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# Design of a Water Quality Monitoring Network for the Limpopo River Basin in Mozambique

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# Design of a Water Quality Monitoring Network for the Limpopo River Basin in Mozambique


Master of Science Thesis
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**Dedication**

I dedicate this work to my parents, Gonçalo Chilundo and Maria Nhabete "Thanks for guiding me through the dark paths towards knowledge", and to my lovely wife Sonia and to my entire family for the given support!

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**Abstract**

An important means of characterising the health of streams is through measurement and assessment of its chemical, physical and biological parameters. Thus, cost effective and targeted water quality monitoring programmes are required for proper assessment, restoration and protection of such streams.

This research reports on the development of a water quality monitoring network for the Limpopo River Basin in Mozambique located in the Southern part of Africa. In this catchment, anthropogenic influences as well as natural processes are responsible for the degradation of surface waters, impairing their use for various purposes (e.g. drinking, industrial, recreation). The localization of the basin in a drought-prone zone, associated with the constant increase on water demand by the four riparian countries (Botswana, South Africa, Zimbabwe and Mozambique) exacerbated the situation when it comes to preservation of the aquatic environment further downstream.

For that purpose various physico-chemical, biological and microbiological characteristics of 23 sites within the Limpopo River Basin in Mozambique were studied in November (2006) and January (2007). Ecological parameters like dissolved oxygen (DO), pH, nitrate ($NO_3^-$ - N), total phosphorus, ammonium ($NH_4^+$-N), heavy metals, chloride ($Cl^-$), total dissolved solids (TDS), sodium adsorption ratio (SAR), benthic macroinvertebrates and faecal coliforms were analyzed in-situ or in laboratory and compared with standards limits to investigate the influence of different sources of pollution for the final condition of the water. For that, the Mozambican guidelines for receiving waters and the environmental water quality standards for effluent discharges together with the WHO guidelines for drinking water quality were used.

The obtained data indicated that sites located at proximities to the border with upstream countries were highly contaminated with heavy metals. In contrast, further downstream, the ions concentration, faecal coliforms and elevated organic loads derived from discharge of untreated wastewater were responsible for the deterioration of water quality at sampled sites. The Elephants subcatchment a tributary of Limpopo was found with a better water quality whereas the Changane subcatchment together with the effluent point discharges were polluted as indicated by low DO and high TDS, electric conductivity (EC), total hardness, SAR and low benthic macroinvertebrates taxa. The differences of some parameters were statistically significant ($p<0.05$) when the concentrations found in November and in January were tested, suggesting a possible influence of flow increase for the change of concentrations.

It was also found that it is possible to apply biological investigations using benthic macroinvertebrates for assessment of water condition, but additional investigation is required to adapt the index scoring to tropical ecosystems since it was developed for temperate environments.

Aiming at a better understanding of water quality trends; detection of receiving waters standards violations; information gathering for future environmental flow assessment; all to ensure a better water management, a systematic water quality monitoring network composed of 16 stations was proposed. Ambient, operational, effluent and early warnings are the main monitoring types recommended. Furthermore, the study recommends additional research at a Basin scale to identify the sources and fates of pollutants, its transport along the main subcatchments and impacts for the downstream ecosystem.

**Keywords:** Environmental flows, Limpopo River Basin, water quality monitoring, water management.

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**List of Symbols and Acronyms**

| | |
|---|---|
| APHA | American Public Health Association |
| ASPT | Average Score Per Taxon |
| AWWA | American Water Works Association |
| BMWP | Biological Monitoring Working Party |
| CFU | Colony Forming Units |
| D12, D14 | Point Discharges |
| DNA | Direcção Nacional de Águas (National Directorate of Waters) |
| DO | Dissolved Oxygen |
| DRIFT | Downstream Respond to Imposed Flow Transformation |
| DWAF | Department of Water Affairs and Forestry, South Africa |
| EC | Electrical Conductivity |
| EF | Environmental Flows |
| EFA | Environmental Flows Assessment |
| GEMS | Global Environment Monitoring System |
| GPS | Global Positioning System |
| INE | Instituto Nacional de Estatística (National Institute for Statistics) |
| INGC | Instituto Nacional de Gestão de Calamidades (National Institute for Disaster Management) |
| L1, L3 | Sampling sites at Limpopo River |
| LRB | Limpopo River Basin |
| MDG | Millennium Development Goal's |
| MICOA | Ministério para a Coordenação da Acção Ambiental (Ministry for Coordination of Environmental Affairs) |
| MISAU | Ministério da Saúde (Ministry of Health) |
| $NH_4$-N | Ammonia-Nitrogen |
| $NO_3$-N | Nitrate – Nitrogen |
| PCA | Principal Component Analysis |
| $PO_4$-P | Phosphate |
| SADC | Southern African Development Community |
| SAWQG | South African Water Quality Guidelines |
| TSS | Total Suspended Solids |
| TC15, TC16 | Sampling Sites at Changane River |
| TDS | Total Dissolved Solids/Salts |
| TE5, TE6 | Sampling Sites at Elephants River |
| TN2 | Sampling sites at Nuanedzi River |
| UEM | Eduardo Mondlane University |
| WHO | World Health Organisation |
| WPCF | Water Pollution Control Federation |
| WQ | Water Quality |
| WQM | Water Quality Monitoring |
| WQI | Water Quality Index |

**Glossary of Water Quality Monitoring Terms**

**Ambient monitoring** – all forms of monitoring conducted beyond the immediate influence of a discharge pipe or injection well and may include sampling of sediments and living resources (USEPA, 2006).

**Aquatic ecosystem** – is the stream channel, lake or estuary bed, water, and (or) biotic communities and the habitat features that occur therein.

**Basin –** is a drainage area or region of land where water from rain or snowmelt drains downhill into a body of water, such as a river, lake, dam, estuary, wetland, sea or ocean.

**Guidelines** – may be numerical or descriptive and provide an indication of desired concentrations of substances in water or wastewater and are not legally enforceable (Hirji *et al*., 2002).

**Monitoring –** the repeated (periodic or continuous) measurement of some parameters to assess the current status and changes over time of the parameters measured.

**Non-point sources of pollution –** represent land use areas and activities that result in the mobilization and discharge of pollution in any manner other than through a discrete or discernible conveyance (WRC, 2001).

**Objectives –** are numerical or descriptive targets for desired quality of water or wastewater, and may or may not be legally enforceable (Hirji *et al*., 2002).

**Point's source of pollution** – are discernable and confined sources of pollution that discharge from a single (point) conveyance, such as pipe, ditch, channel, tunnel or conduit (WRC, 2001).

**Pollution** – the introduction by man into the environment of substances or energy liable to cause hazards to human health, harm to living resources and ecological ecosystems, damage to structure or amenity, or interference with legitimate uses of the environment (Mason, 1991). Change in the physical, chemical, radiological, or biological quality of a resource (air, land, or water) caused by man or due to man's activities that is injurious to existing, intended, or potential uses of the resource.

**Standards –** are numerical concentrations of substances which are allowed in water and wastewater, and which are legally enforceable (Hirji *et al*., 2002).

**Water quality –** term used to describe the chemical, physical and biological characteristics of water, usually in respect to its suitability for and intended purpose. The characteristics are controlled by substances, which are either dissolved or suspended in water (Dallas and Day, 2004).

**Water quality assessment** – the overall process of evaluation of the physical, chemical and biological nature of water in relation to natural quality, human effects and intended uses, particularly those affecting human and aquatic system health (Chapman, 1996).

**Water quality monitoring –** an integrated activity for collection of information at set locations at regular intervals for evaluating the physical, chemical and biological character of water in relation to human health, ecological conditions and designated water uses and to establish trends and management procedures.

**Water quality standards –** are means by which water quality can be managed in order to qualitatively and quantitatively satisfy the users requirements.

**CHAPTER ONE**

# INTRODUCTION

## 1.1. Background and Problem Statement

Pollution of surface water with toxic chemicals and excessive nutrients, resulting from a combination of transboundary transport, storm water runoff, point and non-point leaching and groundwater discharges has become an issue of environmental concern worldwide (Ouyang, 2005). One of the drivers of pollution events is the recent world population growth that resulted in increasing urbanization and industrialization. Therefore, water pollution and reduction of river flows has become a major threat for the public and environmental health in such a way that the policy makers have called for the design and operation of monitoring networks in river systems to minimize the negative effects of those pollutants (Park *et al.*, 2006).

The development of surface water monitoring programmes with emphasis on environmental flows requirements (Maran, 2004) spatial and temporal variations on water quality are seen as a critical elements on the assessment, restoration and protection of such waters (Ouyang, 2005). Thus, monitoring programmes which include frequent water samplings at different sites and determination of physico-chemical and biological parameters are ultimately spread worldwide (Simeonov *et al.*, 2003).

In Africa, especially on the Southern African Development Community (SADC) countries, where water quality is impaired by natural and anthropogenic factors, only some countries (e.g. South Africa and Botswana) have established water quality monitoring networks. Mozambique is a member of the SADC community, with more than 50% of its territory being part of international river basins. Although the high vulnerability of the country in relation to deterioration of stream water quality derived from its downstream position, there is not yet in the country a well-structured and optimal water quality monitoring network for its streams (Hirji *et al.*, 2002).

The downstream localization of the country in relation to those basins increases its vulnerability in terms of water availability (quantity and quality) imposed by the countries upstream, particularly in the southern region of the country, where more than 80% of the mean annual runoff is generated in the neighbouring upstream countries (DNA, 1999; Vaz, 2000).

The Limpopo River Basin is located in the southern part of the country and is shared with other three SADC countries viz. South Africa, Botswana and Zimbabwe (Ashton *et al.*, 2001) and is still deprived of an truly downstream (Mozambican) water quality monitoring network, given that the current monitoring of water quality is done at some gauging stations which were not designed for that purpose. The lack of systematization and regular monitoring are other factors impairing a good water management in the country.

The poor understanding of the relation between the water quality condition and the flows in the river is other important issue with lack consideration in the basin. The increase of flow regulations at upstream countries (e.g. RSA) affects the whole Limpopo river ecosystem including changes on its water quality. Thus, while defining the water quality monitoring networks, it is important to take into account the future needs in term of the amounts of water to be left or provided to the river (environmental flows) (Hirji *et al.*, 2002).

Previous studies have reported that the situation is even worse in terms of water management, since the upstream activities such as: mining; increase of impoundments and water abstraction; agriculture; industrial and domestic discharge of untreated wastewater combined with downstream activities, increase the pollutants load (DNA, 1994; Louw and Gichuki, 2003). The combined effects of such factors, result on the reduction of the quality of water for different socio-economic activities and endanger the sustainability of downstream aquatic (estuarine) and terrestrial ecosystems (Falkenmark and Rockström, 2004; FAO-SAFR, 2004).

The design and establishment of a water quality programme for the downstream Limpopo will contribute to improve the management of water in Mozambique and in the region. The improvement of communities rural livelihood standards is believed to be accomplished since the Limpopo river basin is of extreme importance in the region and the second largest in Mozambique, where the biggest irrigation scheme in the country is located (Chókwè Irrigation Scheme). Furthermore, the location of the basin in a region constantly suffering from diversified extreme climatic conditions (erratic rainfall, high evapotranspiration rates, droughts and floods) increase its importance for poverty alleviation and thus contribute to the achievement of the millennium development goals (MDG's).

Hence, this study attempts to contribute to the existing knowledge, for a better understanding of the water quality situation along the Limpopo River and its tributaries. The focus will be on the design of a water quality monitoring network suitable for the local conditions. Such monitoring network will take into account the requirements for different water uses as well as the needs for environmental flows assessment.

## 1.2. Research Objectives, Questions and Significance of Study

It is intended with the present study to contribute for a better management of water, i.e. generation of information in the Limpopo River Basin through design and establishment of a downstream water quality monitoring network (Mozambique).

The specific objectives include:

1. Assessment of water quality in the Limpopo River Basin and its main tributaries;
2. Evaluation of the impacts of different sources of pollution in the river (chemical and biological);
3. Proposition of procedures for the establishment of a water quality monitoring network that will allow a systematic collection of data in the basin;
4. Evaluation of the influence of environmental flows needs on the design of the monitoring network for the Limpopo River.

Based on existing hydrology (flows) and water quality data and supplementary field measurements, the main questions to be answered are:

1. To which extents do the diffuse and point sources of pollution influence water quality in the river?
2. What is the influence of upstream countries on water quality downstream (i.e. water flowing into Mozambique)?
3. What is the degree of self-purification of the river between the sampled stations?
4. Are there any potential threats for the aquatic ecosystem and other potential water using activities taking into account the current status of water quality?

5. Which water quality monitoring is required in the basin and where would it be suitable to be implemented?
6. Which information should be generated by the water quality monitoring network to allow a future assessment of environmental flows in the basin?

The successful accomplishment of the above objectives and questions are expected to contribute to the improvement of surveillance activities around water quality management at local, national and regional levels. Specifically findings from this study will be applied as:

- Background information and procedures for future studies in the basin, such as the assessment of required flows to meet specific desired ecosystem conditions;
- Basic tools to enhance the understanding of water quality trends over time in the basin and to propose better pollution control measures for its preservation by the local water management institutions (e. g. DNA).

## 1.3. Study Approach and Report Presentation

The research was conducted through a preliminary field study (assessment of pollutants) to gain knowledge of the water quality status at various sites throughout the Limpopo River Basin in Mozambique. The water quality data and information gathered from the preliminary survey, backed with literature review on the concept of freshwater monitoring design was later used to recommend a water quality monitoring network for the downstream Limpopo in Mozambique.

Results from a preliminary study, conducted in two months (November, 2006 and January, 2007) were together with flows registered at neighbouring gauging stations analysed taking into account the national and the WHO water quality guidelines, to better understand the present conditions of water quality along the basin. Later, results from the preliminary study and literature information were used to discuss and recommend better water monitoring practices and thus prepare a set of background information to be used on future assessment of environmental flows.

This report is presented in six chapters. The first of those gives a brief introduction to the topic, the description of the problem to be tackled and the importance of the study. The research objectives, questions and the significance of the study are also presented.

The second chapter on its turn deals with the secondary information (literature review), surrounding the topic. The concepts of water quality and water quality monitoring design are deeply presented. On its presentation experiences and findings of past studies in the field are highlighted and discussed.

The third chapter presents the materials and methods used on the study. It entails a brief description of the study area as well as the major sources of pollution in the basin. The field, laboratory and desk study activities are also described.

Chapter four presents the main findings of the study, including results from the preliminary field survey as well as information gathered from secondary sources.

Chapter five entails the discussion of the results obtained from the preliminary survey and together with the secondary sources of information the suitable water quality monitoring objectives are proposed. Further design (e.g. sampling sites, parameters, frequency) for the Limpopo River Basin are presented.

The main conclusions and recommendations of the report are presented in chapter six.

**CHAPTER TWO**

# LITERATURE REVIEW

## 2.1. The Concept of Water Quality

According to Bartram and Ballance (1996) and DWAF (2004), "water quality" is a term used to express the suitability of water to sustain various uses or processes. Such suitability includes the physical, chemical and biological characteristics of the water. Furthermore, Pegram and Görgens (2001) add that those characteristics should match the requirements for functioning of the aquatic ecosystem and human uses. The uses may include, among others, drinking water purposes, irrigation, recreation and nature conservation. The aesthetic values are added to above definition by Tharme and King (1998), as important to determine the fitness for a multiple use and for the protection of the health and integrity of aquatic ecosystems.

DWAF (2004), in their review on aquatic ecosystems and water quality, recognise the "water quality" as a combined effect on a "user" of the physical attributes and chemical constituents of a sample of water. Furthermore, the same authors refer that the water quality is a human construction, implying value or usefulness, since the definition of "water quality" will depend on the point of view of the final user.

Generally water perceived as having a good quality should be accepted by all users including the ecosystem, while water of poor quality may have adverse impact on the health of its potential users, so it should be improved before it is sent to the final users (Pegram and Görgens, 2001).

## 2.2. Water Quality in Rivers

### 2.2.1. Factors Affecting Water Quality in Streams

The pollution of water has become the major global concern in water resources management (Dobbis and Zabel, 1996; Sweeting, 1996), since water quality is an important factor determining the aquatic processes and maintenance of major environmental, social and economic values. Physical, chemical and biological water quality in rivers is affected by several interconnected factors (Gustafsson and Johansson, 2006). These factors can be divided into natural and human.

Natural factors such as geology, hydrology (DWAF, 2004), natural erosion derived from hydrogeologic and climatic processes (Bartram and Ballance, 1996) are recognised as the main factors leading to changes on the quality of water, as it flows over the land surface and subsurface (groundwater).

On the other hand wide ranges of anthropogenic pollutants are nowadays recognised (Kelderman, 2004). They derive essentially from human intervention on the ecosystem: dams construction, discharge of untreated wastes, mining, agriculture runoff, wetlands draining and flows diversion (Bartram and Ballance, 1996).

Past water quality studies in the region of Fez (Morocco) by Koukal *et al*. (2004), revealed high anthropogenic influence on deterioration of water quality, given that all sites located close to the most urbanised and industrialised areas were severally impaired due to discharge of untreated waste. The same experience was observed on the River Rhine, one of the most important and densely populated (over 50 million) rivers in Europe. It was reported (Hogervorst, 1993) that the past degradation of its ecosystem derived essentially from anthropogenic activities, such as navigation, discharge of domestic and industrial untreated wastewater, hydroelectric power generation and agriculture.

Furthermore, other studies have indicated other sources of pollution, such as the case of Lean River in China (Liu *et al.*, 2002) where acid mine drainage and discharged waste containing cupper (Cu), lead (Pb) and zinc (Zn) conducted to a deterioration in the surrounding environments. The deforestation, urbanization, agricultural development, land drainage, pollutant and flow regulation are pointed out by Bellos and Sawidis (2005) as the general main human activities that contributed to deterioration of water, as is the case of River Pinios in Greece. The Danube Delta which ranks third on world reserve areas is an additional example of strong anthropogenic influence for the local habitat deterioration and loss of species. The main processes pointed as affecting the water quality included: the eutrophication and pollution with heavy metals, pesticides and other pollutants. All those sources derived from direct human activities such as: hydro-technical works on the Delta; upstream dams construction and agricultural and fish polders (David and Hulea, 2000).

According to Hamilton *et al.* (2004) areas with the same human settings may show different water quality due to differences in natural factors. The major types and the extent of deterioration in freshwater quality by anthropogenic pollutants are summarised in Table 2.1.

**Table 2.1.** Anthropogenic sources of pollution in aquatic environment

| Source | Bacteria | Nutrients | Trace elements | Pesticides/ herbicides | Industrial organic micropollutants | Oils and greases |
|---|---|---|---|---|---|---|
| Atmosphere | - | X | xxxG | xxxG | xxxG | - |
| **Point sources** | | | | | | |
| Sewage | xxx | xxx | xxx | x | xxx | - |
| Industrial effluents | - | X | xxxG | - | xxxG | xx |
| **Diffuse sources** | | | | | | |
| Agriculture | xx | xxx | x | xxxG | - | - |
| Dredging | - | X | xxx | xx | xxx | x |
| Navigation and harbours | x | X | xx | - | x | xxx |
| **Mixed sources** | | | | | | |
| Urban run-off and waste disposal | xx | xx | xxx | xx | xx | xx |
| Industrial waste disposal | - | X | xxx | x | xxx | x |

x – low local significance xx – moderate local/regional significance xxx – high local/regional significance

G – globally significant

Source: Chapman (1996); Bartram and Ballance (1996)

Although most studies point the anthropogenic activities as the major causes of water quality deterioration, others point the natural and environmental conditions as responsible for such WQ changes. An example comes from a case study on small and medium Greek catchments by Skoulikidis *et al.* (2005), where it was found that the spatial and temporal variation of aquatic quality (water quality) was mainly governed by geological and hydrogeological factors, since rivers situated within different zones revealed stronger dissimilarities in their water quality, although were under same human use.

The water quality situation in developing countries is highly variable reflecting social, economic and physical factors as well as the state of development. And while, not all countries are facing a crisis of water shortage, all have to a greater or lesser extent serious problems associated with degraded water quality (Ongley, 2000). In general such water degradation in the catchment or basin may interfere with vital and legitimate water uses at various scales (Table 2.2)

**Table 2.2.** Limits to water use due to water quality degradation

| Pollutant | Use | | | | | |
|---|---|---|---|---|---|---|
| | **Drinking water** | **Aquatic wildlife, fisheries** | **Recreation** | **Irrigation** | **Industrial use** | **Power and cooling** |
| Pathogens | xx | o | xx | x | xx | na |
| Suspended solids | xx | xx | xx | x | x | x |
| Organic matter | xx | x | xx | + | xx | x |
| Algae | x | x | xx | + | xx | x |
| Nitrate | xx | x | na | + | xx | na |
| Salts | xx | xx | na | xx | xx | na |
| Trace elements | xx | xx | x | x | x | na |
| Organic micropollutants | xx | xx | x | x | ? | na |
| Acidification | x | xx | x | ? | x | x |

**x** – minor impairment **xx** – marked impairment causing excluding the desired use

**o** – no impairment **?** – effects not yet realised **na** – not applicable **+** – degraded water quality may be beneficial for this use

Source: Adapted from Chapman (1996)

Among the human factors, the man-made constructions, such as dams/reservoirs, weirs and interbasin transfers are considered to be the biggest threats to water resource management in Southern Africa (Boon *et al.*, 2000). Dams interrupt the natural flood pulse concept (periods of natural flooding), reduce the load of suspended sediment, and change the temperature, reduce the nutrients, change the morphology of the downstream river reaches and the estuarine deltas. Low flows downstream dams for example are considered as the main causes for increased WQ degradation due to seawater intrusion (Hirji *et al.*, 2002).

The further improvements on the water quality management in a basin level require a complete assessment and understanding of trends of the status of biological life, particulate matter, chemical properties and the physical characteristics of the water body. Therefore such research will require the establishment of a functional water quality monitoring network on the watershed.

### 2.2.2. Self-purification of Streams or Rivers

The principle of self-purification of a river is known as a "*partial or complete restoration, by natural processes, of a stream pristine condition following the introduction (usually anthropogenic) of foreign matter in water to cause measurable change in physical, chemical and/or biological characteristics of the stream*" (Benoit, 1971). It is based on the fact that the water environment reacts to the input of polluting substances by means of a number of mechanisms aiming to restore its original conditions (Vagnetti *et al.*, 2003). Thus, the self-purification of a river consists of a recycling of materials.

According to Vagnetti *et al.* (2003) the natural self-purification process consists of various complex phenomena involving: (i) *physical processes* (adsorption, dilution, sedimentation, and volatilization); (ii) *chemical processes* (acid-base reactions and precipitation reactions) and (iii) *biological processes* (bacterial degradation and assimilation by plants). A study by Prati and Richardson (2003) on the PO River (Italy) has shown that he natural dilution process of the river was one of the primary self-purification mechanisms for the restoration of the river.

Therefore, the ability for restoration will greatly depend on their natural flow, bacterial breakdown of organic matter and other undesired substances. Thus, the time required will then be dependent on the degree of pollution and on the character of the stream. In general fast flowing stream are likely to be saturated with oxygen and thus increase the speed of purification since oxygen is an important parameter for bacterial action (Smith and Smith, 2000).

Attention should call to the fact that the process of self-purification may be for only a short periods of time. Typical examples are the sedimentation of suspended solids or nutrients consumed by plants, since, as soon as the materials decay the nutrients may eventually return to the water or the solids will re-suspend.

## 2.3. Water Quality Monitoring

### 2.3.1. General Concepts on Water Quality Monitoring

Water quality monitoring is a fundamental tool in the management of freshwater resources. Defined by Chapman (1996) and UN/ECE (2000) as "*a programmed and repetitive process of sampling, measuring and recording various water characteristics in conformity to specified objectives*", it obtains information through assessment of physical, chemical and biological characteristics of water via statistical sampling (Sanders *et al.*, 1983). Hence, different types of monitoring can be distinguished (Table 2.3). The selection of a particular monitoring type will depend on the objectives to be achieved, on the information to be generated and on the effectiveness of such monitoring, taking into account the particular use(s) of the river or stream.

According to Kristensen and Bøgestrand (1996); Hirji *et al*. (2002) the objectives of monitoring programmes will range from detection of drinking water standards violations, to determination of the environmental state and analysis of temporal trends on water quality. The generated information based of these objectives is thus, used by policy makers for an adequate management and allocation of the water resources in the watershed. Furthermore, water quality monitoring is important to reinforce environment protection policies and programmes, and help controlling pollution and strengthen the state of the environment in general (ANZECC, 2000). Hence, water quality monitoring may potentially serve as basis to estimate loads of material in the catchments (sediments, nutrients, pesticides and other pollutants), to allow a better understanding and management of the stream health (Newham *et al*., 2001).

**Table 2.3.** Types of monitoring and main objectives

| Monitoring type | Objectives |
|---|---|
| Background | ▪ Assessment of background levels, used as reference point for pollution and impact assessment. |
| Ambient or trend | ▪ Status and spatial/temporal variations of water quality<br>▪ Testing of water quality standards<br>▪ Loads calculations |
| Effluent | ▪ Calculation and control of discharge standards<br>▪ Monitoring of plant performance |
| Early warning | ▪ Warning any sudden and unpredictable change in water quality<br>▪ Protection of downstream functions |
| Operational | ▪ Monitoring for operational uses (e.g. irrigation, industrial use, inlets for water treatment, etc.) |

Source: Adapted from Chapman (1996); Bartram and Ballance (1996)

### 2.3.2. Biological Monitoring of Water Quality

The biological monitoring is the systematic use of living organisms or their responses to determine the quality of the environment on which they live (Calow and Pettes, 1994). The biological monitoring of water quality is based on the premises that the organisms tend to integrate all the stresses placed on the aquatic system and they reflect a combined effect over an extended period of time (Mason, 1991; David and Hulea, 2000), or either, river communities reflect the environment quality of the river and thus indicate water quality of their surroundings (De Pauw and Hawkes, 1993). The benthic macroinvertebrates are the most popular community used as indicators. Several advantages are pointed as backing the benthic macroinvertebrates as indicators of water quality:

- They are reasonably sedentary, with comparatively long lives, so that they can be used to assess water quality at a single site over a long period of time (Mason, 1991; Chapman and Jackson, 1996);
- They are ubiquitous and abundant in aquatic ecosystems and relatively easy to collect and identify (Chapman and Jackson, 1996);
- The sampling procedures are relatively well developed and there are identification keys for most groups (Mason, 1991);
- Possible be used to detect other sources of impacts, such as flows changes, habitat destruction, excessive use of biological resources (Karr, 1981);
- Since they are relatively easy to collect, no expensive equipment is necessary for their collection. So, it is possible to get a qualitative impression of water quality compared with chemical assessment (Chapman and Jackson, 1996).

The major drawback is related to the fact that, a large number of samples are required to obtain a representative sample of the site. Other drawback is related to sampling problems in deep waters and identification problems of tubificid worms in lowland reaches of rivers or lakes (Mason, 1991; Guinot *et al*., 2001). Several methods are currently used to score the macroinvertebrates. Such methods include the *Saprobic* approach, which relies on species response to organic pollution and Biotic Indexes and Scores, both based on species and communities responses to pollutant loads.

The Biological Monitoring Working Party (BMWP) is an example of British biotic index (Armitage *et al*., 1983; Mason, 1991; Guinot *et al.*, 2001), which uses a list of indicator values for most families of invertebrates living in rivers and streams (Appendix 2). The values range from 1 (poor quality) to 10 (excellent quality), depending on a perceived susceptibility to pollution, where those taxa least tolerant, such as mayflies and stoneflies families are given the highest scores. Accordingly, for a particular sampled site the BMWP score is obtained by summing all the scores of the taxa, each taxon only being counted once. Since BMWP depends on the sample size, the Average Score Per Taxon (ASPT) is also considered on the assessment by dividing the BMWP score by the number of taxa (Appendix 8). The use of both scores has proven to be much more reliable than one alone (Mason, 1991). The overall assessment of the water quality is thus, done taking into account the Lincoln Quality Index values (Table 2.4).

**Table 2.4.** Lincoln Quality Index Values and its interpretation

| Overall quality rating | Index | Interpretation |
|---|---|---|
| 6.0+ | A++ | Excellent quality |
| 5.5 | A+ | Excellent quality |
| 5.0 | A | Excellent quality |
| 4.5 | B | Good quality |
| 4.0 | C | Good quality |
| 3.5 | D | Moderate quality |
| 3.0 | E | Moderate quality |
| 2.5 | F | Poor quality |
| 2.0 | G | Poor quality |
| 1.5 | H | Very poor quality |
| 1.0 | I | Very poor quality |

Source: Adapted from Mason (1991) and Guinot *et al*. (2001)

Several studies using biological indices and benthic macroinvertebrates have shown positive relation with the water quality condition, proving its worldwide applicability (Azrina *et al.,* 2005; Czerniawska-kusza, 2005; Smith *et al.,* 2006).

### 2.3.3. Chemical and Physical Measures of Water Quality

Traditionally, physico-chemical monitoring of water quality formed the backbone of water quality monitoring (Dallas and Day, 2004). Although the importance of the common physical and chemical attributes of water for determining the type and concentration of pollutants entering a river, lake or water body, they are limited to the period of sample collection and to the physical and chemical observations performed (Dallas and Day, 2004).

Physical variables include among others, the discharge (for streams), water temperature, specific conductance, turbidity, suspended-sediment concentration, particle-size distribution, taste and odour. On the other hand the chemical variables include the nutrients, trace metals, etc (Sanders *et al.*, 1983). Although advantages of use of chemical and physical assessment of water quality may be highlighted, such as quick assessment of water quality several limitations are also recognised (Dallas and Day, 2004):

- Unless samples are collected continuously, the intermittent nature of the assessment may lose pulse events such as short time release of effluents;
- Routine assessment only limited to not-toxic determinants such as temperature, conductivity, total alkalinity, etc;
- Routine testing is unrealistic because of assessment of part of toxic compound (e.g. trace metals, biocides), since their number and variety is vast;
- In some cases there is low sensitivity of chemical analytical methods when toxic and persistent substances are present in low concentrations;
- Possible synergism or antagonism of the toxic components, so single effects might be lost.

For this reason, Dallas and Day (2004) citing Hawkes (1997) suggest that the biological assessment of water quality (bioassessment) and physico-chemical monitoring should complement each other in order to produce more reliable data.

## 2.4. The Concept of Monitoring Cycle

The process of monitoring and assessment is a sequence of related activities that starts with the definition of the information needs, and ends with the use of the information product (Figure 2.1). These successive activities in the monitoring cycle should be specified and designed on the required information product as well as the preceding part of the chain (Ward *et al.*, 2004).

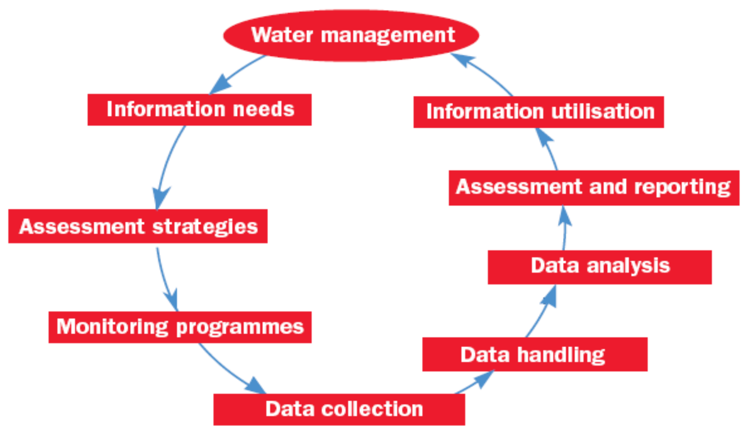


**Figure 2.1.** Monitoring cycle (UN/ECE, 2000)

The ultimate goal of a monitoring programme is to provide the information needed to answer specific questions during decision making process, thus it is important to clearly define and specify the requirements in terms of information. After the specification of the information needs, assessment strategies are followed by the design and operation in such a way that the required information is obtained.

The design and operation of monitoring programmes includes many aspects, such as field measurements, sampling (collection, pre-treatment, storage methods and transport), chemical analysis and data collection (Ward *et al.*, 2004). The data generated by the monitoring programmes should be validated, archived and made accessible, but at the same time it should be converted into information that will meet the specified objectives. Reporting is the final step in the process of gathering information. The main issue is to present and interpret the data in an accessible way to the final information users (e.g. river basin technical committee, decision makers and other stakeholders).

## 2.5. Design of Water Quality Monitoring Networks

### 2.5.1. Water Quality Monitoring Design and Main Objectives

Monitoring stream water quality is an important task for the quantification of the health of a stream. Besides the monitoring types and objectives presented in Table 2.1, three modes of monitoring are normally covered when designing a water quality monitoring network. Such modes include surveillance, operational and investigative (Bartram and Ballance, 1996; Allan *et al.,* 2006; Park *et al.,* 2006). Under the European Water Framework Directive (EWFD) they are defined as follows (Allan *et al.*, 2005):

(i) *Surveillance* - designed to assess long-term changes in natural conditions or as a result of anthropogenic activity; enable adequate preparation of future monitoring programmes and supplement and validate impact assessment procedures.

(ii) *Operational* - aims to provide information to classify the status of water bodies identified as being at risk of failing their environmental objectives.

(iii) *Investigative* - undertaken to understand possible failure of other monitoring modes.

Under this strategic monitoring, when good water quality status in the river or water body is reached, only surveillance monitoring is required. However, when water bodies are classified with moderate or poor quality, further information is required for management purposes, and therefore, both operational and investigative monitoring is applied (Allan *et al.*, 2005).

As mentioned in previous chapters (see chapter 2.2), the first design criterion in any water quality programme is to determine or define the objectives (Table 2.1) (Ongley, 2000). However, the study type and scope are seen by ANZECC (2000) as the first steps, which would be followed by the definition of sampling sites, spatial variability, frequency, parameters, precision and accuracy and costs. According to Sanders *et al.* (1983) and Newham *et al.* (2001) the final definition of objectives will depend on the type of required information, thus clear data requirements, information needs (e.g. for public health preservation; regulatory concerns) and monitoring modes are required to be established prior to commencement of water sampling. Nevertheless, Canna and Christodoulidou (2000) recognise that the goal of monitoring networks should not focus only on information generation, but also on predictions and trends to forecast future situations.

In view of that, monitoring programmes may focus on the spatial distribution of the water quality (large number of samples), on trends (high sampling frequency) or on pollutants (in-dept inventories) (Pond *et al.*, 2000). The water quality monitoring in the Danube Delta for instance was developed to protect and maintain populations of species and habitats with high ecological values, manage the water circulation in the Delta and to ensure ecological integrity of strict protected areas (David and Hulea, 2000). All these objectives fall within the ones presented in Table 2.3.

### 2.5.2. Selection of Sampling Sites and Stations

The sampling sites and stations in general are selected within the area to be studied or monitored (water-course system, catchments area, river and all its tributaries, streams, brooks, ditches, canals, lakes or ponds) and they are of extreme importance during the design of water quality monitoring networks (Bartram and Ballance, 1996).

The first important step on such process is to establish the "macro locations" (the general area of a water body from which samples are to be taken) or the sampling site and later the "micro locations" (the exact place at which the sample is taken, i.e. stations) (Bartram and Ballance, 1996). The selection of a particular sampling location is strongly dependent on the monitoring objectives and on the existing knowledge of the geography of the water-course system (Table 2.5) and Figure 2.2.

**Table 2.5.** Types of site as a function of monitoring objectives

| Type of site | Location | Objectives |
|---|---|---|
| Baseline site | Headwater lakes or undisturbed upstream river stretches | To establish natural water quality conditions<br>To provide a basis for comparison with stations having direct human impacts<br>To test for the influence of long-range transport of contaminants and effects of climate change |
| Trend site | Major river basins, large lakes or major aquifers | To test for long-term changes in water quality<br>To provide a basis for statistical identification of the possible causes of measured conditions or identified trends |
| Global river flux site | Mouth of a major river | To determine trends of critical pollutants from river basin to ocean or regional sea |

Source: Adapted from Bartram and Ballance (1996)

According to ANZECC (2000) the variability between sites and between times, determines the ideal number of sites/stations, number of replicates and the frequency of sample collection. Thus, the smallest differences or changes that may be detected determine the number of sampling stations needed. Bartram and Ballance (1996) recommend that sampling stations in rivers should be as a general rule established at places where the water is sufficiently well mixed to collect a single sample. In case of doubts of the extent of mixing, other characteristic variables should be measured (e.g. temperature) at several points across the width of the river. On the other hand differences between the left and the right bank water qualities can yield important information, e.g. pollution sources, contamination sources by garbage and other anthropogenic materials (Bartram and Ballance, 1996; Kelderman, 2004).

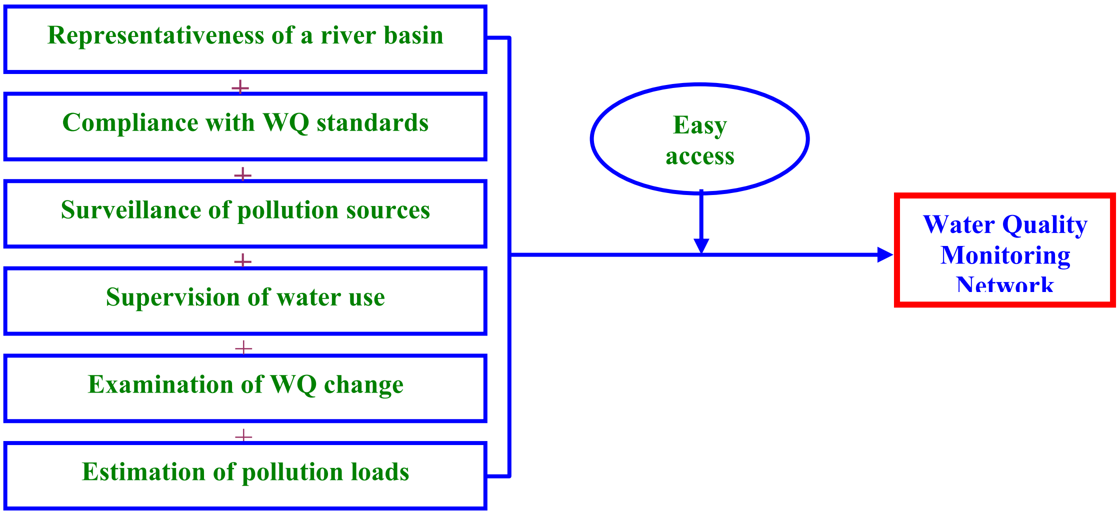


**Figure 2.2.** Criteria to be observed for selection of WQM stations (Park *et al.*, 2006)

Bridges are considered excellent locations for the placement of sampling stations, since they are normally located in an accessible part of the river and the station can be precisely described. Other sites might be spots or point sources of pollution (e.g. effluent discharges from industrial or water treatment facilities). The safe access of the sites should be ensured under all conditions, so that they may be reachable during the wet season. One way to ensure such identification is through use of Global Positioning System (GPS) technique to back-up records and descriptions of the sites.

Experiences from an Australian water quality monitoring network designed for Murrambidgee River Catchment's demonstrates that sites for monitoring should be co-located on existing stream gauges, with telemeters facility, with vehicular access in wet season also considering statistical variability of the parameters to be measured (Newham *et al.*, 2001).

The Sharp's method is another approach that is largely used to locate the sampling sites and stations. The method is described by Sanders *et al.* (1983), where water quality monitoring stations are positioned by a systematic subdivision of the river network into portions which are relatively equal in terms of the number of contributing tributaries. Thus, each exterior tributary or link contributing to the mainstream of a river is assigned a magnitude of one; the stream resulting from intersection of two exterior tributaries becomes a second order tributary and so on until the mouth of the final river where the order will be the sum of previous tributaries orders. This method is generally recommended when the primary object of the monitoring network is to detect, isolate and identify sources of pollution. Moreover, the Sharp's method takes into consideration aspects such as accessibility, costs, storage facilities and distance to laboratories (Sanders *et al.*, 1983; Newham *et al.*, 2001; Park *et al.*, 2006).

### 2.5.3. Selection of Monitoring Media and Variables

The selection of monitoring media and variables in a monitoring programme depend on the objectives and on the existing and forecasted uses of the water (Bartram and Ballance, 1996). Thus, the ranking of those variables is important to construct a cost effective programme. Sanders *et al.* (1983) suggest a hierarchical division of water quality variables for purposes of information procurement (Table 2.6). The hierarchical division comprises four levels, such that the first and highest level address more aspects of water quantity and the fourth level and last is more detailed to specific compounds.

**Table 2.6.** Hierarchical ranking of water quality variables

| Variable type | Parameters category | Measurable variables | Level |
|---|---|---|---|
| Primary, basic variables | Water quantity, carrier variables | Quantity discharge, water level | First |
| Secondary, associated quality variables | Quality variables of aggregated effects | Temperature, pH, turbidity, BOD, DO, cations, anions, conductivity, chlorides, radioactivity | Second |
| Aggregate-producing quality variables | Quality variables that produce aggregated effects | Radioactivity-producing variables: strontium, cesium, tritium. Turbidity-producing variables: suspended matter, colloids, biota groups, dissolved minerals | Third |
| Specific compounds or species producing effects in aggregation | Most detailed classification of quality variables | Minerals affecting turbidity: iron oxide, manganese compounds, alumina, etc. | Fourth |

Source: Modified from Sanders *et al*. (1983)

For the most typical monitoring programmes the United Nations Environmental Programme (UNEP) Technical Advisory Group for Global Environmental Monitoring Systems (GEMS/Water) has recommended a set of core water quality variables that monitoring programmes should endeavour to collect information (see Table 2.7). These have been selected to cover the potential impacts of key issues that are considered to be of significance at the global and/or continental or sub-continental level (UNEP/GEMS, 2005). Additional variables such as BOD, COD, some heavy metals and pesticides are also included. In case of limited resources minimum parameters such as total suspended solids, temperature and pH, electrical conductivity, dissolved oxygen and nutrients (nitrate, ammonia and ortho-phosphate) are assessed.

**Table 2.7.** Sampling parameters proposed by WHO-GEMS

| Water Quality Category | Parameters |
|---|---|
| Hydrological | Instantaneous water discharge or level |
| Physical/Chemical | Temperature, Dissolved oxygen, pH, Electrical conductivity |
| Major ions and dissolved salts | Calcium, Magnesium, Sodium, Potassium, Chlorine, Sulphate, Alkalinity |
| Nutrients | Nitrate and Nitrite, Ammonia, Total phosphorus, Dissolved phosphorus, Reactive Silica |
| Organic matter | COD, BOD, Chlorophyll a |
| Microbiology | Faecal coliforms and Total coliforms |
| Metals and Inorganic contaminants | Aluminium, Arsenic, Boron, Cadmium, Chromium, Copper, Iron, Lead, Manganese, Mercury, Nickel, Selenium, Zinc. |
| Organic contaminants | Aldicarb, Aldrin, Altrazine, Benzene, DDT, Dieldrin, Lindane, PCBs, Phenols, Toxaphene, Total hydrocarbons, Total chlorinated hydrocarbons, Total polyaromatic hydrocarbons, PBDEs. |

Source: UNEP/GEMS (2005)

The New Zealand monitoring programme as described by Scarsbrook and McBride (2004), takes into account 15 major water quality parameters, all sampled in sites of long-term record. Such parameters include physical (flow, temperature, visual clarity, pH, conductivity, dissolved oxygen and turbidity), chemical (dissolved reactive phosphorus, total phosphorus, nitrate nitrogen, ammoniacal nitrogen, total nitrogen, absorbance and BOD) and biological (periphyton cover and macro-invertebrate). For aquatic monitoring of above parameters, three principal media are recognised by (Bartram and Ballance, 1996; Kristensen and Bøgestrand, 1996). Such media include: (i) water, (ii) particulate matter and (iii) biological indicator organisms or living organisms.

### 2.5.4. Frequency and Timing of Monitoring

The monitoring frequency at stations differs substantially depending on the purpose of the monitoring programme and the variables to be measured (Kristensen and Bøgestrand, 1996). UNEP/GEMS (2005) points that sampling frequency will depend on factors such as: variability of water quality with time; external influences affecting the variability; cyclic variations (annual, monthly and diurnal); nature of the station (e.g. river, lake); variability of individual variables; results from preliminary studies and associated hydrological events. The frequency should be higher when the purpose of the monitoring is to evaluate trends or trace water quality changes in stations with high variability. To assess the general status of the waterbody, low frequency of sampling might be observed.

Although it is recognised by Sanders *et al.* (1983) the existence of few quantitative criteria for designating appropriate sampling frequencies, intervals of one month between the collections of individual samples at a station is generally acceptable for characterising water quality over a long period whereas control purposes may require a weekly sampling. Table 2.8 presents the sampling frequencies according to GEMS (Bartram and Ballance, 1996; UNEP/GEMS, 2005).

**Table 2.8.** Recommended annual sampling frequencies for the GEMS stations

| **Type of monitoring station** | **Type of water body** | **Sampling frequency** | |
|---|---|---|---|
| | | **Minimum** | **Optimum/maximum** |
| **Baseline** | Streams | 4 per year, including high and low water stages | 24 per year (every second week); weekly for TSS |
| | Headwater lakes | 1 per year at turnover, sampling at lake outlet | 1 per year at turnover, plus 1 vertical profile at end of stratification season |
| **Trend** | Rivers | 12 per year for large drainage areas, approximately 100000 km$^2$ | 24 per year for small drainage area, approximately 10000 km$^2$ |
| | Lakes/reservoirs | 1 per year at turnover | 2 per year at turnover, 1 at maximum thermal stratification |
| | Groundwater | 1 per year for large, stable aquifers | 4 per year for small, alluvial aquifers |
| | | Kastic aquifers: same as rivers | |

Source: UNEP/GEMS (2005)

Under the water quality monitoring programmes of the Gomti River in India (Singh *et al*., 2004) and Northern Greece Catchments (Simeonov *et al*., 2003) for example, samples are collected monthly (between 11$^{th}$ and 14$^{th}$ day) across the river width. The main objective of such monitoring is to trace changes caused by the seasonal hydrological cycle.

Statistical analyses also play a role in the definition of sampling frequency. If significant differences are suspected or detected, samples may have to be collected daily or in a continuous basis (Bartram and Ballance, 1996). Moreover, sample collection should be frequent enough to enable an accurate calculation of the mean concentrations, taking into account the effects of local natural variability, the desired level of confidence (i.e., standard deviation and confidence interval), the importance of power and the sample size required to perform the desired comparisons (Sanders *et al*., 1983; Bartram and Ballance, 1996; Cavanagh *et al.*, 1998). An example of such frequencies is given in Table 2.8. A new programme, however, with no advance information on quality variation should be preceded by a preliminary survey and then begin with a fixed sampling schedule that can be revised when the need becomes apparent (Bartram and Ballance, 1996).

## 2.6. Optimisation of Water Quality Monitoring Networks

Optimisation of water quality monitoring networks is related to the collection or generation of the same amount of information required for decision making process using less financial resources. According to Ongley and Ordoñez (1997) the primary goal of an optimisation process is to simplify parameter schedules and therefore to save resources. This can be done by providing screening information to determine appropriate parameters to be sampled and also by identifying indicator parameters that are easy to measure and interpret. Finally relevant data to end users is produced and the efficiency of the monitoring program is increased.

Such optimisation processes are conducted once sufficient data has been generated by the water quality monitoring network, so that statistic research can be carried out to maximise the spatial accuracy or to minimise the variance error between stations. Past studies on this matter were done by several authors (Sanders *et al*., 1983; Breukel *et al.*, 2000; Nunes *et al*., 2005; Ouyang, 2005). As an example the network optimisation program at IJsselmeer area (Netherlands) revealed after statistical research, that higher sampling frequency (12 times a year) at less locations (50% less) provides more information than a lower frequency at large number of locations, and reduces the cost by 35-50% (Breukel *et al.*, 2000). In the same study it was advised to select parameters which can be analysed with the same analytical method to allow a cost-effective operation of the laboratories.

Ouyang (2005) applied on his optimisation studies complex multivariate statistical techniques to identify important components or factors that explain most of the variances of the monitoring system. Results illustrated that there was a potential for improving the efficiency and economy of the monitoring network by reducing the number of monitoring stations from 22 to 19 in the Lower St. Johns River. Such reduction would result in cost savings without sacrificing important water quality data if followed by reduction of the sampled parameters from 42 to only 20.

The major constraint for the application of any of the above techniques is the availability of complete data set on water quality for all the studied stations. Thus, a first sampling stage with dense monitoring stations is undertaken in order to collect more data (Nunes *et al*., 2005). After determining the spatial covariance of those stations, an optimal water quality monitoring network can be recommended.

### 2.7. WQM Outputs and Management of Water in a Basin Scale

Water pollution impairs the use of water in several ways. It may directly impacts public health and functioning of ecosystem. The management of present and future water quality in regions with water scarcity, such as Southern Africa is fundamentally important for the continued existence of both the resource and the populations reliant on the resource (Hirji *et al*., 2002). The monitoring of water quality on its essence should not be used only to pinpoint the sources and levels of pollution, but in addition, propose methods that can be used to abate the pollution. So, according to Hirji *et al*. (2002) is essential to incorporate the water quality monitoring outcomes into the management organisation of the basin or catchment. In cases of identification of the pollution indicators through WQM network, a sanitary survey, for example, of the source the pollution and water body affected should be carried out.

Management of water needs largely to be related to policy and planning, regulatory control, investment planning for water infrastructures, public relations and international obligations (Ongley and Ordoñez, 1997). The main purpose of such relation is to make sure that the information generated through the WQM network after appropriate assessment, analysis and reporting, is used as a management tool to improve the conditions of the aquatic ecosystem in general and of the affected stretch of water in particular (Figure 2.3). In case the information generated is not appropriated for a particular management situation, it is important to consider possible scenarios (simulations) of management so that later can be used for the re-adjustment of the monitoring network.

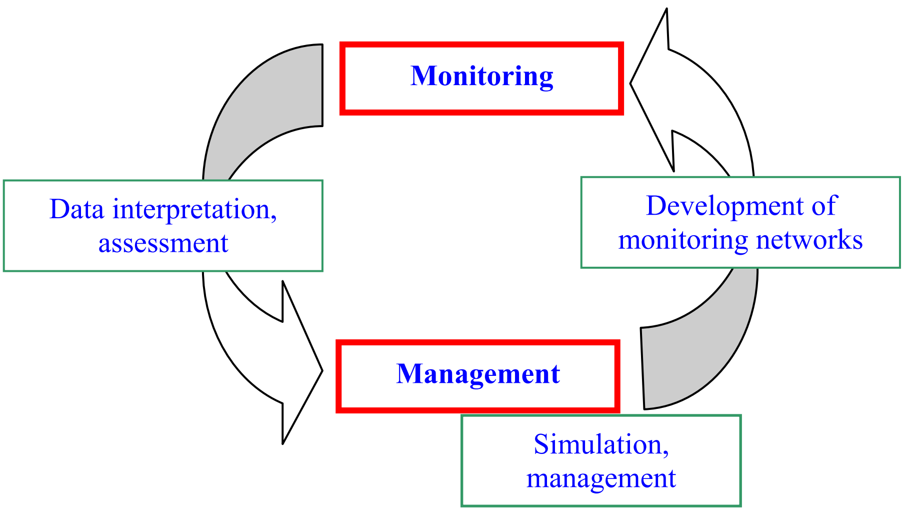


**Figure 2.3.** Link between management and water quality monitoring

Furthermore, successful implementation of water quality protection and management is dependent on the cooperation of institutions and stakeholders. Thus, close cooperation among local level (responsible for pollution control), regional and national levels (responsible to define water quality standards and enforce regulations) is required for effective implementation and use of water quality monitoring systems (Davis and Hirji, 2003b).

## 2.8. The Role of Environmental Flows in Monitoring Networks

### 2.8.1. Concepts

Recent legislation developments on the context of Integrated Water Resource Management worldwide tend to consider environmental flows (EF) as an important factor for decision on water allocation (Maran, 2004). Thus, it is crucial to incorporate environmental flows on water quality monitoring networks, since they contribute with better information for decision makers.

Environmental flows, also designated "instream flows" are defined by Tharme and King (1998) "*as the water regime provided or left within a river, wetland or coastal zone to maintain the aquatic ecosystems health and their benefits where competing water uses prevail and where flows are regulated*". Through those benefits they also provide critical contributions to economic development and poverty alleviation to society (Dyson *et al*., 2003). Unfortunately the manipulation of the flow regimes in rivers, to meet the increasing demands of the growing population, has resulted in a decline of the riverine ecosystems condition (health) (Tharme and King, 1998). According to Davis and Hirji (2003a) the flows of the world's rivers are increasingly being modified through impoundments such as dams and weirs, abstractions for agriculture and urban supply and structures for flood control. Altogether, these interventions contribute to reduce the seasonality of flows and the size and frequency of floods. In many cases such modifications have adversely affected the ecological and hydrological services provided by water ecosystems, which in turn have increased the vulnerability of people, especially those (poor) depending on such services.

The methodology linking downstream water resource degradation and their social consequences are still lacking. According to Davis and Hirji (2003a), the need of this kind of link was already recognised by the World Bank in 1993, as an important Water Resource Management tool (policy), which would include the need of water for rivers ecosystems, wetlands and fisheries in decisions concerning the operation of reservoirs and the allocation of water.

The supply of EF, that is, an adequate flow regime both in terms of quantity, quality and timing in rivers (e.g. Limpopo river) is seen as an important instrument for sustaining the health of rivers and other aquatic ecosystems downstream (Dyson *et al*., 2003).

### 2.8.2. Environmental Flow Assessment

Environmental flow assessments are increasingly used as part of environmental assessments (impacts of water resource development), as well as tools in water resource management (Davis and Hirji, 2003a). Hirji *et al*. (2002) presents three ways to reduce the impacts, namely: (i) reserving some water for river maintenance (ii) ensuring that the reserved water is made available at the times when it is most appropriate for river maintenance and (iii) by defining the water quality, physical habitat and biotic characteristics that typify the desired condition of the river (guidelines).

Tunbridge and Glenane (1988) specified four flow levels (three environmental flows and one flushing flow) for the Gellibrand River and Estuary in Victoria (Australia):

i. *An optimum flow* - for fish production and recovery after periods of stress, e.g. drought, overfishing;

ii. *minimum flow* - to avoid reduction in fish population for average rainfall years;

iii. *A survival flow* - important for preservation of species for low-rainfall years and;

iv. *A short-term flushing flow* (to maintain the freshwater section of the river by removing the salt wedge in the estuary).

The assessment of a particular EF will depend on the level of detail and can range from a simple statement of water depth to provide wetted habitat for a valued fish species, to a comprehensive description of a flow regime with intra-annual and inter-annual variability of low flows and floods in order to maintain the whole river systems (Hirji *et al.*, 2002).

Several methods are currently applied for assessing the EF. The selection of a particular method will depend on the timeframe and scale, constraints in terms of availability of data, legislative framework, finances, expertise and manpower (Hirji *et al.*, 2002; Dyson *et al.*, 2003). Thus, simple methods such as hydrological index; hydraulic ranking and habitat simulation have been largely used. Recently the focus is on the holistic methods which incorporate the simple methods, since they assess the whole ecosystem. The most used holistic methods include (Tharme and King, 1998; Hirji *et al.*, 2002; Dyson *et al.*, 2003):

- *In-stream flow incremental methodology (IFIM)* – addresses the impacts in river ecosystems because of changes on a river flow regime;
- *Building block methodology (BBM)* – based of the fact that some flows within the complete hydrological regime of a river are more important than others for maintenance of the riverine ecosystem, and that these flows can be identified, and described in terms of their magnitude, duration, timing and frequency;
- *The downstream response to imposed flow transformation methodology (DRIFT)* – developed in Southern Africa region, is an interactive top-down approach based on the same conceptual tenets and multidisciplinary, workshop-based interactions as the BBM;
- *The flow restoration methodology (FLOWRESM)* – developed in Australia, is aimed specifically at addressing EF requirements in river systems exhibiting a long history of flow regulation and requiring restoration.

According to Dyson *et al*. (2003), there is no single best way for environmental flow assessment. The use of historic trends of flows seems to be a simple method to get insight to flows requirements when the time is the major constraint.

### 2.8.3. Environmental Flows Assessment and Design of WQM Network

Changes in river discharges resulting from human activities in a catchment level have a significant impact on the downstream environmental characteristics. Past studies on the relation between EF and water quality concluded that the final quality of water, either its concentration of salts, pathogens, sediments, nutrients, oxygen content, persistent or degradable pollutants depend on a large extend on the regime characteristics of the river (Penning *et al.*, 2003).

Monitoring of EF is carried out to assess whether or not the recommended flows are achieving their objectives. The monitoring network should be designed to address five main questions relating to geomorphology and aquatic ecosystem. Table 2.9 present these questions as well as the recommended monitoring methods and frequencies (Tharme and King, 1998).

**Table 2.9.** Monitoring protocol for geomorphologic and aquatic ecosystem

| Question | Method | Monitoring frequency |
|---|---|---|
| Do the recommended flows discharges achieve the required stage levels in relation to morphological features? | Related sections with stage records at each monitoring site should be established | Continuous |
| Do the recommended flows maintain required habitat diversity within the different morphological units? | Hydraulic biotope assessment | Twice yearly to monitor wet and dry season base flows |
| Are favourable conditions being maintained? | Site surveys of size distribution of bed particles, and bed conditions (embeddedness, clustering and siltation) | Once a year during the dry season |
| Are morphological chances within the limits required by the ecological management class and guided by the long-term natural channel dynamics? | Site assessments of channel morphology and aerial surveys of reaches | Once every five years in the dry season |
| Do the recommended flows maintain the required (guidelines) water quality in the river or stream? | Site visits according to water quality monitoring network | According to water quality monitoring network specifications |

Source: Adapted from Tharme and King (1998)

According to Carolyn *et al.* (1998), two major attributes of a river that affect ecosystem structure and functioning should be included when monitoring and defining EF. Such attributes include water quantity (flow, velocity, depth and other hydraulic parameters) and water quality (nutrients, ions, pesticides, heavy metals, etc.), because the aquatic organisms respond to it and exhibit specific tolerance ranges and preferences for different chemical composition of the water.

For the assessment of environmental flows either using BBM methodology or the DRIFT approach it is important to prepare a clear background set of information. According to Brown and King (2002) three main fields of data are required for a comprehensive EFA, since its assessment is strongly linked to the quality of data used.

Those fields include biophysical, social and economic data. Particularly for the biophysical data, it is important to have a long-term, accurate hydrological data, either measured or simulated, to allow the links between the flow of the river and processes within the river. Similarly to discharge data, long term water chemistry records of the river are required. Specific issues that should be addressed by the set of data are presented in Table 2.10.

Given that most of the information presented in Table 2.10 is not likely to be present, is important to consider the role that might be played by water quality monitoring networks in providing such kind of information. The main objective of implementing a WQM is the generation of information, thus, its link to other information potential users is important. Although the information and data required by BBM or DRIFT methods, it is important to recall the need of specialists for the different fields, i.e. each of the ecosystem components to turn the process feasible (Brown and King, 2002).

**Table 2.10.** Main data requirements for EFA

| Data field | Main issues during EFA |
|---|---|
| Hydrology | ▪ Natural, present and projected future daily flow regimes at selected points along the river. |
| Hydraulics | ▪ Relationship between discharge and channel depth, width and water velocity at selected cross-sections of the river. |
| Channel morphology | ▪ Present nature of river channel<br>▪ Which lengths are similar in nature and functioning<br>▪ Future vulnerability to changes<br>▪ Influence of flow change on change of the channel |
| Water quality/chemistry | ▪ Past (daily) conditions of water chemistry/quality and temperature<br>▪ Main concerns in terms of water quality<br>▪ Future trend of water quality as function of flow regime |
| Biotic communities | ▪ Composition of downstream and cross-channel distribution<br>▪ Conditions of the riparian and instream plant and animal communities<br>▪ Relationship between river flows and communities<br>▪ Changes of communities composition as response of change of flow and water quality<br>▪ Recommended flows for the most sensitive species<br>▪ Identification of rare and endangered species |

Source: Adapted from Brown and King (2002)

CHAPTER THREE

# MATERIALS AND METHODS

## 3.1. Description of the Study Area

### 3.1.1. Geographic Localisation

The Limpopo River Basin is located in the east of Southern Africa between approximately latitudes 20°S - 26°S and longitudes 25°E - 35°E. It is almost circular in shape with a mean altitude of 840 m above sea level and covers an area of about 413000 km$^2$ (FAO-SAFR, 2004). The basin straddles four countries (Figure 3.1), South Africa (RSA) (47%), Botswana (17.7%), Zimbabwe (16%) and Mozambique (19.3%).

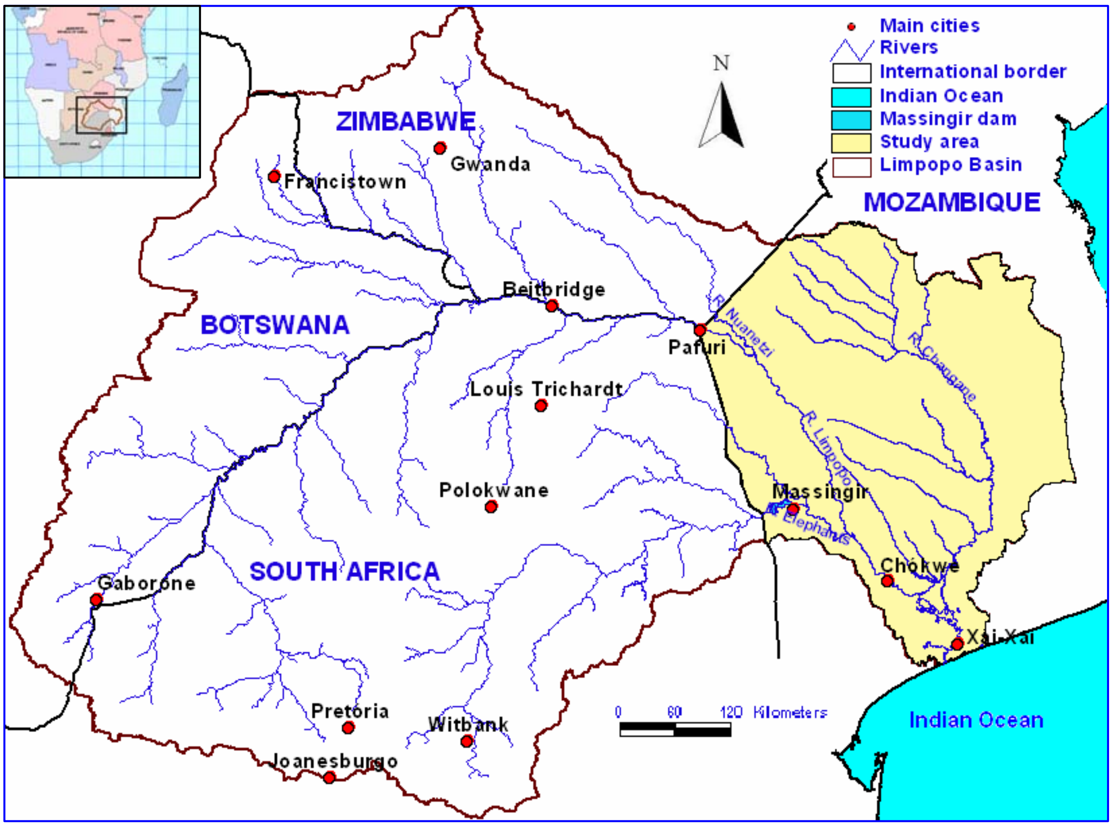


**Figure 3.1.** Limpopo Basin and the study area in Mozambique

The Limpopo River has got an extension of about 1750 km, forming the borders between South Africa and Botswana and the entire boarder between South Africa and Zimbabwe (Figure 3.1) (Amaral and Sommerhalder, 2004). In Mozambique the river flows on an extension of about 561 km (slope of 1.03 m/km) until it drains into the Indian Ocean approximately downstream of the town of Xai-Xai (Figure 3.1; Louw and Gichuki, 2003).

### 3.1.2. Climate

The climate of the basin varies considerably, as it lies at the transition of major climatic zones. According to the Köppen classification the basin is predominantly semi-arid, dry and hot (FAO-SAFR, 2004 citing Köppen, 1918). Rainfall varies dramatically across the basin, from an excess of 1500 mm per annum in the eastern highlands to less than 300 mm per annum in the arid central regions (Louw and Gichuki, 2003). The majority of the catchment receives less than 500 mm of rainfall per year. The rainfall seasonality both during the summer months (October to March) and winter months (April to September), is explained by the presence of anti-cyclonic conditions over the whole southern Africa (FAO-SAFR, 2004). Approximately 95% of the annual rainfall in Mozambique occurs between October and March, in a number of isolate rain days and isolated locations, characterizing the cyclic seasonal, erratic and unreliable rainfall (cyclic droughts and floods events) (Amaral and Sommerhalder, 2004). It shows a sea to land gradient, with a maximum ranging from 800 to 1000 mm/yr and a minimum of 400 mm in the dry interior bordering with Zimbabwe.

The daily average maximum temperature in the LRB in Mozambique is between 30 and 35 ˚C during the hottest month (January) and a minimum of 9 to 12 ˚C during the coolest month (June). The evaporation has an average of 1970 mm, ranging from 800 to 2400 mm/yr, which means a higher evaporation rate than rainfall (IWMI/ARC, 2003).

### 3.1.3. Topography, Soils and Landscape

Geologically, the coastal plain of the basin is dominated by the Mananga deposits. In some coastal areas, aeolian sands cover these colluvial deposits, which are sodic in most places. The floodplains of the larger rivers are alluviated. Inland, towards the borders with Zimbabwe and South Africa (Figure 3.1), the coastal plain abuts against clastic sediments. Thus, mining activities in the basin are significant in upstream part (IWMI/ARC, 2003).

In terms of soils the Limpopo Basin in Mozambique is characterized by occurrence of Arenosols (sands, not highly weathered) at the cost, but the Solonetz soils cover the bulk of the countries coastal plain (DNA, 1996; Louw and Gichuki, 2003).

Generally the climatic conditions of the basin give rise to five broad vegetation types: (i) dry deciduous mopane savanna (ii) vegetation on alluviums (iii) acacia woodlands (iv) vegetation of saline soils and (v) littoral thicket and forest of recent dunes. Generally in the LRB, arid area covers 47%, the forest 1%, and the wetlands 3% (Louw and Gichuki, 2003).

### 3.1.4. Water Resources and Hydraulic Infrastructures

The Limpopo River and its larger tributaries all exhibit marked seasonal cyclical patterns of high and low flows and many of the smaller tributaries are entirely seasonal or episodic (Ashton *et al.*, 2001). Along its course the Limpopo River is joined by eight tributaries. Among those tributaries the Elephants or Olifants sub-catchment ranks first in terms of area, covering 17% of the basin (Amaral and Sommerhalder, 2004; FAO-SAFR, 2004). In Mozambique three important tributaries join the River. The Nuanedzi River on the right hand side of Limpopo (rising entirely in Zimbabwe) and joins Limpopo after running for about 60 km in Mozambique; the Changane River (rising close to Zimbabwe border) joins the Limpopo close to its mouth on the coast near to

Xai-Xai town (SARDC, 2003); the Elephants River joins the Limpopo River after the Massingir reservoir (Figure 3.2) (Louw and Gichuki, 2003).

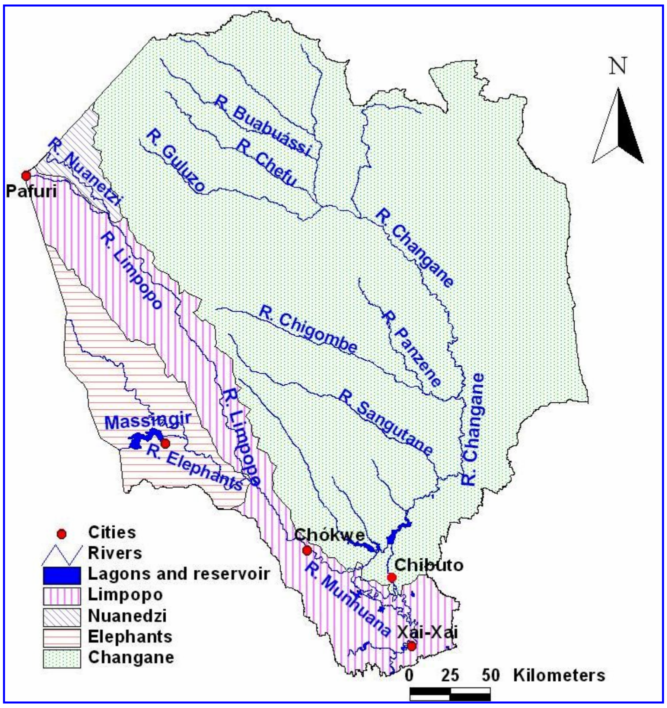


**Figure 3.2.** Water resources network and main subcatchments in the LRB

The total annual runoff from the basin is in the order of 5500 $Mm^3$ per annum, which equates an average surface runoff of 13 mm. The flow in the river is characterized by considerable inter and intra-annual variation. The river is not perennial in all years and in some years is dry for several months (Louw and Gichuki, 2003). In Mozambique, the Limpopo River has an average annual discharge of 4.8 $km^3$ (FAO-SAFR, 2004). Other important water resources in the Limpopo River Basin in Mozambique are the wetlands, which generally are found distributed throughout the swamps areas along the rivers, e.g. swamps after the confluence of Limpopo River with the Elephant River, riverine floodplains as the Limpopo River approaches the confluence with the Changane River (Brito *et al.*, 2003).

The major structures influencing the flow in the River in Mozambique are the Massingir and Macarretane dam. This last with the main purpose of lifting the water (± 5 m) to allow diversion of water to Chókwè irrigation scheme is totally dependent on the flows discharged by Massingir dam. The Macarretane dam is placed at the Limpopo River (main course) close to Chókwè town (16 km upstream) and has a small reservoir with a maximum capacity of 4 $Mm^3$ (SAFEGE, 1995). On the other hand, the Massingir dam is placed at the Elephants River (tributary of Limpopo) (Figure 3.2) and has a reservoir with a maximum capacity of 2800 $Mm^3$ (DNA/ARA-Sul, 2006).

### 3.1.5. Demography

The Limpopo River Basin in Mozambique is characterized by an accumulation of population along the rivers; at the southern part of the basin high density of population is found, because of the proximity to the main national road (INGC/UEM/FEWS NET, 2003). According to the 1997 census, the total population in the LRB in Mozambique was about 856000 people, which was about 6% of the countries population. Out of these population 20% lives in urban areas along the Limpopo River (INE, 1997).The density ranges from one person per $km^2$ (upstream Changane River) to over 1000 people per $km^2$ in the Xai-Xai city. The average population density is 21.07 people per $km^2$ (INGC/UEM/FEWS NET, 2003). The Villages in the southern part are more numerous and larger than in the rest of the Basin and progressively they reduce in size and population when moving upstream Limpopo River and its tributaries, although the Massingir Village could be considered an exception.

The projections made by INE (1997) suggest a population growth in the Basin to about 1.9 million in 2010. Most of this population is expected to be concentrated in the most densely populated urban areas such as Chókwè and Xai-Xai. So, problems of water quality deterioration are expected to worsen if no wastewater treatment is installed (INGC/UEM/FEWS NET, 2003).

### 3.1.6. Main Economic Activities in the Catchment

At the upstream part of the basin, the mining operations as well as different forms of agriculture (subsistence and commercial cultivation, game farming, livestock and dairy production) are the economics mainstays of the catchment. As an example, in 1995 the area under irrigation in the basin was about 328000 hectares corresponding to 0.79% of the entire Limpopo River Basin (FAO-SAFR, 2004).

In Mozambique, agriculture is the main activity developed, where the Chókwè irrigation scheme is the largest irrigated area (potential of 30000 ha). Currently only about 2000 ha are exploited (DNA/ARA-Sul, 2006). Further downstream a total of about 40000 ha of potential irrigated area are available (Louw and Gichuki, 2003). Other important economic activities include: (i) fishing and livestock keeping, which are carried out mainly by communities for subsistence, (ii) trading, manufacturing and service industry. The existing manufacturing activities are mainly formed by informal sector trading in food, repair workshops and light furniture and other small scale family-based enterprises (SARDC, 2003).

The tourism is other important activity developed in the basin. The basin is well known for its large parks such as the Greater Limpopo Park, which involves management areas from South Africa, Zimbabwe and Mozambique. Tourism presents considerable interest in the coastal area of Gaza province, mainly in Xai-Xai because of the unique environmental features of its coastal area (SARDC, 2003).

### 3.1.7. Factors Leading to Catchment Degradation

Erosion and salinization are of great concern in the basin, and constitutes the great sources of diffuse loads and pollutants to the river. The basin shows relatively advanced eroded conditions, and often shows younger and shallower soils as compared to less eroded surrounding areas (FAO-SAFR, 2004). In the Limpopo River Basin (LRB) the over utilisation of water resources and pollution arising from high-density urban settlements, river regulation, upstream mining activities and other industrial development are seen as the main activities leading to the continuous deterioration of the environment downstream (IWMI/ARC, 2003).

Recent studies in the basin by DNA (1999) and Ashton *et al.* (2001) indicate that throughout the length of the Limpopo, the main water quality problems and threats include: (i) increasing salinity; (ii) discharge of untreated or partially treated domestic and industrial effluents; (iii) declining of river flows due to escalating demands for water; (iv) discharge of untreated loads from upstream mining activities. The Elephants River is a clear example of pollution source as a consequence of mining activities, where heavy metals, such as cupper (Cu), Nickel (Ni) and Iron (Fe) were found in the gills, liver, muscle and skin of sampled fish. These metals derive from different industrial productive activities since there in no wastewater treatment system (Louw and Gichuki, 2003).

In Mozambique the main sources of pollution to the Limpopo River include, among others, the intense agricultural activities in the Chókwè region (use of fertilizers and pesticides) worsened by the deficient drainage of water in the Chókwè irrigation system. In addition, high loads of salts and other contaminants are likely to drain into the river because of the salty geologic formation of the river bed (e.g. Changane River) and of erosion and low permeability of the predominant soils (mananga) (DNA/ARA-Sul, 2006). Non-point domestic effluent discharges from rural and small towns along the river and tributaries, salt intrusion and mineralisation of waters due to reduced flows are other sources of pollution (refer to Table 3.1).

**Table 3.1.** Factors contributing to spatio-temporal diversity of water quality in the LRB in Mozambique

| **Natural dynamics** |
|---|
| ▪ Season (weather): flow velocity due to low and erratic rainfall, high temperatures, high evapotranspiration;<br>▪ River drainage over an arid zone (high mineralisation)<br>▪ Space: reduced flow velocity due to low topographical gradient, long distance from the sources of pollution in some cases, transport of sediments;<br>▪ Natural conditions along the river on the neighbouring countries (e.g. geology, climate)<br>▪ Salt intrusion due to high tides (± 55 km upstream river mouth) |
| **Human impacts** |
| Physical and chemical disturbances<br>▪ Diffuse discharge of untreated urban and small enterprises wastewaters<br>▪ Discharge of sewer systems (e.g. Chókwè and Xai-Xai)<br>▪ Discharge of untreated wastewater from small scale industries<br>Diffuse sources of pollution<br>▪ Agriculture (fertilizers and pesticides)<br>▪ Soil erosion and sedimentation<br>▪ Drainage of saline soils at Chókwè irrigation scheme<br>▪ High livestock population (manure)<br>▪ Mining activities<br>Structural and morphological<br>▪ Upstream water quantity management (weirs, dams, artificial embankments)<br>▪ Physical pollution during rainy season (wood debris) |

The Massingir dam had been pointed as a potential physical infrastructure that would worsen the water quality in the Limpopo River because of possible drainage of high salted bottom layers of water. Pilot studies by DNA/ARA-Sul (2006) proved that for the specific case of the Massingir, the drained water has a low concentration of salts, although is admitted that in case of reduction of flows in the river the water quality may deteriorate.

Altogether these pollutants or loads reduce the water availability (quality) further downstream the basin, interfering with vital and legitimate water uses such as drinking, aquatic wildlife, recreation, irrigation and industrial use. The degradation of wetlands, coastal ecosystems, Indian Ocean bottom morphology and mangroves vegetation at the Limpopo banks are other risks that may derive from the increased pollution of the Limpopo water or by reduction of its flows (Louw and Gichuki, 2003). All these problems associated with the cyclic drought and flush floods worsen the livelihood in Mozambique.

### 3.1.8. Gauging Network and Monitoring of Water Quality

The process of gathering information and data from the Mozambican rivers is under direct responsibility of the National Directorate of Waters, through its Regional Administration of Water (ARA's). The hydrometric network is Mozambique is composed by a total of 36 stations; of these 18 are on the Limpopo River, 11 at Elephants sub-catchment and 7 at Changane sub-catchment (DNA, 1994). Recently a limited part of those stations (9) is operational (DNA, 1996), and readings of hydrometric heights and discharges are performed.

The monitoring network throughout the country is still being re-established (construction of telemetric stations) after the long period of civil conflict that resulted on destruction of major gauging infrastructures. The monitoring of water quality at lower Limpopo in Mozambique is done since 1981 (Louw and Gichuki, 2003), and the emphasis is given to the suitability of water for irrigation and drinking. At the past years the measurements have become irregular as a result of infrastructure destruction (DNA, 1996). It covers a total of 11 stations, which were not strictly projected to monitor water quality (Figure 3.3). Sampling frequency is variable from monthly to quarterly, depending on budget and distance to monitoring points. Thus, the data has prolonged gaps.

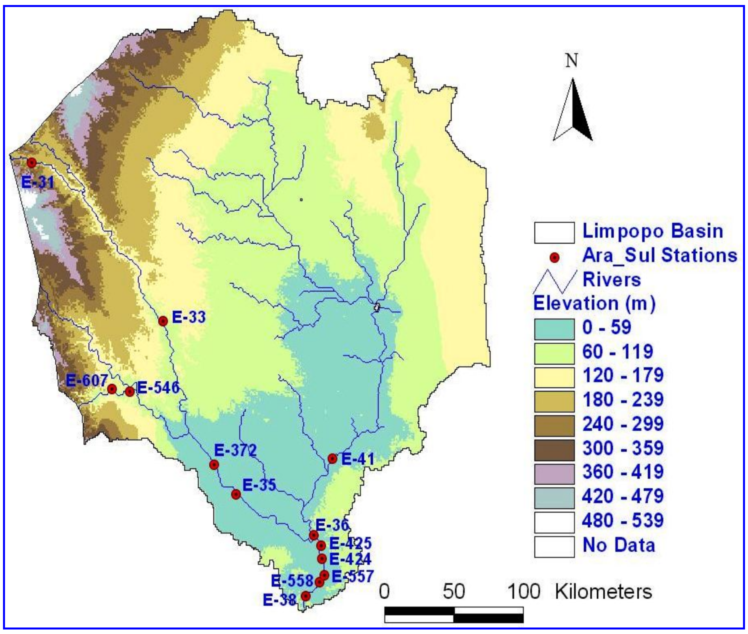


**Figure 3.3.** Stations with water quality monitoring (source: adapted from DNA, 1996)

The monitoring uses a standard list of physical, chemical and microbiological parameters (e.g. EC, temperature, turbidity, phosphates, nitrates, ammonium, organic matter, dissolved oxygen, biological oxygen demand, chemical oxygen demand, sodium absorption ratio and chloride). Data on metals, pesticides and macroinvertebrates is not collected.

### 3.1.9. Sanitation System at Main Urban Areas

At the main towns and cities along the LRB in Mozambique, the solid waste and wastewater management is under responsibility of the Ministry for Coordination of Environmental Affairs and the local Municipalities (FIPAG/DNA, 2004).

The sanitation in the Xai-Xai (Figure 3.2) comprises a combined stormwater network in the lower town centre, which collects rain water and overflows from septic tanks. At the upper part of the city the soils present better permeability allowing houses to discharge effluent into the soil trough infiltration pits. The existing system has been designed to discharge the effluents directly into the Limpopo River. The sludge generated from empting septic tanks in the lower area and those of the high area are discharged without any treatment to thalwegs, which later connect to the main course of the Limpopo River (FIPAG/DNA, 2004).

The city of Chókwè, the second biggest after Xai-Xai is situated on the southern embankment of the Limpopo River (Figure 3.2). Its sanitation system comprises a stormwater network, which collects stormwater and overflow from septic tanks. This system is directly connected to main sewage systems (general collector) and only benefits part of the citizens. The remainder of the families in town are served by latrines and septic tanks which are frequently emptied by wastewater pumping trucks. The combined stormwater network and the sludge are discharged into the Limpopo River without any pre-treatment (FIPAG/DNA, 2004).

## 3.2. Legal Framework and Surface Water Quality Guidelines in Mozambique

Aiming to meet the millennium development goals (MDG's), supply safe drinking water and improve sanitation for its population till 2015 the country has created its water law (Water Law Act N° 16 of 1991) and legislative instruments to deal with the water resources management including water pollution (Hirji *et al.*, 2002; SDC, 2003). In spite of its weak enforcement, the Law puts a special focus on the shared river basins and on cooperation with other watercourse states due to the country vulnerable downstream position (DNA, 1994). Other important objectives to be attained include: improvement of coordinated management, the equitable utilisation of common water resources, the exchange of information on issues of common interest and water quality control as well as the prevention of pollution and soil erosion.

The National Directorate of Water (DNA) is the main institution responsible for the management of the water sector in the country; its main tasks include: water policy making, inventories of water resources, data gathering and storing, water allocation planning (DNA, 1994; Vaz and Pereira, 2000). The Regional Water Administrations (ARA's) operate under the DNA and are only engaged on operational activities (administration of licences and payments from private users, management of hydraulic works). Furthermore, ARA-Sul is on duty to monitor the water quality, through implementation of water quality guidelines (SWECO, 2005).

Mozambique has developed in 2004 the Standards for receiving waters (Article 10 of Law n. 20/97) and Environmental Water Quality Standards for Effluent Emissions (Article 10 of Law n. 20/97). Since it is a new instrument established in the country, it is not yet spread throughout the key sectors for water management. It is found that in most of those institutions (e.g. ARA-Sul) the WHO guidelines for drinking and recreational uses are still applied. Gustafsson and Johansson (2006) refer in their report that guidelines for drinking water were ultimately defined by the Ministry of Healthy in Mozambique and are currently in use.

### 3.3. Field and Laboratory Study

#### 3.3.1. Sampling Sites and Methodology

The sampling of the river water was done in the summer, at the end of dry season (November, 06) and during the middle of the wet season (January, 07). It covered 25 stations (throughout the basin) on the main water courses running within the LRB in Mozambique. The covered rivers from upstream view of the basin were: (i) Nuanedzi at the left hand side; (ii) Elephants at the right hand side; (iii) Changane at the left hand side and (iv) the main course of Limpopo River (Figure 3.4).

Based of the conditions (e.g. accessibility, distance) found during the first visit (November, 06), 23 sites were selected as representative and were repeated in November, 07, covering the most important tributaries and sources of pollution (Appendix 1). Furthermore, due to the size of the catchment, sampling had to be done during 6-8 consecutive days. Usually the sites far upstream the basin (e.g. L1, TN2, TE6, etc) (Figure 3.4) which are close to the neighbouring countries were sampled during the firsts days of each field visit followed by the others further downstream the basin on the next days. Each of the visited sites was mapped using a portable Global Positioning System (Garmin IV).

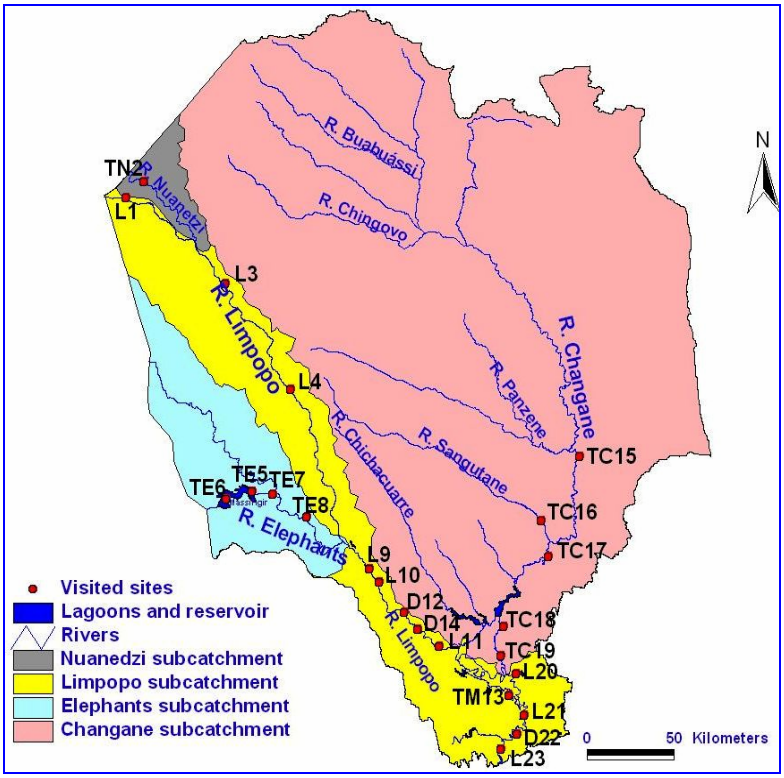


**Figure 3.4.** Sampled points during the preliminary study at LRB

Grab samples were taken in running water, perpendicular to the flow, at a depth varying from 10-20 cm below the water surface and as close as possible to the middle of the River. With a help of polyethylene cup (500 ml), a composite sample was prepared on each site trough filling the cup three times in the same number of stops. In cases of high level of water in the river and where possible, local boats were used to prepare the composite sample across the river.

Samples for chemical analysis at local laboratory were collected and stored in high-grade polyethylene bottles of 1.5 L capacity. However, samples for microbiological analysis (faecal coliforms) were taken in 500 ml sterilised glass bottles. In addition to the above mentioned samples (analysed at the local laboratory - MISAU laboratory), 46 bottles (23*20 ml + 23*10 ml) were collected and analysed for heavy metals at the laboratory of UNESCO-IHE in Delft.

All sample bottles were filled completely to avoid air bubbles. No preservation was done other than storing the samples in a cool box with ice-packs and later in the refrigerator at 4 ˚C till transport to the laboratory for analysis. Therefore, in some cases due to long distances to the laboratory, the ice packs melted. Thus, possible increase on samples temperature may have influenced the final results obtained.

Samples analysed for faecal coliforms were brought to the local laboratory within 12 hours after collection, while those meant for chemical analysis were taken to the laboratory at an interval ranging from 2 to 6 days. Furthermore, samples analysed for heavy metals were transported to the laboratory and analysed after 30 days of collection.

### 3.3.2. Parameters and Analysis Methods

During the field visits, parameters such as; pH, electrical conductivity (EC), temperature (T˚C), dissolved oxygen (DO) were measured on spot using portable equipments (WTW) according to Standard Methods (APHA/AWWA/WPCF, 1985). The analysis of nutrients (ammonia = $NH_4^+$-N; nitrate = $NO_3^-$ -N and ortho-phosphate = $PO_4$-P) were also done on spot in filtered samples. For that, GF Whatman filters (110 mm), and the "LASA 100 *Dr. Lange Fieldkit*" method were used, through application of specific test tubes and wave length on the photometer.

Since the results obtained for ortho-phosphate analysis were too high for most of the sampled sites compared to those obtained on past measurements, a photometric reanalysis for total phosphorus (TP) was done at UNESCO-IHE laboratories, for the samples collected during the last field visit (wet season). Given that, the results obtained at UNESCO-IHE laboratory for TP were far lower than those obtained from field assessment, only the former were considered for further analysis at this study.

Besides the spot measurements, the concentrations of some chemical components were determined in laboratory for all sampled sites according to Standard Methods (APHA/AWWA/WPCF, 1985). Out of those, at MISAU's laboratory the total hardness, Calcium ($Ca^{2+}$) and Chloride ($Cl^-$) were measured titrimetrically; the Magnesium ($Mg^{2+}$) and Sodium ($Na^+$), photometrically and the total dissolved solids (TDS) through drying at 180 ˚C. The microbiological analyses (faecal coliforms - Ecoli) were done using the membrane filter technique only for 9 sites on the two seasons. The sites analysed are: L11, L12, D13, D14, TC18, TC19, L21, D22 and L23. The other sites were left behind because of the long distance (> 300 km) separating them to the laboratory.

At UNESCO-IHE laboratory the suspended solids (SS) were determined photometrically; the heavy metals (Pb, Cu, Cd, Zn, Fe, Cr) using an Atomic Absorption Spectrometer (AAS).

### 3.3.3. Biological Monitoring

The biological assessment of the water quality was done taking into account the Biological Monitoring Working Party (BMWP) method described by Mason (1991) and referred to by Guinot *et al.* (2001). Altogether, 14 sites were sampled for macroinvertebrates in November, 06. At each site, two or three samples were taken from various locations by a means of a standard pond net sampler (3 minutes kick/sweep). The sampling was carried perpendicular to the river flow, in such a way that all possible habitats would be covered (bottom substrata, vegetation, margins, etc.) (Figure 3.5) (Mason, 1991; Norhayati, 1997; Czerniawska-kusza, 2005). The collected individuals were preserved in 70% ethanol. Identification was done in the laboratory using an electrical microscope (stereozoom microscope) and special "identification key" (up to the family level) (Mason, 1991; Azrina *et al.*, 2005).

**Figure 3.5.** Macroinvertebrates sampling in Elephants River (TE8)

## 3.4. Desk Study

### 3.4.1. Secondary Sources of Information

The secondary information (maps, flow and hydrological records in the basin, water quality data, guidelines for water quality, industries along the rivers, main agriculture activities, mining activities, tourism) was gathered from various Mozambican institutions such as: National Directorate of Water (DNA); Regional Administration of Waters - South (ARA-Sul); Hydraulic of Chókwè (HICEP); Ministry of Agriculture; Ministry of Health; Ministry of Tourism and Ministry of Industry and Commerce. In addition, about 4 informal interviews were conducted with farmers operating at Chókwè Irrigation Scheme and also local distributors of fertilizers and pesticides to understand the historical use of these products in the region.

The gathered information on hydrology can be seen in Appendix 3. The data summarizes the flows observed in stations located at vicinities of the sampled sites during the preliminary survey. Since for some stations the Regional Administration of Waters (ARA-Sul) did not have the readings, the flows were estimated based in historical data for the same sites.

### 3.4.2. Data Handling and Analysis

The overall biological assessment of water quality was carried out by using the Biological Monitoring Working Party method as described by Armitage *et al*. (1983); Mason (1991) and Guinot *et al* . (2001). Thus after assessing the scoring of each sampled site, the overall water quality was obtained taking into account the Lincoln Quality Index values (Table 2.4).

The assessment of physical, chemical and microbiological condition of the water was done taking into account the Mozambican and the WHO water quality guidelines. In addition an adapted water quality index (WQI) was used to assess the overall water quality on each station, in view of the fact that the original methods are based in parameters such as $BOD_5$, COD, $NO_3$, $NH_3$+$NH_4^+$, etc. Given that not all these parameters were measured an adaptation was done to include the EC, SAR, $Cl^-$, TP, $NO_3^-$ - N and $NH_4^+$-N in substitution of some of the original parameters (Appendix 9). Similarly to the physico-chemical parameters WQI, a heavy metals index was also adapted (Appendix 10). This index is divided into 5 main classes (ranking the WQ from "unpolluted" to "heavily polluted"), and is based on 7 heavy metals, given their strong contribution for water quality deterioration.

The temporal (from November to January) variations in water quality along the Basin were evaluated through Paired *t-test*. Correlation analysis was also performed to understand particular relation between parameters. All statistical analysis were done using the software SPSS 12.0.1. for Windows. Literature review later was used to discuss the results.

## 3.5. Quality Assurance and Control (QA/QC)

The quality assurance and quality control was assured by use of certified and calibrated equipment for the field and laboratory measurements. For that reason, the candidate was involved in a short training at UNESCO-IHE to improve technical skills on sample collection, transport and analyses in the laboratory. Since replicate samples were not collected because of budget limitations, the single sample analysed was obtained through mixture of several samples collected at different points for each sampling site. Care was also taken to rinse all material and equipment used with demineralised water before using for a different sample.

For the field measurements of nutrients the *"Dr. Lange Fieldkit"* was used, since is certified equipment and method, which has proven, world-wide to generate reliable results.

For sample analysis in the laboratory, sterilised, calibrated and certified materials and equipments were used. For the specific case of heavy metals and pesticides determination reference samples and blanks were used to control the quality of the tests results.

## CHAPTER FOUR

## RESULTS

### 4.1. Physico-chemical Quality of Water in the Limpopo River Basin

Various physical and chemical characteristics of the Limpopo River in Mozambique were measured during two different months: (1) November, 06 and (2) January, 07. In the following section, the information gathered is presented and explained regarding the parameters measured. The results are presented according to each subcatchment (total of three, viz. Limpopo, Nuanedzi/Elephants and Changane) (Figure 4.1), and main point source wastewater discharges and they are limited to the two above sampled months.

In addition, evaluation on the water "condition" is done whenever possible according to the Mozambican Water Quality Guidelines or either the WHO water quality guidelines (Appendices 13, 14 and 15).

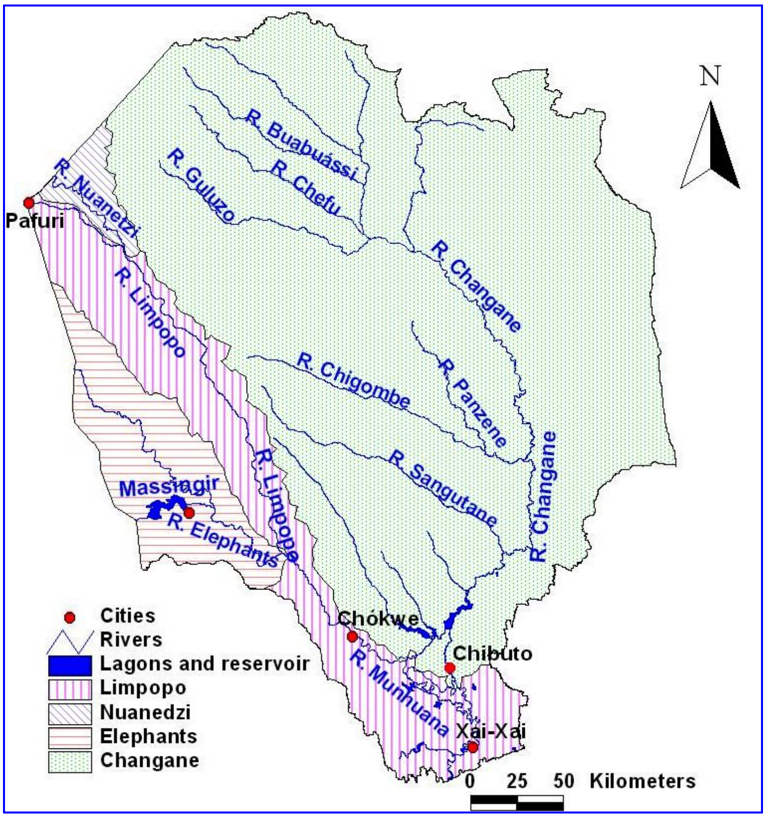


**Figure 4.1.** Limpopo Basin divided into four main subcatchments

#### 4.1.1. The Limpopo Subcatchment

The results of the analytical data measured at 9 sites along the Limpopo subcatchment are presented in Appendix 5 and 6 and summarized in Table 4.1.

At most of the sampling points along the Limpopo subcatchment, the physico-chemical parameters (Table 4.1) were found meeting the Mozambican and the WHO water quality guidelines for receiving waters and drinking purposes respectively (refer to Appendices 13 and 14 for guidelines values).

The pH values on the sampled months varied from 7.7 – 8.7, with a mean of 8.2 ± 0.2 ($p<0.05$, 95% confidence interval will be used here); the temperature from 24 to 33 ˚C, and the oxygen from 6 to 10 mg/L, with an average of 8.2 ± 0.7, showing a low variability between the two sampled months.

**Table 4.1.** Characteristics of Limpopo subcatchment waters; mean values are given with their 95% confidence interval. For details see Appendix 5 and 6.

| **Parameters** | **Nov., 06** | | | **Jan., 07** | | |
|---|---|---|---|---|---|---|
| | Mean±CI | Median | Range | Mean±CI | Median | Range |
| T (˚C) | 29.0±2.4 | 28.1 | 24.5-33.5 | 29.0±1.0 | 28.7 | 27-31 |
| pH | 8.2±0.2 | 8.3 | 7.7-8.7 | 8.2±0.2 | 8.3 | 7.7-8.4 |
| DO (mg/L) | 8.2±0.7 | 8.2 | 7.1-10.1 | 8.2±0.6 | 8.3 | 6.8-9.1 |
| Total hardness (g $CaCO_3$/L) | 0.3±0.2 | 0.2 | 0.1-0.8 | 0.2±0.1 | 0.2 | 0.08-0.5 |
| TDS (g/L) | 1.1±1.3 | 0.5 | 0.2-5.5 | 0.5±0.4 | 0.4 | 0.1-1.9 |
| Chloride (g/L) | 0.9±1.7 | 0.2 | 0.03-6.9 | 0.04±0.01 | 0.03 | 0.02-0.07 |
| EC (mS/cm) | 1.9±2.7 | 0.7 | 0.2-11.3 | 0.6±0.5 | 0.4 | 0.2-2.4 |
| SAR | 71.0±103.0 | 23 | 6.0-426.0 | 12.0±8.8 | 6.9 | 4.0-34.0 |
| Total phosphorus (mg P/L) | - | - | - | 0.23±0.1 | 0.22 | 0.03-0.65 |
| $NH_4^+$-N (mg/L) | 0.14±0.07 | 0.12 | 0.07-0.36 | 0.13±0.08 | 0.09 | 0.06-0.40 |
| $NO_3$-N (mg/L) | - | - | <0.23*-0.38 | - | - | <0.23*-1.05 |
| TSS (mg/L) | - | - | - | 389±456 | 44 | 8.0-1584.0 |

*Values below detection limit

The spatial and temporal distribution of total dissolved solids (TDS), electrical conductivity (EC), sodium adsorption ratio and chloride during the two sampled months is presented in Figure 4.2. For the four parameters illustrated in Figure 4.2., the highest concentrations were observed in November, compared to January, and there was a slight increasing trend when moving from site L1 to L23. Such results may be explained by the increase of flows from November to January, thus, dilution might occur.

Site L23 located downstream Xai-Xai registered the highest values for TDS (>5 g/L), EC (>10 mS/cm), Chloride (>8 g/L) and SAR (>400) (Figure 4.2**a**, **b**, **c** and **d**). Its proximity to the river mouth and thus possible impacts of ocean tides seem to have effect on the recorded concentrations.

The sodium adsorption ratio (Figure 4.1**d**) is an important indicator of water quality for irrigation, which bonds together the concentrations of magnesium, calcium and sodium; the SAR was found high (>10) at most of the sampled sites along the Limpopo River and it does not transmit a clear trend towards river mouth. The recorded values revealed a potential risk of soils sodicity derived from the use of water for irrigation.

Total hardness (TH) is other important parameter assessed, measuring the calcium and magnesium contents. Results found (Table 4.1 and Appendix 5 and 6) shows occurrence of hard waters (TH > 0.10 g $CaCO_3$/L) at sites L21 and L23 (both located close to the river mouth) and an increase from upstream to downstream. As the other parameters assessed the highest concentrations were found in November, probably due to reduced river flows.

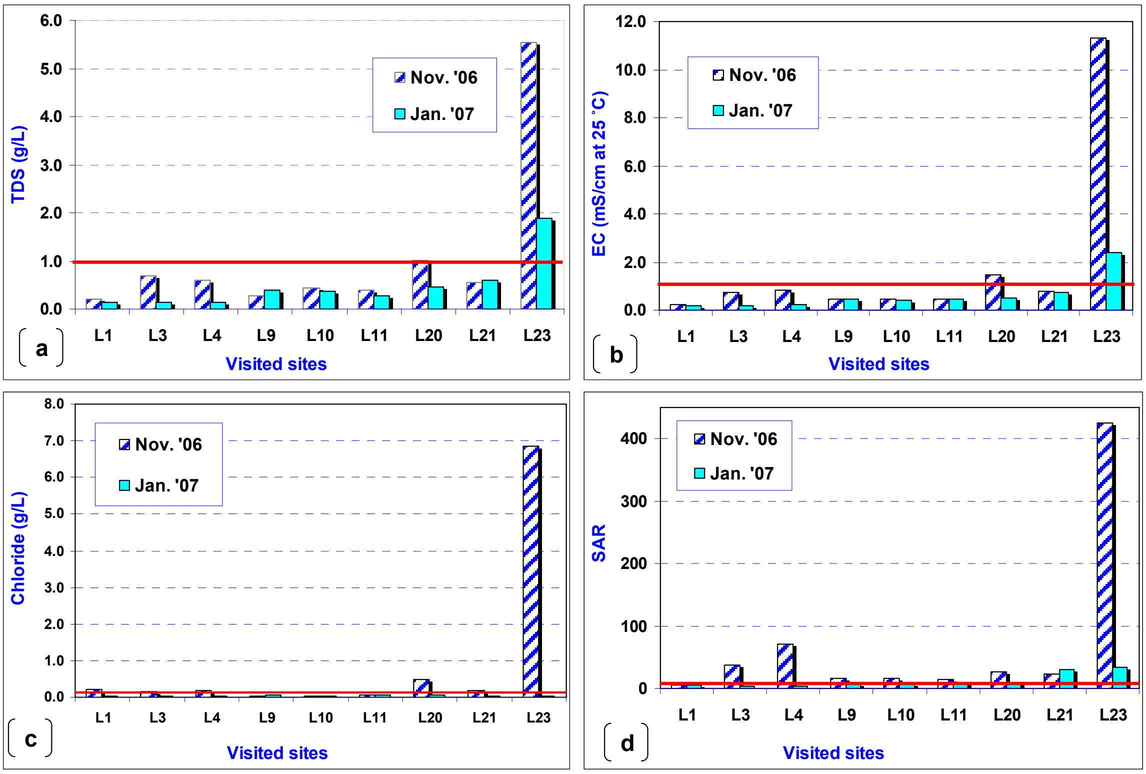


**Figure 4.2.** Spatio-temporal variability of the WQ in the Limpopo subcatchment. *The horizontal red/bold line indicates the Mozambican standards*. For detailed results, see Appendix 5 and 6.

Analysis for total metals (Figure 4.3) revealed that zinc (Zn), copper (Cu), cadmium (Cd) and Iron were present in all sampled sites and in concentrations higher that the national standards, except for sites, L20 (for zinc), L20, L21and L23 (for copper).

Although not pronounced, all heavy metals exhibited a declining trend when shifting from upstream subcatchment towards the river mouth (Figure 4.3). Thus, problems with water taste and metal toxicity may occur along the river. These concentrations seem to derive from sediment transport along the river coming from upstream mining areas.

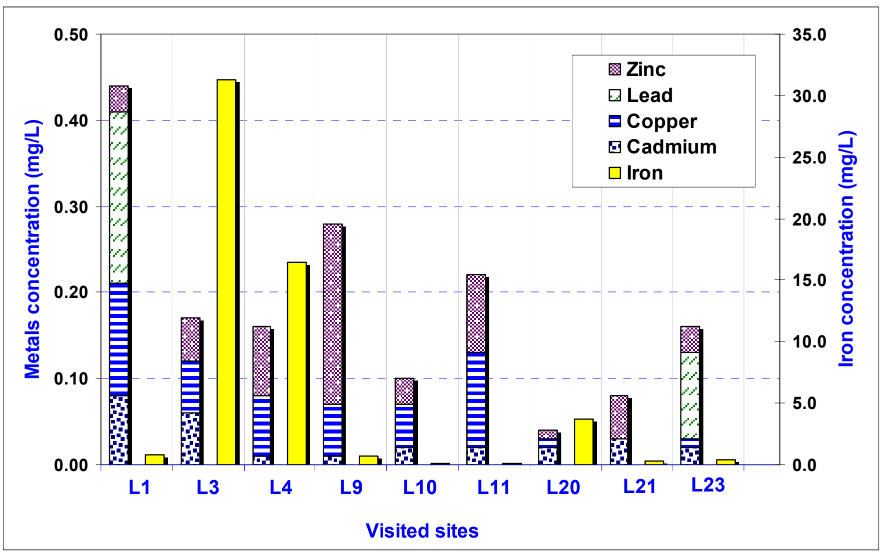


**Figure 4.3.** Metal concentrations along the Limpopo subcatchment

Although analysed, chromium was not found in this subcatchment (Appendix 7). Lead was identified in two sites (L1 and L23) with concentrations higher that the national standards (>0.01 mg/L). Diffuse sources such as sewage sludge, mining effluents, solid waste (e.g. batteries and transformers) seem to be main causes of the high concentrations of lead on sites L1 and L23, since L1 is located at downstream of industrial and mining sites and L23 after a largest urban settlement in Mozambique (Xai-Xai city).

Concerning the nutrients concentrations along the Limpopo subcatchment, the results for the major nutrients that contribute to eutrophication, i.e., nitrate ($NO_3^-$-N), ammonium ($NH_4^+$-N) and total phosphorus (TP) are presented in Table 4.1 and Figure 4.4. Nitrate ($NO_3^-$ -N) was found to be lower than the detection limit of Dr. Lange photometer (<0.23 mg/L) for almost all visited sites in November and January. So, there was not any sight of pollution by nitrate. Higher concentrations of nitrate were recorded at sites L1, L3 and L4 in January, probably due to increase in the river flow, which brought loads rich in nitrate, derived from upstream anthropogenic activities (e.g. agriculture).

TP and ammonium exhibit a declining trend along the river (from L1 to L23), and the ammonium values do not show a clear difference between the two assessed months (November and January). Risks for eutrophication due to TP content was observed on site L9 (Macarretane dam reservoir, upstream Chókwè), which recorded a value >0.60 mg/L of phosphorus. At this site, is admitted that the dam is acting as a sink of suspended matter and thus of TP, since phosphorus is likely to bind to suspended matter. The highest concentration of ammonium was found in January on site L20. Since this site is located after confluence with Changane tributary, is believed that this high values derive from additive effect of loads of Limpopo and Changane Rivers.

Moreover, almost all assessed sites were found with lower nutrients concentrations when compared to the national guidelines for receiving waters and the WHO guidelines for drinking purposes (Appendix 13 and 14).

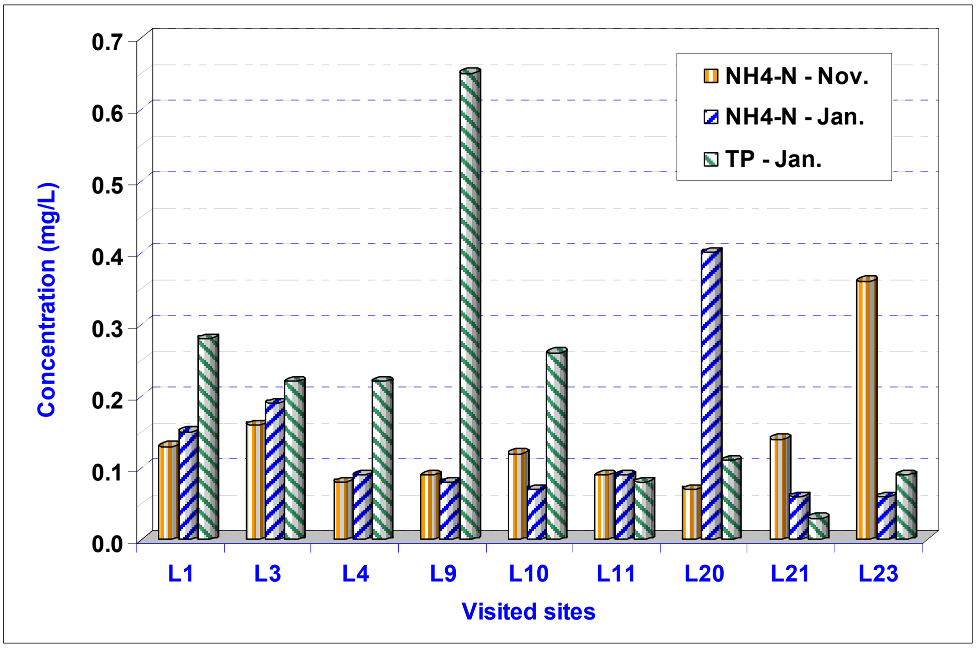


**Figure 4.4.** Levels of ammonium and total phosphorus in Limpopo waters

### 4.1.2. The Elephants and Nuanedzi Subcatchments

The Nuanedzi subcatchment (site TN2) was only sampled in January, given that in November the river was found completely dry. On the other hand, the Elephants subcatchment has flowing waters due to the presence on its main course of a dam (Massingir) which regulates water. Spatio-temporal distributions of the physico-chemical parameters is presented in Appendix 5 and 6 and summarized in Table 4.2.

**Table 4.2.** Characteristics of Elephants and Nuanedzi subcatchments waters; mean values are given with their 95% confidence interval. For details see Appendix 5 and 6.

| Parameters | Nov., 06 | | | Jan., 07 | | |
|---|---|---|---|---|---|---|
| | Mean±CI | Median | Range | Mean±CI | Median | Range |
| T (˚C) | 26.5±3.6 | 26.1 | 24.2-29.6 | 27.9±1.4 | 27.7 | 26.5-29.7 |
| pH | 7.9±0.4 | 8.0 | 7.6-8.1 | 8.2±0.2 | 8.2 | 7.7-8.4 |
| DO (mg/L) | 9.1±1.0 | 9.4 | 8.3-9.6 | 8.2±1.4 | 9.7 | 7.6-10.2 |
| Total hardness (g $CaCO_3$/L) | 0.2±0.04 | 0.19 | 0.18.0-0.23 | 0.16±0.06 | 0.17 | 0.08-0.20 |
| TDS (g/L) | 0.4±0.38 | 0.38 | 0.30-0.41 | 0.3±0.10 | 0.31 | 0.14-0.35 |
| Chloride (g/L) | 0.03±0.03 | 0.03 | 0.01-0.06 | 0.04±0.02 | 0.04 | 0.02-0.07 |
| EC (mS/cm) | 0.5±0.07 | 0.4 | 0.4-0.5 | 0.4±0.1 | 0.4 | 0.2-2.4 |
| SAR | 7.7±7.0 | 8.5 | 1.7-12.2 | 6.3±0.9 | 6.1 | 5.5-7.1 |
| Total phosphorus (mg P/L) | - | - | - | 0.11±0.1 | 0.11 | 0.03-0.23 |
| $NH_4^+$-N (mg/L) | 0.11±0.01 | 0.11 | 0.10-0.12 | 0.08±0.05 | 0.07 | 0.04-0.14 |
| $NO_3$-N (mg/L) | - | - | <0.23*-0.31 | - | | <0.23*-0.64 |
| TSS (mg/L) | - | - | - | 26.0±8.3 | 26.0 | 20.0-32.0 |

*Values below detection limit

Having a tropical setting just as in the Limpopo subcatchment, the water temperature varied from 24 to 30 ˚C during the two sampled months. The pH values were found ranged from 7.6 to 8.5. The dissolved oxygen (DO) values ranged from 7.6 to 10.2 were found high in both subcatchments. The sites TE6 and TE7 (Massingir reservoir) registered the highest DO values, probably due to atmospheric diffusion of oxygen, since the organic matter content is reduced as a result of settling in the reservoir. All the three parameters (temperature, pH and DO) were found within acceptable ranges according to the national guidelines.

In contrast to the Limpopo subcatchment, the values of TDS, EC, Chloride and SAR were found in low concentrations and in accordance with the Mozambican guidelines for receiving waters, except in November for the SAR at site TE7, where the ratio was found high (>10 mg/L) (Figure 4.5, **a** and **c**).

At these subcatchments, non clear differences were observed on the readings made in November and January. Such behaviour might derive from the controlled discharges made at Massingir dam, which create conditions for a low change on water quality parameters since its discharges were more or less constant and always made from the bottom layers. Reasonable increases of chloride were observed in January on sites TE7 and TE8, while the SAR values dropped at same sites.

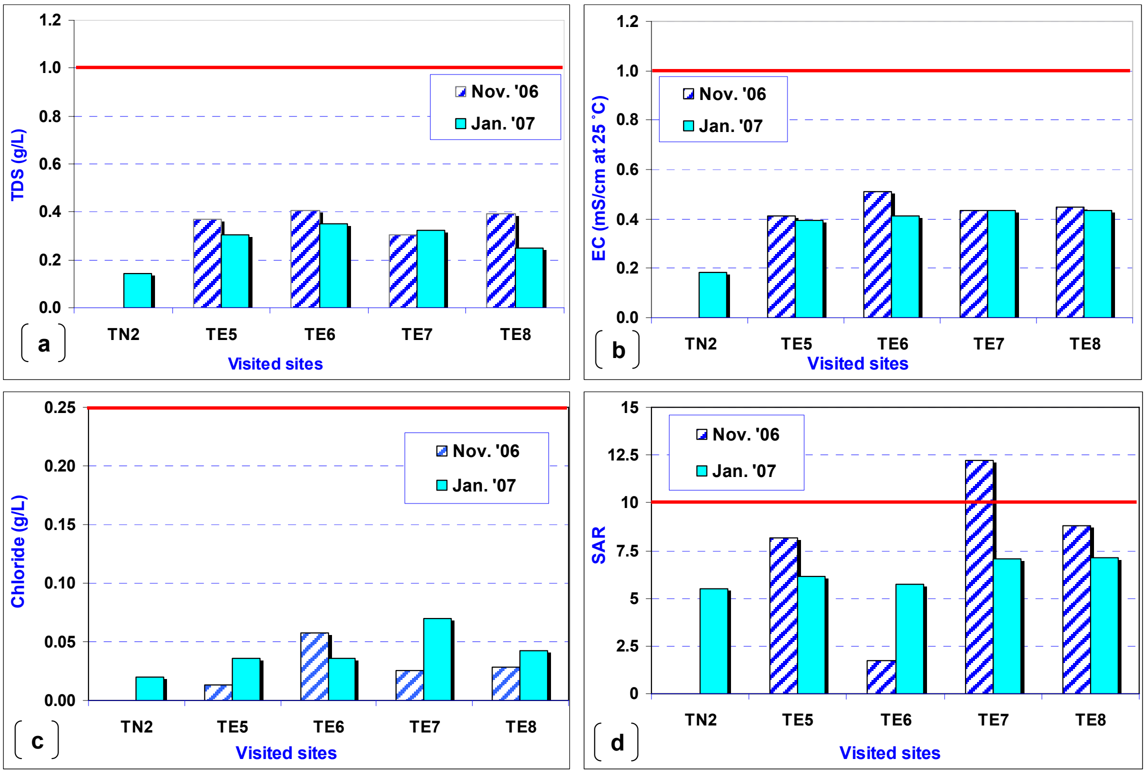


**Figure 4.5.** Spatio-temporal variability of WQ in the Nuanedzi and Elephants subcatchments. *The horizontal red/bold line indicates the Mozambican standards*. For detailed results, see Appendix 5 and 6.

As above mentioned, the water of all evaluated sites and on assessed months was found meeting the national guidelines for receiving waters and the WHO guidelines for drinking water (Appendix 13 and 14) for, EC (<1.0 mS/cm), TDS (<1.0 g/L), chloride (<0.25 g/L), SAR (<10) and hardness (TH<500 mg/L) (refer to red and bold line in Figure 4.5).

With respect to heavy metals in these subcatchments (Figure 4.6 and Appendix 7), similar to the Limpopo subcatchment, chromium was not found in any of the assessed sites. Out of the five registered metals on these subcatchments, particular emphasis should be given to lead, which was found on sites TN2 (Nuanedzi River) and TE6 (Massingir reservoir), in concentrations higher than the Mozambican standards (>0.10 mg/L). As mentioned before (chapter 4.1.1.) the mining activities developed at upstream countries (South Africa and Zimbabwe) together with natural weathering, generate loads with high content of metals in general and of Lead in particular. This reasoning is also backed by the high iron loads on site TN2 (> 12 mg/L), located in Nuanedzi River, which flows into Mozambique, after crossing mining zones in Zimbabwe. Zinc, Copper and Cadmium were other heavy metals found at these catchments, all at concentrations higher than the national guidelines. The same reasoning for occurrence of lead is applicable for these metals. All exhibited a declining trend toward the confluence with Limpopo main course (TN2, or TE6 to TE8). Therefore, attention on heavy metals monitoring should be considered mainly during the high flow conditions in these subcatchments (Elephants and Nuanedzi), since they appear to be primary sources of heavy metals pollutants.

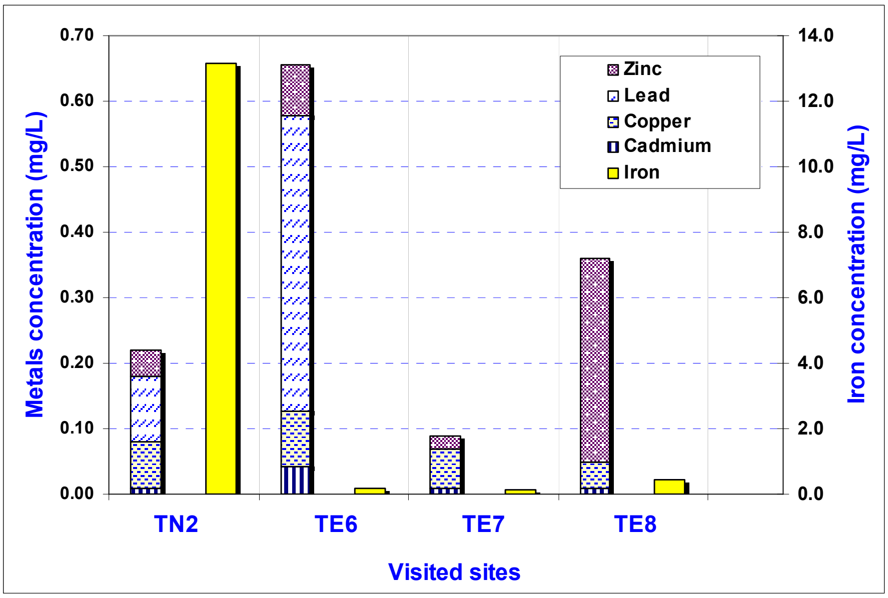


**Figure 4.6.** Metal concentrations in the Nuanedzi and Elephants subcatchments

The nutrients concentrations on these subcatchments are presented in Table 4.2 and illustrated in Figure 4.7. Just as in the Limpopo subcatchment the nutrients assessed at these subcatchments were found with lower nutrients concentrations when compared to the national guidelines for receiving waters and the WHO guidelines for drinking purposes (Appendix 13 and 14).

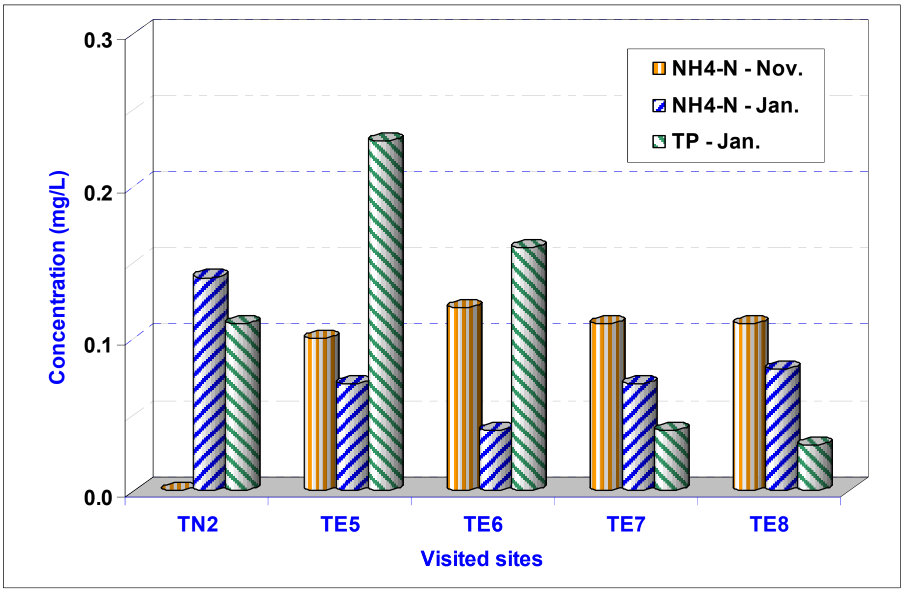


**Figure 4.7.** Ammonium and total phosphorus levels in Elephants and Nuanedzi rivers

Contamination with total phosphorus (TP) was found higher in three sites (TN2, TE5 and TE6), representing possible risks for eutrophication, since the concentrations were >0.03 mg/L. Highest phosphorus levels were recorded on sites TE5 and TE6 located at the Massingir reservoir (>0.16 mg/L) (Figure 4.18). Similarly high TP values were found in the Limpopo subcatchment in a dam reservoir, so possibly the same reasoning might be applicable here (refer to chapter 4.1.1). Further downstream the TP values tend to decrease, probably due to dilution or settling down of sediments. The range of $NH_4^+$-N values observed in all five sampled sites were below the national standards for receiving waters (0.4 mg/L) and the WHO guidelines for drinking waters (<1.5 mg/L). Nevertheless, the values were found in general to be higher in November compared to January, and they show a reducing trend towards the confluence with Limpopo River, although constant values are observed from site TE7 to TE8. The Nitrate values were found following the same trend as in the Limpopo subcatchment. Lower concentration and <0.23 mg $NO_3^-$ -N/L were observed in almost all sites, with exception of sites TN2 and TE6. But all $NO_3^-$-N values were found to be below the national standards for receiving waters.

### 4.1.3. The Changane Subcatchment

The Changane subcatchment was also sampled in the two months covered by this study. A total of 5 sites were assessed. The results obtained are presented in Appendix 5 and 6 and summarized in Table 4.3. Generally, a bad water quality was found in the Changane subcatchment, which is a tributary of the Limpopo River, in contrast to the Limpopo and Elephants+Nuanedzi subcatchments. This holds for the majority of the physico-chemical properties of water (Table 4.3).

**Table 4.3.** Characteristics of Changane subcatchment waters; mean values are given with their 95% confidence interval. For details see Appendix 5 and 6.

| Parameters | Nov., 06 | | | Jan., 07 | | |
|---|---|---|---|---|---|---|
| | Mean±CI | Median | Range | Mean±CI | Median | Range |
| T (˚C) | 28.4±3.7 | 27.9 | 25.5-32.0 | 31.3±5.7 | 28.7 | 27.5-37.2 |
| pH | 7.8±0.6 | 7.8 | 7.0-8.3 | 7.8±0.4 | 7.9 | 7.4-8.1 |
| DO (mg/L) | 7.0±2.1 | 7.5 | 4.7-9.2 | 6.5±2.7 | 7.7 | 4.1-8.4 |
| Total hardness (g $CaCO_3$/L) | 5.1±4.4 | 6.7 | 0.7-8.7 | 2.8±2.34 | 3.8 | 0.4-4.6 |
| TDS (g/L) | 15.5±1.3 | 15.8 | 3.7-34.2 | 8.9±9.4 | 6.7 | 2.5-20.6 |
| Chloride (g/L) | 7.6±7.1 | 5.95 | 11.6-15.9 | 5.2±4.7 | 4.1 | 1.8-9.6 |
| EC (mS/cm) | 19.3±18.1 | 17.9 | 4.1-41.2 | 11.6±10.7 | 9.4 | 3.0-22.9 |
| SAR | 408±450 | 277 | 95.7-986 | 306±215 | 278 | 96-534 |
| Total phosphorus (mg P/L) | - | - | - | 0.32±0.2 | 0.32 | 0.18-0.58 |
| $NH_4^+$-N (mg/L) | 0.22±0.10 | 0.17 | 0.15-0.31 | 0.34±0.10 | 0.34 | 0.25-0.47 |
| $NO_3$-N (mg/L) | - | - | <0.23*-0.37 | 0.72±1.10 | 0.37 | 0.24-2.28 |
| TSS (mg/L) | - | - | - | 193±136 | 244 | 72-316 |

* Values below detection limit

As in the other subcatchments, the temperature varied from 26 to 37 ˚C during the two assessed months. The pH values were found within the recommended range 6.5-8.5 for potability, according to the national guidelines. The average value of pH was 7.8±0.6 and values ranged from 7.0 to 8.3. The dissolved oxygen levels were found high in some sites (e.g. TC17, TC19), but lower values such as 4.1 were registered in January (site TC15). The high salinity associated with elevated temperatures seems to determine the low DO levels observed, since no organic matter loads were visible in the water. Thus, risks for aquatic life stress may be observed.

Differences with other subcatchments were found clear, when analysing the trend of total hardness, TDS, EC, chloride and SAR (Figure 4.8). An overall analysis of these five parameters demonstrates that at the two sampled months (November and January) the values at all sites were far above the national guidelines for receiving waters and of WHO guidelines for drinking purposes (Appendix 13 and 14). Additionally, it was observed that TDS, EC and chloride show an increasing trend when moving from site TC15 to TC17. Later, and suddenly the values drop at the following sites (Figure 4.8). Moreover, concentrations in November were generally higher than in January.

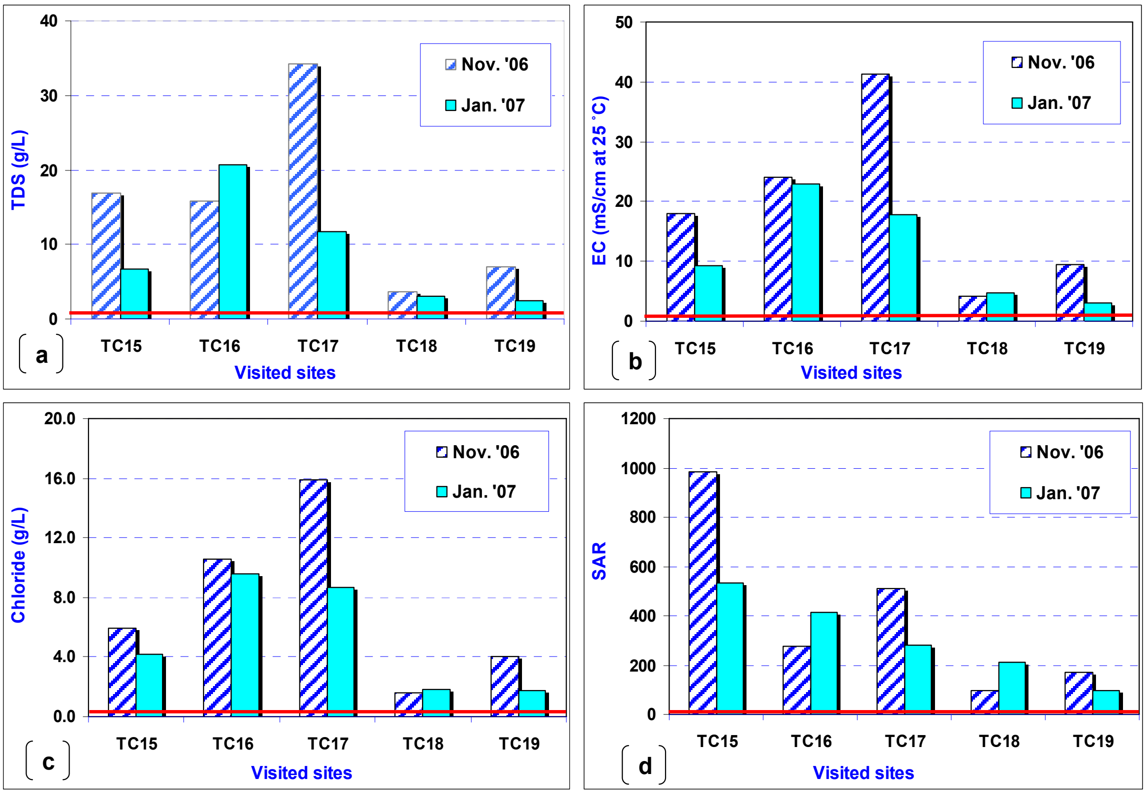


**Figure 4.8.** Spatio-temporal variability of WQ in the Changane subcatchment. *The horizontal red/bold line indicates the Mozambican standards.* For detailed results, see Appendix 5 and 6.

Considering the reduced human activities (e.g. agriculture or urban waste discharges) at this subcatchment, it is probable that the natural geologic formation of the area is acting as the major determinant for the deterioration of the water. The abrupt reduction of the concentration from site TC17 to TC18 can be explained by occurrence of lakes along the Changane River course, which in certain manner are acting as buffers for the loads and contaminants present in the water. Similarly to Limpopo subcatchment, the water of this subcatchment was not found suitable for irrigation, since SAR values >10 were observed. Furthermore, in both months the SAR values shows a reducing trend when moving from the upstream subcatchment toward the confluence with the Limpopo River (Figure 4.8**d**).

The data collected in this particular subcatchment point out its relevance as a natural and primary source of ions (cat and anions). Thus, its monitoring should be of primary concern, together with Elephants and Nuanedzi subcatchments.

Elevated concentrations of metals above the recommended standards were observed in the site TC16 (Figure 4.9 and Appendix 7). Given that the site TC16 was located at an old bridge, with its metallic structure in contact with water, is believed that the corroding metal may contain leaded solders, which are adding up lead into the water, since the bridge was built before 1975, period that leaded joint were still in use for construction. In addition it was observed that iron, zinc and cadmium occurred in all five sampled sites, and their concentrations were above the national standards for receiving waters, i.e. 0.3 mg/L, 0.01 mg/L and 0.005 mg/L, respectively, with exception of site TC15 for iron.

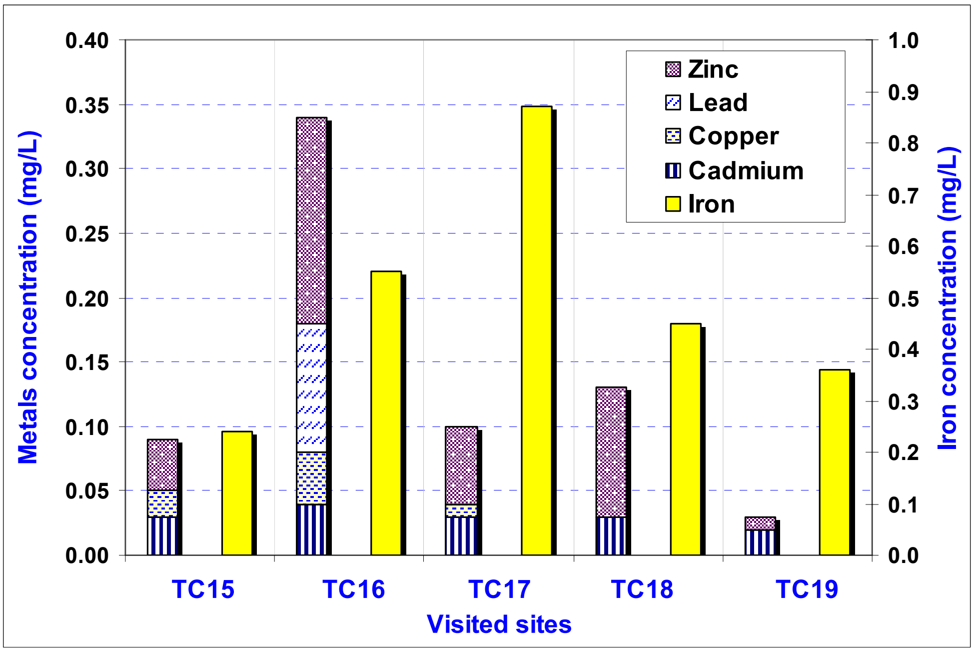


**Figure 4.9.** Metal concentrations in the Changane subcatchment

All metals with exception of iron show a decreasing trend when the river approaches the confluence with the Limpopo River main course after site TC19. The risk of pollution by nutrients was found to be high at this subcatchment when compared to Limpopo and Elephants+Nuanedzi subcatchments, since high values of TP, ammonium and nitrate were recorded (Figure 4.10). The occurrence of natural wetlands systems, which by nature are rich in organic matter, and thus of nutrients, may be the reason of such elevated contents of nutrients.

In contrast to Limpopo, Elephants and Nuanedzi subcatchments, in this subcatchment the nutrients concentrations in January were found to be higher that those registered in November. The possible addition of loads coming from agricultural farms runoff seems to be the main reason for these trends. TP, ammonium and nitrates show a drop from site TC15 to TC19 in November, while in January the trend was increasing towards site TC19. As mentioned before, the increase of runoff from neighbouring agricultural farms and urban areas (e.g. Chibuto) seems to be the origin of extra concentrations. Although the nutrients concentrations were far above the national guidelines for receiving waters, the colonisation by aquatic plants (eutrophication) is not likely to occur at this subcatchment because of the high levels of salinity of Changane waters. Pollution by nutrients is expected to take place downstream Limpopo Basin, as observed on site L20, where the ammonium concentration was high, probably influenced by loads discharged by the Changane River into the Limpopo River main course.

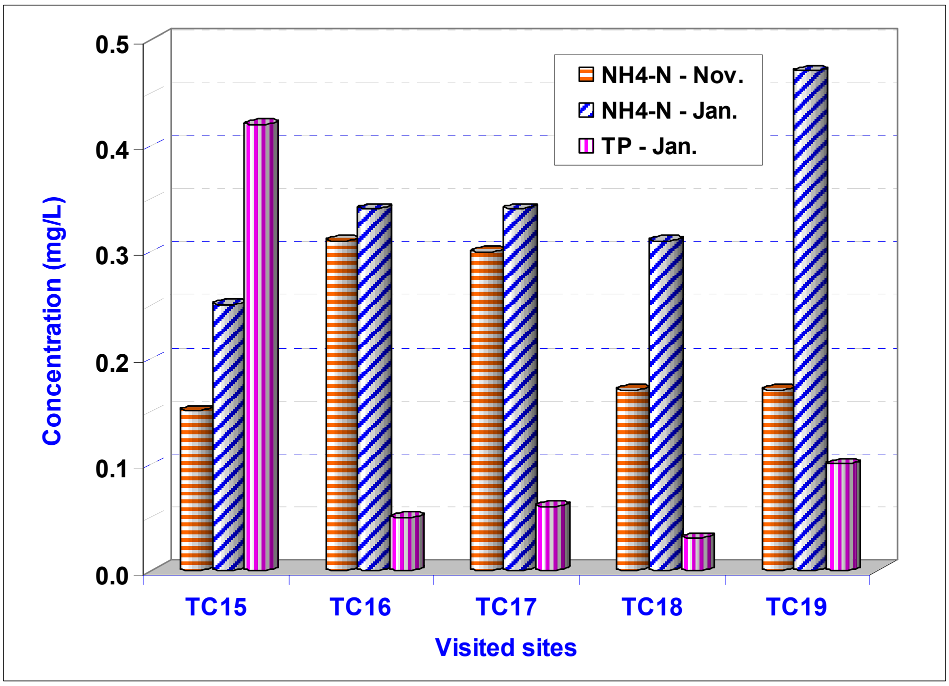


**Figure 4.10.** Levels of ammonium and total phosphorus in the Changane River

It is remarkable that ammonia is low compared to total-P in all assessed sites along the Limpopo Basin subcatchments. Hence, low ammonia concentrations seem to be an indication of low loads derived from domestic wastewater and animal manure, although it was observed that the domestic wastewaters are discharged without any pre-treatment into the nearest river course.

### 4.1.4. Physico-chemical Characteristics of Discharged Waters

Results of the wastewater analysis at visited points along the Limpopo are presented in Appendix 5 and 6 and summarized in Table 4.4. The standards that regulate the discharges in the Limpopo River are established in the Mozambican environmental water quality standards for effluent emissions (Article 10 of Law n. 20/97, refer to Appendix 15).

The results show that the temperature varied from 24 to 30 ˚C. The pH values were found to be slightly lower than in the Limpopo, Elephants+Nuanedzi and Changane subcatchments, and varied from 7.0 – 7.9 during both sampled months. The DO values were found low and ranging from 2.2 to 5.1 mg/L in November and between 2.2 and 4.1 mg/L in January. These concentrations may constitute a risk for the maintenance of the aquatic ecosystem, since these waters are discharged into the Limpopo River without any pre-treatment, and given the fact that oxygen is one of the most important components for organisms survival.

**Table 4.4.** Characteristics of discharged waters; mean values are given with their 95% confidence interval. For details see Appendix 5 and 6.

| Parameters | Nov., 06 | | | Jan., 07 | | |
|---|---|---|---|---|---|---|
| | Mean±CI | Median | Range | Mean±CI | Median | Range |
| T (˚C) | 26.3±2.2 | 26.6 | 24.4-27.5 | 28.1±2.4 | 27.9 | 26.5-30.0 |
| pH | 7.4±0.6 | 7.5 | 7.0-7.9 | 7.4±0.3 | 7.3 | 7.2-7.6 |
| DO (mg/L) | 3.3±2.1 | 2.9 | 2.2-5.1 | 2.7±1.5 | 2.3 | 2.2-4.1 |
| Total hardness (g $CaCO_3$/L) | 0.5±0.5 | 0.5 | 0.2-0.8 | 0.3±0.2 | 0.3 | 0.2-0.4 |
| TDS (g/L) | 1.4±1.9 | 1.3 | 0.3-2.8 | 1.2±1.3 | 1.1 | 0.4-2.0 |
| Chloride (g/L) | 0.7±0.9 | 0.7 | 0.09-1.2 | 0.5±1.5 | 0.09 | 0.05-1.9 |
| EC (mS/cm) | 1.8±2.1 | 1.8 | 0.6-3.1 | 1.7±1.8 | 1.7 | 0.6-2.8 |
| SAR | 73.5±103 | | 30-136.4 | 51±8.8 | | 9.5-149.7 |
| Total phosphorus (mg P/L) | - | - | - | 1.3±1.0 | 1.2 | 0.6-2.1 |
| $NH_4^+$-N (mg/L) | 0.78±2.2 | 0.11 | 0.07-2.8 | 0.49±1.14 | 0.2 | 0.07-1.6 |
| $NO_3$-N (mg/L) | - | - | <0.23*-1.27 | - | - | <0.23*-0.31 |
| TSS (mg/L) | - | | - | 389±456 | | 8.0-1584.0 |

* Values below detection limit

The discharged water was found to have high hardness in November, but in January the total hardness at the sampled sites was lower than 0.50 g/L (threshold for hardness), probably due to dilution effects (Table 4.4). Taking into account that this water is re-used, future attention should be given to the effluents quality.

TDS, EC, chloride and SAR values (refer to red bold lines in Figure 4.11) were found in both sampled months higher that the Mozambican Environmental Water Quality Standards for Effluent Emissions in all sites, with exception for EC on sites D12 (Chókwè municipality discharges) and D14 (agricultural discharges).

As a general trend, the TDS, EC, Chloride and SAR were found to be higher in November than in January (Figure 4.11). As mentioned before, the observed rainfall during the samplings (January) in these sites may have led to dilution effects, since the sampled points are situated at the margins of Limpopo River, far from the main sources, either Chókwè municipality or irrigation systems. On the two sampled months, the highest values for TDS (> 2.0 g/L), EC (> 2.5 mS/cm), chloride (> 1.0 g/L) and SAR (>120) were registered on sites TM13 and D22. The TM13 receives waters draining from the biggest irrigation system in the Basin (Chókwè irrigation system), while D22 drains wastewater generated in the biggest urban area in the Basin (Xai-Xai). Thus, it is important in the future to monitor these effluents, since they may be a reason for further deterioration of water quality in the Limpopo River.

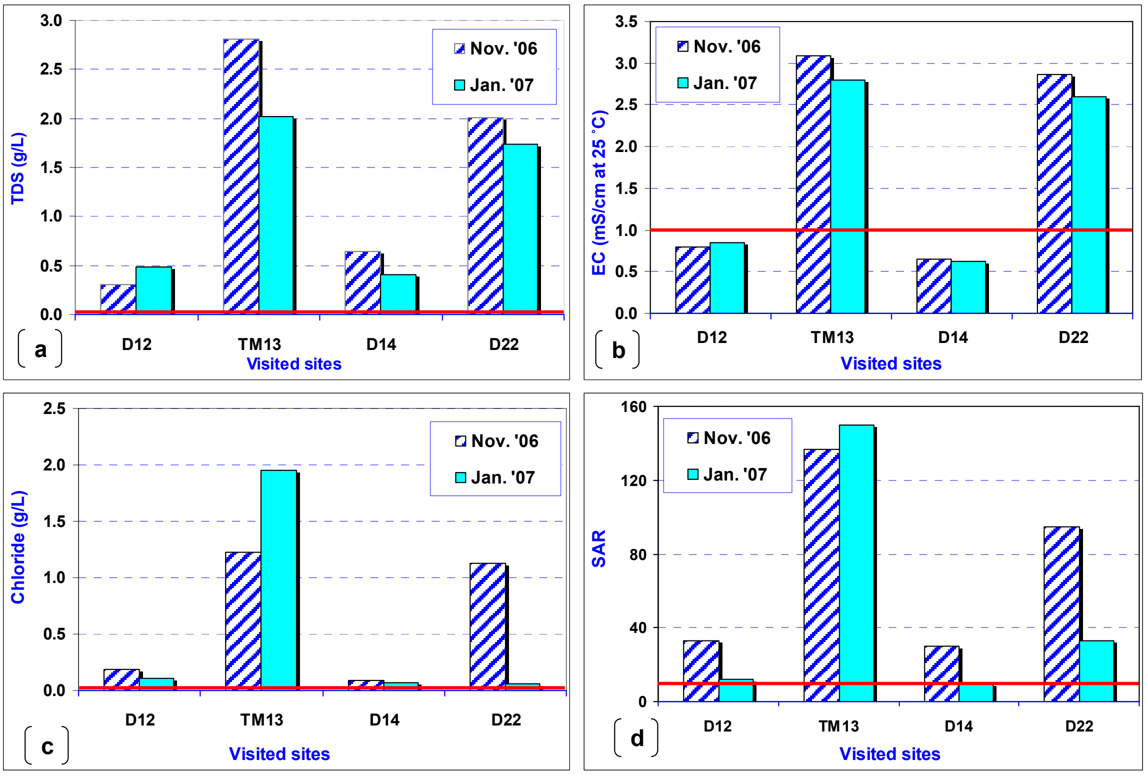


**Figure 4.11.** Spatio-temporal variability of the WQ at discharge points along the Limpopo Basin. *The horizontal red/bold line indicates the Mozambican standards for effluent discharges*. For detailed results, see Appendix 5 and 6.

Out of six metals evaluated, five were identified as occurring in the discharged waters (Figure 4.12 and Appendix 7). Considering the environmental water quality standards for effluent emissions, the lead concentration on site TM13 was found beyond the allowable discharge concentration (>0.1 mg/L). However, Pb was only found on the effluents from the agriculture areas (sites TM13 and D14), maybe because of use of pesticides containing lead for pest control.

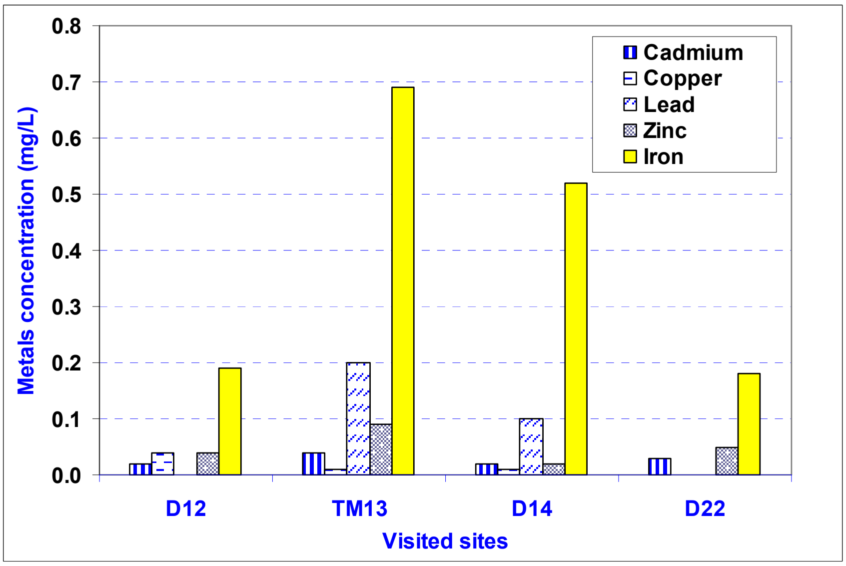


**Figure 4.12**. Metal concentrations present in discharged waters

Concerning the other metals, the concentrations were found meeting the national standards, although iron, on sites TM13 and D14 exhibited concentrations higher than 0.5 mg/L (Figure 4.12). Still they were not sufficient to overtop the guideline set to a maximum of 1.0 mg/L. Considering the Mozambican guidelines for receiving waters and the WHO guidelines for drinking purposes (Appendix 13 and 14), all discharged sites would fall within the classification of not suitable for human consumption or use.

The nutrient contents in the discharged waters (Table 4.4 and Figure 4.13) show an increase compared to the contents in November and assessed in January. The mix of runoff waters containing nutrients together with urban or agricultural wastewaters may be the explanation of such increase. Discharges from sites TM13, D14 and D22 were found to be the major threats for possible aquatic deterioration in general and water quality decline in particular, since the concentration for ammonium and TP were above the Mozambican standards for receiving waters, either in November or in January (Figure 4.13). However, the discharged waters contained concentrations lower than the national environmental water quality standards for effluent discharge.

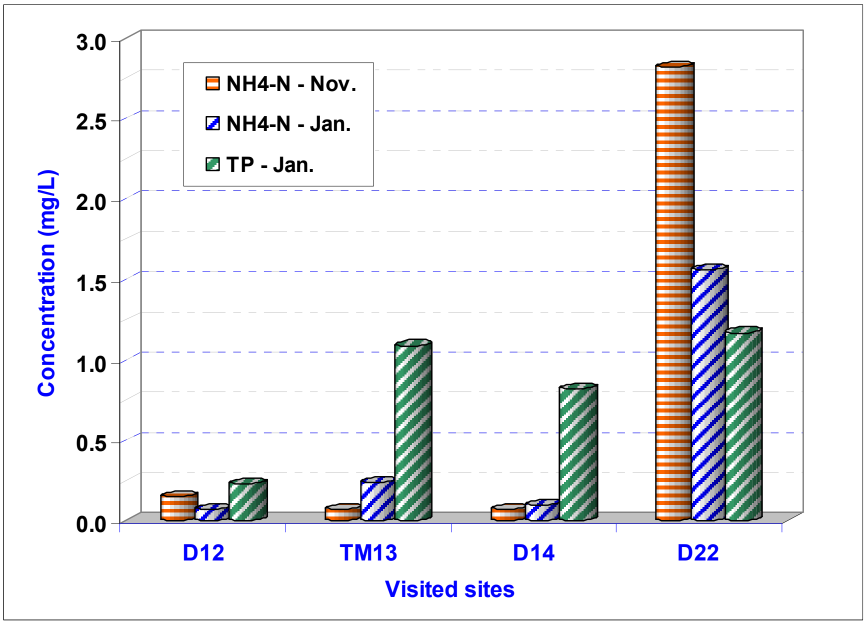


**Figure 4.13.** Levels of ammonium and total phosphorus in discharged waters

The highest concentrations of nitrates were found in November on sites D14 (0.29 mg $NO_3^-$ - N/L) and D22 (1.56 mg $NO_3^-$ - N /L). In January the concentrations were very low, i.e. below detection limit (<0.23 mg/L). Occurrence of reeds and other aquatic plants along the earth canals transporting the wastewater to the Limpopo River may be the cause for nutrients depletion in these waters.

## 4.2. Microbiological Pollution Assessment in Limpopo River Basin

The microbiological assessment at sites along the Limpopo Basin resulted in the findings presented in Figure 4.14. All sampling sites were found to be contaminated with coliform bacteria but the highest counts were found on sites L11 (Limpopo after Chókwè and Guijá urban areas), D12 (Chókwè sewage discharges), TC18 (before Chibuto town on Changane River), TC19 (after Chibuto town), D22 (Xai-Xai) sewage discharges and L23 (site on Limpopo River after Xai-Xai city), which scored more than 24000 CFU/100 ml.

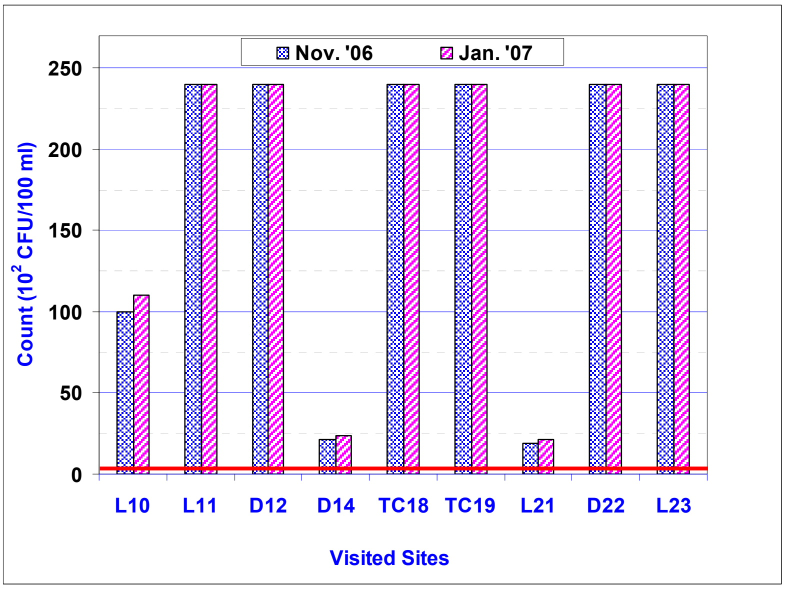


**Figure 4.14.** Bacterial contamination at Limpopo River Basin

Comparing the sampling months (November and January) the result was nearly the same for all sites. Coliforms counts were >1000 CFU/100 ml on sites L10, L11, D12, TC18, TC19, D22 and L23 during the sampled months. Sites D14 (agriculture discharges) and L21 (Limpopo River after agricultural loads) recorded the lower number of colonies on both months (up to 2500 CFU/100 ml) (Figure 4.14). At all sites the counts were above the national environmental water quality standards for effluent emissions (400 CFU/100 ml, red line in Figure 4.21) and the WHO guidelines for drinking waters (Appendix 13), which is 0 CFU/100 ml. Although the other sites in the Limpopo Basin were not assessed for coliform is believed that most of them would be contaminated, since the sanitation facilities are not yet developed throughout the basin.

### 4.3. Biological Assessment of Water Quality in Limpopo River Basin

The assessment of macrobenthic macroinvertebrates was done only in November due to the high water level observed in the river in January.  The identified macrobenthic invertebrates families on each site are shown in Appendix 4. The Hydrobiidae (snails) and Sphaeridae (mussels) were found to be the dominant families (groups) throughout the Basin. Considering the results by sites (Figure 4.15), different taxa of macroinvertebrates were found, although not in all sites. The lower number of taxa was observed at downstream Limpopo Basin sites (1-3 taxa) while the highest taxa were found at sites located upstream Limpopo (4-7) (Appendix 4).

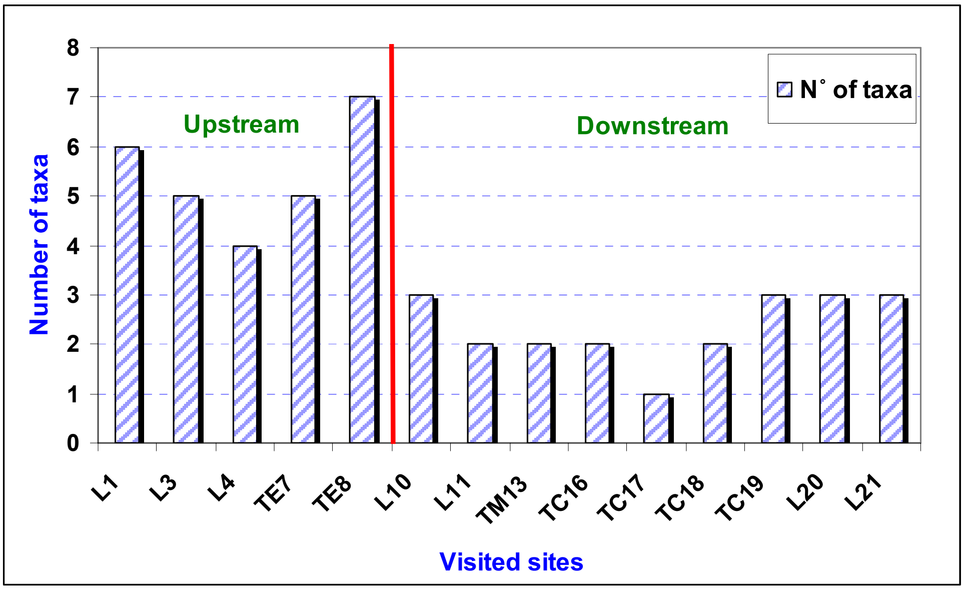


**Figure 4.15.** Number of taxa identified along the Limpopo River Basin

The overall assessment for biological investigation are presented by the Biological Monitoring Working Party (BMWP) scores and Average Score Per Taxon (ASPT) and Lincoln Quality Index values as described in chapter 2.3.2 and Appendix 8. The results of overall classification of water quality per subcatchment are indicated in Table 4.5.

**Table 4.5.** Overall water quality according to presence of macroinvertebrates

| Sampled sites | BMWP | | ASPT | | Overall quality rating | Lincoln index | Overall water quality |
|---|---|---|---|---|---|---|---|
| | Score | X | Score | Y | $\frac{X+Y}{2}$ | | |
| | | | Limpopo subcatchment | | | | |
| **L1** | 27 | 3 | 4.5 | 6 | 4.5 | B | Good |
| **L3** | 29 | 3 | 5.8 | 7 | 5.0 | A | Excellent |
| **L4** | 24 | 2 | 6.0 | 7 | 4.5 | B | Good |
| **L10** | 14 | 2 | 4.7 | 6 | 4.0 | C | Good |
| **L11** | 6 | 1 | 3.0 | 2 | 1.5 | H | Very poor |
| **L20** | 9 | 1 | 3.0 | 2 | 1.5 | H | Very poor |
| **L21** | 10 | 2 | 3.3 | 3 | 2.5 | F | Poor |
| | | | Elephants subcatchment | | | | |
| **TE7** | 17 | 2 | 3.4 | 3 | 2.5 | F | Poor |
| **TE8** | 31 | 3 | 4.4 | 5 | 4.0 | C | Good |
| | | | Changane subcatchment | | | | |
| **TC16** | 9 | 1 | 4.5 | 6 | 3.5 | D | Moderate |
| **TC17** | 3 | 1 | 3.0 | 2 | 1.5 | H | Very poor |
| **TC18** | 5 | 1 | 2.5 | 2 | 1.5 | H | Very poor |
| **TC19** | 6 | 1 | 2.0 | 1 | 1.0 | I | Very poor |
| | | | Point discharges | | | | |
| **TM13** | 5 | 1 | 2.5 | 2 | 1.5 | H | Very poor |

The results in Table 4.5 and Figure 4.16 show that the quality of water for the sampled sites is generally of bad quality for aquatic organisms to live in. The high BMWP scores (14-31) are shared by sites located upstream Limpopo and Elephants subcatchments (Table 4.5). These sites together with the high taxa found were categorized as having "good to excellent water quality", thus proving to have good conditions for aquatic organisms. However, the low BMWP scores (3-10) for the downstream sites, which include sites in Changane and Limpopo subcatchments were categorized as having "moderate to poor water quality", consequently exhibiting bad environments for the survival of aquatic organisms.

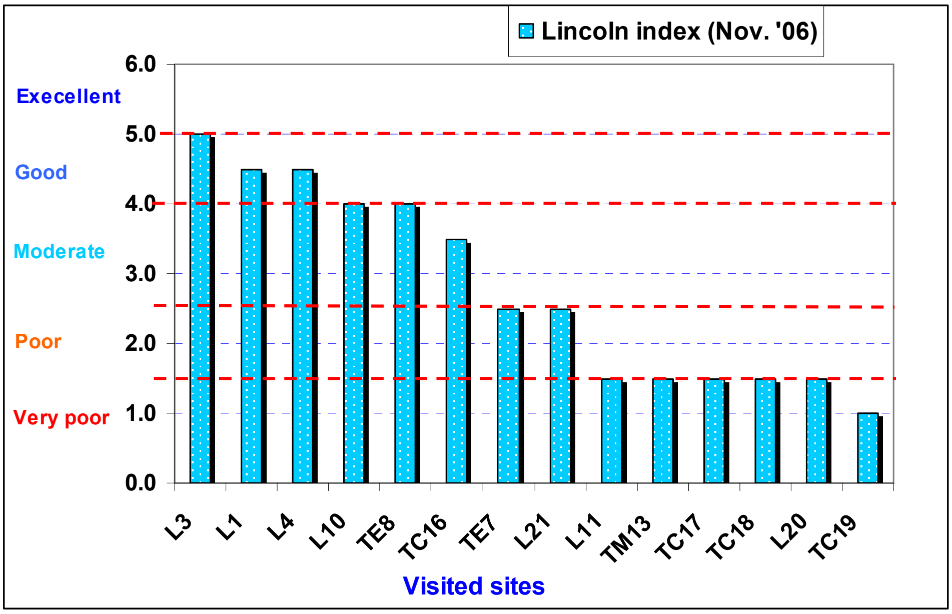


**Figure 4.16.** Lincoln Index per site at Limpopo River Basin. *The dashed red line indicates the threshold to be assigned with specific quality*.

Site TE8 in Elephants subcatchment gave different results indicating that between the distances separating this site to TE7, there is a significant improvement of water conditions for organisms life. The difference in water quality between these two sites may be attributed to changes of flow velocity, since TE7 is situated immediately after Massingir dam discharge, while TE8 is located in an area without a pronounced slope.

Almost all sites in Changane subcatchment scored <1.5 points on Lincoln index (Table 4.5 and Figure 4.16); hence they fell under the condition of very poor water quality. As mentioned in chapter 4.1.3, low DO values (< 4.1) associated with high EC and TDS concentrations seem to determine the harsh environmental for aquatic organisms and thus determine their low abundance. On the other hand, at upstream Limpopo where the heavy metals were found as the major threats for water quality, high Lincoln scores were obtained. However, is believed that the number of taxa recorded is very low compared to unpolluted conditions.

**CHAPTER FIVE**

# DISCUSSION

## 5.1. Water Quality in the Limpopo River Basin

### 5.1.1. Physico-chemical Results

The results which were presented in the previous section (chapter 4) suggest that the temporal and spatial variability on the physico-chemical parameters and thus of water quality were both the result of different human activities, hydrological and natural conditions variability throughout the basin.

The hydrological regime in the Basin was found to be the major determinant for the variability of the loads at different sites, since in general the concentrations in January were lower than in November, probably due to dilution effect. Therefore, observations made in November at the same sites, when water level was low, suggest a marked variation in the concentration of total dissolved solids (TDS), electrical conductivity (EC), chloride ($Cl^-$), sodium adsorption ratio (SAR) , total hardness (TH), etc. (Figures 4.2; 4.5; 4.8 and 4.11). Factors such as the natural geology and anthropogenic activities (e.g. agricultural, land use pattern, livestock, and discharge of domestic untreated wastewater) were found as the major determinants for point and non-point pollution events in the Basin. Above factors were also pointed out in several studies as major determinants of water quality variability at a Basin level (Bartram and Ballance, 1996; Hirji *et al.*, 2002; DWAF, 2004; Skoulikids *et al.*, 2005; Koukal *et al.*, 2004).

The physicochemical data in the Limpopo subcatchment indicated a slight increasing trend when moving from upstream to downstream sites (L1 to L23). This variability was associated to influence of diffuse loads (e.g. agricultural and untreated wastewater discharge). The peaks or maximum values of TDS, EC, $Cl^-$ and SAR were found at site L23, which is located downstream Xai-Xai city. Thus the high concentrations observed here are attributed to cumulative effect of the factors mentioned above, together with urban loads and impacts of mixing up of river water and seawater (ocean tides), which has high levels of dissolved ions (Muschal, 2005).

This last factor is also explained and supported by occurrence of high concentrations of EC, TDS and $Cl^-$ (>6000 mg/L in November and >21 mg/L in January). WHO (2003) also recognises large effects of ocean waters, when the chloride concentrations are higher than 10 mg/L, given that unpolluted waters are likely to have concentrations lower than 1 mg/L. Earlier assessment (done from January to July) in the Basin (DNA/ARA-Sul, 2006) and in the proximity of the river mouth also confirmed the effects of ocean tides, mainly during the low flows in the Limpopo River, which was the case in November.

However, along the sites in the Elephants and Nuanedzi subcatchments and in both sampled months, the values of parameters such as: pH, DO, TDS, EC, $Cl^-$ and SAR were lower and within the Mozambican and WHO recommended range for river water quality. The assessment of temporal changes at site TN2 was not performed because the river was found dry during the November visit. On the other hand, sites located along the Elephants River did not exhibit much temporal variability (refer to chapter 4.1.2) compared to the Limpopo subcatchment. This behaviour can be attributed to the impact of the Massingir dam, which is acting has a filter, because of the high hydraulic retention time and dilution effects in the reservoir. Kurunc *et al.* (2006) reported similar effects and pointed the low variability of effluents physico-chemical parameters as a result of impoundments and constant flow discharge.

The SAR in the same subcatchment did not follow the same trend as the other parameters, possibly due to errors during lab determination, since the concentrations of sodium, calcium and magnesium are likely to follow the EC and TDS trends (Dallas and Day, 2004). Clear differences with other subcatchments were found in the Changane subcatchment. The relative high concentrations of TH, TDS, EC, $Cl^-$ and SAR in the two sampled months derived from the natural geologic formation of the river, since no major agricultural or industrial activities are developed in the catchment. The same reasoning was used by Silva (2003) in a study to assess the quality of irrigation water in Sri Lanka.

Comparisons between the assessed physico-chemical characteristics (*t*-test) on the two sampled months (Table 5.1) reveal that parameters such as EC, TDS, SAR and TH had significantly changed ($p<0.01$) from November (06) to January (07) in the 23 sampled sites. The increase of the river discharge in November (Figure 5.4) seems to be the major factor contributing to the changes in the parameters concentration. This agrees with the observations by Ngoye and Machiwa (2004) in analysis of seasonal changes in water quality in Ruvu river watershed.

However, parameters such as pH, DO and $NH_4^+$-N did not experience any significant change during the same period. Although under different conditions, similar behaviour was observed by other authors (Dallas and Day, 2004; Sánchez *et al.*, 2006; Sarkar *et al.*, 2006).

**Table 5.1.** Results of paired *t*-test for significant differences between the two sampling months for some physico-chemical variables at LRB

| Variable | Average November'06 | Average January'07 | Paired *t*-test (*p*value) |
|---|---|---|---|
| pH | 7.9 | 8.0 | 0.610 |
| Electrical conductivity (EC) | 5571 | 3132 | 0.003** |
| Total dissolved solids (TDS) | 4300 | 2390 | 0.002** |
| Sodium adsorption ratio (SAR) | 136 | 82 | 0.006** |
| Total hardness (TH) | 1430 | 790 | 0.000** |
| Dissolved oxygen (DO) | 7.2 | 7.2 | 0.840 |
| Temperature (T) | 27.8 | 29.0 | 0.023* |
| Chloride ($Cl^-$) | 2227 | 1248 | 0.073 |
| Ammonium ($NH_4^+$-N) | 0.27 | 0.23 | 0.592 |

**P<0.05; **P<0.01*

The DO is an important parameter which did not show a significant difference between the two sampled months. The lowest values were found in the sites located at municipalities and agricultural wastewater discharge points (e.g. sites TM13, D14 and D22), indicating possible impact of organic pollution or sewage outfalls. Possible risks for aquatic life are admitted since most organisms do not tolerate DO levels lower than 2.4 mg/L (Koukal *et al.*, 2004).

The break-down of organic matter causing the reduction of DO concentration and thus an increase on its deficit have been reported widely (Azrina *et al.*, 2005; Bellos and Sawidis, 2005; Sánchez *et al.*, 2006). The occurrence of high temperature, salinity

(Dallas and Day, 2004) and chloride concentrations are also likely to reduce the solubility of oxygen in water, which was the case for sites located in the Changane subcatchment (e.g. sites TC15 and TC18). The site TC15 recorded an average of 4.2 mg DO/L and 4150 mg $Cl^-$/L while site TC18 registered an average of 5.9 mg DO/L and 1808 mg $Cl^-$/L.

Concerning the nutrients loads, ammonia did not show a significant seasonal change, ($P>0.05$) according to results from the paired *t*-test (Table 5.1). Ammonia is toxic to aquatic life (especially fish) even at low concentrations (Bowie *et al.*, 1985). Also WHO guidelines highlight that ammonia can cause odour and taste problems at concentrations above 1.5 and 35 mg/L, respectively (WHO, 2004). In this study the highest value for ammonium was found on site D22 (2.82 mg $NH_4^+$-N/L), displaying the high risks that the discharge of wastewater represent for the ecosystem quality (Sánchez *et al*., 2006).

The natural backgrounds levels of total phosphorus in riverine waters are usually < 0.01 mg P/L (Dallas and Day, 2004). In the present study the levels of phosphorus were only assessed in January. Generally, relative higher concentrations were observed once more on the sites located immediately downstream urban and agriculture wastewater drainage (D12, TM13, D14 and D22). The high risks of eutrophication imposed by high levels of phosphorus seem to derive from untreated domestic wastewater and agriculture fertilizers. Upstream sites (TE5, TE6 and L1 to L9) form other important sources of phosphorus loads, which in this case may derive from upstream neighbouring economic activities (e.g. South Africa). Similar results have been reported by other authors such as Sarkar *et al.* (2006).

The highest levels of nitrate were observed in January at sites L1, TN2, L3, L4 and from TC15 to TC19. Land based nutrients, especially nitrates, from the adjacent agricultural farms to upstream sites L1, TN2, L3, L4 and TC19 maybe have contributed to some extent to these concentrations. Additionally, the levels of nutrients recorded at sites L1, TN2, L3 and L4, located at proximities to the international border, may derive from runoff generated in the upstream neighbouring countries (South Africa and Zimbabwe), since at the Mozambican part of the basin around those sites, there are no major agricultural activities. This agrees with the suggestion by Sarkar *et al.* (2006) where on their study, levels of different pollutants were related to river system transport and to socio-economic activities along the stream. Elevated loads (30% increase) of water quality variables, including nitrate was also reported in a study in the Nile Delta (El-Sayed, 2000), indicating the influence of upstream pollutants loads in water quality at downstream part of the Basin.

### 5.1.2. Microbiological Results

As indicated in Figure 4.14, the sites studied in November and January show that bacterial contamination in the rivers (faecal coliforms bacteria) is found to be one of the major problems in the Limpopo River Basin. The highest coliforms counts were observed in the sites located downstream main urban areas within the Limpopo Basin, viz. L11 (after Chókwè and Guijá urban areas), D12 (Chókwè municipally discharges), D22 (Xai-Xai municipally discharges), L23 (after Xai-Xai urban area) and TC18 and TC19 located before and after Chibuto urban area in Changane subcatchment. The values were much higher than the WHO guidelines for faecal coliforms in drinking waters, set to be absent (0 CFU/100 ml) (WHO, 2004).

At these sites, the major factors contributing to the coliform problems include: (1) point discharge of contaminated wastewater (Kim and Lee, 2005); and (2) contamination through diffuse sources, given that between the sampled sites, most of the population settlements are served by latrines and septic tanks which frequently leak, thus contaminating the Limpopo waters (FIPAG/DNA, 2004). Other important sources of faecal coliform bacteria contamination are the faeces of animal grazing throughout the Basin, since it offers good pasture lands in the swamp areas. Taking into account some of the important uses of water in the Basin (e.g. direct drinking, swimming, fishing, etc.) it is important to consider the frequent monitoring of coliforms bacteria throughout the basin, so that appropriate measures are taken if standards are overtopped.

### 5.2. Overall Physical and Chemical assessment of water quality

Different water quality information can be obtained depending on the way the data are analysed.

#### 5.2.1. Adapted Water Quality Index (WQI)

The first approach used to assess the overall WQ in the Basin was an adapted WQI. The original WQI is described by Prati *et al.* (1971) and Abbasi (2005). The original method is based on 8 parameters; viz. pH, $\%O_2$, $BOD_5^{20}$, COD, suspended solids, $NH_3$+$NH_4^+$, $NO_3$ and $Cl^-$. Since in the present study COD and BOD were not measured, new parameters were introduced.

The adapted WQI is based on 9 parameters, viz. $NO_3^-$-N, pH, $NH_4^+$-N, TP, DO, $Cl^-$, SAR and TDS. All parameters were assigned weights according to their importance to aquatic life (Prati *et al.*, 1971; Abbasi, 2005; refer to Appendix 9). This method takes into account a weighting factor (Pi) which ranges from 1 to 4 and a (Ci) score for each parameter variation, ranging from 0 to 100.

Since the WQI is based on the comparison of the water quality parameter with respective regulatory standards (Boyacioglu, 2006), one of the important steps was the weighting of the parameters included in the index. In the adapted index (Appendix 9) the DO and TSS were assigned the maximum weight because of their importance as limiting factors for the use of water for both humans and organisms (operational monitoring parameters). The following group assigned a weight "3" is formed by nutrients ($NO_3^-$-N, $NH_4^+$-N, TP) and pH which represent chemical pollution derived from anthropogenic activities. The variation on their concentrations is known to impair the aquatic conditions, through algal blooms. The last group is formed by parameters indicating natural and man-made pollutants (pH, EC, SAR and $Cl^-$) which magnitude may not at first impair the water conditions for both human and aquatic uses. In addition, indices described by Praty (1971); Abbasi (2005) and Boyacioglu (2006) were taken into account for the final weighting of the parameters.

Figure 5.1 show the values of water quality index along the Limpopo River Basin in January. In November two parameters, TSS and total P were not measured so the index was not applied to this month. As a general trend, this method illustrates that the water quality worsens from upstream to downstream in the Limpopo Basin. Higher scores were observed in the Elephants subcatchment (TE sites) and some other sites along the Limpopo subcatchment (e.g. sites L9, L10, L11 and L21). The TC sites located at Changane subcatchment scored the lowest points (Figure 5.1). The water quality ranged from "bad" (site TC15) to "good" (sites L4, TE5, TE6, TE7, TE8, L9, L10, L11, L21 and L23). The remainder of sites were classified as having "medium" water quality.

As expected the water quality at sites TM13, D22 showed the worst class (i.e. bad) since they represent wastewater discharge points. However, the remainder wastewater discharge sites (D12 and D14) were classified as discharging water with a medium quality. The water discharged at sites D12 (Chókwè municipally) and D14 (irrigation area) is transported in open canals before it reaches the Limpopo River where the sampling sites were located. Thus is believed that the pollutants contained in the water (e.g. nutrients) are likely to be reduced by plants uptake, since reeds and other aquatic plants were found populating the canals. Furthermore, sites TM13 (drainage of Chókwè irrigation excess waters) and D22 (Xai-Xai wastewater discharges) receive huge quantities of wastewater compared to the other two point discharge, so the natural removal of pollutants is insignificant.

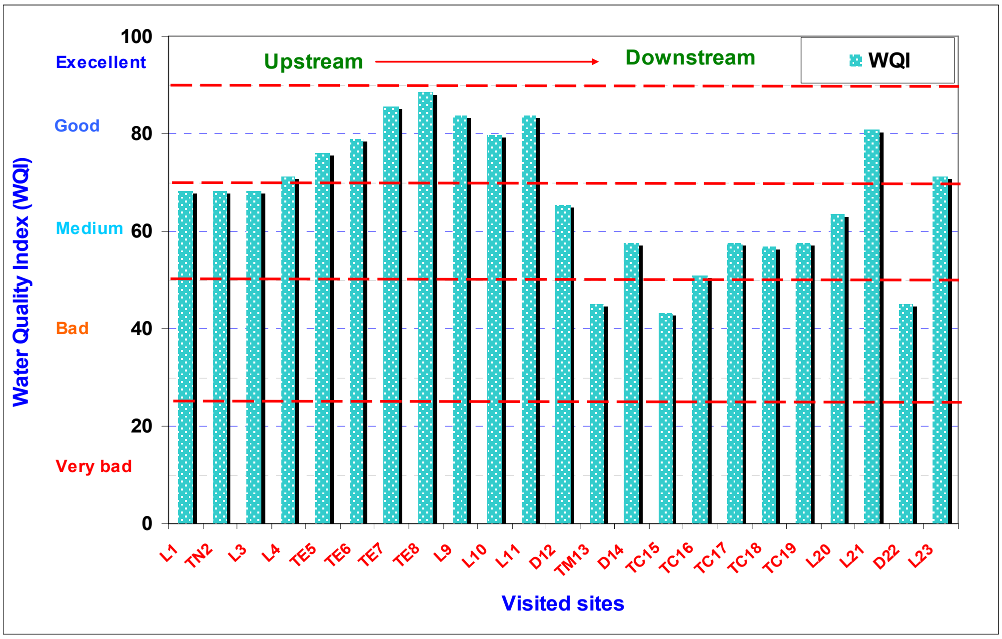


**Figure 5.1.** Variation of the water quality index (WQI) for different sites in LRB. *The dashed red/bold lines indicate the threshold to be assigned with specific quality.*

Given that the heavy metals also play an important role for the overall condition of water quality, a quality index was also developed here (Appendix 10). This index is based on seven (7) main heavy metals (Hg, Cu, Pb, Cd, Cr and Zn), which concentrations were distributed in 5 main classes (ranging from unpolluted to heavily polluted). All values assigned to different classes were compiled from various guidelines and considered diverse final uses of water (Zabel, 1993; MICOA, 2004; WHO, 2004; and USEPA, 2006). In addition, each class was assigned a score (Ci) value to match with the WQI scoring system. The weights were assigned taking into account the toxicity rank of the metals, i.e., mercury with the maximum weight "4" and nickel with lower weight "2". Taking into account the heavy metals based WQI (Appendix 10) the visited sites along the Limpopo River Basin were assessed for their overall water quality. The Figure 5.2 illustrates the points scored by each site.

In contrast to the physico-chemical adapted WQI, results from this classification shows that more sites located at the upstream part of the basin were found below the minimum scores to be classified as having "good water quality" (refer to dashed red lines in Figures 5.1 and 5.2). Thus, the sites L1, TN2, TE5 and TE6 were found with "bad" water quality as well as sites TM13, D14, TC16 and L23 in the downstream part (Figure 5.2). Out of this classification only the site TE8 (situated along the Elephants River) was found with a "good" water quality. The other sites fell under the category of "medium" water quality.

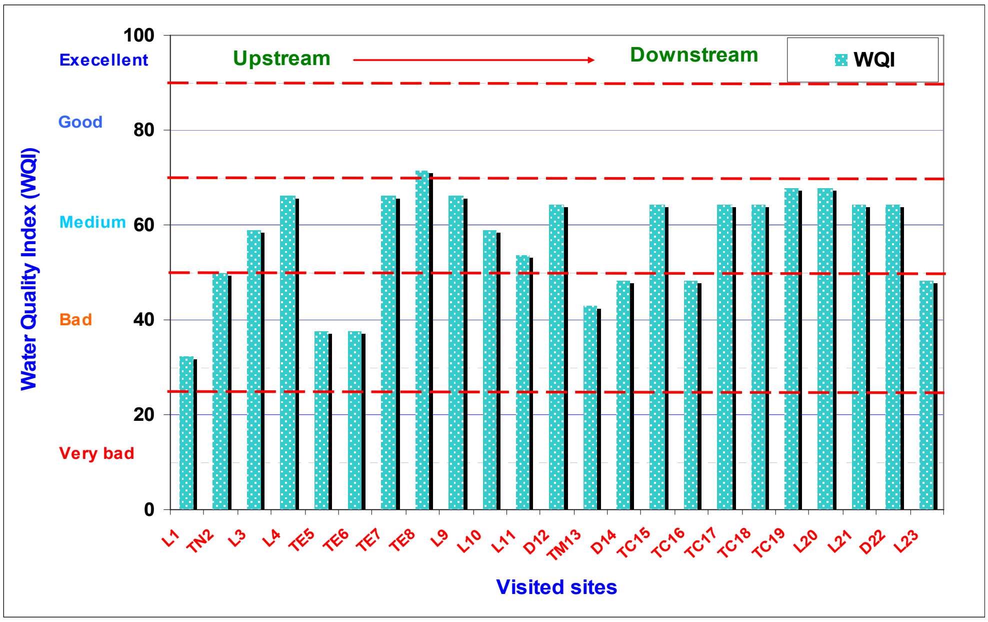


**Figure 5.2**. Variation of the water quality index (WQI) based on heavy metals content at different sites. *The dashed red/bold lines indicate the threshold to be assigned with specific quality*)

### 5.2.2. Macroinvertebrates Index (BMWP index)

The other approach used to assess the water quality in the Basin was the Biological Monitoring Working Party Score, which is based on the fact that the distribution of macroinvertebrates is influenced by their response to various factors, such as food availability (Chapman and Jackson, 1996; Peeters *et al.*, 2004), hydraulic conditions, substrate composition (Chapman and Jackson, 1996; Sandin and Hering, 2004) and increase of nutrient loads (Camargo *et al.*, 2004). Moreover, the invertebrate fauna is known to respond in different ways to water-quality variations (Chapman and Jackson, 1996). In the present study, the percentage distribution of the water quality classes (I to V) is given in Table 5.2 (refer to Appendices 4 and 8).

**Table 5.2.** Distribution of water quality classes based on mean values of BMWP and ASPT, in the Limpopo subcatchments (for more details refer to chapter 4.3).

| Subcatchment | Total Sampled sites | Water quality classes (%) | | | | |
|---|---|---|---|---|---|---|
| | | I (excellent) | II (good) | III (Moderate) | IV (poor) | V (very poor) |
| Limpopo | 7 | 14.3 | 42.8 | - | 14.3 | 28.6 |
| Elephants | 2 | - | 50 | - | 50 | - |
| Changane | 4 | - | - | 25 | - | 75 |
| Discharges | 1 | - | - | - | - | 100 |

According to this scoring system, in the LRB only 1 site (14.3% - site L3) would be classified as having excellent water quality. All other sites ranked from "very poor" to "good" water quality in terms of presence on benthic macroinvertebrates. Although not assessed, is believed that the discharge of effluents with elevated concentrations of organic matter, which in turn lower the oxygen content (e.g. site TM13) due to its break-down (Mason, 1991; Dallas and Day, 2004), is the reason for the bad water quality at wastewater discharge points. In addition, the dominance of worms (Oligochaeta) at the same sites also supports the above statement, since these organisms are known as able to tolerate unfavourable conditions such as low DO and high organic pollutants concentration (Azrina *et al.*, 2006).

The consistent presence and abundance of pollution resistant organisms such as *midges, worms and snails* (Appendix 11) at sites TC17, TC18 and TC19, associated with elevated dissolved ions (EC >3000 µS/cm), may explain the deterioration of the Changane waters due to natural and anthropogenic pollutants, since the river passes through populated areas (ex. Chibuto). Similar results were reported by some authors (Azrina *et al.,* 2005; Czerniawska-Kusza, 2005). The bad quality assigned to sites L11 and L20 seem to follow above reasoning, since L11 is situated downstream Chókwè city and L20 after confluence of Limpopo and Changane River, thus both sites seem to receive organic pollutants of natural and human origin.

Pollution sensitive families (taxa) such as, Cordulegasteridae, Gomphidae and Aphelocheiridae as well as the highest taxonomic richness (4-7) were found at sites located in Limpopo and Elephants subcatchments. Hence is believed that that better aquatic conditions prevail at upstream part of the basin (Azrina *et al.*, 2006).

This method is easy to apply, reliable and reasonable in terms of costs (Mason, 1991), thus may suite the future needs for water quality monitoring in the Limpopo Basin. However, since biomonitoring tools and indices used for the present assessment were developed taking into account European conditions, it is important to undertake further investigation in Mozambique and in Limpopo Basin to adequate it to tropical climate conditions.

### 5.2.3. Overall Assessment of Water Quality Considering all Indices

As mentioned before, the adapted physico-chemical WQI ranked the visited sites from "bad" to "good", with most sites falling in the "good" and "medium" classes. In the Changane subcatchment 80% of the visited sites fell on the "medium" class and the reminder 20% on "poor". A division between "medium" and "poor" quality of water was found at the point discharge sites, each with 50% (Table 5.3).

**Table 5.3.** Distribution of water quality scores (WQI) in LRB subcatchments

| Subcatchment | Total sampled sites | Water quality classes (%) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Physico-chemical adapted WQI | | | | Metals adapted WQI | | | |
| | | I | II | III | IV | I | II | III | IV |
| Limpopo | 9 | - | 67 | 33 | - | - | - | 73 | 23 |
| Elephants+Nuanedzi | 5 | - | 80 | 20 | - | - | 20 | 20 | 60 |
| Changane | 5 | - | - | 80 | 20 | - | - | 80 | 20 |
| Discharges | 4 | - | - | 50 | 50 | - | - | 50 | 50 |

I – Excellent; II – Good; III – Medium; IV – Bad or poor

The distribution of water quality classes in Table 5.3 are strictly related to the DO and TSS values in each site, since these parameters received the maximum weights in the index, given their importance for aquatic life. Thus, in Limpopo, Elephants and Nuanedzi subcatchments for example, where oxygen levels were found ranging from 6.8 – 10.1 mg/L (refer to Appendices 5 and 6 for more details) most of the sites fell in the "good" class. However, in the Changane subcatchment the low DO at site TC15 (<5 mg DO/L) strongly contributed for the "medium" water quality observed at this site, although other factors such as ions concentration (EC >22000 mg/L) may play an important role.

On the other hand, the use of metals adapted WQ index, which consider the heavy metals as important parameters (Hg, Cu, Pb, Cd, Cr, Zn and Ni), resulted on the shift of the percentages to class III (medium) and IV (poor) for all the sites assessed in different subcatchments (Table 5.3). The effects of heavy metals on aquatic life and on other water parameters had been reported by several authors (Berkun, 2004; Koukal *et al.*, 2004). Hence, it is clear that the utilization of a single index (i.e. biological, physico-chemical or a metal-based) does not appear to be the best approach to assess the overall quality of water in streams, since differences in end results are likely to be found.

Comparisons of the results obtained by physico-chemical, metals and biological diversity indices between upstream and downstream sites along the Limpopo River Basin are presented in Table 5.4. The three indices seem to give better information about the water condition under effect of both natural and anthropogenic pollution events, than the use of an individual index. The data in Table 5.4 shows that, using different approaches to assess the overall water quality of a particular site, the results are likely to be different. Therefore, the overall water quality of a site should take into consideration the "worst scenario" (last column in Table 5.4), where the water of a particular site would be assigned the worst class indicated by one of the three used methods.

According to these criteria, 17 sampled sites in the Limpopo River Basin fall within the class of "bad" water quality. The "bad" water quality at sites L1, TN2, TE5, TE6 and TE7 would be determined by the heavy metals content. This classification seems to be reasonable, because these sites are located close to the border with countries with high mining activities and with a natural geology rich in metals (Ashton *et al.*, 2001). At downstream Limpopo the sites L23, TC16 and D14 are strongly influenced by heavy content.

Furthermore, the "bad" water quality at downstream sites TC15 and D22 is determined by poor physico-chemical parameters, while a larger group composed by sites TE7, L11, TM13, TC17, TC18, TC19, L20 and L21 are notably influenced by the BMWP index. Since the biological index seemed to be more restricted in water quality classification in comparison to physico-chemical and metals index, is once more highlighted the importance of undertaking further investigation in the Basin to adapt it to tropical ecosystems. Czerniawska-Kusza (2005) also refers the importance of a clear understanding of the mechanisms, which lead to the presence or absence of species in the environment for an effective use of biological indices, although the BMWP score system have been successfully applied in other countries (e.g. Spain, Argentina, Canada and Thailand).

**Table 5.4.** Comparison of different water quality assessment techniques

| Sampled Site | Biological index | Physico-chemical WQ index | Heavy metals WQ index | Worst scenario |
|---|---|---|---|---|
| **L1** | Good | Medium | Bad | Bad |
| **TN2** | - | Medium | Bad | Bad |
| **L3** | Excellent | Medium | Medium | Medium |
| **L4** | Good | Good | Medium | Medium |
| **TE5** | - | Good | Bad | Bad |
| **TE6** | - | Good | Bad | Bad |
| **TE7** | Bad | Good | Medium | Bad |
| **TE8** | Good | Good | Good | Good |
| **L9** | - | Good | Medium | Medium |
| **L10** | Good | Good | Medium | Medium |
| **L11** | Very bad | Good | Medium | Bad |
| **D12** | - | Medium | Medium | Medium |
| **TM13** | Very bad | Bad | Bad | Bad |
| **D14** | - | Medium | Bad | Bad |
| **TC15** | - | Bad | Medium | Bad |
| **TC16** | Medium | Medium | Bad | Bad |
| **TC17** | Very bad | Medium | Medium | Bad |
| **TC18** | Very bad | Medium | Medium | Bad |
| **TC19** | Very bad | Medium | Medium | Bad |
| **L20** | Very bad | Medium | Medium | Bad |
| **L21** | Very bad | Good | Medium | Bad |
| **D22** | - | Bad | Medium | Bad |
| **L23** | - | Good | Bad | Bad |

## 5.3. Spatio-temporal Changes of Loads in LRB as Function of River Discharges

The analysis of spatio-temporal changes of loads in the Limpopo River Basin were based on hydrological data observed in gauging stations located at vicinities of the sampled sites. Table 5.5 shows the change of flows in the Limpopo River during the two assessed months. As a general trend, higher discharges were observed in January compared to November.

**Table 5.5.** Limpopo River discharges and total solids loads at sampled sites

| ARA-Sul Station | | Preliminary survey visited sites | River discharge ($m^3/s$) | | Suspended solids (ton/d) |
|---|---|---|---|---|---|
| | | | November, 06 | January, 07 | January, 07 |
| E-31 | Pafúri | L1 | 0.2* | 7.1* | 319.0 |
| E-232 | Nuanedzi | TN2 | 0.0 | 5.7* | 213.1 |
| E-32 | Mapai | L3 | 0.2* | 12.8 | 1309.1 |
| E-33 | Combomune | L4 | 0.2* | 12.8 | 1751.4 |
| E-546 | Massingir | TE7 | 35.0 | 35.0 | 84.8 |
| E-372 | Macarretane | L10 | 35.2 | 47.8 | 82.7 |
| E-35 | Chókwè | L11 | 35.2 | 47.8 | 108.7 |
| E-40 | Chibuto | TC19 | 1.3 | 3.6 | 22.3 |
| E-36 | Sicacate | L20 | 36.5 | 51.4 | 352.1 |
| E-38 | Xai-Xai | L23 | 51.5 | 66.4 | 241.4 |

* Flow estimated based in historical data. Source: ARA-Sul (2007, not published)

The flows recorded at site TE7 located downstream to discharges of Massingir dam (Elephants tributary) do not differ in the two sampled months due to constant and controlled discharges made at the dam. The immediate consequence of such flows regulation (i.e. constant flows) is the modification of the normal ecosystem composition downstream dam discharges, since only few aquatic species (animal and plants) are likely to cope with the new imposed conditions. As mentioned before (chapter 4.1.2 and chapter 5.1.1) the low flow change due to dam regulation is also likely to reduce the downstream variability of physico-chemical parameters and consequently of loads (Kurunc *et al.*, 2006). These observations agree with the low variability of TDS and EC in Elephants subcatchment between November and January.

On the other hand, the sites located along the Limpopo River main course, illustrated changes on the concentration of assessed parameters as a result of the river flow increase from November to January (refer to chapter 4.1.1). Therefore, those changes were not pronounced, probably because of the low increase of flows between assessed months. Is thus, believed that during picks of rainfall in the entire Limpopo Basin, the concentrations and loads of various contaminants may observe a major change of any sort (i.e. increase or reduction), as a result of high runoff and consequent high flows.

The dilution and settling of those contaminants are example of processes that are likely to occur during high or low flow events (Vagnetti *et al.*, 2003). Therefore, the analysis of the capacity of the streams within the Limpopo River Basin for self-purification was not possible due to limitations of the available data. More information relating the river flow and concentrations of major pollutants, such as: the total dissolved solids; BOD or COD would be necessary for a better understanding of the intrinsic capacity of the rivers for removal or settling of these pollutants and loads.

An example of loads transport in the Limpopo River and main tributaries is given in Figure 5.3.

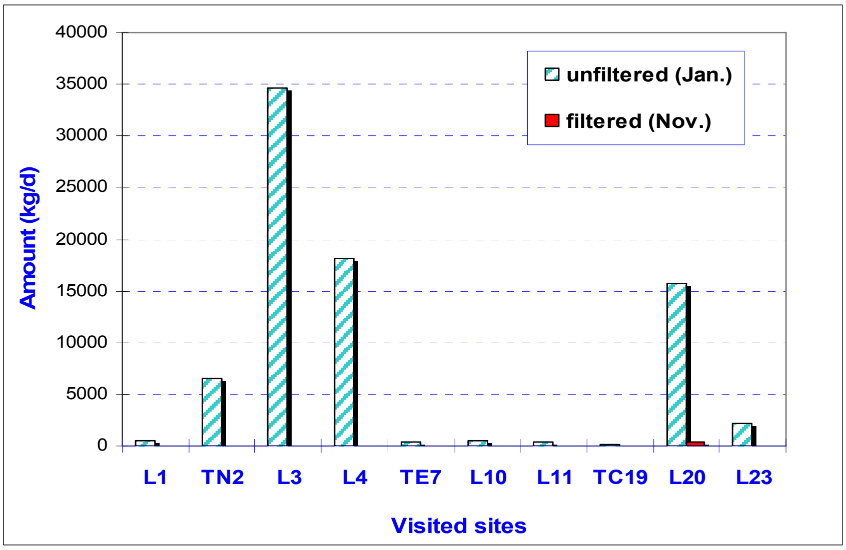


**Figure 5.3.** Change in Iron loads as a result of flow change “hypothetic settling here represented by filtered samples”

This particular case illustrates that high amounts of iron (maximum of 34600 kg/d) are expected to be transported during wet periods (high flows) together with suspended solids (> 22 ton/d, refer to Table 5.5 for suspended solids amounts), compared to the dry periods with low flows (filtered samples in Figure 5.3). At this last period the dissolved iron concentrations are likely to drop to minimum values or even not be present in dissolved phase. Although the current analysis is limited to a single observation (January) and devoted to a single parameter, the findings by Skoulikidis *et al.* (2006) also point the hydro-morphological variations (stream density and water flow) as responsible for the hydrochemical differences found at difference seasons in small/medium Greek catchments.

From above analysis is clear that in January the increase in the river flow (Table 5.5) tends to boost the loads (i.e. resuspension), of iron already settled from previous events. However, during dry events, the natural and induced reduction of river flows, with a consequent drop of the flow velocity (filtered samples in Figure 5.3), seems to increase the chances for settling and thus enabling conditions of low contaminants levels. Nevertheless the possible relation between dilution and settling processes that may occur in the two periods is not clear and is beyond the objectives of present report.

A further analysis of effects of flow changes on the observed concentrations is presented in Figure 5.4. Here, the changes of some of the assessed parameters are compared through use of a dilution value (*D*) between the analysed months. The *D* value indicates the rate of change for each parameter at a particular subcatchment and is calculated as the ratio between the average concentration in November and the average concentration in January. The sequence of the parameters for the Limpopo subcatchment (line in Figure 5.4) were arranged in ascending order through the value of *D* in order to compare it with other subcatchments.

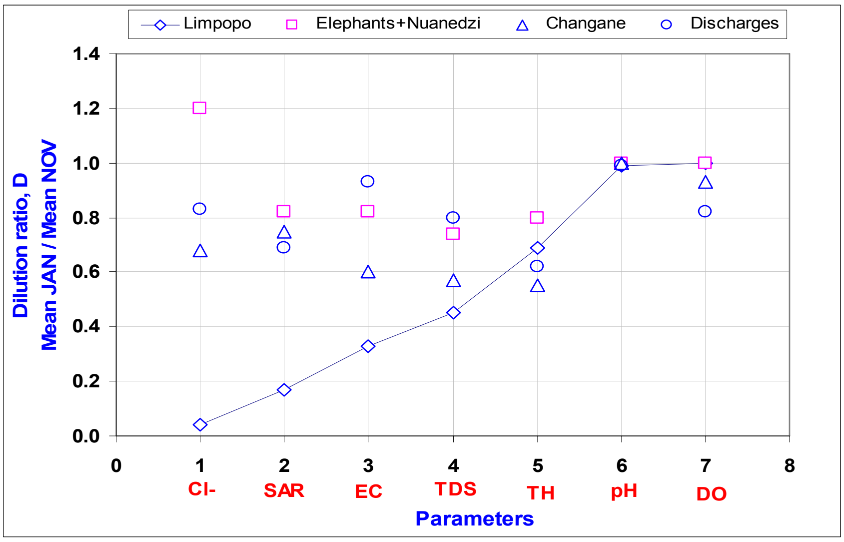


**Figure 5.4.** Changes in concentrations of different parameters in LRB

The parameters that showed the highest changes are those that show lower values of *D*, appearing at the beginning of the X-axis. Between the two sampled months, the parameters in Limpopo subcatchment ($Cl^-$, SAR, EC and TDS) exhibited the highest changes, since the *D* values were found lower. However, parameters such as DO and pH (*D* values ≥ 1) do not exhibit change in the concentrations as a result of river flows variation in all subcatchments (Figure 5.4). When compared to other subcatchments, the parameters in Limpopo subcatchment exhibited the highest changes, although the site L23 appears to largely influence the results obtained, due to its proximity to the river mouth. On the other hand, the Elephants subcatchment which benefits from constant flows regulated at Massingir dam, recorded high *D* values confirming the influence of this infrastructure for the low downstream variability, since its reservoir acts as a sink for pollutants. This process was observed in most studies analysing the impacts of impoundments for the river ecosystem (Vagnetti *et al.*, 2003; Kurunc *et al.*, 2006).

## 5.4. Proposal of the monitoring network and its application on LRB

### 5.4.1. Information needs and objectives

Water quality monitoring networks are generally used to obtain information to satisfy the requirements of national legislation, international agreements, classification schemes and local water management activities (Caggiati *et al.*, 2000). For the case of the LRB, instruments such as the Mozambican Water Policy (Law Act N° 16 of 1991) and its legislative instruments were designed to regulate the water resources management issues, including water pollution (Hirji *et al.*, 2002; SDC, 2003). The importance of environmental monitoring in Mozambique was recently addressed when the country developed in 2004 the standards for receiving waters (Article 10 of Law n. 20/97) and environmental water quality standards for effluent emissions (Article 10; Law n°. 20/97).

The enforcement of these regulatory instruments and other environmental standards on surface waters requires reliable data sets and information. Thus, an optimal water quality monitoring network is required that describes and collects data about the quality and management of surface waters in the country. Furthermore, water quality monitoring in the LRB will be essential to understand the relation between river flows and pollution loads; human and natural impacts on water quality and interpretation of water quality changes in respect to time. Such information will be vital to recommend future environmental flows, aiming at the preservation of aquatic ecosystem and the coastal estuary, since Mozambique is located at the downstream part of the Basin.

The ultimate goal of a monitoring programme is to provide information needed to potential water end users in the Basin (Mäkelä and Meybeck, 1996). In the Limpopo River Basin, the final users of the information are formed by water managers (e.g. National Directorate of Waters), local farmers, communities and the Limpopo Basin Technical Committee formed by the four nations sharing the Basin (viz. Botswana, South Africa, Zimbabwe and Mozambique).

Thus, the information to be generated through this monitoring network is meant to answer the following basic questions (based on Ongley and Ordoñez, 1997): (i) how the quality and quantity of water in the Limpopo River meet the requirements of different users; (ii) how the water quality and quantity relate to the national standards; (iii) to which extent the water in the river is affected by natural and anthropogenic pollution; (iv) to which extent existent waste discharge points meet the national regulations and standards; (v) how far from the point of discharge does the effluent affect the receiving water; (vi) how does the effluent affect the aquatic ecosystem and the ambient water quality; (vii) how will developments in the Basin affect the water quality and (viii) to understand the effects on plants and aquatic organisms derived from deterioration of water in the Limpopo River and its main tributaries, or in the vicinities of these streams.

As presented and explained in Chapter 2.5, the design of a water quality monitoring entails four main design principles, viz. (i) *selection of the sampling sites and stations* (Bartram and Ballance, 1996; Park *et al.*, 2006), (ii) *definition of water quality objective and types of monitoring* (Bartram and Ballance, 1996; Allan *et al.,* 2006; Park *et al.,* 2006), (iii) *selection of monitoring media and variables* (Sanders *et al*., 1983; UNEP/GEMS, 2005) and (iv) *frequency and timing of monitoring* (Sanders *et al*., 1983; Kristensen and Bøgestrand, 1996; UNEP/GEMS, 2005).

### 5.4.2. Selection of sampling sites

According to Bartram and Ballance (1996) sampling sites should be placed in points where the water is sufficiently well mixed if only one sample is to be collected. In addition, Park *et al.* (2006) refer that sampling sites should be located at the confluence of each discharging basin in order to observe parameters for both water quality and water quantity. The selection of the future sampling sites at the present study considered the following major aspects: (i) variability of the sites in terms of water quality characteristics (pollutants concentrations) between the sampled months (refer to chapter 2.5.2 for more details; ANZECC, 2000; Park *et al.*, 2006); (ii) access and existing infrastructures (Newham *et al.*, 2001); (iii) the representativeness of the site; the identified sources of pollution; main water intakes; control of compliance with water quality standards (Park *et al.*, 2006); and (iv) the Sharp's method, which takes into account the number of contributing tributaries in the Basin and its order (refer chapter 2.5.2 for more details; Sanders *et al.*, 1983)

Based on the above criteria a total of 16 sampling sites are proposed viz., 7 sites for Limpopo subcatchment, 2 in Elephants subcatchment, 2 in Changane subcatchment, 1 in Nuanedzi subcatchment and 4 point wastewater discharges. The suggested location and the selection criteria are presented in Table 5.6.

**Table 5.6.** Proposed sampling sites in the Limpopo River and main tributaries

| Subcatchment | Site # | Source of water | Location | Selection criteria |
|---|---|---|---|---|
| Limpopo | L1 | Limpopo river | Pafúri | Receives water from South Africa (mining and natural upstream pollution) |
| | L4 | Limpopo river | Mapai | Human activities upstream and confluence of Limpopo and Nuanedzi |
| | L9 | Limpopo river | Chókwè | Abstraction of water for irrigation and confluence with Elephants river |
| | L11 | Limpopo river | Chókwè | Human activities (urban wastewaters and agricultural activities) |
| | L20 | Limpopo river | Chibuto | Confluence of Changane and Limpopo |
| | L21 | Limpopo river | Xai-Xai | Confluence of Limpopo and Munhuana (agricultural loads) |
| | L23 | Limpopo river | Xai-Xai | Quality of the water entering the sea and pollution from urban area |
| Elephants | TE6 | Elephants river | Massingir reservoir | Receives water from South Africa (mining, agriculture and natural upstream pollution) |
| | TE8 | Elephants river | Massingir | Dam effluents, human activities (agricultural), quality before confluence with Limpopo |
| Changane | TC17 | Changane river | Changanine | Confluence of Changane with Sangutane and monitoring for ions loads (natural salinity) |
| | TC19 | Changane river | Chibuto | Pollution derived from Chibuto urban area (point and diffuse pollution) |
| Nuanedzi | TN2 | Nuanedzi river | Chicualacuala | Receives waters from Zimbabwe (mining and natural upstream pollution) |
| Point discharges | D14 | Chókwè irrigation scheme discharges | Chókwè | Agricultural wastewaters discharge |
| | TM13 | Water draining from Chinanga lake | Chibuto | Agricultural wastewater discharge |
| | D12 | Chókwè municipality discharges | Chókwè | Chókwè city wastewater discharge |
| | D22 | Xai-Xai municipality discharges | Xai-Xai | Xai-Xai city wastewater discharge |

### 5.4.3. Water quality monitoring objectives

In order to meet the objectives given above, different types of monitoring were proposed for the sampling sites as shown it Table 5.7. The proposed locations to be used as water quality monitoring stations were visualized using the geographic information system. The detailed map illustrating these sampling sites and the type of monitoring is given in Appendix 11.

The locations of the 16 proposed monitoring stations were compared with those in the existing network (refer to Figure 3.3 in chapter 3.1.8). In all, about 7 of the 16 proposed station locations coincided with existing monitoring sites; the rest of them represent new locations. This means that in order to improve the effectiveness of the Limpopo River Basin monitoring in Mozambique, some stations should be relocated and others added as part of a future expansion plan.

**Table 5.7.** Proposed types of monitoring to be implemented in the monitoring sites

| Monitoring type | Sites | Objectives* |
|---|---|---|
| Ambient/trend and impact monitoring | L1, TN2, TE6, TC17, TC19, and L23 | ▪ To assess the status, trend and spatial/temporal variations of water quality and the impacts of sea water intrusion<br>▪ Tests and adequate water quality standards<br>▪ Calculation of loads<br>▪ Control of minimum flows for aquatic ecosystem maintenance |
| Effluent monitoring | D14, TM13, D12 and D22 | ▪ Calculation and control of effluent discharge standards |
| Early warning** and biological monitoring | L1, TN2, TE6 | ▪ Downstream warning of any sudden and unpredictable change in water quality for the protection of downstream functions and uses |
| Operational monitoring | TE8, L4, L9, L11, L20, L21 and L23 | ▪ Ensure good water quality for operational uses (e.g. irrigation, drinking, swimming, industry water abstraction and other uses). |

*Adapted from (Sanders *et al*., 1983; Chapman, 1996; Bartram and Ballance, 1996)
**Require additional investigation to recommend representative and sensitive organisms

### 5.4.4. Parameters and sampling procedure

The selection of parameters was based on the results of the multiple correlations (refer to Appendix 12) and to the relative importance of each parameter for the overall water quality condition in each subcatchment. The selection of the most meaningful parameters (optimum parameters), was thus in light with the rules presented by Sanders *et al.* (1983); Bartram and Ballance (1996) and UNEP/GEMS (2005).

Table 5.8 shows the proposed indicator parameters to be monitored at a preliminary phase, taking into account the above mentioned criteria and in accordance with the monitoring types and objectives presented in chapter 5.4.1 and in Table 5.7. The physico-chemical variables selected to assess the water quality of aquatic ecosystems are: temperature, pH, DO, EC, Na, water level and discharge, nutrients (Phosphorus, $NH_4$-N) and metals (Cd, Zn, Pb, Cu). Although not assessed during the preliminary survey, COD and BOD are together with other parameters important indicators of organic pollutants and thus, can be used for testing the compliance with water quality standards (Bartram and Ballance, 1996; David and Hulea, 2000).

The monitoring of above parameters in river waters should be done in three principal media as recommended by Bartram and Ballance (1996) and Kristensen and Bøgestrand (1996). Such media include: (i) water, (ii) particulate matter and (iii) biological indicator organisms or living organisms. Furthermore, a single sample should be prepared by a composite mix obtained at different points of the river width and always perpendicular to the river flow, in such a way that all possible habitats and stream velocities are covered (Bartram and Ballance, 1996).

**Table 5.8.** Proposed measurable parameters as function of monitoring type

| Monitoring type | Parameters category and type | Measurable variables |
|---|---|---|
| Ambient* | Water quantity and physico-chemical variables | Temperature, pH, DO, EC** , Phosphorus, $NH_4^+$-N, Cd, Zn, Na, Pb, Cu, COD, BOD, water level and discharge |
| | Biological | Faecal coliform and macroinvertebrates |
| Effluent* | Water quantity and physico-chemical variables | Temperature, pH, DO, EC** , $NH_4^+$-N, Phosphorus, COD, BOD, Cd, Zn, Na, Pb, Cu and discharge |
| | Biological | Faecal coliform |
| Earl warning | Biological | Macroinvertebrates*** |
| Operational | Water quantity and physico-chemical variables | Temperature, pH, DO, SAR, EC** , Phosphorus, Cd, Zn, Pb, Cu, COD, BOD, water level and discharge |
| | Biological | Faecal coliform and macroinvertebrates |

* Although not evaluated on this study, COD and BOD should be assessed
** EC, $Cl^-$, Hardness and TDS show a strong correlation, the assessment of EC is representative
***Requires additional investigation to be implemented

### 5.4.5. Frequency and timing of sampling

According to Sanders *et al.* (1983) there are very few quantitative criteria for designating appropriate sampling frequencies which can be applied to plan a water quality monitoring and data collection network. On the other hand, Bartram and Ballance (1996) suggest that the sampling frequency at stations where water quality varies considerably should be higher than in stations where quality remains relatively constant. Observations made at present study, suggested certain variability in some physico-chemical parameters in a space of one month between the two assessments (refer to chapter 5.1.1). Thus, an interval of one month between the collections of individual samples at a station is generally acceptable (Sanders *et al.*, 1983).

Therefore, for operationalization of the proposed water quality monitoring network is suggested that for sites aiming to evaluate the changes and trends of water quality (ambient monitoring), the frequency of sampling should be 12 times per year and across the river width. Similar intervals are in use throughout the world, for example: the monitoring in the Danube Delta (David and Hulea, 2000); the Gomti River in India (Singh *et al*., 2004) and Northern Greece Catchments (Simeonov *et al.*, 2003).

The projected early warning stations should register the changes on the proposed parameters (Table 5.8) at a continuous basis during the wet season, since is during this period that the upstream generated pollutants, both natural and anthropogenic (e.g. heavy metals) are likely to be transported to the downstream part of the Basin. In view of future problems that may occur because of the costs involved, the early warning monitoring would be adapted to operate during the months of occurrence of the peak flows. However, for a successful biological early warning it is important to identify the sensitive and representative organisms, prior to its implementation, fact that will require further investigation.

The operational monitoring is meant to ensure a good water quality for operational uses, thus a monthly sampling is here recommended, in line with the observed variability of some important parameters for water use (ex. SAR, refer to chapter 4). The frequency for operational monitoring can later be reduced for three times per year, if the results do not show much change at monthly basis as recommended by David and Hulea (2000). For the effluent discharges a monthly monitoring is also recommended, but during the dry season, when the flows are reduced, violations of a waste water discharge regulation and its possible environmental effects may be easy to detect, so the proposed monthly sampling regime may be adapted accordingly.

### 5.4.6. Costs of the monitoring network

As mentioned by Bartram and Ballance (1996) the implementation of a monitoring programme requires access to resources, including equipped laboratory, office space, and equipment for field work, transport and trained personnel. In addition factors such as sample collection, cost of analytical services and reporting should also be considered.

Assuming that most of the basic requirements to carry monitoring activities on the Limpopo River Basin have already been created by the National Directorate for Waters (DNA) and the Regional Administration for Water (ARA-Sul), the costs presented here will merely focus on operational expenses on a yearly basis.

Furthermore, the operational costs will take into account factors such as: (i) costs of manpower; (ii) field equipment and maintenance; (iii) annual needs for sample collection; (iv) transport; (v) analytical costs and (vi) reporting. Table 5.9 gives an estimate of the monitoring activities per year.

According to estimates made, the total cost of the monitoring network is about US$ 56000 per year. This budget was found reasonable when compared to other monitoring networks. An example comes from the WQ monitoring network for the Bug River Basin (39400 km$^2$, shared by Poland, Belarus and Ukraine), where a total cost of 74000 Euro (about 94000 $US) was estimated for its establishment and operation (Uczciwek and Zan, 2004).

As a way of reducing the financial constraints imposed by water quality monitoring activities, the Mozambican governmental agency responsible for implementation of monitoring activities (ARA-Sul) should include on its efforts, the following: (i) promotion of regional partnership on water quality monitoring; (ii) promotion of public and private sector partnerships; (iii) establishment of linkages with relevant donors interested in WQ monitoring in the region or in the basin and (iv) trade of data and data services which are directly generated and funded by government. The “polluter pays” principle is another strong instrument that can be enforced throughout the basin, since is already defined in the water act.

**Table 5.9.** Estimated costs of WQM network for LRB

| Item | Description | | Input | Cost/year (US$) |
|---|---|---|---|---|
| Sample collection | Weekly: 2 man-day for 3 days | | 50US$*2*3*48 | 14400 |
| | Monthly: 2 man-day for 5 days | | 50US$*2*5*12 | 6000 |
| Transport | Fuel/year | | 1US$*7000 L | 7000 |
| | Maintenance (25% of fuel cost) | | 1US$*7000 L*0.25 | 1750 |
| Laboratory analysis | Ambient monitoring | 12 samples/year (6 sites) | 95US$*12*6 | 7980 |
| | Effluent monitoring | 12 samples/year (4 sites) | 95US$*12*4 | 4560 |
| | Operational monitoring | 12 samples/year (7 sites) | 95US$*12*7 | 7980 |
| Office expenses | Stationary and reporting material | | US$1000 | 1000 |
| **Subtotal** | | | | **50670** |
| **Others (10% subtotal)** | | | | **5067** |
| **Total estimated cost** | | | | **55737.0** |

Based on estimations by Kemikimba (2006)

### 5.4.7. Quality control and quality assurance

To ensure a good operation of the WQ monitoring system and thus a system which generates reliable data and information, a good system of quality control and assurance should be taken into consideration.

This process on the present water quality monitoring network should include practices such as:

i. Facilitation of appropriate inter-calibration routines for the involved chemical laboratories (Bartram and Ballance, 1996; Chapman, 1996; David and Hulea, 2000; Deelstra *et al.*, 2004);

ii. Development of common routines for data control (e.g. measured data in line with the standards procedures recommended by APHA/AWWA/WPCF, 1985) (Bartram and Ballance, 1996; David and Hulea, 2000; Deelstra *et al.*, 2004);

iii. Development of common methods and approaches for data analysis and reporting (Bartram and Ballance, 1996; Deelstra *et al.*, 2004);

iv. Staff training to ensure that proper procedures are followed (Bartram and Ballance, 1996; Chapman, 1996; David and Hulea, 2000);

v. Regular production of reports summarizing the results of the monitoring activities (Bartram and Ballance, 1996, Deelstra *et al.*, 2004). The reports should be factual and written on a way that they can be understood by persons other than scientists.

In order to achieve a good implementation of such instruments is important that whenever possible appropriate training courses are taken by the staff involved on issues related to the monitoring process. Network meetings and workshops at Limpopo basin scale should also be promoted to improve communication between the involved countries; between the network managers and the interested parties, such as, scientists, advisers and the public authorities.

## 5.5. Water quality monitoring and environmental flows assessment

As presented in chapter 2.8, the assessment of environmental flows is increasingly used as part of environmental impact assessments (impacts of water resource development), as well as tools in water resource management (Davis and Hirji, 2003a). Therefore, several methods have been developed and are currently applied for assessing the EF. Out of those methods, the focus is on the holistic methods which incorporate simple methods (e.g. hydrology rating), given that they assess the whole ecosystem by a mean of scenarios analysis.

Methods such as *in-stream flow incremental methodology (IFIM)*, *building block methodology (BBM) and downstream response to imposed flow transformation methodology (DRIFT)* are being applied worldwide with a high success (Tharme and King, 1998; Hirji *et al*., 2002; Dyson *et al*., 2003). The Limpopo River Basin, similarly to other major basins in Southern Africa region, is still deprived from such recommended water requirement in order to maintain different components and uses on its ecosystem.

Since the use of holistic methods, mentioned above, is dependent on factors such as: the timeframe and scale, finances, expertise and manpower availability and most important by availability of biophysical data (Hirji *et al*., 2002; Dyson *et al*., 2003), is important to consider the possibility of integrating some ecological assessments on current water monitoring networks. Thus, monitoring stations can largely be used to record temporal characteristics of the flow regime, which have an important influence for the overall character of a river ecosystem. Furthermore, the indication of the flow regime or annual river hydrograph is important to understand the condition of the different parts of the aquatic ecosystem so that future EF can be defined.

Holistic methods for assessing EF, such as the BBM and DRIFT, not only require annual hydrograph of daily flows, they also demand for past information on water quality, so that, future desired condition of the river can be recommended (Davis and Hirji, 2003a). Hence, surveys to understand the relationship between flow, water depth, velocity, area of inundation and water quality need to be developed.

Consequently, since monitoring networks are interactive processes whereby the condition of key components is measured at repeated intervals following a disturbance and the results compared with background data, they are seen as strong instruments to gather data for EF analysis (Tharme and King, 1998).

The water quality monitoring network discussed and presented in this report, centre part of its objectives on the need to control minimum flows for aquatic ecosystem maintenance (ambient monitoring). In addition the need to describe current state of water resources for water ecosystems in different landscapes affected by different levels of pollution, is also highlighted (refer to chapter 5.4.3).

The lack of trained personal to carry out these studies is at the moment the major drawback. So, as a major priority and in light with the future EF needs, the transmission of basic skills on aquatic assessment is required for the personnel of ARA-Sul, so that the reference condition of the Limpopo River can the assessed based on the current water quality monitoring network. After gathering the information on hydrology, macroinvertebrates or species composition for different flow levels and at a particular site, the basin information will then be available to run the biophysical scenario at downstream Limpopo River Basin, within future assessments of EF.

### 5.6. Ways Forward in WQ Networks Design and Monitoring

Monitoring stream water quality is an important tool for the quantification of the health of a stream (Newham *et al.*, 2001). Recently, as urbanization and industrialization have increased and water pollution has become a threat for more areas, both the general public and policy makers have called for improvements in the design and operations of monitoring networks in river systems (Park *et al.*, 2006).

Nevertheless, traditionally the water quality monitoring networks have been designated on the basis of experience and intuition in keeping with increased management needs related to preventing water quality deterioration, rather than being based on a systematic design involving statistics and other mathematics tools (Park *et al.*, 2006). Since the monitoring networks in general involve huge financial inputs, there is a need to optimize the monitoring networks, number of water quality parameters, reducing these without losing useful information.

The multivariate statistical techniques and exploratory data analysis are an example of appropriate tools for a meaningful data reduction and interpretation of multi-constituent chemical and physical measurements (Singh *et al*., 2004; Solidoro *et al*., 2004). Cluster analysis, factor analysis, principal component analysis (PCA) and discriminant analysis have at last times been widely used in analysis of water quality data for drawing meaningful information (Singh *et al*., 2004). In monitoring design, the cluster analysis helps in grouping sites into classes (clusters) on the basis of their similarity so that the selection of representative sites of each group is possible. In addition, the factor analysis, which includes the PCA allows the reduction of data or parameters to smaller group with inter-related variables, while retaining as much as possible the variability present in the original data set, thus allowing an optimization of the parameters selection.

So, through use of above mentioned tools it is possible to make that all researches select their sampling points and parameters within the same network with a good consistency.

Considering the provision of information for decision making process as the ultimate goal of a monitoring network, it is important to turn the monitoring networks into predictive means rather than retrospective (Canna and Christodoulidou, 2000). Hence, the design and management of water quality monitoring networks has to be in light with policy and planning, regulatory control, investment planning for water infrastructures in the basin, public relations and international obligations (Ongley and Ordoñez, 1997).

Generally is recommended in this report that the design and application of WQM networks should not be restrict to the state of the water, since the major need is to manage the environmental pressures and its socio-economic drivers according to responses of the society (Addrianse *et al.*, 2000). Once the state is known, its driving forces and pressures (sources and causes of pollution) should be assessed and later the major impacts on the environment predicted or evaluated so that new adaptations are made on the monitoring networks to have a satisfactory performance.

**CHAPTER SIX**

# CONCLUSIONS AND RECOMMENDATIONS

## 6.1. Conclusions

In the light of the objectives and the results obtained from this study, the following conclusions can be made:

i. Water quality in most of assessed sites along the Limpopo Basin was found to be deteriorated and not meeting the Mozambican and WHO guidelines for potable water. Such deteriorations derive from different sorts of pollutants, both point (urban wastewater discharges) and non-point sources (e.g. agriculture);

ii. The overall classification of the water quality ranged from “bad” to “good”. Parameters such as heavy metals (Elephants subcatchment), ions (Changane subcatchment) and faecal coliform were found as the major threats impairing the water quality for uses such as, drinking, irrigation, swimming and aquatic ecosystem preservation;

iii. A combined overall assessment of water quality taking into account the biological index (BMWP), physico-chemical WQI and metals WQI was found adequate to be used for the conditions of the Limpopo River Basin, although there are limitation for the biological index which has not yet been adapted to tropical ecosystems;

iv. Natural and anthropogenic derived contaminants generated at upstream countries (Zimbabwe and South Africa) such as heavy metals and nutrients were found to contribute for water quality deterioration at downstream Limpopo Basin;

v. This study has shown that the Limpopo subcatchment exhibited the highest changes on the assessed parameters as a result of flow increase from November 2006 to January 2007;

vi. In the Limpopo River Basin, an expansion of the water quality monitoring network can be made taking into account 16 proposed sampling sites. Such water quality monitoring will focus on ambient, effluents and operational monitoring;

vii. A basic set of physico-chemical, organic, inorganic, biological and microbiological parameters was identified as representative for water quality assessment in the Basin. They include: T°, pH, DO, EC, $NH_4^+$-N, $PO_4$-P, Na, Cu, Cd, Zn, Pb, COD, BOD, SAR, faecal coliforms and benthic macroinvertebrates.

viii. The study has shown the possibility of using benthic macroinvertebrates for water quality assessment. However, studies and training are required to adapt the indices used for biological assessment and to identify the representative and sensitive aquatic organisms to be used in early warning monitoring.

## 6.2. Recommendations

i. Studies at a Basin level, including South Africa, Zimbabwe and Botswana, should be carried out to develop a better understanding of origins and fate of major pollutants in the Limpopo River. The study would aim at developing better guidelines for water quality according to the sources and locations of the pollutants;

ii. Due to their major role in impairing the quality of water at downstream Limpopo Basin for various uses such as irrigation and drinking, the ions transport along the subcatchments (e.g. Changane) should be investigated to understand the processes of its transport in dissolved phase and its effects for aquatic system and the surroundings;

iii. It is strongly recommended that future water allocations in the Basin take into account the maintenance of environmental flows, since the level of water abstraction has strong influence on the maintenance of water quality and thus of aquatic ecosystems sustainability;

iv. As microbial contamination impair the use of water for irrigation, bathing and drinking, a strict control should be placed in raw and discharged water in the Limpopo River and tributaries, since most of the water is likely to be used without any pre-treatment;

v. Due to their importance for the final status of water quality, the heavy metals should be assessed (surface water and sediments) throughout the year at the same sites covered by this study to obtain accurate information on their concentrations and seasonal variations.

vi. Future studies on the same topic should assess the COD and BOD since these parameters are essential for water quality definition. Statistical techniques such as, cluster analysis and principal component analysis should be used for design and optimization of water quality monitoring systems, given their consistency in outputs.

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# APPENDICES

**Appendix 1.** Stations description and sampled parameters

| Site # | Latitude | Longitude | Description | Parameters | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Physico-chemical | Macro-invertebrates | Heavy metals | Total suspended solids | Total phosphorus | Micro-biological |
| | | | | Nov. + Jan. | Nov. | Jan. | Jan. | Jan. | Nov. + Jan. |
| L1 | 22˚ 25' 57.7" | 31˚ 20' 48.1" | After the boarder with RSA (Limpopo River) | X | X | X | X | X | - |
| TN2 | 22˚ 18' 49.3" | 31˚ 28' 11.5" | Limpopo tributary (R. Nuanedzi) coming form Zimbabwe | X | X | X | X | X | - |
| L3 | 22˚ 50' 20.7" | 31˚ 57' 29.2" | After mixing of Limpopo and Nuanedzi -Mapai | X | X | X | X | X | - |
| L4 | 23˚ 28' 10.1" | 32˚ 26' 57.4" | River self purification/other pollutants (Combomune – Limpopo river) | X | X | X | X | X | - |
| TE5 | 23˚ 54' 28.1" | 32˚ 09' 11.3" | Massingir reservoir | X | X | X | X | X | - |
| TE6 | 23˚ 54' 12.2" | 32˚ 07' 02.8" | Massingir reservoir | X | X | X | X | X | - |
| TE7 | 23˚ 52' 19.6" | 32˚ 11' 52.0" | After Massing Dam discharge (Elephants river) | X | X | X | X | X | - |
| TE8 | 24˚ 10' 09.5" | 32˚ 30' 53.0" | After mixing of Elephants and Singuedzi river | X | X | X | X | X | - |
| L9 | 24˚ 21' 55.7" | 32˚ 51' 03.8" | Limpopo before Macarretane dam | X | X | X | X | X | - |
| L10 | 24˚ 24' 31.6" | 32˚ 52' 55.5" | Limpopo after Macarretane dam | X | X | X | X | X | X |
| L11 | 24˚ 34' 09.9" | 33˚ 05' 36.3" | Limpopo after Chókwè and Guijá cities | X | X | X | X | X | X |
| D12 | 24˚ 32' 48.5" | 33˚ 02' 55.9" | Chókwè discharges | X | X | X | X | X | X |
| TM13 | 24˚ 49' 22.9" | 33˚ 29' 12.4" | Munhuana – Irrigation drainage | X | X | X | X | X | - |
| D14 | 24˚ 34' 35.0" | 33˚ 04' 49.8" | Agriculture discharge | X | X | X | X | X | X |
| TC15 | 23˚ 42' 02.6" | 33˚ 56' 49.4" | Changane after mixing with Panzene | X | X | X | X | X | - |
| TC16 | 24˚ 06' 30.8" | 33˚ 47' 20.9" | Sangutane river | X | X | X | X | X | - |
| TC17 | 24˚ 07' 07.1" | 33˚ 46' 46.2" | Changane after mixing with Sangutane | X | X | X | X | X | - |
| TC18 | 24˚ 40' 24.5" | 33˚ 30' 13.6" | Changane before Chibuto | X | X | X | X | X | X |
| TC19 | 24˚ 43' 04.5" | 33˚ 32' 13.7" | Changane after Chibuto | X | X | X | X | X | X |
| L20 | 24˚ 44' 49.9" | 33˚ 32' 40.2" | Mixing of Limpopo and Changane | X | X | X | X | X | - |
| L21 | 24˚ 55' 35.0" | 33˚ 40' 02.0" | Limpopo after Agriculture loads | X | X | X | X | X | X |
| D22 | 25˚ 02' 21.6" | 33˚ 38' 25.6" | Sewage discharge Xai-Xai | X | X | X | X | X | X |
| L23 | 25˚ 03' 16.6" | 33˚ 36' 35.0" | Limpopo after Xai-Xai city | X | X | X | X | X | X |

**X – The site was investigated**; Physico-chemical (T, EC, TDS, DO, pH, $NH_4^+$-N, $NO_3^-$ - N, Hardness, $Cl^-$, $Mg^{2+}$, $Ca^{2+}$, $Na^+$); Heavy metals (Cd, Cr, Cu, Pb, Zn, Fe); Microbiological (Faecal coliforms).

**Appendix 2.** Biological Monitoring Working Party (BMWP) score for different families of macro-invertebrates (Mason, 1991; Chapman, 1996)

| Group | Family | Score |
|---|---|---|
| Mayflies | Siphlonuridae, Heptageniidae, Leptophlebiidae, Ephemerellidae, Potamanthidae, Ephemeridae, | |
| Stoneflies | Taeniopteerygidae, Leuctridae, Capniidae, Perlodidae, Perlodidae, Chloroperlidae | 10 |
| River Bug | Aphelocheiridae | |
| Caddisflies | Phyryganeidae, Molannidae, Beraeidae ,Odontoceridae , Leptoceridae, Goeridae, Lepidostomatidae, Brachycentridae, Sericostomatidae | |
| Crayfish | Astacidae | |
| Dragonflies | Gomphidae, Cordulegasteridae, Aeshnidae, Corduliidae, Libellulidae, Lestidae, Agriidae | 8 |
| Caddisflies | Psychomyiidae, Phylopotamidae | |
| Mayflies | Caenidae | |
| Stoneflies | Nemouridae | 7 |
| Caddisflies | Rhyacophilidae (Glossosomatidae), Polycentropodidae, Limnephilidae | |
| Snails | Neritidae, Viviparidae, Ancylidae (Acroloxidae) | |
| Caddisflies | Hydroptilidae | |
| Mussels | Unionidae | 6 |
| Shrimps | Corophiidae, Gammaridae (Crangonyctidae) | |
| Dragonflies | Platycnemididae, Coenagriidae | |
| Waterbugs | Mesovelidae, Hydrometridae, Gerridae, Nepidae, Naucoridae, Notonectidae, Pleidae, Corixidae | |
| Waterbeetles | Haliplidae, Hygrobiidae, Dytiscidae (Noteridae), Gyrinidae, Hydrophilidae (Hydraenidae), Clambidae, Helodidae, Dryopidae, Elminthidae, Chrysomelidae, Curculionidae | |
| Caddisflies | Hydropsychidae | 5 |
| Craneflies | Tipulidae | |
| Blackflies | Simuliidae | |
| Flatworms | Planariidae, Dendrocoelidae | |
| Mayflies | Baetidae | |
| Alderflies | Sialidae | 4 |
| Leeches | Pisicolidae | |
| Snails | Valvatidae, Hydrobiidae, Lymnaeidae, Physidae, Planorbidae | |
| Cockles | Sphaeriidae | |
| Leeches | Glossiphoniidae, Hirudinidae, Erpobdellidae | 3 |
| Hoglouse | Asellidae | |
| Midges | Chironomidae | 2 |
| Worms | Oligochaeta | 1 |

**Appendix 3.** Limpopo River Discharge at Monitored Sites

| ARA-Sul Station | | Preliminary survey visited sites | River discharge ($m^3/s$) | |
|---|---|---|---|---|
| | | | November, 06 | January, 07 |
| E-31 | Pafúri | L1 | 0.2 | 7.1 |
| E-232 | Nuanedzi | TN2 | 0.0 | 5.7* |
| E-32 | Mapai | L3 | 0.2 | 12.8 |
| E-33 | Combomune | L4 | 0.2 | 12.8 |
| E-546 | Massingir | TE7 | 35.0 | 35.0 |
| E-372 | Macarretane | L10 | 35.2 | 47.8 |
| E-35 | Chókwè | L11 | 35.2 | 47.8 |
| E-40 | Chibuto | TC19 | 1.3 | 3.6 |
| E-36 | Sicacate | L20 | 36.5 | 51.4 |
| E-38 | Xai-Xai | L23 | 51.5 | 66.4 |

* Flow estimated based in historical data

**Appendix 4.** Composition of macroinvertebrates found at each sampled site

| Classification | Family (Taxa) | Score | L1 | L3 | L4 | TE7 | TE8 | L10 | L11 | TM13 | TC16 | TC17 | TC18 | TC19 | L20 | L21 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Key 1** | | | | | | | | | | | | | | | | |
| ***Caddisflies (caseless)*** | Sialidae | 4 | | | | | x | | | | | | | | | |
| | Gammaridae | 6 | | | | | | | | | | | | | | x |
| **Key 2** | | | | | | | | | | | | | | | | |
| ***Mayflies*** | Baetidae | 4 | | | | | | | | x | | | | | | |
| ***Dragonflies*** | Cordulegasteridae | 8 | x | x | x | x | x | | | | | | | | | |
| | Gomphidae | 8 | | | | | | x | | | | | | | | |
| **Key 3** | | | | | | | | | | | | | | | | |
| ***Waterbugs*** | Aphelocheiridae | 10 | x | x | x | | x | | | | | | | | | |
| ***Waterbeetles*** | Elminthidae | 5 | | x | | | | | | | | | | | | |
| **Key 4** | | | | | | | | | | | | | | | | |
| ***Midges*** | Midges | 2 | x | | | x | x | | | | | | x | x | | |
| ***Worms*** | Worms | 1 | x | | | x | x | | | x | | | | x | | x |
| ***Snails*** | Hydrobiidae | 3 | x | x | x | | x | x | x | | | | | x | x | |
| | Lymnaeidae | 3 | | | | x | | | | | x | x | x | | x | |
| ***Mussels and Cockles*** | Sphaeridae | 3 | x | x | x | x | x | x | x | | | | | | x | x |
| | Unionidae | 6 | | | | | | | | | x | | | | | |
| **Total BMWP Score (a)** | | | **27** | **27** | **24** | **17** | **31** | **14** | **6** | **5** | **9** | **3** | **5** | **6** | **9** | **10** |
| **Total no. of taxa (b)** | | | **6** | **5** | **4** | **5** | **7** | **3** | **2** | **2** | **2** | **1** | **2** | **3** | **3** | **3** |
| **ASPT Score (a/b)** | | | **4.5** | **5.8** | **6.0** | **3.4** | **4.4** | **4.7** | **3.0** | **2.5** | **4.5** | **3.0** | **2.5** | **2.0** | **3.0** | **3.3** |

X – Family identified at particular site

**Appendix 5.** Field and laboratory results from preliminary study (November, 2006)

| Station # | Description | Date | Latitide | Longitude | T (°C) | EC µS/cm (at 25 °C) | TDS (mg/l) | $O_2$ (mg/l) | $O_2$ (% sat.) | pH | TP (mg/l) | $NH_4$-N (mg/l) | $NO_3$-N (mg/l) | Total Hardness (mg $CaCO_3$/l) | $Cl^-$ (mg/l) | $Mg^{2+}$ (mg/l) | $Ca^{2+}$ (mg/l) | $Na^+$ (mg/l) | E-Coli (CFU/100 ml) | SAR |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| L1 | Limpopo pafuri | 15.11.06 | 22° 25' 57.7" | 31° 20' 48.1" | 24.5 | 210 | 197 | 7.2 | 88.3 | 7.7 | - | 0.13 | <0.23 | 102 | 200.7 | 10.7 | 22.9 | 23.5 | - | 5.7 |
| TN2 | Tributary- Nuanedzi | 15.11.06 | 22° 18' 49.3" | 31° 28' 11.5" | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| L3 | Limpopo - Mapai | 15.11.06 | 22° 50' 20.7" | 31° 57' 29.2" | 33.5 | 718 | 695 | 10.1 | 142.2 | 8.7 | - | 0.16 | 0.58 | 205 | 153.6 | 33.3 | 26.5 | 204.6 | - | 37.4 |
| L4 | Limpopo - Combomune | 15.11.06 | 23° 28' 10.1" | 32° 26' 57.4" | 32.4 | 810 | 602 | 8.1 | 113.5 | 8.4 | - | 0.08 | <0.23 | 112 | 190.6 | 9.9 | 28.3 | 306.7 | - | 70.2 |
| TE5 | Massingir reservoir | 16.11.06 | 23° 54' 28.1" | 32° 09' 11.3" | 25.8 | 412 | 367 | 9.2 | 115.3 | 7.8 | - | 0.10 | <0.23 | 181 | 13.3 | 22.8 | 34.4 | 43.7 | - | 8.2 |
| TE6 | Massingir reservoir | 16.11.06 | 23° 54' 12.2" | 32° 07' 02.8" | 26.3 | 511 | 408 | 9.6 | 126.0 | 8.1 | - | 0.12 | 0.31 | 230 | 57.6 | 33.4 | 36.4 | 10.3 | - | 1.7 |
| TE7 | Elephants after Massingir | 16.11.06 | 23° 52' 19.6" | 32° 11' 52.0" | 24.2 | 436 | 302 | 8.3 | 99.9 | 7.6 | - | 0.11 | <0.23 | 190 | 25.6 | 21.2 | 40.8 | 67.9 | - | 12.2 |
| TE8 | Elephants after mix Singuedzi | 16.11.06 | 24° 10' 09.5" | 32° 30' 53.0" | 29.6 | 447 | 393 | 9.5 | 126.1 | 8.1 | - | 0.11 | <0.23 | 186 | 28.6 | 24.5 | 33.6 | 47.5 | - | 8.8 |
| L9 | Limpopo before Macarretane dam | 17.11.06 | 24° 21' 55.7" | 32° 51' 03.8" | 28.1 | 453 | 267 | 7.1 | 90.1 | 8.3 | - | 0.09 | <0.23 | 270 | 33.7 | 42.9 | 36.5 | 96.2 | - | 15.3 |
| L10 | Limpopo after Macarretane dam | 17.11.06 | 24° 24' 31.6" | 32° 52' 55.5" | 29.2 | 447 | 434 | 9.3 | 122.5 | 8.3 | - | 0.12 | <0.23 | 220 | 24.5 | 30.8 | 36.7 | 90.6 | 10000 | 15.6 |
| L11 | Limpopo after Chókwe and Guija cities | 17.11.06 | 24° 34' 09.9" | 33° 05' 36.3" | 31.0 | 462 | 402 | 8.2 | 111.1 | 8.3 | - | 0.09 | <0.23 | 215 | 55.4 | 27.8 | 39.6 | 81.2 | 24000 | 14.0 |
| D12 | Chokwe discharges | 17.11.06 | 24° 32' 48.5" | 33° 02' 55.9" | 27.0 | 794 | 310 | 5.1 | 52.3 | 7.5 | - | 0.15 | <0.23 | 323 | 186.5 | 43.6 | 56.7 | 233.8 | 24000 | 33.0 |
| TM13 | Munhuana - Irrigation drainage | 19.11.06 | 24° 49' 22.9" | 33° 29' 12.4" | 26.1 | 3090 | 2812 | 2.2 | 27.3 | 7.9 | - | 0.07 | <0.23 | 797 | 1224.3 | 152.1 | 65.8 | 1423.4 | - | 136.4 |
| D14 | Agriculture discharge | 21.11.06 | 24° 34' 35.0" | 33° 04' 49.8" | 24.4 | 645 | 640 | 3.4 | 37.0 | 7.0 | - | 0.07 | 0.29 | 235 | 90.7 | 36.3 | 33.6 | 177.4 | 2100 | 30.0 |
| TC15 | Changane after mixing with Panzene | 18.11.06 | 23° 42' 02.6" | 33° 56' 49.4" | 27.9 | 17950 | 16873 | 4.7 | 57.0 | 7.6 | - | 0.15 | <0.23 | 645 | 5950.6 | 111.5 | 72.4 | 9455.7 | - | 986.1 |
| TC16 | Sangutane river | 18.11.06 | 24° 06' 30.8" | 33° 47' 20.9" | 31.0 | 24000 | 15840 | 6.3 | 83.0 | 8.3 | - | 0.31 | <0.23 | 7540 | 10581.0 | 1511.7 | 500.2 | 8798.3 | - | 277.4 |
| TC17 | Changane after mixing with Sangutane | 18.11.06 | 24° 07' 07.1" | 33° 46' 46.2" | 32.0 | 41200 | 34196 | 9.2 | 125.0 | 8.2 | - | 0.30 | 0.37 | 8670 | 15891.6 | 1670.4 | 688.1 | 17532.8 | - | 510.6 |
| TC18 | Changane before Chibuto | 19.11.06 | 24° 40' 24.5" | 33° 30' 13.6" | 25.5 | 4140 | 3685 | 7.5 | 91.0 | 7.8 | - | 0.17 | <0.23 | 2100 | 1577.6 | 406.5 | 163.5 | 1615.1 | 24000 | 95.7 |
| TC19 | Changane after Chibuto | 19.11.06 | 24° 43' 04.5" | 33° 32' 13.7" | 25.8 | 9400 | 7050 | 7.5 | 92.0 | 7.0 | - | 0.17 | <0.23 | 6740 | 4058.7 | 1567.3 | 87.6 | 4898.4 | 24000 | 170.3 |
| L20 | Mixing of Limpopo and Changane | 19.11.06 | 24° 44' 49.9" | 33° 32' 40.2" | 25.8 | 1481 | 1022 | 8.3 | 100.8 | 8.3 | - | 0.07 | <0.23 | 190 | 490.1 | 23.2 | 37.4 | 150.1 | - | 27.3 |
| L21 | Limpopo after Agricultural loads | 20.11.06 | 24° 55' 35.0" | 33° 40' 02.0" | 26.6 | 778 | 552 | 7.5 | 94.2 | 8.1 | - | 0.14 | <0.23 | 750 | 177.5 | 124.5 | 92.8 | 241.0 | 1900 | 23.1 |
| D22 | Sewage discharge Xai-Xai | 20.11.06 | 25° 02' 21.6" | 33° 38' 25.6" | 27.5 | 2870 | 2009 | 2.4 | 30.2 | 7.5 | - | 2.82 | 1.27 | 745 | 1126.0 | 99.3 | 132.7 | 1019.4 | 24000 | 94.6 |
| L23 | Limpopo after Xai-Xai City | 20.11.06 | 25° 03' 16.6" | 33° 36' 35.0" | 26.3 | 11310 | 5542 | 8.2 | 101.6 | 8.0 | - | 0.36 | <0.23 | 815 | 6859.3 | 147.1 | 81.2 | 4550.7 | 24000 | 425.9 |

L – Limpopo; TN – Tributary Nuanedzi; TE – Tributary Elephants; D – Discharge points; TC – Tributary Changane; TM – Tributary Munhuana

**Appendix 6.** Field and laboratory results from preliminary study (January, 2007)

| Station # | Description | Date | Latitide | Longitude | T (°C) | EC µS/cm (at 25 °C) | TDS (mg/l) | $O_2$ (mg/l) | $O_2$ (% sat.) | pH | TP (mg/l) | $NH_4$-N (mg/l) | $NO_3$-N (mg/l) | Total Hardness (mg $CaCO_3$/l) | $Cl^-$ (mg/l) | $Mg^{2+}$ (mg/l) | $Ca^{2+}$ (mg/l) | $Na^+$ (mg/l) | E-Coli (CFU/100 ml) | SAR | TSS (mg/l) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| L1 | Limpopo pafuri | 15.11.06 | 22° 25' 57.7" | 31° 20' 48.1" | 28.3 | 181 | 132.1 | 9.1 | 110.4 | 7.9 | 0.28 | 0.15 | 0.86 | 87 | 23.8 | 7.9 | 20.8 | 21.4 | - | 5.6 | 520.0 |
| TN2 | Tributary- Nuanedzi | 15.11.06 | 22° 18' 49.3" | 31° 28' 11.5" | 29.7 | 184 | 141.9 | 9.4 | 127.2 | 8.2 | 0.11 | 0.14 | 0.64 | 76 | 19.5 | 6.8 | 19.2 | 20.0 | - | 5.5 | 432.0 |
| L3 | Limpopo - Mapai | 15.11.06 | 22° 50' 20.7" | 31° 57' 29.2" | 28.7 | 191 | 135.7 | 9.0 | 118.0 | 8.0 | 0.22 | 0.19 | 0.96 | 140 | 17.7 | 20.9 | 21.6 | 18.0 | - | 3.9 | 1184.0 |
| L4 | Limpopo - Combomune | 15.11.06 | 23° 28' 10.1" | 32° 26' 57.4" | 26.5 | 208 | 143.5 | 7.7 | 98.0 | 7.7 | 0.65 | 0.09 | 1.05 | 80 | 19.5 | 6.8 | 20.8 | 16.0 | - | 4.3 | 1584.0 |
| TE5 | Massingir reservoir | 16.11.06 | 23° 54' 28.1" | 32° 09' 11.3" | 27.8 | 396 | 304.9 | 9.7 | 125.4 | 8.4 | 0.23 | 0.07 | <0.23 | 172 | 35.5 | 22.4 | 32.0 | 32.0 | - | 6.1 | 24.0 |
| TE6 | Massingir reservoir | 16.11.06 | 23° 54' 12.2" | 32° 07' 02.8" | 27.7 | 410 | 348.5 | 10.2 | 132.2 | 8.4 | 0.16 | 0.04 | 0.27 | 200 | 35.5 | 29.8 | 32.0 | 32.0 | - | 5.8 | 20.0 |
| TE7 | Elephants after Massingir | 16.11.06 | 23° 52' 19.6" | 32° 11' 52.0" | 27.6 | 434 | 321.2 | 10.2 | 129.2 | 8.0 | 0.04 | 0.07 | <0.23 | 170 | 69.4 | 20.9 | 33.6 | 37.0 | - | 7.1 | 28.0 |
| TE8 | Elephants after mix Singuedzi | 16.11.06 | 24° 10' 09.5" | 32° 30' 53.0" | 26.5 | 436 | 248.5 | 7.6 | 94.5 | 8.2 | 0.03 | 0.08 | <0.23 | 170 | 42.5 | 21.9 | 32.0 | 37.0 | - | 7.1 | 32.0 |
| L9 | Limpopo before Macarretane dam | 17.11.06 | 24° 21' 55.7" | 32° 51' 03.8" | 28.1 | 437 | 380.2 | 8.3 | 106.2 | 8.4 | 0.37 | 0.08 | <0.23 | 240 | 49.6 | 40.0 | 30.4 | 39.0 | - | 6.6 | 8.0 |
| L10 | Limpopo after Macarretane dam | 17.11.06 | 24° 24' 31.6" | 32° 52' 55.5" | 28.2 | 436 | 379.3 | 8.7 | 112.2 | 8.4 | 0.26 | 0.07 | <0.23 | 200 | 44.3 | 30.2 | 30.4 | 38.0 | 11000 | 6.9 | 20.0 |
| L11 | Limpopo after Chókwe and Guija cities | 17.11.06 | 24° 34' 09.9" | 33° 05' 36.3" | 29.4 | 467 | 266.2 | 8.9 | 117.3 | 8.4 | 0.08 | 0.09 | <0.23 | 174 | 69.4 | 23.4 | 31.2 | 42.0 | 24000 | 8.0 | 28.0 |
| D12 | Chokwe discharges | 17.11.06 | 24° 32' 48.5" | 33° 02' 55.9" | 26.5 | 845 | 481.7 | 4.1 | 49.7 | 7.3 | 0.23 | 0.07 | <0.23 | 246 | 108.1 | 34.2 | 42.4 | 73.0 | 24000 | 11.8 | 40.0 |
| TM13 | Munhuana - Irrigation drainage | 19.11.06 | 24° 49' 22.9" | 33° 29' 12.4" | 28.4 | 2800 | 2016 | 2.2 | 28.0 | 7.6 | 1.09 | 0.24 | 0.31 | 390 | 1949.8 | 66.8 | 46.4 | 1126.5 | - | 149.7 | 44.0 |
| D14 | Agriculture discharge | 21.11.06 | 24° 34' 35.0" | 33° 04' 49.8" | 27.4 | 621 | 403.6 | 2.4 | 29.0 | 7.2 | 0.82 | 0.10 | <0.23 | 216 | 63.8 | 34.6 | 29.6 | 54.0 | 2400 | 9.5 | 40.0 |
| TC15 | Changane after mixing with Panzene | 18.11.06 | 23° 42' 02.6" | 33° 56' 49.4" | 27.5 | 9350 | 6732 | 4.1 | 58.1 | 7.4 | 0.42 | 0.25 | 0.37 | 448 | 4149.8 | 77.5 | 52.1 | 4300.0 | - | 534.2 | 248.0 |
| TC16 | Sangutane river | 18.11.06 | 24° 06' 30.8" | 33° 47' 20.9" | 35.3 | 22900 | 20610 | 7.7 | 112.5 | 8.1 | 0.05 | 0.34 | 0.25 | 3760 | 9571.5 | 697.8 | 360.7 | 9500.0 | - | 412.9 | 316.0 |
| TC17 | Changane after mixing with Sangutane | 18.11.06 | 24° 07' 07.1" | 33° 46' 46.2" | 37.2 | 17800 | 11748 | 8.2 | 119.5 | 8.0 | 0.06 | 0.34 | 0.46 | 4600 | 8685.0 | 1090.6 | 521.0 | 7900.0 | - | 278.3 | 244.0 |
| TC18 | Changane before Chibuto | 19.11.06 | 24° 40' 24.5" | 33° 30' 13.6" | 27.9 | 4700 | 3008 | 4.3 | 53.0 | 7.6 | 0.03 | 0.31 | 0.24 | 1200 | 1808.0 | 231.8 | 100.2 | 2700.0 | 24000 | 209.6 | 84.0 |
| TC19 | Changane after Chibuto | 19.11.06 | 24° 43' 04.5" | 33° 32' 13.7" | 28.7 | 3000 | 2460 | 8.4 | 106.0 | 7.9 | 0.10 | 0.47 | 2.28 | 4100 | 1786.2 | 980.6 | 435.5 | 2540.0 | 24000 | 95.5 | 72.0 |
| L20 | Mixing of Limpopo and Changane | 19.11.06 | 24° 44' 49.9" | 33° 32' 40.2" | 29.3 | 515 | 468.7 | 6.8 | 82.0 | 8.3 | 0.11 | 0.40 | <0.23 | 180 | 56.7 | 22.9 | 34.4 | 47.0 | - | 8.8 | 84.0 |
| L21 | Limpopo after Agricultural loads | 20.11.06 | 24° 55' 35.0" | 33° 40' 02.0" | 31.1 | 725 | 594.5 | 7.5 | 101.0 | 8.3 | 0.03 | 0.06 | <0.23 | 425 | 30.6 | 60.5 | 35.6 | 210.0 | 2100 | 30.3 | 32.0 |
| D22 | Sewage discharge Xai-Xai | 20.11.06 | 25° 02' 21.6" | 33° 38' 25.6" | 30.0 | 2600 | 1742 | 2.2 | 29.0 | 7.4 | 1.17 | 1.56 | <0.23 | 444 | 54.9 | 33.6 | 122.6 | 290.0 | 24000 | 32.8 | 48.0 |
| L23 | Limpopo after Xai-Xai City | 20.11.06 | 25° 03' 16.6" | 33° 36' 35.0" | 29.2 | 2400 | 1896 | 8.2 | 105.0 | 8.2 | 0.10 | 0.06 | <0.23 | 460 | 21.3 | 84.9 | 44.8 | 270.0 | 24000 | 33.5 | 44.0 |

L – Limpopo; TN – Tributary Nuanedzi; TE – Tributary Elephants; D – Discharge points; TC – Tributary Changane; TM – Tributary Munhuana

**Appendix 7.** Total (unfiltered) and dissolved (filtration over around 47 mm GF/C Whatman filter) heavy metals

| | | Unfiltered Samples | | | | | | Filtered Samples | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Description** | **Station #** | **Cadmium (mg/l)** | **Chromium (mg/l)** | **Copper (mg/l)** | **Lead (mg/l)** | **Zinc (mg/l)** | **Iron (mg/l)** | **Cadmium (mg/l)** | **Chromium (mg/l)** | **Copper (mg/l)** | **Lead (mg/l)** | **Zinc (mg/l)** | **Iron (mg/l)** |
| **Limpopo pafuri** | **L1** | 0.08 | 0.00 | 0.13 | 0.20 | 0.03 | 0.76 | 0.02 | 0.00 | 0.01 | 0.00 | 0.01 | 0.00 |
| **Tributary- Nuanedzi** | **TN2** | 0.01 | 0.00 | 0.07 | 0.10 | 0.04 | 13.15 | 0.01 | 0.00 | 0.00 | 0.10 | 0.03 | 0.91 |
| **Limpopo - Mapai** | **L3** | 0.06 | 0.00 | 0.06 | 0.00 | 0.05 | 31.30 | 0.02 | 0.00 | 0.01 | 0.00 | 0.03 | 0.28 |
| **Limpopo - Combomune** | **L4** | 0.01 | 0.00 | 0.07 | 0.00 | 0.08 | 16.40 | ***0.02**** | 0.00 | 0.01 | 0.00 | 0.07 | 0.19 |
| **Massingir reservoir** | **TE5** | 0.04 | 0.00 | 0.09 | 0.50 | 0.08 | 0.19 | 0.02 | 0.00 | 0.01 | 0.10 | 0.03 | 0.00 |
| **Massingir reservoir** | **TE6** | 0.05 | 0.00 | 0.07 | 0.30 | 0.07 | 0.18 | 0.02 | 0.00 | 0.00 | 0.20 | 0.02 | 0.00 |
| **Elephants after Massingir** | **TE7** | 0.01 | 0.00 | 0.06 | 0.00 | 0.02 | 0.14 | 0.02 | 0.00 | 0.02 | 0.00 | ***0.04**** | 0.00 |
| **Elephants after mix Singuedzi** | **TE8** | 0.01 | 0.00 | 0.04 | 0.00 | 0.31 | 0.44 | 0.00 | 0.00 | 0.02 | 0.00 | 0.01 | 0.00 |
| **Limpopo before Macarretane dam** | **L9** | 0.01 | 0.00 | 0.06 | 0.00 | 0.21 | 0.75 | 0.00 | 0.00 | 0.01 | 0.00 | 0.03 | 0.00 |
| **Limpopo after Macarretane dam** | **L10** | 0.02 | 0.00 | 0.05 | 0.00 | 0.03 | 0.12 | 0.01 | 0.00 | 0.00 | ***0.10**** | ***0.05**** | 0.00 |
| **Limpopo after Chókwe and Guija cities** | **L11** | 0.02 | 0.00 | 0.11 | 0.00 | 0.09 | 0.11 | 0.01 | 0.00 | 0.00 | 0.00 | 0.02 | 0.00 |
| **Chokwe discharges** | **D12** | 0.02 | 0.00 | 0.04 | 0.00 | 0.04 | 0.19 | 0.01 | 0.00 | 0.01 | ***0.10**** | 0.04 | 0.11 |
| **Munhuana - Irrigation drainage** | **TM13** | 0.04 | 0.00 | 0.01 | 0.20 | 0.09 | 0.69 | 0.01 | 0.00 | 0.00 | 0.00 | 0.03 | 0.00 |
| **Agriculture discharge** | **D14** | 0.02 | 0.00 | 0.01 | 0.10 | 0.02 | 0.52 | 0.01 | 0.00 | 0.01 | 0.00 | ***0.07**** | 0.00 |
| **Changane after mixing with Panzene** | **TC15** | 0.03 | 0.00 | 0.02 | 0.00 | 0.04 | 0.24 | 0.02 | 0.00 | 0.00 | ***0.10**** | 0.04 | 0.00 |
| **Sangutane river** | **TC16** | 0.04 | 0.00 | 0.04 | 0.10 | 0.16 | 0.55 | 0.00 | 0.00 | 0.01 | 0.00 | 0.01 | 0.00 |
| **Changane after mixing with Sangutane** | **TC17** | 0.03 | 0.00 | 0.01 | 0.00 | 0.06 | 0.87 | 0.02 | 0.00 | 0.00 | ***0.10**** | 0.06 | 0.00 |
| **Changane before Chibuto** | **TC18** | 0.03 | 0.00 | 0.00 | 0.00 | 0.10 | 0.45 | 0.01 | 0.00 | 0.00 | 0.00 | 0.01 | 0.00 |
| **Changane after Chibuto** | **TC19** | 0.02 | 0.00 | 0.00 | 0.00 | 0.01 | 0.36 | 0.00 | 0.00 | 0.00 | ***0.10**** | ***0.04**** | 0.00 |
| **Mixing of Limpopo and Changane** | **L20** | 0.02 | 0.00 | 0.01 | 0.00 | 0.01 | 3.75 | 0.01 | 0.00 | 0.00 | 0.00 | ***0.05**** | 0.14 |
| **Limpopo after Agricultural loads** | **L21** | 0.03 | 0.00 | 0.00 | 0.00 | 0.05 | 0.30 | 0.01 | 0.00 | ***0.01**** | 0.00 | 0.01 | 0.00 |
| **Sewage discharge Xai-Xai** | **D22** | 0.03 | 0.00 | 0.00 | 0.00 | 0.05 | 0.18 | 0.01 | 0.00 | ***0.01**** | 0.00 | 0.01 | 0.00 |
| **Limpopo after Xai-Xai City** | **L23** | 0.02 | 0.00 | 0.01 | 0.10 | 0.03 | 0.39 | 0.01 | 0.00 | 0.01 | 0.10 | 0.02 | 0.01 |

* Values left behind on the evaluation given that in filtered samples were found higher than in row samples.

**Appendix 8.** Standard rating derived from BMWP and ASPT scores

| BMWP | Rating X | ASPT | Rating Y |
|---|---|---|---|
| 121+ | 7 | 5.0+ | 7 |
| 101 – 120 | 6 | 4.5 – 4.9 | 6 |
| 81 – 100 | 5 | 4.1 – 4.4 | 5 |
| 51 – 80 | 4 | 3.6 – 4.0 | 4 |
| 25 – 50 | 3 | 3.1 – 3.5 | 3 |
| 10 – 24 | 2 | 2.1 – 3.0 | 2 |
| 0 – 9 | 1 | 0 – 2.0 | 1 |

Source: Adapted from Mason (1991) and Guinot *et al*. (2001)

The overall quality rating (OQR) is derived as: $OQR = \frac{X + Y}{2}$

Additional information on how to use and interpret the results please refer to chapter 2.3.2 “Biological Monitoring of Water Quality”.

**Appendix 9.** Physico-chemical water quality index worksheet, based on 9 parameters

| | Pi | Ci | | | | |
|---|---|---|---|---|---|---|
| **Parameter (mg/L)** | | **100** | **75** | **50** | **25** | **0** |
| | | **Class 1** | **Class 2** | **Class 3** | **Class 4** | **Class 5** |
| **Range of analytical value** | | | | | | |
| **pH** | **3** | 6.5-8.0 | 6.0-6.4/8.1-8.4 | 5.0-5.9/8.5-9.0 | 3.9-4.9/9.1-10.1 | <3.1/>10.1 |
| **EC (µS/cm)** | **2** | 0-500 | 500-1000 | 1000-1500 | 1500-2000 | >2000 |
| **$NH_4^+$-N** | **3** | 0-0.1 | 0.1-0.3 | 0.3-0.9 | 0.9-2.7 | >2.7 |
| **$NO_3^-$-N** | **3** | 0-1.5 | 1.5-4.0 | 4.0-12 | 12-36 | >36 |
| **TP** | **3** | 0-0.02 | 0.02-0.05 | 0.05-0.1 | 0.1-0.2 | >0.2 |
| **DO** | **4** | 7.6-9.6 | 6.5-7.5/9.7-10.8 | 4.3-6.4/10.9-12.9 | 1.7-4.2/13.0-17.2 | <1.7/>17.2 |
| **$Cl^-$** | **2** | 0-50 | 50-150 | 150-300 | 300-620 | >620 |
| **SAR** | **2** | 0-10 | 10-15 | 15-20 | 20-30 | >30 |
| **TSS** | **4** | 0-20 | 20-40 | 40-100 | 100-278 | >278 |

| | |
|---|---|
| **Class 1** | Unpolluted |
| **Class 2** | Good |
| **Class 3** | Fairly polluted or moderate |
| **Class 4** | Polluted |
| **Class 5** | Heavily polluted |

The overall WQI = $\frac{\sum_i Ci \times Pi}{\sum_i Pi}$ ; Ci – normalized value of the parameter; Pi – relative weight assigned to each parameter (varies from 1 to 4)

**WQI:** 0 – 25 --- Very bad; 25 – 50 ---- Bad; 51 – 70 --- Medium; 71 – 90 --- Good; 90 – 100 --- Excellent

WQI method adapted from: Prati *et al.* (1971); Abbasi (2005) and Sánchez *et al.* (2006)

**Appendix 10.** Water quality index worksheet for heavy metals

| | Pi | Ci | | | | |
|---|---|---|---|---|---|---|
| **Parameter** | | **100** | **75** | **50** | **25** | **0** |
| **Range of analytical value** | | **Class 1** | **Class 2** | **Class 3** | **Class 4** | **Class 5** |
| **Hg** | **4** | <0.0001 | <0.0005 | <0.001 | <0.002 | >0.002 |
| **Cu** | **3** | <0.04 | <0.10 | <2.0 | <2.5 | >2.5 |
| **Pb** | **3** | <0.001 | <0.01 | <0.05 | <0.10 | >0.10 |
| **Cd** | **4** | <0.001 | <0.003 | <0.005 | <0.01 | >0.01 |
| **Cr** | **2** | <0.001 | <0.05 | <0.1 | <1.0 | >1.0 |
| **Zn** | **2** | <0.005 | <0.01 | <2.0 | <5.0 | >5.0 |
| **Ni** | **2** | <0.02 | <0.03 | <0.10 | <0.15 | >0.15 |

**Class 1** Unpolluted
**Class 2** Good
**Class 3** Fairly polluted or moderate
**Class 4** Polluted
**Class 5** Heavily polluted

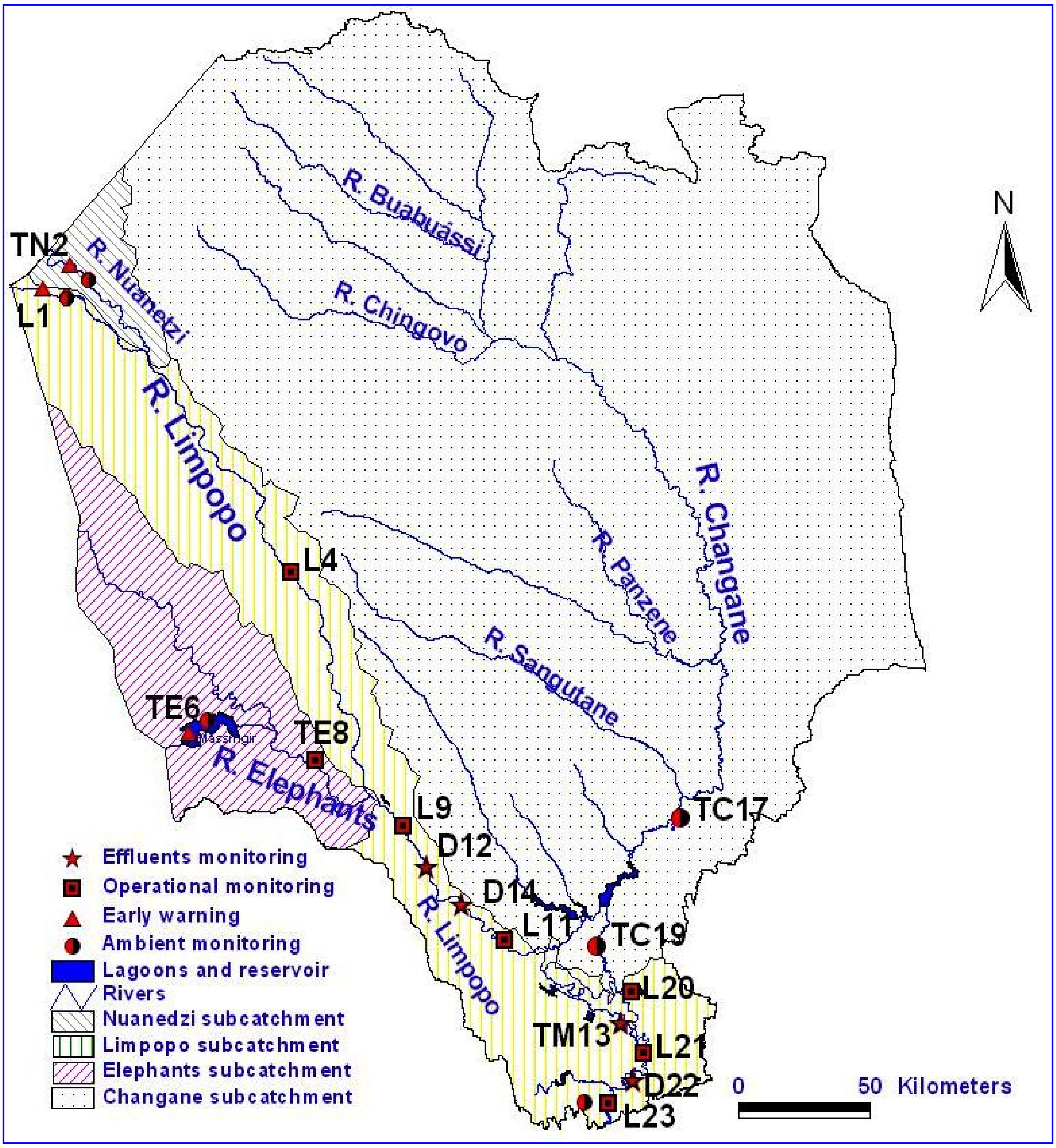
The overall WQI = $\frac{\sum_i Ci \times Pi}{\sum_i Pi}$ Ci – normalized value of the parameter; Pi – relative weight assigned to each metal (varies from 1 to 4)

**WQI:** 0 – 25 --- Very bad; 25 – 50 ---- Bad; 51 – 70 --- Medium; 71 – 90 --- Good; 90 – 100 --- Excellent

**WQI method adapted from:** Garcia *et al.* (2006)

**Classification based on:** North Rhine Westfalia guidelines 1992 (Zabel, 1993); Mozambican water quality guidelines (MICOA, 2004), WHO guidelines (WHO, 2004) and USA EPA WQ guidelines 2006 (USEPA, 2006)

**Appendix 11.** Proposed ambient, operational, effluent and early warning monitoring sites



**Appendix 12.** Multiple correlations between physico-chemical parameters

| Parameters | Temp. | EC | TDS | DO | pH | $NH_4$-N | TH | $Cl^-$ | SAR | $Mg^{2+}$ | $Ca^{2+}$ | $Na^+$ | TSS | Cd | Cu | Pb | Zn | Fe | TP |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Temp.** | 1 | | | | | | | | | | | | | | | | | | |
| **EC** | -.661** | 1 | | | | | | | | | | | | | | | | | |
| **TDS** | -.648** | .988** | 1 | | | | | | | | | | | | | | | | |
| **DO** | -.137 | -.093 | -.066 | 1 | | | | | | | | | | | | | | | |
| **pH** | -.280 | -.105 | -.070 | .817** | 1 | | | | | | | | | | | | | | |
| **$NH_4$-N** | -.325 | .198 | .181 | -.464* | -.366 | 1 | | | | | | | | | | | | | |
| **THardness** | -.629** | .787** | .757** | .061 | -.027 | .232 | 1 | | | | | | | | | | | | |
| **$Cl^-$** | -.644** | .988** | .964** | -.075 | -.103 | .144 | .817** | 1 | | | | | | | | | | | |
| **SAR** | -.362 | .828** | .803** | -.297 | -.304 | .151 | .545** | .831** | 1 | | | | | | | | | | |
| **$Mg^{2+}$** | -.552** | .746** | .713** | -.157 | -.102 | .217 | .894** | .759** | .636** | 1 | | | | | | | | | |
| **$Ca^{2+}$** | -.596** | .774** | .741** | -.164 | -.170 | .471(*) | .939** | .777** | .590** | .925** | 1 | | | | | | | | |
| **$Na^+$** | .116 | -.300 | -.281 | .338 | .067 | -.192 | -.305 | -.278 | -.317 | -.609** | -.501* | 1 | | | | | | | |
| **TSS** | .230 | -.369 | -.354 | .083 | .370 | -.173 | -.287 | -.379 | -.381 | -.077 | -.200 | -.487* | 1 | | | | | | |
| **Cd** | -.311 | .250 | .248 | -.083 | -.088 | .163 | .147 | .250 | .262 | .202 | .170 | -.079 | -.286 | 1 | | | | | |
| **Cu** | -.032 | -.195 | -.177 | .060 | .014 | .379 | .074 | -.223 | -.153 | .072 | .167 | .028 | .051 | .096 | 1 | | | | |
| **Pb** | -.279 | .270 | .329 | -.048 | -.057 | -.104 | .114 | .204 | .110 | .083 | .048 | .209 | -.208 | -.127 | -.328 | 1 | | | |
| **Zn** | .044 | .216 | .229 | .014 | .176 | -.121 | -.044 | .202 | .149 | -.012 | -.035 | -.023 | .210 | -.059 | .032 | -.083 | 1 | | |
| **Fe** | .117 | -.080 | -.077 | -.001 | .074 | .049 | -.091 | -.113 | -.011 | .085 | .075 | -.594** | .558** | .036 | .229 | -.252 | -.036 | 1 | |
| **TP** | .298 | -.239 | -.241 | -.485* | -.478* | .292 | -.332 | -.231 | -.091 | -.332 | -.250 | .165 | .017 | .145 | -.212 | -.029 | -.094 | -.090 | 1 |

**Appendix 13.** WHO 2004 guidelines for drinking water (compiled from WHO, 2004

| # | Parameter | Chemical Symbol | unit | Maximum allowable value or concentration |
|---|---|---|---|---|
| **Metals and toxic elements** | | | | |
| 1 | Aluminium | Al | mg/L | <0.2 |
| 2 | Antimony | Sb | mg/L | 0.02 |
| 3 | Arsenic | As | mg/L | 0.01(P) |
| 4 | Barium | Ba | mg/L | 0.7 |
| 5 | Boron | B | mg/L | 0.5 (P) |
| 6 | Cadmium | Cd | mg/L | 0.003 |
| 7 | Chromium | $Cr^{+3}$, $Cr^{+6}$ | mg/L | 0.05 (P) |
| 8 | Cyanides | CN | mg/L | 0.07 |
| 9 | Lead | Pb | mg/L | 0.01 |
| 10 | Mercury | Hg | mg/L | 0.001 |
| 11 | Nickel | Ni | mg/L | 0.02 (P) |
| 12 | Potassium | K | mg/L | No guideline |
| 13 | Selenium | Se | mg/L | 0.01 |
| 14 | Silver | Ag | mg/L | No guideline |
| 15 | Tin | Sn | mg/L | No guideline |
| 16 | Titanium | Ti | mg/L | No guideline |
| 17 | Uranium | U | mg/L | 0.015 (P) |
| 18 | Copper | Cu | mg/L | 2.0 |
| 19 | Iron | Fe | mg/L | 0.3 |
| 20 | Manganese | Mn | mg/L | 0.4 |
| 21 | Zinc | Zn | mg/L | 5.0 |
| **Affecting both human and ecosystem** | | | | |
| 22 | Asbestos | - | - | No guideline |
| 24 | Disinfectant residual | - | mg/L | 0.2 - 0.5 |
| 25 | Faecal Coliform | - | CFU/100 ml | 0 (Absent) |
| 26 | Fluoride | F | mg/L | 1.5 |
| 27 | Hydrogen Sulfide | $H_2S$ | mg/L | No guideline |
| 28 | Molybdenum | Mo | mg/L | 0.07 |
| 26 | Ammonium | $NH_4$ | mg/L | 1.5 |
| 27 | Nitrates | $NO_3$ | mg/L | 50 |
| 28 | Nitrites | $NO_2$ | mg/L | 3 |
| 29 | Phosphates | $PO_{4-}P$ | mg/L | No guideline |
| **Organoleptic** | | | | |
| 30 | Color | - | TCU | 15 |
| 31 | Turbidity (suspended matter) | - | NTU | < 5 |
| 32 | Taste and odor | - | - | Acceptable |
| 33 | Temperature | - | ˚C | No guideline |
| **Hardness and Salinity** | | | | |
| 34 | Dissolved Oxygen | DO | mg/L | No guideline |
| 35 | Total hardness | $CaCO_3$ | mg/L | 500 |
| 36 | Chloride | Cl | mg/L | 250 |
| 37 | pH | - | - | 6.5 - 8.5 |
| 38 | Magnesium | Mg | mg/L | No guideline |
| 39 | Calcium | Ca | mg/L | No guideline |
| 40 | Sodium | Na | mg/L | 200 |
| 41 | Sulfates | $SO_4^-$ | mg/L | 400 |
| 42 | Total dissolved solids | | mg/L | 1000 |

**Appendix 14.** Mozambican standards for receiving waters (Article 10 of Law n. 20/97; MICOA, 2004)

| # | Parameter (chemical symbol) | | unit | Allowable values |
|---|---|---|---|---|
| 1 | Fluctuating material | - | - | Virtually absent |
| 2 | Oils and grease | - | - | Virtually absent |
| 3 | Substances which produce color, odor and turbidity | - | - | Virtually absent |
| 4 | Substances which produce deposits | - | - | Virtually absent |
| 5 | Artificial pigments | - | - | Virtually absent |
| 6 | Substances and conditions which disturb aquatic life | - | - | Virtually absent |
| 7 | Biological oxygen demand | $BOD_5$ at 5 ˚C | mg/L | ≤ 5 |
| 8 | Dissolved oxygen | DO | mg/L | > 6 |
| 9 | Hydrogen potential | pH | - | 6.5 - 8.5 |
| **Other toxic substances** | | | | |
| 1 | Aluminium | Al | mg/L | 1.5 |
| 2 | Ammonium - nitrogen | $NH_4$ - N | mg/L | 0.4 |
| 3 | Antimony | Sb | mg/L | 0.2 |
| 4 | Arsenic | As | mg/L | 0.05 |
| 5 | Barium | Ba | mg/L | 1 |
| 6 | Beryllium | Be | mg/L | 1.5 |
| 7 | Boron | B | mg/L | 5 |
| 8 | Bromine | Br | mg/L | 0.1 |
| 9 | Cadmium | Cd | mg/L | 0.005 |
| 10 | Lead | Pb | mg/L | 0.01 |
| 11 | Cyanide | CN- | mg/L | 0.005 |
| 12 | Residual chloride | Cl- | mg/L | 0.01 |
| 13 | Copper | Cu | mg/L | 0.05 |
| 14 | Total chromium | Cr6+ | mg/L | 0.05 |
| 15 | Tin | Sn | mg/L | 2 |
| 16 | Phenol | $C_6H_5OH$ | mg/L | 0.001 |
| 17 | Soluble iron | Fe | mg/L | 0.3 |
| 18 | Fluoride | Fl- | mg/L | 1.4 |
| 19 | Manganese | Mn | mg/L | 0.1 |
| 20 | Mercury | Hg | mg/L | 0.0001 |
| 21 | Nickel | Ni | mg/L | 0.1 |
| 22 | Nitrates | $NO_3$ | mg/L | 10 |
| 23 | Nitrites | $NO_2$ | mg/L | 1 |
| 24 | Silver | Ag | mg/L | 0.005 |
| 25 | Selenium | Se | mg/L | 0.01 |
| 26 | Sulfides | $H_2S$ | mg/L | 0.002 |
| 27 | Thallium | Tl | mg/L | 0.1 |
| 28 | Uranium | U | mg/L | 0.5 |
| 29 | Zinc | Zn | mg/L | 0.01 |

**Appendix 15.** Mozambican standards for effluent discharges (Article 10 of Law n. 20/97; MICOA, 2004)

| # | Parameter (chemical symbol) | | unit | Maximum allowable effluent discharge |
|---|---|---|---|---|
| 1 | Ammoniac - nitrogen | $NH_3$ - N | mg/L | 10 |
| 2 | Ammonium - nitrogen | $NH_4$ - N | mg/L | 10 |
| 3 | Arsenic | As | mg/L | 0.5 |
| 4 | Benzene | - | mg/L | 0.05 |
| 5 | Biochemical oxygen demand | $BOD_5$ 20 C | mg/L | 50 |
| 6 | Cadmium | Cd | mg/L | 0.1 |
| 7 | Chemical oxygen demand | COD | mg/L | 250 |
| 8 | Chloride | $Cl^-$ | mg/L | 20 |
| 9 | Chromium | $Cr^{6+}$ | mg/L | 0.1 |
| 10 | Total Chromium | - | mg/L | 10 |
| 11 | Cobalt | Co | mg/L | 0.5 |
| 12 | Copper | Cu | mg/L | 0.5 |
| 13 | Fecal Coliform | - | CFU/100 ml | 400 |
| 14 | Fluoride | $Fl^-$ | mg/L | 20 |
| 15 | Iron | Fe | mg/L | < 1 |
| 16 | Lead | Pb | mg/L | 0.1 |
| 17 | Mercury | Hg | mg/L | 3.5 |
| 18 | Nickel | Ni | mg/L | 0.5 |
| 19 | Oils and fat | - | mg/L | 10 |
| 20 | pH | - | - | 6-10 |
| 21 | Phenol | $C_6H_5OH$ | mg/L | 10 |
| 22 | Phosphate | $PO_4$ - P | mg/L | 3 |
| 23 | Silver | Ag | mg/L | 0.5 |
| 24 | Strontium | Sr | mg/L | 1 |
| 25 | Temperature increase | - | ˚C | ≤ 3 |
| 26 | Tin | Sn | mg/L | 2 |
| 27 | Total cyanide | $CN^-$ | mg/L | 2 |
| 28 | Total hydro-chlorcarbons | - | mg/L | 0.5 |
| 29 | Total nitrogen | N | mg/L | 10 |
| 30 | Total pesticides | - | mg/L | < 0.1 |
| 31 | Total suspended solids | TSS | mg/L | 50 |
| 32 | Total toxic metals | - | mg/L | 5 |
| 33 | Trichloroethane | - | mg/L | 0.5 |
| 34 | Trichloroethylene | - | mg/L | 0.5 |
| 35 | Urea | $CON_2H_4$ | mg/L | 0.6 |
| 36 | Zinc | Zn | mg/L | 2 |