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

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Abstract

The measurement of chemical, physical and biological parameters is important for the characterization of streams health. Thus, cost effective and targeted water quality (WQ) monitoring programmes are required for proper assessment, restoration and protection of such streams. This research proposes a WQ monitoring network for the Limpopo River Basin (LRB) in Mozambique located in Southern Africa, a region prone to severe droughts. In this Basin both anthropogenic and natural driven processes, exacerbated by the increase water demand by the four riparian countries (Botswana, South Africa, Zimbabwe and Mozambique) are responsible for the degradation of surface waters, impairing their downstream use either for aquatic ecosystem, drinking, industrial or irrigation. Hence, physic-chemical, biological and microbiological characteristics at 23 sites within the basin were studied in November-2006 and January-2007. The assessment of the final WQ condition at sampled points was done taking into account the Mozambican guidelines for receiving waters and the environmental WQ standards for effluent discharges together with the WHO guidelines for drinking WQ. The assessed data indicated that sites located at proximities to the border with upstream countries were contaminated with heavy metals. The Elephants subcatchment was found with a relatively better WQ whereas the Changane subcatchment together with the effluent point discharges were found polluted as indicated by the low dissolved oxygen and high total dissolved solids, electric conductivity, total hardness, sodium adsorption ratio and low benthic macroinvertebrates taxa. Significant differences ($p<0.05$) were found for some parameters when the concentrations recorded in November and January were tested, therefore indicating possible need for monthly monitoring of WQ. From this study it was concluded that a systematic WQ monitoring network composed of 16 stations would fit the conditions of the LRB. Ambient, earl warning, operational and effluents are the main monitoring types recommended. Additional research at a Basin scale was

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also recommended to identify the major sources, transport and impacts to the downstream ecosystem.

Key Words: Environmental flows, Limpopo River Basin, water quality monitoring, water management

1. Introduction

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 worldwide 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 for the assessment, restoration and protection of aquatic systems (Ouyang, 2005). In the Southern African Development Community (SADC), even though 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 one of the SADC countries deprived from a well-structured, optimal and established water quality monitoring network, although its high downstream vulnerability in relation to deterioration of surface water quality (Hirji *et al.*, 2002), 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 an international river basin shared with other three SADC countries *viz*. South Africa, Botswana and Zimbabwe (Ashton *et al.*, 2001) is one of the basins deprived from a monitoring network in Mozambique, 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 basin.

Previous studies have reported an increase on the pollutants load in the basin derived from upstream and downstream activities such as: mining; increase of impoundments and water abstraction; agriculture; industrial and discharge of domestic untreated wastewater (DNA, 1994; Louw and Gichuki, 2003). The combined effects of such factors, resulted 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).

Consequently, the design and establishment of water quality programmes 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 provides water for the biggest irrigation scheme in the country, *i.e.* 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).

The aim of the present study was to develop a downstream water quality monitoring network in Mozambique in order to support the surveillance activities around water quality management at local, national and regional levels. In addition, the intent was to satisfy the traditional monitoring objectives of tracking water quality distribution and variation as well as evaluate the different sources of pollution in the river and its tributaries. The assessment was applied to the Limpopo River Basin, the second largest river basin in Mozambique, in order to device an improved and optimal water quality monitoring scheme for the river.

2. Fundamentals of Design Methodology

To accomplish the design and establishment of the water quality monitoring network, the concept of monitoring cycle developed by United Nations Economic Commission for Europe (UN/ECE) was taken into account. According to this concept 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 in light with the required information product as well as the preceding part of the chain (Ward *et al.*, 2004). 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.

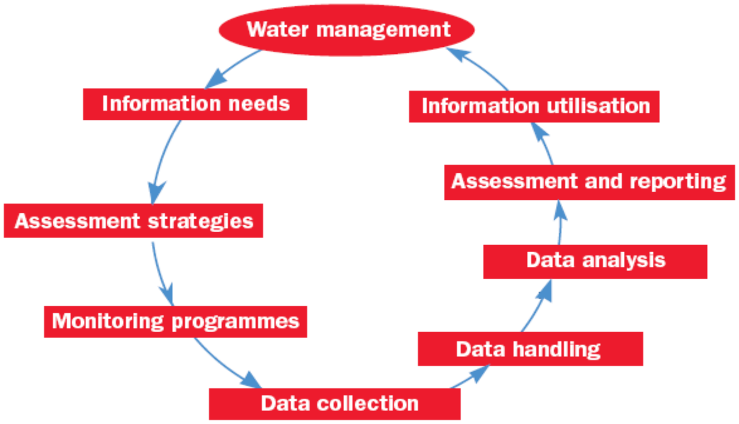

Figure 2.1. Monitoring cycle (UN/ECE, 2000)

According to the UN/ECE monitoring cycle 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 compilation (Ward *et al.*, 2004). The following steps include the validation of the data generated by the monitoring programmes, its storage but simultaneously 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, NGO's, decision makers, farmer associations, public and other relevant stakeholders).

3. Materials and methods

3.1. Site Description

The Limpopo River Basin, the second largest river basin in Mozambique in the east of Southern Africa between approximately latitudes 20°S - 26°S and longitudes 25°E - 35°E. The River drains an area of about 413 000 km^2 (FAO-SAFR, 2004), its main stream within Mozambique is 562 km long (Fig. 3.1). The basin straddles four countries, *viz.* South Africa (RSA) (47%), Botswana (17.7%), Zimbabwe (16%) and Mozambique (19.3%). In Mozambique Three major tributaries join the main course of the Limpopo 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) and the Elephants River which joins the Limpopo River after the Massingir reservoir (Louw and Gichuki, 2003).

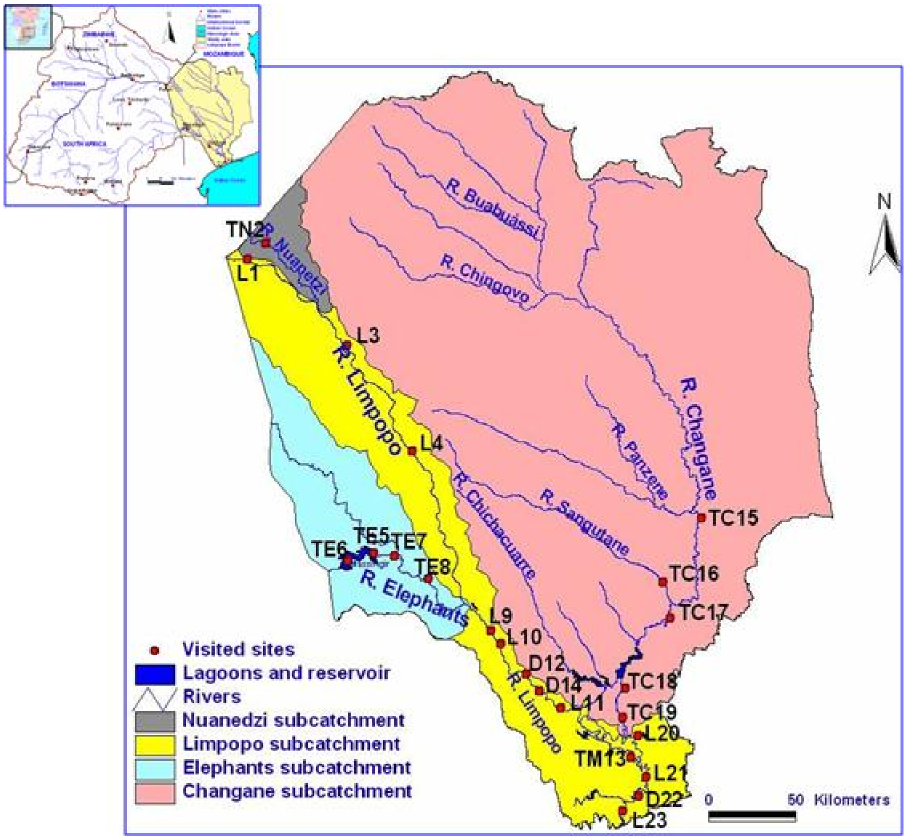

Figure 3.1. Map of the Limpopo River Basin in Mozambique and position of the sampled stations

Rainfall varies dramatically across the basin, from 860 mm year^{-1} near the coast to less than 30 mm year^{-1} in the arid central regions. 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 precipitation in Mozambique occurs between October and March, in a number of isolate rain days and isolated locations, characterizing the cyclic seasonal, erratic and unreliable precipitation (cyclic droughts and floods events) (Amaral and Sommerhalder, 2004). The total annual runoff generated in Mozambique is about 400 Mm^3 $year^{-1}$. 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) are operational (DNA, 1996) where readings of hydrometric heights, discharges are performed. The water quality monitoring is currently irregularly done in 11 stations within the Limpopo River Basin.

3.2. Analytical Methods

Measurement of the selected parameters was carried out in 23 sites both in the field and in the laboratory in November 2006 and January 2007. The covered subcatchments rivers were the Nuanedzi, Elephants, Changane and the main course of Limpopo River. Water temperature, pH value, dissolved oxygen and electrical conductivity were measured immediately on spot using portable equipments (WTW). In addition the “LASA 100 Dr. Lange Fieldkit” equipment was used to assess nutrients (ammonia, nitrate and ortho-phosphate) in samples filtered with GF Whatman filters (110 mm).

The concentrations of the other chemical components of water were determined in the laboratory, according to the recommended analysis methods (APHA/AWWA/WPCF, 1985) whenever possible. Generally, composite samples were grabbed in running water, perpendicular to the flow at a depth varying from 10-20 cm below the water surface with means of a 500 ml polyethylene cup or sterilized glass bottles. 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. The samples for fecal coliforms analysis were taken to the laboratory on the first 12 hours after collection, while those meant for chemical analysis were taken in an interval ranging from 2 to 6 hours.

Furthermore, samples analyzed for heavy metals were transported and analyzed within 30 days after collection. The analytical procedures are here reported in brief, all according to APHA/AWWA/WPCF (1985) procedures:

- Ca^{2+}, Cl^- and total hardness concentrations were quantified titrimetrically;
- Mg^{2+} and Na^+ concentrations were measured photometrically;
- Total dissolved solids were determined through drying at 180 °C;
- The faecal coliforms were analyzed through a membrane filter technique;
- Heavy metals (Cu, Zn, Fe, Cr, Hg, and Pb) were determined by using an atomic-absorption spectrophotometer AAS PE3110 on raw samples.

4. Results

4.1. Limpopo Subcatchment

The results of the analytical data measured at 9 sites along the Limpopo subcatchment are summarized in Table 4.1. At most of the sampling points along this subcatchment, the physico-chemical parameters were found meeting the Mozambican and the WHO standards. The pH values on the sampled months varied from 7.7 – 8.7, with a mean of 8.2 ± 0.2 ($p<0.05$); 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 studied period.

Table 4.1. Characteristics of Limpopo subcatchment waters; mean values are given with their 95% confidence interval.

Parameters	**November 2006**			**January 2007**		
	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 sampled period indicate that the highest concentrations were observed in November, compared to January, and there was a slight increasing trend from upstream to downstream sites (L1 to L23). 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). Its proximity to the river mouth and thus possible impacts of ocean tides seem to have effect on the recorded concentrations.

Analysis for total metals (Figure 4.1) revealed that zinc (Zn), copper (Cu), cadmium (Cd) and Iron were present in all sampled sites and in concentrations higher that the Mozambican standards, except for sites, L20 (for zinc), L20, L21 and L23 (for copper). Lead was identified in two sites (L1 and L23) with concentrations higher than the standards (>0.01 mg/L). Although not pronounced, all heavy metals exhibited a declining trend when shifting from upstream sites toward the river mouth. 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.

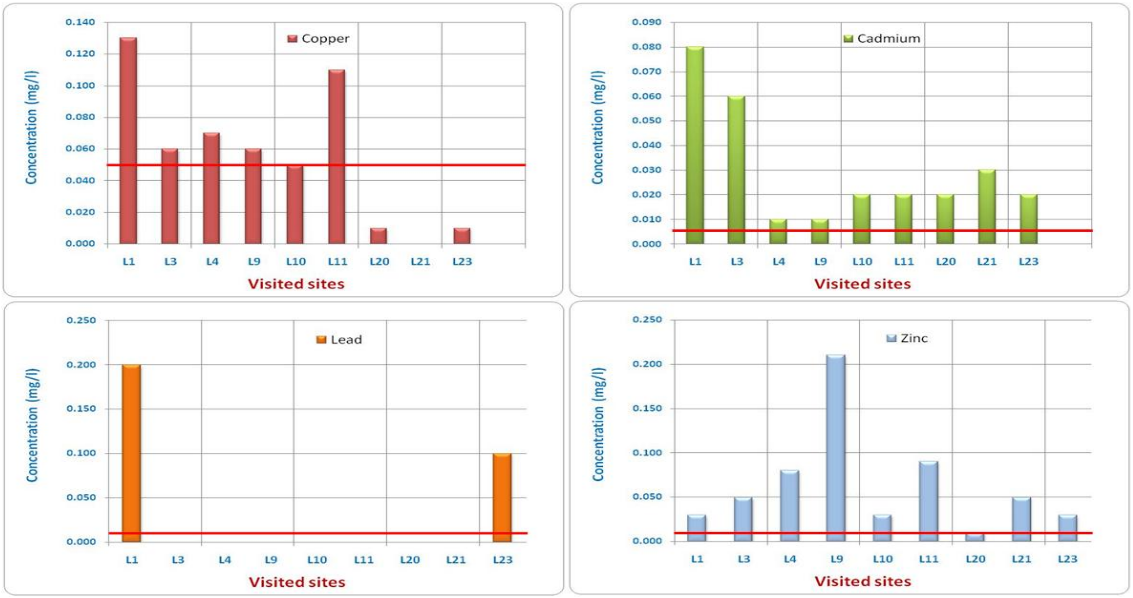

Figure 4.1. Spatio-temporal variability of the WQ in the Limpopo subcatchment. *The horizontal red/bold line indicates the Mozambican standards*.

The sodium adsorption ratio an important indicator of water quality for irrigation was found high (>10) at most of the sampled sites along the Limpopo River and did not transmit a clear trend towards river mouth. The recorded values revealed a potential risk for soils sodicity derived from the use of water for irrigation. Total hardness (TH) results indicated 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.

In addition, the results for the major nutrients that contribute to eutrophication were found lower when compared to the Mozambican and WHO standards. However, risks for eutrophication due to phosphorus were observed on site L9 (Macarretane dam reservoir, upstream Chókwè), with concentrations higher than 0.60 mg/L of phosphorus. At this site, is admitted that the dam is acting as a sink of suspended matter and thus trapping nutrients.

4.2. Elephants and Nuanedzi Subcatchments

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 standards for receiving waters, except in November for the SAR at site TE7, where the ratio was found high (>10) (Table 4.2). 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 variation on water quality parameters since its discharges were more or less constant and always made from the bottom layers. Sound increases of chloride were observed in January on sites TE7 and TE8, while the SAR values dropped at same sites.

Just as in the Limpopo subcatchment generally the nutrients assessed at these subcatchments were found in lower concentrations when analysed against the Mozambican and WHO standards. Contamination with phosphorus was spotted in three sites (TN2, TE5 and TE6), representing possible risks for eutrophication, since the concentrations were >0.03 mg/L. The occurrence of high concentrations on sites TE5 and TE6 both located at the Massingir reservoir indicate possible trapping and sink of nutrients derived from upstream agriculture activities.

Table 4.2. Characteristics of Elephants and Nuanedzi subcatchments waters; mean values are given with their 95% confidence interval.

Parameters	**November 2006**			**January 2007**		
	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

With respect to heavy metals in these subcatchments (Figure 4.2), similar to the Limpopo subcatchment, chromium was not found in any of the assessed sites. Out of the five registered metals, lead was found on sites TN2 (Nuanedzi River) and TE6 (Massingir reservoir), in concentrations higher than the Mozambican standards (>0.10 mg/L). Loads derived from upstream mining activities (South Africa and Zimbabwe) together with natural sources seem to explain the values recorded. Other heavy metals such as Zinc, Copper and Cadmium were also found in concentrations above the Mozambican and WHO standards. Almost all metals exhibited a declining trend toward the confluence with Limpopo main course (*i.e.* from TE6 to TE8). Therefore, monitoring of heavy metals at these catchments seems to be primary, mainly during the high flow conditions due to high sediment transport which may bring bounded metals.

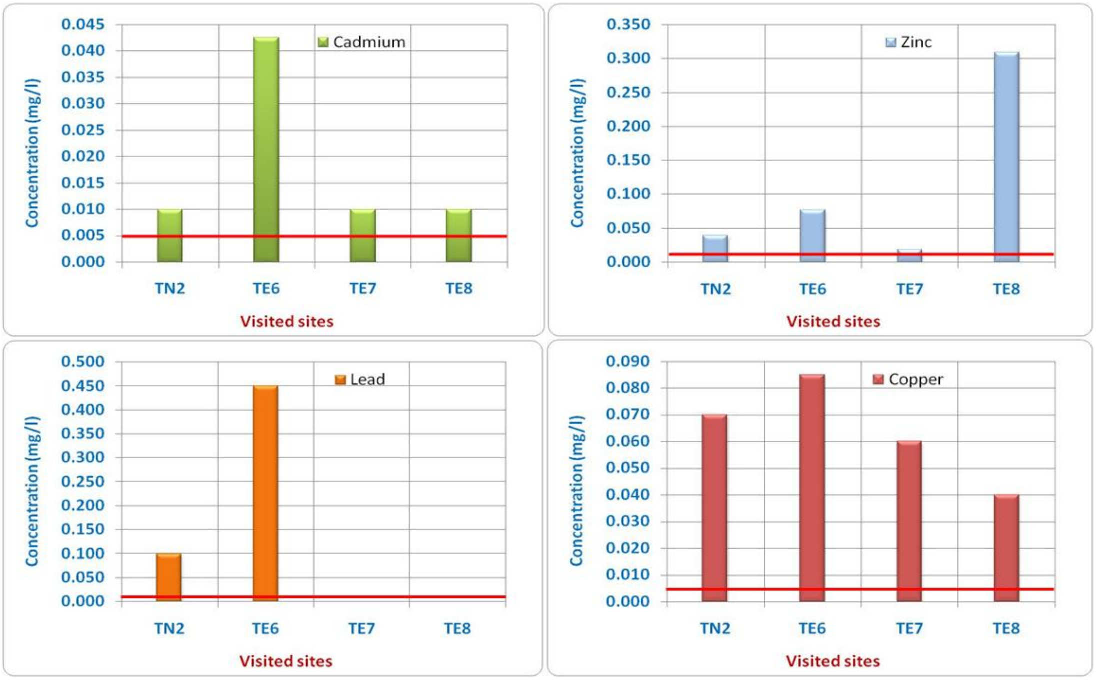

Figure 4.2. Spatio-temporal variability of WQ in the Nuanedzi and Elephants subcatchments. *The horizontal red/bold line indicates the Mozambican standards*.

4.3. Changane Subcatchment

The results at this subcatchment are 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. Differences with other subcatchments were found clear, when analysing the trend of total hardness, TDS, EC, chloride and SAR. 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 Mozambican and WHO standards. Additionally, it was observed that TDS, EC and chloride show an increasing trend from site TC15 to TC17. The natural occurrence of a river bad rich in ions due to natural geology of the area, together with small streams draining at proximities to site TC17 seems to explain the high concentrations observed. In comparison to other catchments the Changane proved to be a natural and primary source of ions (cat and anions). Thus, its monitoring should also be of primary concern for these parameters.

Table 4.3. Characteristics of Changane subcatchment waters; mean values are given with their 95% confidence interval.

Parameters	**November 2006**			**January 2007**		
	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

All metals with exception of iron showed a decreasing trend when the river approaches the confluence with the main course of the Limpopo River. 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 phosphorus, ammonium and nitrate were recorded (Table 4.3). 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.

4.4. Microbiological Pollution Assessment in LRB

The microbiological evaluation along the Limpopo Basin revealed that all assessed media were contaminated with coliforms. 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) revealing that the urban areas are the major sources of contamination. Coliforms counts were >1000 CFU/100 ml on sites L10, L11, D12, TC18, TC19, D22 and L23 during the sampled months, thus not meeting the Mozambican environmental water quality standards for effluent emissions (400 CFU/100 ml, red line in Figure 4.3) and obviously the WHO standards for drinking waters, which is 0 CFU/100 ml.

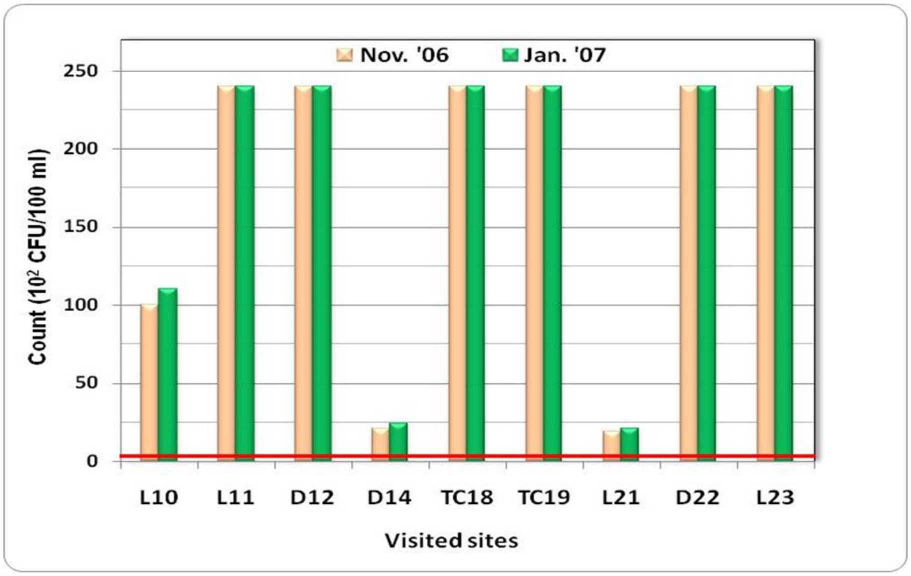

Figure 4.3. Bacterial contamination at Limpopo River Basin

4.5. Biological Assessment of Water Quality in LBR

The assessment of macrobenthic macroinvertebrates was done only in November due to the high water level observed throughout the basin in January. The Hydrobiidae (snails) and Sphaeridae (mussels) were found to be the dominant families (groups) throughout the Basin. Considering the results by sites, different taxa of macroinvertebrates were found, although not in all sites. The lower number of taxa was observed at sites located at downstream Limpopo (1-3 taxa) while the highest taxa were found at sites located upstream Limpopo (4-7). As above mentioned the high Biological Monitoring Working Party

(BMWP) scores (14-31) are shared by sites located upstream Limpopo and Elephants subcatchments. These sites together with the high taxa found were categorized as having “good to excellent water quality”. However, is believed that the number of taxa recorded is very low compared to unpolluted conditions since in these subcatchments heavy metals were found to be the major threats for water quality.

On the other hand, low BMWP scores (3-10) were observed at downstream sites, which include sites in Changane and Limpopo subcatchments, categorized as having “moderate to poor water quality”, consequently exhibiting bad environments for the survival of aquatic organisms.

5. Discussion

5.1. Spatial and Temporal Variation of Water Quality

The results presented in the previous section suggest that the temporal and spatial variability of water quality were both the result of impact of different human activities, hydrological and natural conditions 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 in conditions of a low water level, 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*. 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; Koukal *et al.*, 2004; Skoulikids *et al.*, 2005).

The peak values of TDS, EC, Cl^- and SAR observed at site L23, which is located downstream Xai-Xai city 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). 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 2006) 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.

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 2006 to January 2007 in the 23 sampled sites. The increase of the river discharge in November 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. Nevertheless, parameters such as pH, DO and NH_4^+-N did not experience any significant change during the same period. Yet, under different conditions, similar results were found by other authors (Dallas and Day, 2004; Sánchez *et al.*, 2006; Sarkar *et al.*, 2006).

Table 5.4. 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

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

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) so special attention should be given to its monitoring. 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 discharge (D12, TM13, D14 and D22). The high risks of eutrophication and bacterial contamination imposed by high levels of phosphorus and faecal coliforms 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).

Additionally, the levels of nutrients recorded at sites L1, TN2, L3 and L4, located at proximities to international border, may derive from runoff generated in the upstream neighbouring countries (South Africa and Zimbabwe), since at the proximities to these points in Mozambique, there are no major agricultural activities. This agrees with the suggestion by Sarkar *et al.* (2006) where on their study, they concluded that different levels of 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.

5.2. Overall Water Quality Status

Results obtained by physico-chemical, metals and biological diversity indices between upstream and downstream sites along the Limpopo River Basin are presented in Figure 5.1. 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. Therefore, the overall water quality of a site should take into consideration the “worst scenario”, 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 (74%) in the Limpopo River Basin have fallen within the class of “bad” water quality. The “bad” water quality assigned to sites L1, TN2, TE5, TE6 and TE7 was determined by the heavy metals content. This classification seems to be reasonable, because these sites are located at proximity 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 metal 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 were notably influenced by the BMWP index.

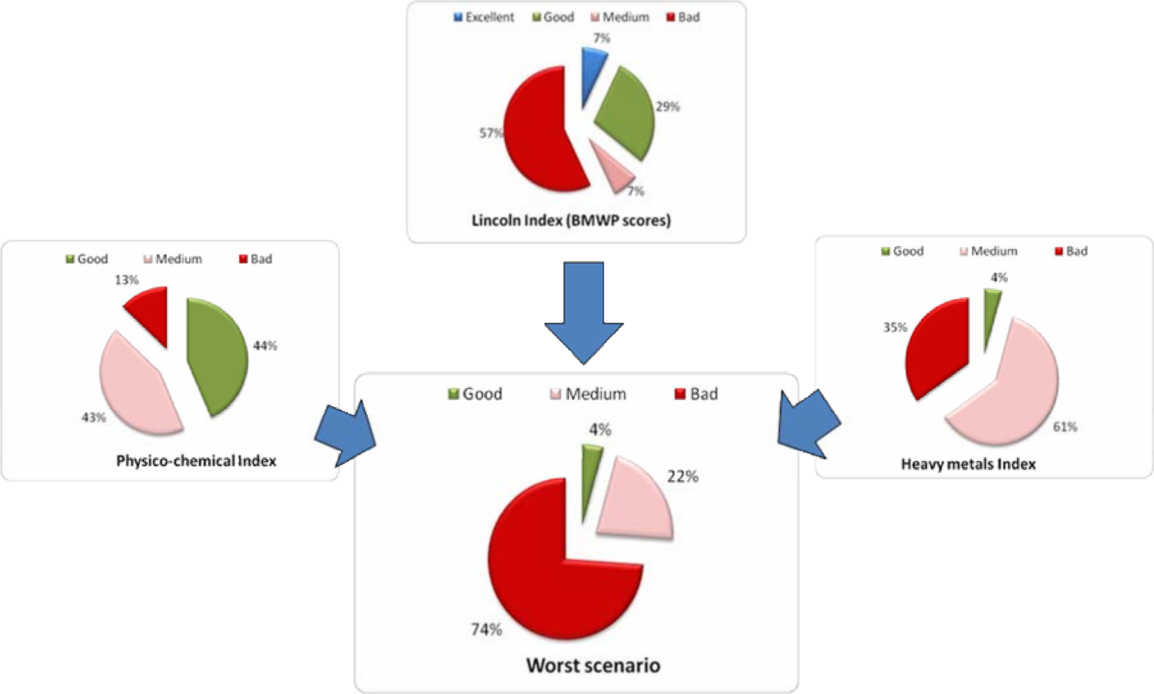

Figure 5.1. Overall water quality assessment (worst scenario approach)

5.3. Proposal of the monitoring network for the LRB

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.

(i) Sampling Stations

The selection of the future sampling sites considered the following major aspects: (i) variability of the sites in terms of water quality characteristics (pollutants concentrations) between the sampled months (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 (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 proposed locations and the selection criteria are presented in Figure 5.2.

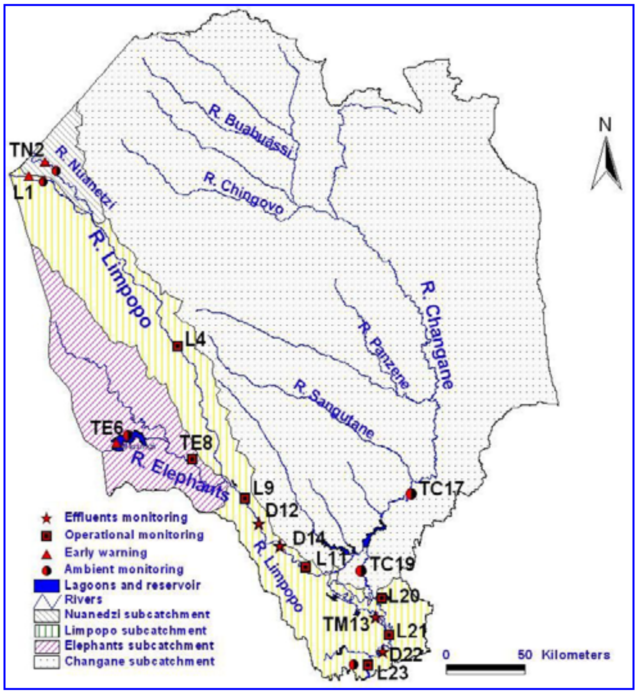

Figure 5.2. Proposed ambient, operational, effluent and early warning monitoring sites

(ii) Monitoring type and objectives

In order to meet the objectives given above, different types of monitoring were proposed for the sampling sites as shown it Table 5.2. The locations of the 16 proposed monitoring stations were compared with those in the existing network. In all, about 7 of the 16 proposed station locations coincided with existing monitoring sites; the remaining 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.

Table 5.2. 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

		▪ Tests and adequate water quality standards ▪ Calculation of loads ▪ 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; Bartram and Ballance, 1996; Chapman, 1996)

**Require additional investigation to recommend representative and sensitive organisms

(iii) Parameters and Measurable Variables

The selection of parameters was based on the results of the multiple correlations 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 5.3 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 (Table 5.2). 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 5.3. 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 coliforms 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 coliforms
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 coliforms 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

(iv) Monitoring Frequency

For the operationalization of the proposed water quality monitoring network is recommended 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 5.3) 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). 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.

(v) Costs of the Monitoring Network

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.

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).

6. Conclusions and Recomendations

i. Water quality in the LRB was found deteriorated and not meeting the guidelines for potability;
ii. Heavy metals (Elephants subcatchment), ions (Changane subcatchment) and faecal coliforms were found as the major threats;
iii. The Combination of biological Index (BMWP), physic-chemical WQI and metals WQI was found adequate to qualify water at LRB conditions;
iv. A monitoring network composed by 16 sites with hydrological, physical, chemical and biological parameters can be implemented in the Basin.
v. Studies at basin level should be promoted to understand the sources and fate of pollutants;
vi. Further studies need to address the transport of ions at Changane subcatchment to assess impacts for water deterioration downstream;
vii. Need to control pathogenic contamination on row and discharged water. Most of it is directly used without treatment;
viii. Management of water in LRB should consider EF requirements, because is vital for preservation of river ecosystem (e.g. mangroves, wetlands, etc.).

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References

Amaral, H. and R. Sommerhalder (2004). The Limpopo River Basin – Case Study on Science and Politics of International Water Management. ETH – Zurich.

APHA/AWWA/WPCF (1985). Standard Methods for the Examination of Waters and Wastewaters 16th ed. Washington, DC, USA.

Ashton, P.J.; D. Love; H. Mahachi and P.H.G.M. Dirks (2001). An Overview of the Impact of Mining and Mineral Processing Operations on Water Resources and Water Quality in the Zambezi, Limpopo and Olifants Catchments in Southern Africa. Contract Report to the Mining, Minerals and Sustainable Development (Southern Africa) Project, by CSIR-Environmentek, Pretoria and Geology Department, University of Zimbabwe - Harare. Report No. ENV-P-C 2001-042.

Bartram, J. and R. Ballance (1996). Water Quality Monitoring – A practical guide to design and implementation of freshwater quality studies and monitoring programmes UNEP and WHO. London.

Chapman, D. (1996). Water Quality Assessments – A guide to the use of biota, sediments and water in environmental monitoring. Second edition. UNESCO, WHO and UNEP. London.

Dallas, H. F. and J. A. Day (2004). The Effect of Water Quality Variables on Aquatic Ecosystems: A Review. Report to the Water Research Commission by Freshwater Research Unit. University of Cape Town. Cape Town.

David, C. and O. Hulea (2000). Water Quality Monitoring in the Danube Delta. In: Proceedings – International Workshop on Information for Sustainable Water Management by J. G. Timmerman, W. Cofino, R. Enderlein, W. Julich, P. Literathy, J. Martin, P. Ross, N. Thyssen, R. Turner and R. Ward (eds): 429-435. Monitoring Tailor – Made III. Nunspeet.

DNA (1994). Actual Situation of water Resources Management in Mozambique – Final draft. Ministry of Public Works and Housing. Maputo.

DNA (1996). Monografia hidrográfica da bacia do rio Limpopo – Texto. Direcção Nacional de Águas – Ministério de Obras Públicas e Habitação. Maputo.

DNA (1999). Water Resources of Mozambique – SYNOPSIS 1999. Ministry of Public Works and Housing. Cooperation Portugal-Mozambique. Maputo.

DNA/ARA-Sul (2006). Salt Balance Study of the Lower Elephants and Limpopo Rivers. Documento de apoio para o Seminário. Prepared by Consulted and Coba. Maputo - Mozambique

DWAF (2004). Strategic Framework for National Water Resource Quality Monitoring Programmes by D. C. Grobler and M. Ntsaba. Report No.

N/0000/REQ0204. Resource Quality Services - Department of Water Affairs and Forestry. Pretoria.

El-Sayed, A. (2000). Effect of the River Nile Flow Regime on the Drainage Water Quality of the Nile Delta. In: Proceedings – International Workshop on Information for Sustainable Water Development by J. G. Timmerman, W. P. Cofino, R. E. Enderlein, W. Jülich, P. Literathy, J. M. Martin, P. Ross, N. Thyssen, R. K. Turner and R. C. Ward: 251-258. Monitoring Tailor – Made III. St. Michielsgestel.

Falkenmark, M. and J. Rockström (2004). Balancing Water for Humans and Nature – The New Approach in Ecohydrology. Earthscan. London.

FAO-SAFR (2004). Drought Impact Mitigation and Prevention in the Limpopo River Basin – A Situation Analysis. Sub-Regional Office for Southern Africa/Harare. Rome.

Hirji, R., P. Johnson and T. M. Chiuta (eds) (2002). Defining and Mainstreaming Environmental Sustainability in Water Resources Management in Southern Africa. SADC, IUCN, SARDC, World Bank: Maseru/Harare/Washington DC.

Koukal, B.; J. Dominik; D. Vignati; P. Arpagaus; S. Santiago; B. Ouddane and L. Benaabidate (2004). Assessment of water quality and toxicity of polluted Rivers Fez and Sebou in the region of Fez (Morocco). Elsevier – Environmental Pollution **131**:163-172.

Kristensen, P. and J. Bøgestrand (1996). Surface water quality monitoring. European Environmental Agency – European Topic Centre on Inland Waters. Copenhagen. [Web].http://reports.eea.europa.eu/92-9167-001-4/en/TopicReportNo02-1996.pdf [Date of access: 21 September 2006].

Louw, A. and F. Gichuki (2003). Limpopo Basin Profile: Strategic research for enhancing agricultural water productivity; [Web].http://www.waterforfood.org. [Date of access: 08 September 2006].

Mäkelä, A. and M. Meybeck (1996). Designing a Monitoring Programme. In: In: Water Quality Monitoring by J. Bartram and R. Ballance (eds). Water Quality Monitoring – A practical guide to design and implementation of freshwater quality studies and monitoring programmes UNEP and WHO. London.

Maran, S. (2004). Environmental Flows and Integrated Water Resource Management: The Vomano River case study. Mediterranean case study. IUCN Mediterranean office.

Muschal, M. (2005). Assessment of risk to aquatic biota from elevated salinity – A case study from the Hunter River, Australia. Elsevier – Journal of Environmental Management **79**:266-278.

Newham, L.; B. Croke and A. Jakeman (2001). Design of Water Quality Programs and Automatic Sampling Techniques. The Australian National University –

Centre for Resource and Environmental Studies. Canberra. [Web]. http://eprints.anu.edu.au/archive/00000648/00/hs_wq.pdf. [Date of access: 23 September 2006].

Ngoye, E. and J. F. Machiwa (2004). The influence of land-use patterns in the Ruvu river watershed on water quality in the river system. Elsevier – Physics and Chemistry of the Earth **29**:1161-1166.

Ongley, E. D. and E. B. Ordoñez (1997). Redesign and modernization of the Mexican water quality monitoring network. Water International, **Vol.22**, **N°. 3**:187-194. Reprinted with permission from the International Water Resources Association.

Ouyang, Y. (2005) Evaluation of river water quality monitoring stations by principal component analysis. Elsevier – Water Research **39**:2621-2635. Florida.

Park, S.; J. H. Choi; S. Wang and S. Park (2006). Design of a water quality monitoring network in a large river system using the genetic algorithm. Elsevier – Ecological Modelling. Florida.

Sánchez, E.; M. F. Colmenarejo; J. Vicente; A. Rubio; M. G. García; L. Travieso and R. Borja (2006). Use of the water quality index and dissolved oxygen deficit as simple indicators of watersheds pollution. Elsevier – Ecological Indicators **7**:315-328.

Sanders, T.; R. Ward; J. Loftis; T. Steele; D. Adrian and V. Yevjevich (1983). Design of Networks for Monitoring Water Quality. Water Resources Publications. Colorado.

SARDC (2003). Limpopo River Basin – Factsheet 1. SADC Water Sector. [Web]. http://www.sardc.net/imercsa/Limpopo/pdf/Limpopo1.pdf [Date of access: 21 September 2006].

Sarkar, S. K.; M. Saha; H. Takada; A. Bhattacharya; P. Mishra and B. Bhattacharya (2006). Water quality management in the lower stretch of the river Ganges, east coast of India: an approach trough environmental education. Elsevier – Journal of Cleaner Production XX (1-9).

Simeonov, V.; J. A. Strabis; C. Samara; G. Zachariadis; D. Voutsa; A. Anthemidis; M. Sofoniou and Th. Kouimtzis (2003). Assessment of the surface water quality in Northern Greece. Elsevier – Water Research **37**:4119-4124.

Singh, K. P.; A. Malik; D. Mohan and S. Sinha (2004). Multivariate statistical techniques for the evaluation of spatial and temporal variations in water quality of Gomti River (India) – a case study. Elsevier – Water Research **38**:3980-3992.

Skoulikidis, N. T.; Y. Amaxidis; I. Bertahas, S. Laschou and K. Gritzalis (2005). Analysis of factors driving stream water composition and systhesis of management tools – A case study on small/medium Greek catchments. Elsevier – Science of the Total Environment **362**:205-241.

Uczciwek, M. L. and T. Zan (2004). Developing Transboundary Monitoring Strategy for the Bug River (Achievements Under the UNECE Bug Pilot Project). In: Proceedings – Information to support sustainable water management: from local to global levels by J. G. Timmerman, H. Willem, A. Behrens, F. Bernardini, D. Daler, P. Ross, K. J. M. van Ruiten and R. C. Ward: 195-206. Monitoring Tailor – Made IV. St. Michielsgestel.

UN/ECE (2000). Guidelines on Monitoring and Assessment of Transboundary Rivers. Task Force on Monitoring and Assessment. RIZA.

UNEP/GEMS (2005). Operational Guide for Data Submission – Version 4. Ontario. [Web].http://www.gemswater.org/common/pdfs/op_guide_for_data_2005.pdf [Date of access: 30 September 2006].

Vaz, A. C. (2000). Coping with floods – the experience of Mozambique. 1st WARFSA/WaterNet Symposium: Sustainable Use of Water Resources. Maputo, 1-2 November.

Ward, R. C., J. G. Timmerman, C. A. Peters and M. Adriaanse (2004). In search of a common water quality monitoring and terminology. In: Proceedings – Information to support sustainable water management: from local to global levels by J. G. Timmerman, H. Willem, A. Behrens, F. Bernardini, D. Daler, P. Ross, K. J. M. van Ruiten and R. C. Ward: 195-206. Monitoring Tailor – Made IV. St. Michielsgestel.

WHO (2004). Guidelines for drinking – water quality. 3rd Edition – Vol. 1. Recommendations. Geneva.