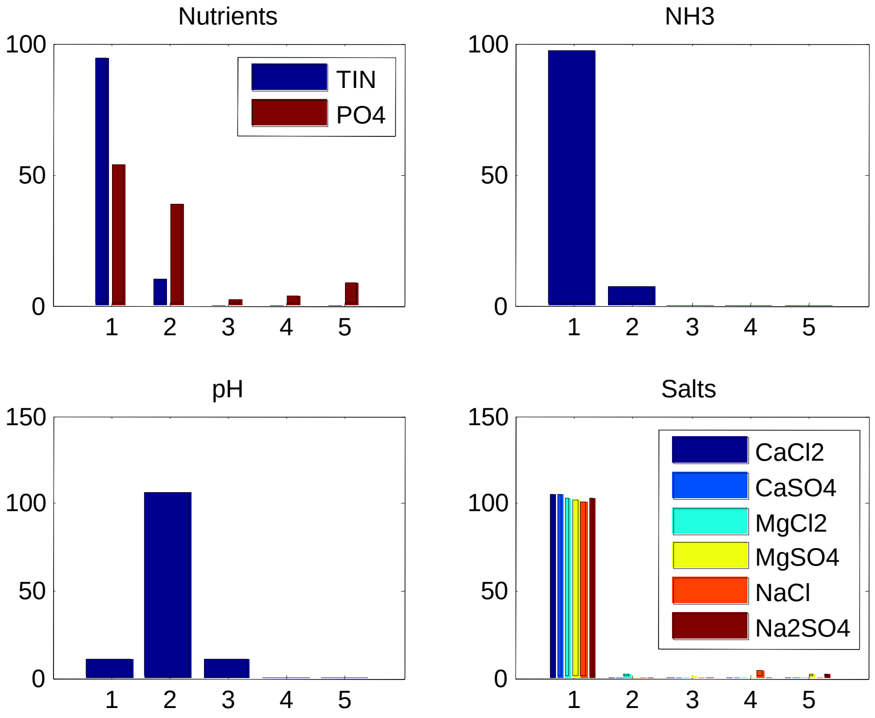


Figure 5: Hazard Distribution Class for the Present State - Adjusted

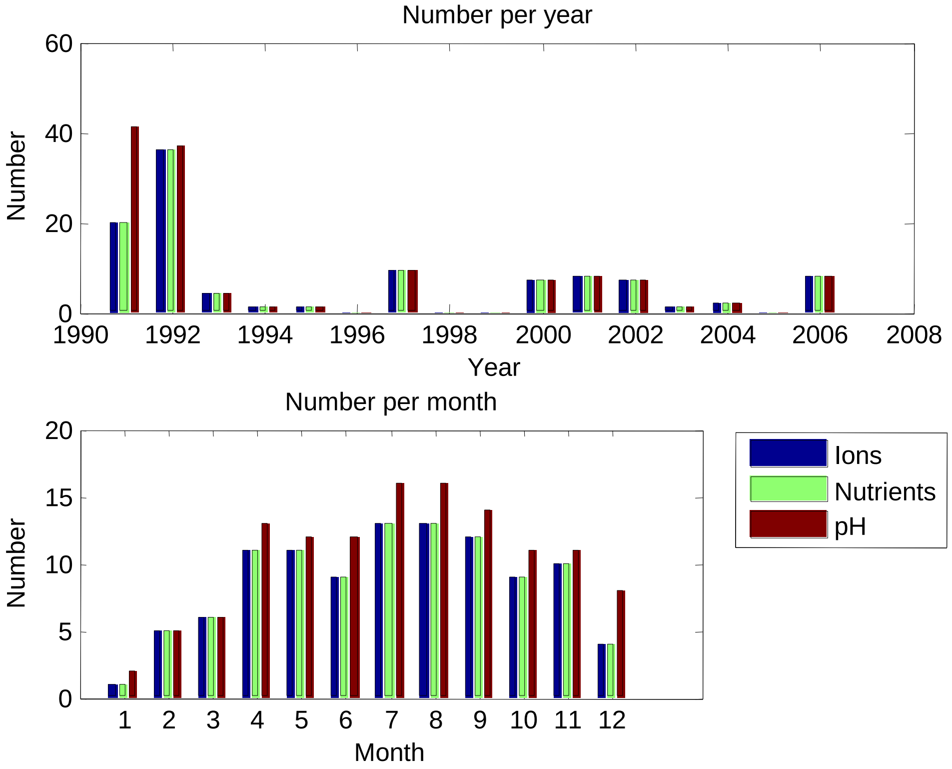


Figure 6: Seasonal variable analysis of the Present State

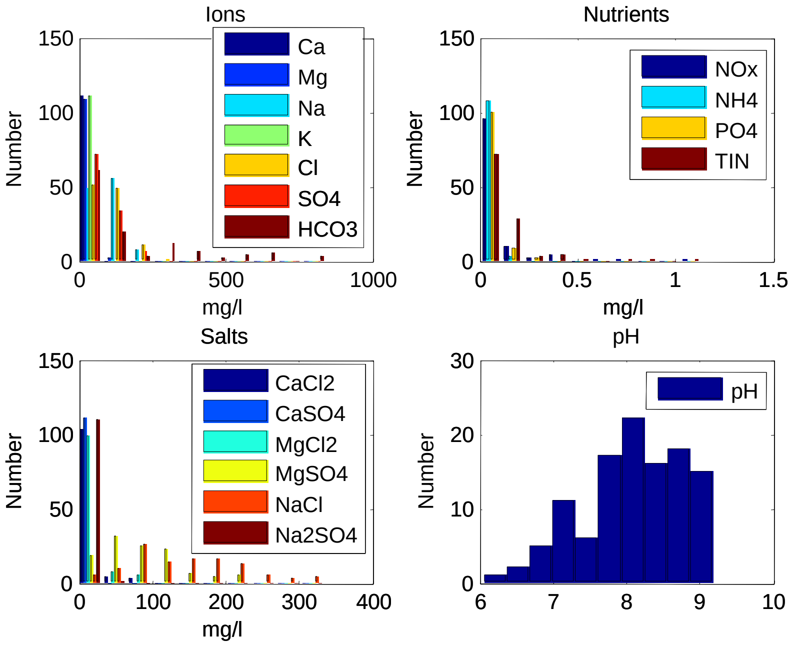


Figure 7: Variable histogram for the Reference Site

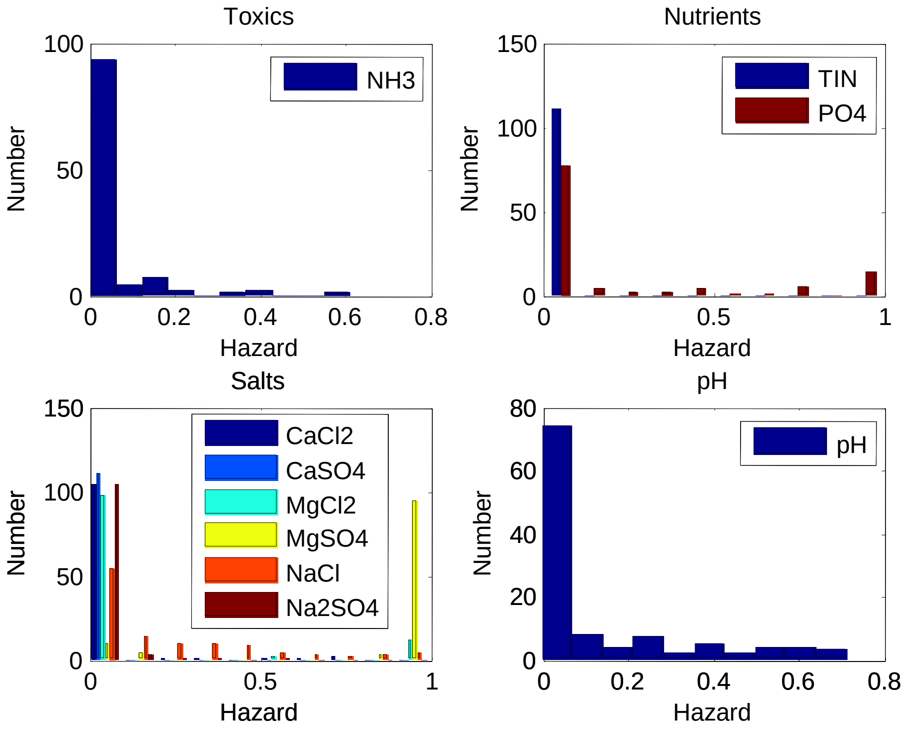


Figure 8: Hazard histogram for the Reference Site

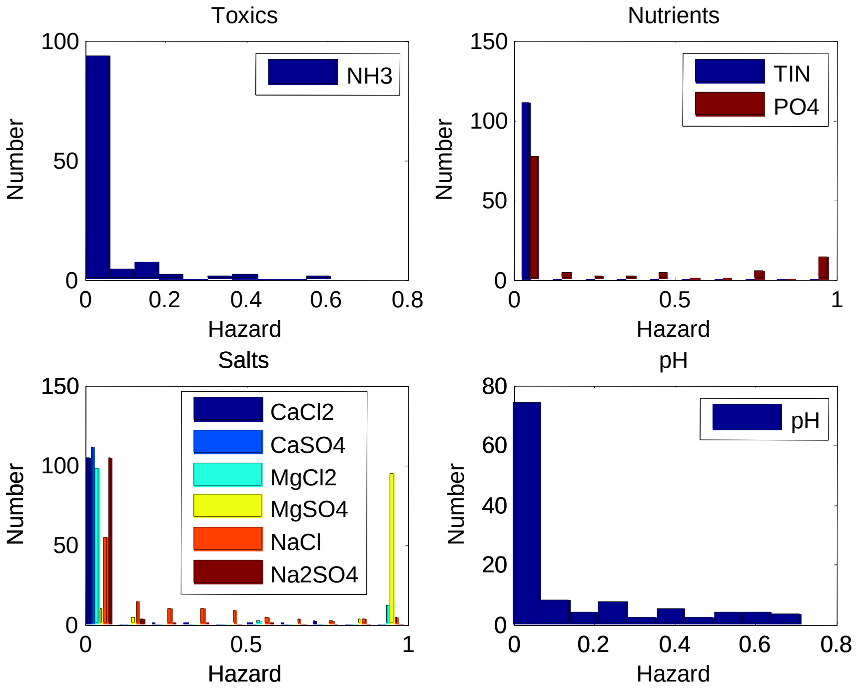


Figure 9: Hazard Distribution Class for the Reference Site

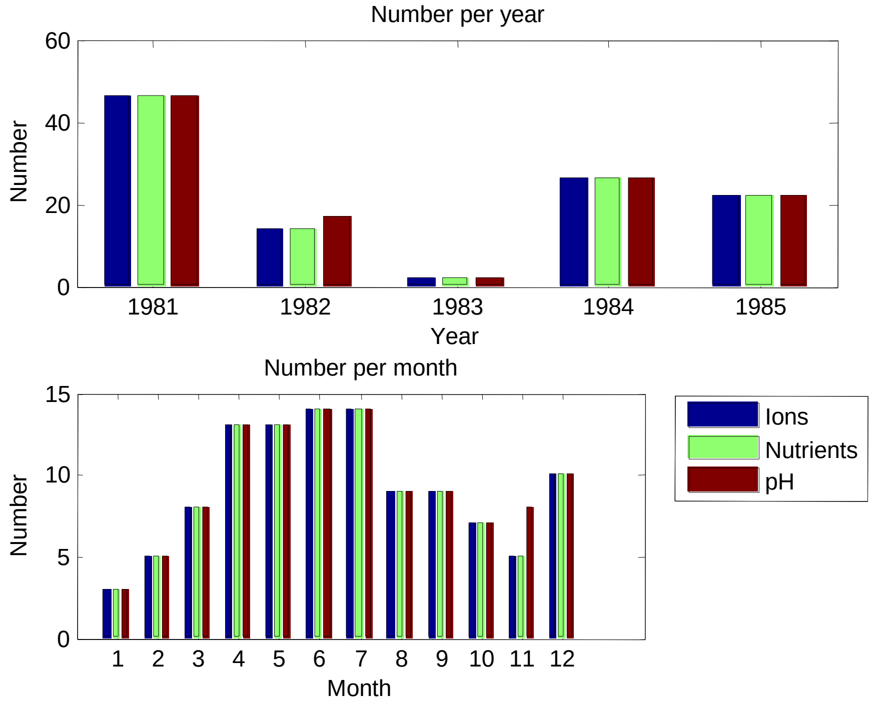
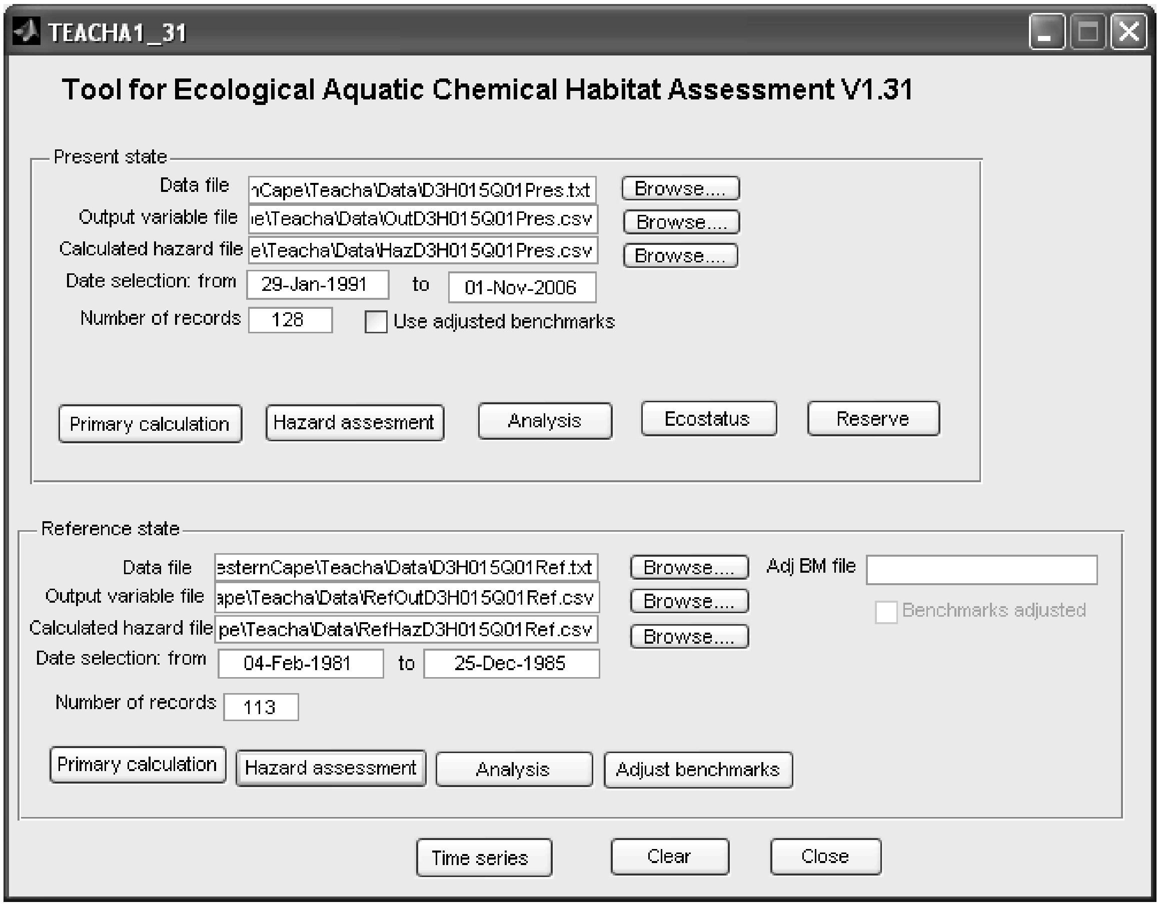


Figure 10: Seasonal variable analysis of the Reference Site

COMMENTS:



Tool for Ecological Aquatic Chemical Habitat Assessment V1.31

Present state

Data file: nCape\Teacha\Data\D3H015Q01Pres.txt
Output variable file: e\Teacha\Data\OutD3H015Q01Pres.csv
Calculated hazard file: e\Teacha\Data\HazD3H015Q01Pres.csv
Date selection: from 29-Jan-1991 to 01-Nov-2006
Number of records: 128
☐ Use adjusted benchmarks

Reference state

Data file: esternCape\Teacha\Data\D3H015Q01Ref.txt
Output variable file: ape\Teacha\Data\RefOutD3H015Q01Ref.csv
Calculated hazard file: pe\Teacha\Data\RefHazD3H015Q01Ref.csv
Date selection: from 04-Feb-1981 to 25-Dec-1985
Number of records: 113
Adj BM file:
☐ Benchmarks adjusted

Reserve for:
Based on data from: NaN
Hydro unit: D32
Resource unit: EIS:

Variable	PES category	Data confidence	Default cat	Recommended cat	Present compliance	Rec.Reserve
CaCl2	B	99.9155	B	B	100	56.6
CaSO4	A	100	A	A	100	350.74
MgCl2	E	99.7902	D	D	97.1154	50.84
MgSO4	E	10.2655	D	D	35.5769	36.91
NaCl	D	10.7072	D	D	96.1538	389.02
Na2SO4	B	54.7891	B	B	98.0769	33.16
NH3	B	44.5477	B	B	95.1923	0.65
TIN	A	100	A	A	90.3846	0.23
PO4	B	98.0182	B	B	83.6538	0.06
pH	C	98.1121	C	C	100	5.6-9.2

Ion	PS	RS	IES	
Ca	51.3452	46.9	6298.437	100
Mg	76.52	80.4	120.3879	99.0385
Na	183.81	176.1	685371.1	100
K	4.74	5	45312.04	100
Cl	179.17	226.2	234.9864	96.1538
SO4	123.88	170.2	3570.998	100
NOx	0.2172	0.35	358899.4	100
HCO3	521.3408	625.5934	603980.4	100
NH3	0.64836	0.54252		95.1923
TIN	NaN	NaN		90.3846
PO4	NaN	NaN		83.6538
pH	7.9-9.0	6.9-9.1		100

Salt concentrations corresponding to Ion EcoSpecs

Salt	PS	RS	Calculated for IES	
CaCl2	20.1986	51.9459	100.9979	100

CaSO4	0.65411	0.6523	0.7344	100
Ca(NOx)2	0.15345	0.016748	7442.071	95.1923
Ca(HCO3)2	39.4992	48.5136	8497.854	95.1923
MgCl2	30.7233	55.6334	50.8443	97.1154
MgSO4	141.8735	200.8776	397.048	35.5769
Mg(NOx)2	0.14042	0.033248	261.613	95.1923
Mg(HCO3)2	70.1922	93.7405	270.5924	95.1923
NaCl	260.489	271.9324	62.6947	96.1538
Na2SO4	18.4778	28.2569	249.6186	98.0769
NaNOx	0.76117	1.7014	2149599	95.1923
NaHCO3	307.0057	309.4924	367187.2	95.1923
KCl	6.199	4.7715	396.0315	95.1923
K2SO4	2.2527	2.5106	2483.846	95.1923
KNOx	0.47517	0.5586	80498.28	95.1923
KHCO3	7.746	3.8177	36309.77	95.1923

Bench Mark Table

	A	B	C	D
CaCl2	20.9811	56.5998	69.2867	104.9055
CaSO4	350.742	708.6847	836.179	1194.122
MgCl2	14.9528	30.1836	35.6086	50.8394
MgSO4	15.9601	24.8506	28.0173	36.9077
NaCl	45.0019	191.0066	243.0115	389.0162
Na2SO4	20	33.1569	37.8431	51
NH3	0.007	0.046471	0.060529	0.1
TIN	0.235	1.8329	2.4021	4
PO4	0.005	0.05593	0.07407	0.125
pH	6.5-8.0	5.9-8.8	5.6-9.2	5.0-10.0

Reference site:

Reserve for: D3H015Q01 SEEKOEI RIVER AT DE EERSTE POORT - ADJUSTED
Based on data from: NaN
Hydro unit: D32

Resource unit:

EIS: Moderate

Variable	PES category	Data confidence	Default cat	Recommended cat	Reason for diff	Present compliance	Rec.Reserve
CaCl2	B	99.9155	B	B		100	87.56
CaSO4	A	100	A	A		100	350.74
MgCl2	E	99.7902	D	D		97.1154	91.52
MgSO4	E	10.2655	D	D		35.5769	221.83
NaCl	D	10.7072	D	D		96.1538	615.95
Na2SO4	B	54.7891	B	B		98.0769	41.41
NH3	B	44.5477	B	B		95.1923	1.1
TIN	A	100	A	A		90.3846	0.23
PO4	B	98.0182	B	B		83.6538	0.07
pH	C	98.1121	C	C		100	5.6-9.2

Example of major ion EcoSpecs corresponding to the proposed Reserve

Ion	PS	RS	IES	PS compliance
Ca	51.3452	46.9	382.3819	100
Mg	76.52	80.4	312.8065	100
Na	183.81	176.1	290.5667	96.1538
K	4.74	5	460.8849	100
Cl	179.17	226.2	267.8834	96.1538
SO4	123.88	170.2	269.0959	100
NOx	0.2172	0.35	398.4181	100
HCO3	521.3408	625.5934	3637.502	100
NH3	0.64836	0.54252		100
TIN	NaN	NaN		90.3846
PO4	NaN	NaN		87.5
pH	7.9-9.0	6.9-9.1		100

Salt concentrations corresponding to Ion EcoSpecs

Salt	PS	RS	Calculated for IES	PS salt compliance
CaCl2	20.1986	51.9459	87.5646	100
CaSO4	0.65411	0.6523	0.73178	100
Ca(NOx)2	0.15345	0.016748	429.8728	95.1923
Ca(HCO3)2	39.4992	48.5136	478.4596	95.1923

MgCl2	30.7233	55.6334	91.5201	100
MgSO4	141.8735	200.8776	200.8776	98.0769
Mg(NOx)2	0.14042	0.033248	740.6275	95.1923
Mg(HCO3)2	70.1922	93.7405	800.1877	95.1923
NaCl	260.489	271.9324	168.2254	100
Na2SO4	18.4778	28.2569	3.34E-07	98.0769
NaNOx	0.76117	1.7014	458.4911	95.1923
NaHCO3	307.0057	309.4924	606.3974	95.1923
KCl	6.199	4.7715	115.9973	95.1923
K2SO4	2.2527	2.5106	4.90E-07	95.1923
KNOx	0.47517	0.5586	509.4515	95.1923
KHCO3	7.746	3.8177	539.4815	95.1923

Bench Mark Table

	A	B	C	D
CaCl2	51.9459	87.5646	100.2516	135.8703
CaSO4	350.742	708.6847	836.179	1194.122
MgCl2	55.6334	70.8642	76.2892	91.52
MgSO4	200.8776	209.7681	212.9348	221.8252
NaCl	271.9324	417.9371	469.942	615.9468
Na2SO4	28.2569	41.4138	46.1001	59.2569
NH3	0.038752	0.078222	0.092281	0.13175
TIN	0.235	1.8329	2.4021	4
PO4	0.022	0.07293	0.09107	0.142
pH	6.5-8.0	5.9-8.8	5.6-9.2	5.0-10.0

Reference site: D3H015Q01 SEEKOEI RIVER AT DE EERSTE POORT at NaN Unit: D32

SUMMARY

The South African National Water Act adopted in 1998, is implemented by means of the National Water Resource Strategy. The NWRS provides the framework for the management of the water resources. Some of the protective measures are designated Resource Directed Measures such as the establishment of the Reserve.

The NWA establishes the ‘Reserve’ consisting of an unallocated portion of water that is not subject to competition with other water uses. It refers to both the quality and quantity of water and is made up from two distinct parts, namely the basic human needs reserve and the Ecological Reserve. The Ecological Reserve describes the quantity, quality and flow variability required to protect and maintain the aquatic ecosystems of the water resource on a sustainable basis. All other water demands are controlled by permits and licenses and met only after the Reserve is secured. The Ecological Reserve has to be set for every major river in the country to be able to comply with the NWA.

Most of the rivers, except the largest rivers in the semi-arid west of southern Africa, are non-perennial with variable flow regimes, governed by stochastic events, with the highest variability in intermittent and ephemeral rivers. This variability is a key factor in shaping the biotic community structure of ephemeral or non-perennial systems.

The hypothesis for the research was that the current, existing water quality methodology for determining the water quality component of the Ecological Reserve, which was developed for perennial rivers, could be used for non-perennial rivers.

This hypothesis was addressed in a phased approach. The existing methodologies were identified through a literature review and from the information collected it was decided to use the holistic approach methodologies.

The Proposed method described and approved by the Department of Water Affairs and Forestry for use on the perennial rivers was applied to the Seekoei River, an example of a typical non-perennial river.

The existing methodology could be used as it is for the water quality component of the Reserve determination. However, the fish, invertebrate and riparian vegetation components of the existing methodology had severe limitations and an alternative methodology was proposed.

Six limitations were identified from the Seekoei River study for all the components and were the following: the establishment of reference conditions; suitable hydrological modeling; understanding pools and the connectivity between pools; the surface water/groundwater interactions and the extrapolation of data.

When comparing the DWA Proposed methodology (Eight step method) applied to the Seekoei River and the Prototype Methodology (Eleven phase method) as applied to the Mokolo River there were several similarities for the water quality input into both methodologies:

- An understanding of the catchment to be able to identify the water quality constituent that will be important for that specific river is required.
- Water quality data, both historical and present day data are required – more data are better and improve the confidence in the output.
- Standard water quality methods could be applied to both methodologies.
- Both require input into a model where response curves were drawn based on different future catchment development scenarios.

The water quality component did not change from the Seekoei River application as the basic steps were the same. The standard methods could be applied to the Mokolo River.

The current methodologies were equally usable to determine the water quality component of the Ecological Reserve for non-perennial rivers as the same basic methods were used to determine the water quality component of the Reserve.

The limitations identified in the Seekoei River study were also the limiting in the Mokolo River study. The key issue is the hydrological modelling. Without a suitable hydrological model the other the other limitations can also not be addressed.

The lack of water quality data remains the single most challenging aspect of determining the water quality status of a river, perennial and non-perennial, especially the lack of historical data. One should be cautious in interpreting once-off sampling data or patchy historical data. The confidence in the data used for the EWA sites were low in many instances as a result of either very little data to no data or patchy historical data. This underlines the importance of systematic monitoring over time, as sampling once is not sufficient to draw credible conclusions. The only way to compensate for a lack of date is to use expert knowledge, local knowledge and catchment information (land use, potential pollution sources, soil types, land cover and geology).

SAMEVATTING

Die Suid-Afrikaanse Nasionale Waterwet van 1998 word toegepas deur middel van die Nasionale Waterhulpbronstrategie. Die NWHS verskaf die raamwerk vir die bestuur van die waterhulpbronne. Van die beskermende maatreëls wat daar gestel is, is die Hulpbron Gerigte Maatreëls soos die bepaling van die Reserwe.

Die Wet bepaal dat die "Reserwe" bestaan uit 'n ontoegewyste gedeelte van water wat nie onderhewig is aan kompetisie met ander water verbruikers nie. Dit verwys na die gehalte en hoeveelheid van die water en het twee segmente: die basiese menslike behoefte reserwe en die Ekologiese Reserwe. Die Ekologiese Reserwe verwys na die hoeveelheid water wat nodig is om die waterekostelsels te beskerm. Alle ander water eise word beheer deur permitte en slegs bevredig nadat die Reserwe bepaal is. Om te voldoen aan die Wet, moet die Ekologiese Reserwe vir elke belangrike waterloop in die land bepaal word.

Alle riviere in die semi-droë weste van suidelike Afrika, behalwe vir die groter riviere is nie-standhoudend. Suid-Afrikaanse riviere, in hulle natuurlike staat, is geneig tot veranderlike vloeipatrone, wat beheer word deur stogastiese gebeurtenisse, met die hoogste veranderlikheid in onderbroke vloei en efemere riviere. Hierdie veranderlikheid is 'n belangrike faktor in die vorming van die biotiese gemeenskapstruktuur van efemere of nie-standhoudende stelsels.

Die hipotese vir die navorsing was dat die huidige, bestaande water kwaliteit metodologie vir die bepaling van die kwaliteit van water komponent van die Ekologiese Reserwe, wat vir standhoudende riviere ontwikkel is, gebruik kan word vir nie-standhoudende riviere.

Hierdie hipotese was aangespreek op 'n gefaseerde benadering. Die bestaande metodes is geïdentifiseer deur middel van 'n literatuuroorsig en van die inligting wat ingesamel is, was besluit om die holistiese benadering metodes te gebruik.

Die voorgestelde metode wat beskryf en goedgekeur was deur die Departement van Waterwese en Bosbou vir gebruik op die standhoudende riviere was by die Seekoei River, 'n voorbeeld van' n tipiese nie-standhoudende rivier, toegepas.

Die bestaande metode van ondersoek kan gebruik word soos dit is vir die water kwaliteit komponent van die bepaling van die Reserwe. Maar die vis, invertebrate en oewerplantegroei komponente van die huidige metode het ernstige beperkinge en 'n alternatiewe metode is voorgestel.

Ses beperkinge op die metode was tydens die Seekoeirivier studie geïdentifiseer en was die volgende: die verduideliking van verwysing toestande; geskikte hidrologiese modelle, die werking van poele en die verbinding tussen die poele; die oppervlakwater/grondwater interaksies en die ekstrapolasie van die data.

Wanneer die DWA Voorgestelde metodologie (Agt stap metode) soos toegepas op die Seekoeirivier en die Prototipe metode (Elf fase metode) soos op die Mokolorivier toegepas, vergelyk word, was daar verskeie ooreenkomste met die waterkwaliteitinsette:

- Kennis van die opvanggebied was nodig om die waterkwaliteitskomponente van belang vir die spesifieke opvanggebied te kon bepaal.
- Waterkwaliteitdata, beide die historiese en hedendaagse data, word benodig – hoe meer data, hoe beter is die betroubaarheid van die uitsette.
- Standaard waterkwaliteitsmetodes kon toegepas word op beide metodes.
- Beide metodes vereis insette in 'n model waar die reaksie kurwes wat getrek is, gebaseer op verskillende toekomstige opvanggebiedontwikkelingscenario's, insette is.

Die watergehalte komponent het nie verander vir die Seekoei River studie nie aangesien die basiese stappe dieselfde was. Die standaard metodes kon aangewend word vir die Mokolo-rivier.

Die huidige metodes was ewe bruikbaar vir die watergehalte komponent van die Ekologiese Reserwe vir nie-standhoudende riviere aangesien dieselfde basiese metodes gebruik is om die water kwaliteit komponent van die Reserwe te bepaal.

Die beperkinge wat in die Seekoeirivier studie geïdentifiseer is, was ook die beperking in die Mokolorivier studie. Die belangrikste kwessie is die hidrologiese modellering. Sonder 'n geskikte hidrologiese model kan die ander beperkinge ook nie aangespreek word nie.

Die gebrek aan water kwaliteit data bly die enkele mees uitdagende aspek in die bepaling van die kwaliteit van die waterkwaliteitstatus van 'n rivier, standhoudend en nie-standhoudend, veral die gebrek aan historiese data. Interpretasie van ‘n eenmalige streekproefneming se data moet versigtig hanteer word. Die vertroue in die data wat gebruik word vir die Ekologiese Water Bepaling by ‘n spesifieke terrein was laag in baie gevalle as gevolg van óf baie min of geen data of onderbroke historiese data. Die belangrikheid van gereelde monitering met verloop van tyd word hierdeur beklemtoom omdat ‘n enkel monster nie vodoende is om geloofwaardige gevolgtrekkings te maak nie. Die enigste manier om te vergoed vir 'n gebrek aan data is om deskundige en plaaslike kennis en opvanggebied inligting (land gebruik, om potensiële besoedeling bronne, grond tipes, grond bedekking en geologie) te gebruik.