Evaluation of seasonal patterns of water quality in the Zambezi River Basin, using Zambezi River Authority (ZRA) data of 2011

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Abstract

The study reports the seasonal variation of the water quality, along Lake Kariba, Zambezi River and its tributaries in 2011. To evaluate the water pollution quality, the following ten parameters were analysed: water temperature, pH, Electroconductivity (EC), Dissolved Oxygen (DO), Total Dissolved Solids (TDS), Total Suspended Solids (TSS), alkalinity as $CaCO_3$, turbidity, Total Phosphorus (TP), and ammonia-nitrogen (NH_3-N). The study found that water quality along the Zambezi River and its tributaries was most polluted in the Late Rain Season (LRS), that is, January to March, with a Water Pollution Index (*WPI*) of 4.02. The water quality was least polluted during the Late Dry Season (July to September) with a *WPI* of 0.44. It is also made clear that the water exiting Lake Kariba is generally free of any significant pollution across all seasons.
Key words: Zambezi River, Lake Kariba, seasonal variation of water quality, water pollution index

1. Introduction

The Zambezi is the fourth-longest river in Africa, and the largest flowing into the Indian Ocean. The area of its basin is 1,570,000 square kilometres. The 2,574 kilometres-long river has its source in Zambia and flows through Angola, along the border of Namibia, Botswana, Zambia, and Zimbabwe, to Mozambique, where it empties into the Indian Ocean (Zambezi River, 2008). Dangerous levels of bacteria have been found in the backwaters of the Zambezi River, where fish have been, recently, found suffering from an unknown and apparently fatal disease (Zambezi river pollution warning, 2007; Magadza, 2006). Pollution of surface and groundwater resources and the atmosphere have become major environmental problems for the Zambezi River Basin. The increase in pollution discharges is largely attributed to urbanisation, increased industrial and agricultural activities, mining and soil erosion. The urban centres produce sewage effluent, industries emit greenhouse gases and other industrial wastes, and the agricultural sector uses fertilisers and other pesticides which all contribute to the pollution of the surface and groundwater resources. In the Zambezi River Basin, gold panning is prevalent resulting in soil erosion and water resources pollution. Mine wastes, if not disposed and managed properly, result in heavy metal water pollution (Tumbare, 2004).

There is an act which mainly deals with the management of the Zambezi River for economic, industrial and social development with particular emphasis on water usage for energy purposes governed by an inter-state Act (with Zimbabwe) called the Zambezi River Authority Act Chapter 467 (Nwasco, n.d.). Much of the basin's waters are used to generate hydroelectric power (HEP) primarily from the two largest human-made lakes, Kariba, 5,250 km^2 holding 156 km^3; and Cabora Basa, 2,739 km^2 holding 56 km^3 (Mpande & Tawanda, 1998). With the river flowing through five countries, there is a likelihood of interstate conflict resulting from mismanagement of the river. Although pollution of water resources has not yet created regional conflicts, the likelihood of such conflict exists in the future. The issue, however, has the potential of becoming a regional problem, particularly regarding pollution from heavy metals, as evidenced by the existence of dichlorodiphenyltrichloroethane (DDT) and heavy metals in Lake Kariba (ibid). The riparian countries, therefore, need to cooperate in formulating and monitoring legislation to prevent such contamination. Furthermore, Mpande and Tawanda (1998) suggest that legislation should include the establishment of limits on effluent as well as punitive measures for offenders. The world over, four principle theories or doctrines have been maintained by riparian states regarding the rights on international waters. 1) The theory of absolute territorial sovereignty maintains that a watercourse states enjoys exclusive authority over the waters of an international watercourse within its territory. 2) According to the theory of absolute territory integrity, a watercourse state has a right to the natural flow of water into its territory. 3) The theory of limited territory sovereignty of a state over its territory is limited by obligation to use the territory in a way that does not cause significant harm to other nations. And lastly 4) according to the theory of community of interests, the physical unity of the watercourse creates a community of interests in the water (Dombrowsky, 2007). It is not very apparent as to which theory guides the management of the Zambezi River amongst the riparian countries. However, the theory of community of interests seems to be at play as evidenced by the recent reference to 'shared water courses' in the protocol on Shared Watercourse Systems in the Southern African Development Community (SADDC) of 1995 (ibid).

It has been stated that the upper part of the Zambezi River is thinly populated by pastoralist farmers and fishermen and that wildlife is sparse; it is remarkably free of pollution (Zambia National Tourist Board, n.d.). However, with the coming of new mines near the source of the river in Kabompo, there is a possibility of new sources of pollution. The pollution in the Kabompo River, which feeds into the Zambezi River, would affect hundreds of thousands of people further downstream. It is the purpose of this study to provide current information (in 2011) about the seasonal variations of the water quality along the Zambezi River. This study therefore is intended to analyse and disseminate hydrological and environmental data and environmental conditions of the Zambezi River, its tributaries and the Lake Kariba.

2. Method

Water quality data of Lake Kariba/Zambezi River and its tributaries were obtained from the Zambezi River Authority (ZRA)-Lusaka. The water samples were collected from January to December in 2011. The samples were collected from 17 locations namely; Victoria Falls, Kariba at Charara area, Lake Kariba at Andora Harbour, Lake Kariba Dam-Wall Downstream, Lake Kariba Dam-Wall Upstream, Lake Kariba at Nyaozda, Lake Kariba at Gatche Gatche, Lake Kariba at Sanyati Mouth, Lake Kariba at Sanyati Mouth-Further, Lake Kariba at B51, Lake Kariba at Manchinchi Bay, Lake Kariba at Ulkrs, Lake Kariba at Crocodile Farm, Deka River, Kalomo River, Quayi and Kanzinze Rivers. Figure 1 shows the study area and the water sampling points.

Diverse methods were used to determine different parameters (actual details about sample handling and the instruments used can be obtained from the ZRA offices in Lusaka). Ten parameters: temperature, pH, electroconductivity (EC), dissolved oxygen (DO), total suspended solids (TSS), total dissolved solids (TDS), alkalinity as $CaCO_3$, turbidity, total phosphorus (TP) and NH_3-N were considered in this study.

The data analysis compared the variation of water quality over a period of one year. The seasons were categorised as follows: October to December-Early Rain Season (ERS); January to March-Late Rain Season (LRS); April to June-Early Dry Season (ERS); July to September-Late Dry Season (LDS). A one-way analysis of variance (ANOVA) was used to analyse season variation in water quality across the four seasons and Post-hoc comparisons using the Tukey's Honestly Significant Difference (HSD) were performed to show which season(s) was significantly different from the others. Furthermore, Pearson correlation (r) was performed on the water parameters to show which parameters correlated over a period of one year. Attempt to group the water quality parameters was done by principal factor analysis (PCA). All the analyses were done by SPSS statistical package version 17.0 (SPSS Inc., Chicago, III). The water quality map was generated by ArcGIS 9.3.

Part of the analysis involved the use of the Nemerow–Sumitomo Water Pollution Index (*WPI*). In this study, 17 different locales along the Lake Kariba, Zambezi River and its tributaries, and 10 different parameters were analysed. The *WPI* was used to evaluate the pattern of pollution by season and location. The function of this method was to standardize the concentration ranges for the parameters such that the different concentration ranges for each water parameter were rescaled by the equation to produce a relative value that lies within a comparable range (Nemerow and Sumitomo, 1970). The *WPI* is a function of relative values (C_i/L_i), where C_i represents the concentration of parameter i and L_i represents the permissible values (PV) of parameter i defined by a regulation.

$$WPI = \text{a function of } (C_i/L_i)\text{'s} \quad \ldots\ldots(1)$$
$$= f\,(C_1/L_1,\ C_2/L_2,\ C_3/L_3 \ldots C_n/L_n)$$

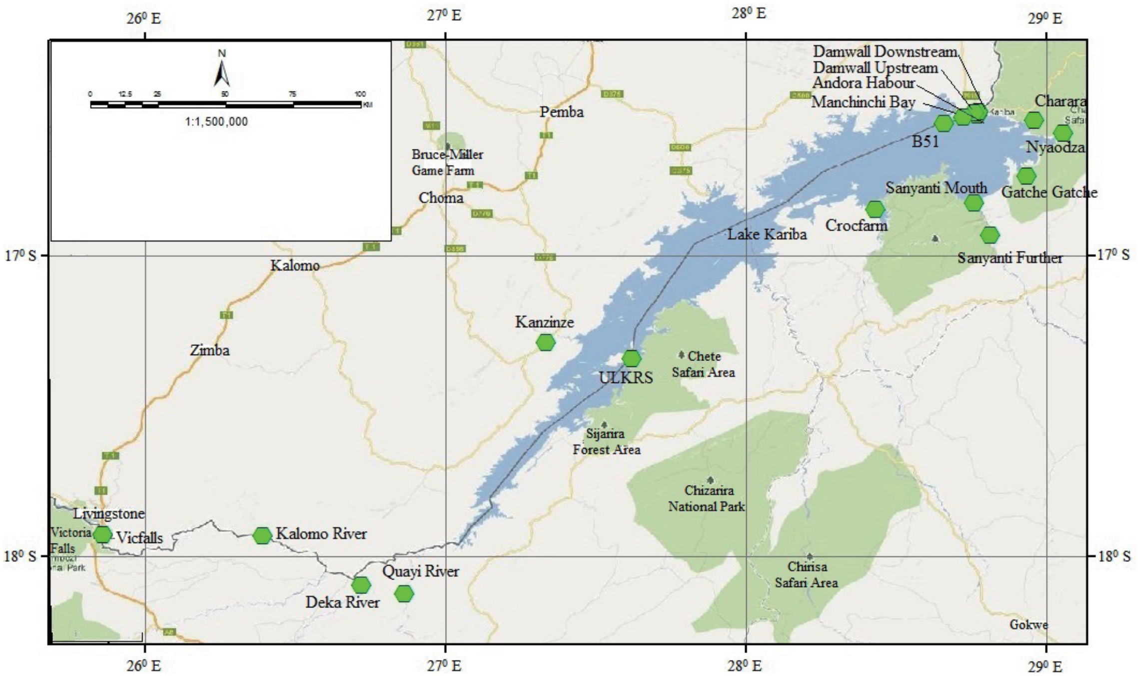

Figure 1. Sampling sites along the Zambezi River, Lake Kariba and its tributaries
Source: Map data ©2012 Google

(i= 1, 2, 3…, n)

Then, the *WPI* for a specific water use j (WPI_j) is further expressed by the following equation:

$$WPI = \sum_{i=1}^{n} \sqrt{\frac{(C_i/L_{ij})^2_{max} + (C_i/L_{ij})^2_{ave}}{2}} \quad \text{.......(2)}$$

Where C_i is the measured concentration of parameter i, L_{ij} is the *PV* for the parameter i determined for water use j, and $(C_i/L_{ij})_{max}$ and $(C_i/L_{ij})_{ave}$ are maximum and average values of C_i/L_{ij} for water use j, respectively.

For the water parameters for which the higher value represents a higher level of pollution, such as turbidity and ammonia-nitrogen, the values of C_i/L_{ij} obtained from the field measurements can be directly calculated using the above equation, with a prerequisite. The prerequisite is that if the value of C_i/L_{ij} obtained from measurement is greater than 1.0, then the C_i/L_{ij} value must be standardized by applying the following equation:

$(C_i/L_{ij})_{new} = 1.0 + x \log (C_i/L_{ij})_{ave}$ ....(3)

Where x is a constant value (as a standard value for a relative comparison, 5.0 is arbitrary employed for x value in the application of the index for the existing pollution).

For the parameters where the lower value represents a higher level of pollution, such as dissolved oxygen (DO), the C_i/L_{ij} values obtained from the field measurements must be standardized by using the following equation:

$$(C_i/L_{ij})_{new} = \frac{C_{im} - C_i}{C_{im} - L_{ij}} \quad \text{.......(4)}$$

Where C_{im} is the saturation value for any parameter at room temperature.

For parameters for which the *PV* (L_{ij}) is defined by a range of numbers, such as for pH, where the *PV* ranges from 6 to 9, a standardized value of C_i/L_{ij} is required, which is calculated by the following equation:

If $C_i \leq$ average L_{ij}

$$(C_i/L_{ij})_{new} = \frac{C_i - (L_{ij})_{ave}}{(L_{ij})_{min} - (L_{ij})_{ave}} \quad \text{.......(5)}$$

If $C_i >$ average L_{ij}

$$(C_i/L_{ij})_{new} = \frac{C_i - (L_{ij})_{ave}}{(L_{ij})_{max} - (L_{ij})_{ave}} \quad \text{.......(6)}$$

Where $(L_{ij})_{min}$ and $(L_{ij})_{max}$ are, respectively, the maximum and minimum values of L_{ij} (e.g., pH: min = 6, max = 9). The $(L_{ij})_{ave}$ is the average value of L_{ij} (e.g., pH: (6 + 9)/2 = 7.5).

Based on chemical loadings relative to their *PVs*, the results from the water samples are classified into 4 categories. The classification used in this study reflects the suitability of the water for human consumption (after low cost treatment e.g. filtration, boiling or chlorination). The *PVs* for effluent and drinking water were used in this study. For example the *PVs* used for EC, alkalinity as $CaCO_3$ and ammonia-nitrogen were for drinking water standards as shown in Table 1 and Table 5. In addition, the *WPI* in this study does take into account of water contamination due to biological activities. So if the water meets the clean water criteria, it may still need some form of treatment (e.g. chlorination) but at a far lower cost.

Utilizing the *PVs* obtained from Environmental Council of Zambia (ECZ) /Zambia Bureau of Standards (ZBS) and WHO as shown in Table 1, the *WPI* was classified into four categories expressing the Zambezi River water pollution levels as listed below.

$0.0 \leq WPI \leq 1.0$ = clean water (meets the *PV* criteria)
$1.0 < WPI \leq 5.0$ = slightly polluted water
$5.0 < WPI \leq 10.0$ = moderately polluted water
$WPI > 10.0$ = highly polluted water

Table 1. Water Parameters and their Corresponding Permissible Values used for the Zambezi River

	No	Parameter	Unit	Permissible value: Drinking Water Quality (ZBS)	Permissible value: ECZ Waste water into Aquatic Environment, 1993
Physical	1	Temperature	°C	nd	40°C at entry point
	2	Electroconductivity	μS/cm	2300	4300
	3	Total Suspended Solids	mg/L	nd	100
	4	Total Dissolved Solids	mg/L	nd	3000
	5	Turbidity	NTU	10	15
Chemical	6	Dissolved Oxygen	mg/L	nd	after mixing > 5
	7	pH		nd	6 - 9
	8	Alkalinity as $CaCO_3$	mg/L	120**	nd
	9	Total Phosphorus	mg/L	nd	1.0
	10	Ammonia	mg/L	1.5*	10.0

ZBS - Zambia Bureau of Standards, NTU.-Nephelometric Turbiduty Units
nd: not determined
*Based on WHO (1993), Levels likely to give rise to consumer complaints
** Based on Lehr (1980)
** Ammonia [mg/L] was converted to ammonia-nitrogen [mg/L] for all calculations

3. Data Analysis

3.1 Analysis of the Boxplots of the Nine Parameters

The individual parameters were analysed using descriptive statistics, where the boxplots were used as a convenient way of graphically depicting the parameters by the seasonal numerical data through the five-number summaries: the smallest observation (sample minimum), lower quartile (Q1), median (Q2), upper quartile (Q3), and largest observation (sample maximum). The boxplots were used to indicate which parameter in a given season, if any, might be considered outliers of the Zambezi River data.

The boxplots display differences between populations without making any assumptions of the underlying statistical distribution as they are non-parametric. The spacing between the different parts of the box help to indicate the degree of dispersion (spread) and skewness in the data, and identify outliers.

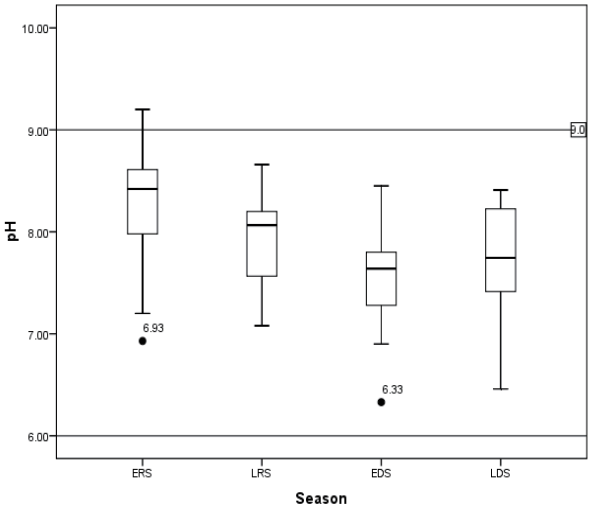

Figure 2. Boxplot for pH

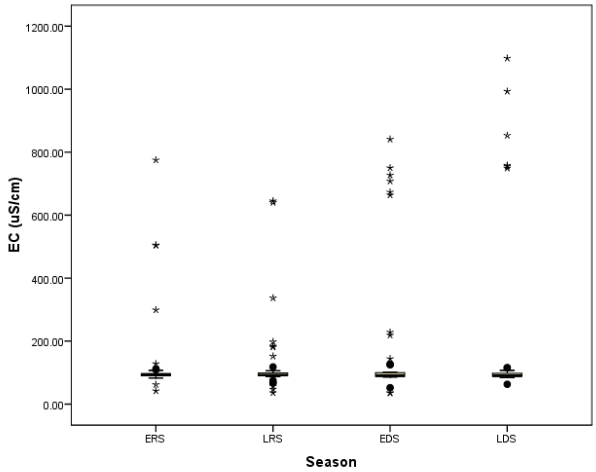

Figure 3. Boxplot for Electroconductivity

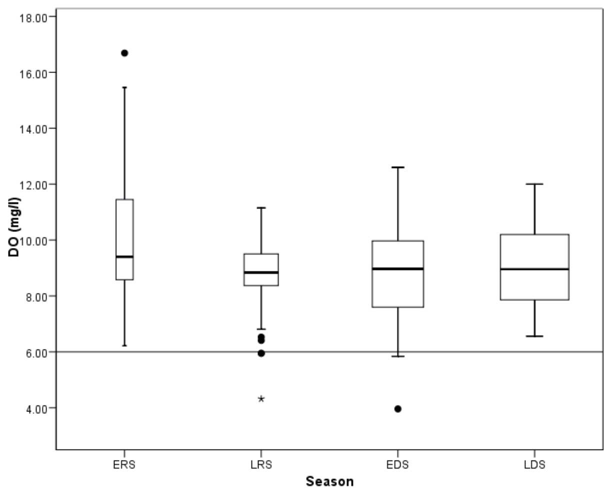

Figure 4. Boxplot for Dissolved Oxygen

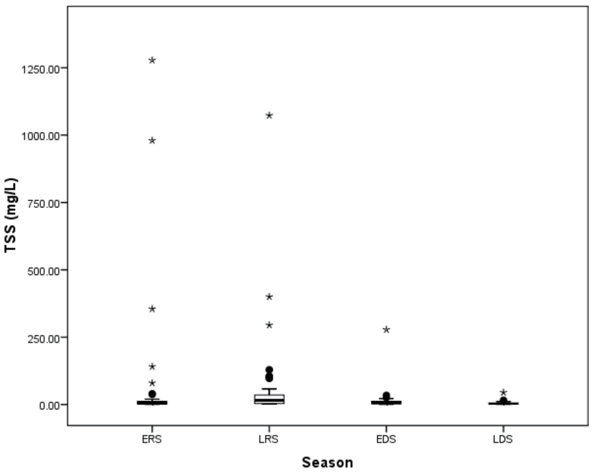

Figure 5. Boxplot for Total Suspended Solids

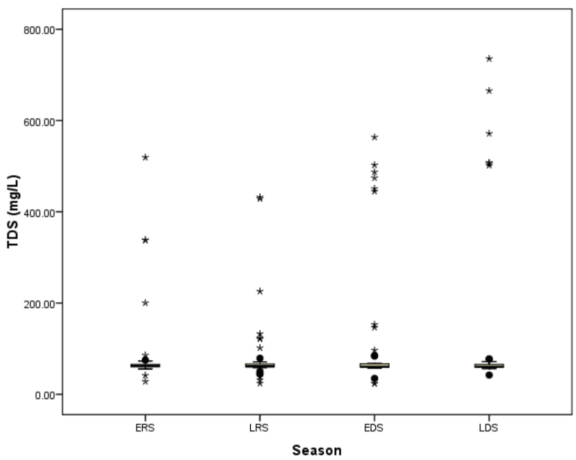

Figure 6. Boxplot for Total Dissolved Solids

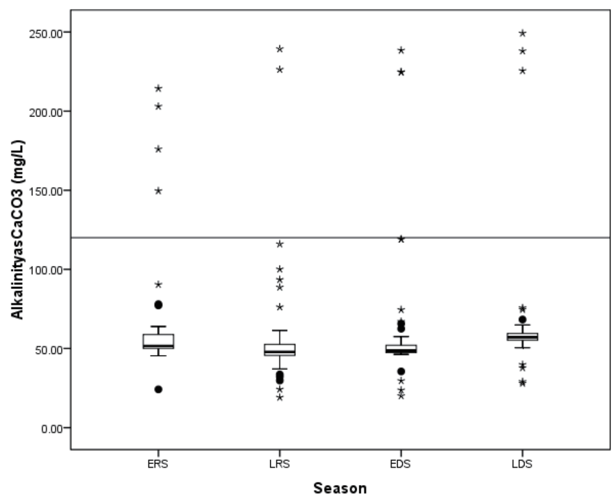

Figure 7. Boxplot for Alkalinity as $CaCO_3$

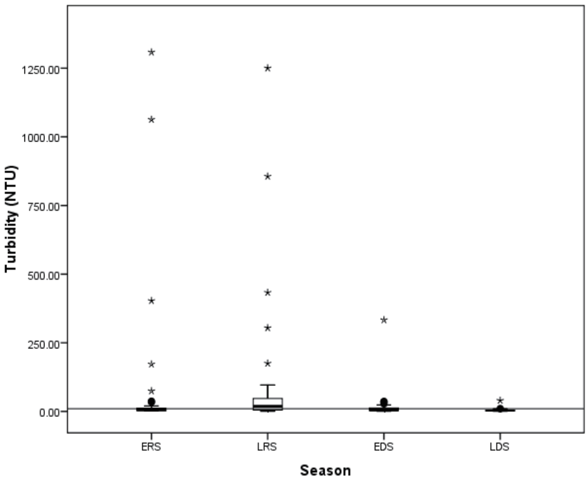

Figure 8. Boxplot for Turbidity

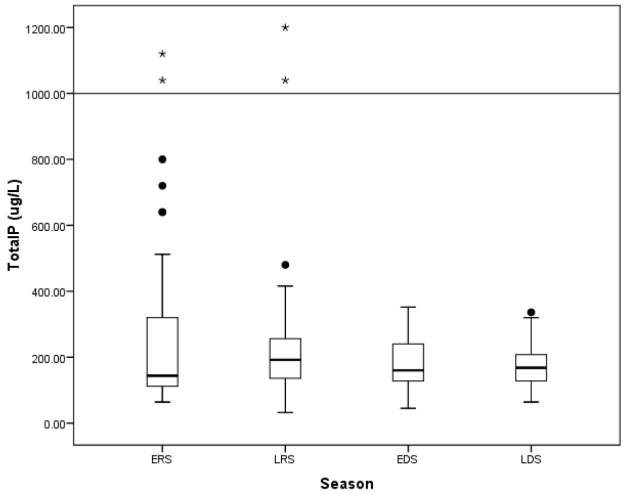

Figure 9. Boxplot for Total Phosphorus

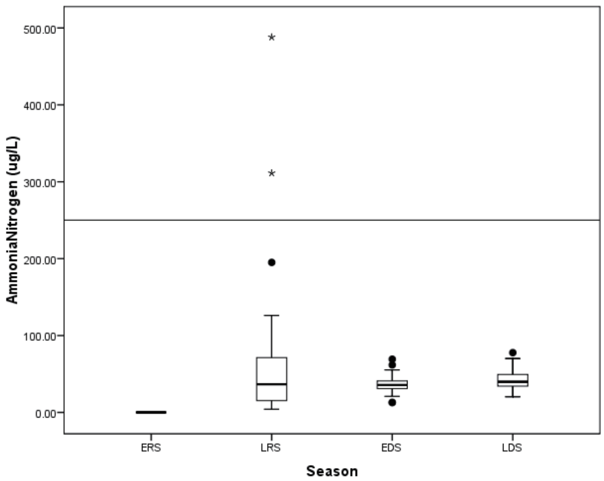

Figure 10. Boxplot for Ammonia-Nitrogen

Boxplots of the individual parameters in the four seasons were examined. Figure 2 to Figure 10 show an example of boxplots for some meaningful variables related to the quality of the Zambezi River, Lake Kariba and its tributaries such as ammonia-nitrogen, DO, and total phosphorus. The line across the box represents the median, whereas the bottom and top of the box show locations of the first and third quartiles (Q1 and Q3). The whiskers are the lines that extend from the bottom and top of the box to the lowest and highest observations inside the region defined by Q1-1.5(Q3-Q1) and Q3+1.5(Q3-Q1), individual points with values outside these limits (outliers) are plotted with asterisks (Vega et al., 1998). Boxplots provide a visual impression and shape of the underlying distributions. For example, boxplots (such as that for turbidity) indicate that the underlying distribution is skewed towards higher levels. Boxplots with large spread indicate large seasonal variations of the water compositions (see pH boxplots). By inspecting these plots it was possible to perceive differences among the four seasons. For example, pH is higher in the ERS (exceeding the effluent water standards of pH 9 in some locations) and lowest in EDS. The high pH in the ERS is probably an indicator of stormy water with high levels of organic material and inorganic nutrients which tend to increase the water pH.

3.2 Principal Component Analysis (PCA)

Principal Component Analysis (PCA) did not find any ambiguity in the component matrix (Table 2). After analysing the rotated matrix, it was even clearer that four components emerged. As shown in Table 2, component 1 (F1) was comprised of Turbidity, TSS, TP and NH_3-N. Component 2 (F2) constituted of EC, TDS and Alkalinity as $CaCO_3$ and the third component (F3) was made up of DO and pH as shown in Table 2. Temperature constituted the last component (F4). Table 3 shows that the four parameters explained 81.37% of the variance.

Table 2. Pattern and Structure Matrix

Pattern Matrix					Structure Matrix				
	Component					Component			
	1	2	3	4		1	2	3	4
Turbidity	.958				Turbidity	.954			
TSS	.918				TSS	.915			
TP	.813				TP	.813			
Ammonia-Nitrogen	.550				Ammonia-Nitrogen	.557			
EC		.963			TDS		.966		
TDS		.963			EC		.966		
Alkalinity as $CaCO_3$		.812			Alkalinity as $CaCO_3$		.810		
DO			.918		DO			.888	
pH			.788		pH			.841	
T				.965	T				.962

Table 3. Total Variance Explained

	Initial Eigenvalues			Extraction sums of squared loadings			Rotation Sums of Squared Loadings
Component	**Total**	**% of Variance**	**Cumulative %**	**Total**	**% of Variance**	**Cumulative %**	**Total**
1	2.916	29.160	29.160	2.916	29.160	29.160	2.756
2	2.479	24.788	53.947	2.479	24.788	53.947	2.590
3	1.674	16.737	70.684	1.674	16.737	70.684	1.694
4	1.069	10.690	81.374	1.069	10.690	81.374	1.273
5	.712	7.125	88.499				
6	.428	4.280	92.779				
7	.382	3.820	96.599				
8	.281	2.812	99.411				
9	.059	.589	100.000				
10	.000	.000	100.000				

Table 4. Pearson Correlation

	T	pH	EC	DO	TSS	TDS	Alkalinity as $CaCO_3$	Turbidity	TP	Ammonia Nitrogen	Season	Location
T	1											
PH	.337**	1										
EC	-.143	.050	1									
DO	-.071	.577**	.172*	1								
TSS	.060	.043	.024	.167*	1							
TDS	-.143	.050	1.000**	.172*	.025	1						
Alkalinity as $CaCO_3$	.144*	.214**	.635**	.184*	.091	.635**	1					
Turbidity	.060	.016	.014	.140	.930**	.015	.077	1				
TP	.089	.068	.045	.190**	.618**	.045	.094	.710**	1			
Ammonia-Nitrogen	-.074	-.146*	.063	-.101	.343**	.063	.064	.390**	.298**	1		
Season	-.571	-.414**	.142	-.180*	-.180*	.142	.032	-.179**	-.216**	.220**	1	
Location	.037	.172*	.497**	.198**	.202**	.497**	.345**	.232**	.242**	.139	.000	1

** Correlation is significant at the 0.01 level (2-tailed)
* Correlation is significant at the 0.05 level (2-tailed)

3.3 Pearson Correlation

Correlations were observed between several parameters and among them the significant ones were between: TDS and EC (r = 1.0); between turbidity and TSS (r = .93); between total phosphorus and turbidity (r = .71) and between alkalinity as $CaCO_3$ and both EC and TDS (r = .635). In addition, location [site] was correlated positively with almost all the parameters except ammonia-nitrogen and temperature. The turbidity and TSS of the water is likely made up of phosphorus containing constituents as there was a strong correlation between these parameters. Equally, there was a strong correlation between TDS and EC. The findings suggest that high TDS brings the onset of high EC in specific locations. The findings further suggest that changes in season bring about turbidity and high TSS as there was a very strong correlation between them.

3.4. Multiple Comparison of Water Parameters

One-way analysis of variance was used to compare the mean scores (M) of the ten pollution parameters. The study was intended to uncover the impact of season (the independent variable) on the water quality parameters (dependent variables). ANOVA only uncovered information on whether the water quality across the seasons differed significantly, but did not reveal any significant difference. An F (degrees of freedom between groups, degrees of freedom within groups) ratio was also calculated, which represented the variance between the groups, divided by the variance within the groups. A large F ratio indicates that there is more variability between the groups (caused by the independent variable or season) than there is within each group (referred to as the error term). A significant F test indicates that we can reject the null hypothesis, which states that the population means are equal. It does not, however, tell us which of the groups differ. To uncover where the difference was, a post-hoc test was conducted to determine which groups were significantly different from one another. Furthermore, eta squared statistics have been reported in this study. Eta squared can range from 0 to 1 and represents the proportion of variance in the dependent variable that is explained by the independent (group) variable. Effect size statistics provide an indication of the magnitude of the differences between the groups (not just whether the difference could have occurred by chance) (Pallant, 2007). In this study, if the Sig. value and/or probability value (p) is less than or equal to .05, it meant there was a significant difference somewhere among the mean scores on the pollution parameter for the four seasons.

The ten parameters were compared against season and the results are reported in the subsequent sections.

3.4.1 Temperature

A one-way between-groups analysis of variance was conducted to explore the impact of season on temperature, as measured over a period of twelve months. The seasons were divided into four (season 1: Oct to Nov-ERS; season 2: Jan to Mar-LRS; season 3: Apr to Jun-EDS; season 4: Jul to Sep-LDS). There was a statistically significant difference at the $p < .05$ level in temperature for the four seasons: F (3, 182) = 36.10, p = .00. Despite reaching statistical significance, the actual difference in mean scores between the groups was quite small. The effect size, calculated using eta squared, was .37. Post-hoc comparisons using the Tukey HSD test indicated that the mean score for ERS (M = 27.40, SD = 1.90) and LRS (M = 27.30, SD = 2.20) was significantly different from EDS (M = 25.60, SD = 2.80) and LDS (M = 23.00, SD = 2.20). In addition EDS differed significantly from LDS.

Thermal pollution occurs when humans change the temperature of a body of water. The most common point source of thermal pollution is cooling water, which is used to cool machines. Thermal pollution may also be caused by stormwater runoff from warm surfaces such as streets and parking lots. Soil erosion is another cause, since it can cause cloudy conditions in a water body. Cloudy water absorbs the sun's rays, resulting in a rise in water temperature. Thermal pollution may even be caused by the removal of trees and vegetation which normally shade the water body. Novotny (2002) also argues that temperature and turbidity are special cases of physical pollutants that affect other pollutants and impair aquatic life. The most important impact of thermal pollution is a decrease in dissolved oxygen. Less oxygen in the environment may affect aquatic organisms and the overall health of the ecosystem.

Thermal pollution can result in significant changes to the aquatic environment. Most aquatic organisms are adapted to survive within a specific temperature range. Thermal pollution may also increase the extent to which fish are vulnerable to toxic compounds, parasites, and disease. If temperatures reach extremes of heat or cold, few organisms will survive. Judging by the effluent water standards from ZBS, all the water samples were within the permissible range although there were significant seasonal temperature differences. This is expected because of natural seasonal fluctuations which bring about variations in temperature.

3.4.2 pH

A one-way between-groups analysis of variance was conducted to explore the impact of season on pH, as measured over a period of twelve months. The seasons were divided into four (season 1: Oct to Nov-ERS; season 2: Jan to Mar-LRS; season 3: Apr to Jun-EDS; season 4: Jul to Sep-LDS). There was a statistically significant difference at the $p < .05$ level in pH for the four seasons: F (3, 182) = 21.40, p = .00. Notwithstanding reaching statistical significance, the actual difference in mean scores between the groups was relatively small. The effect size, calculated using eta squared, was .26. Post-hoc comparisons using the Tukey HSD test indicated that the mean score for ERS (M = 8.30, SD = .49) was significantly different from LRS (M = 7.90, SD = .42), EDS (M = 7.60, SD = .42) and LDS (M = 7.80, SD = .49). In addition, LRS differed significantly from EDS.

The pH of natural water depends on several factors, which include the bicarbonate buffering system, types of rocks, types of soil, and nature of discharged pollutants. The concentration of carbonates and carbon dioxide is the main influence on the pH of clean water. High concentrations of bicarbonate produce alkaline waters (high pH), while low concentrations usually produce acidic waters (low pH).

Acidic and alkaline compounds can be weathered into the stream from the different types of rock present. When limestone ($CaCO_3$) is present, carbonates can be released, affecting the alkalinity of the water. The types of soil in the drainage area also affect the pH. Drainage water from forests and marshes is often slightly acidic, due to the presence of humic acids produced by decaying vegetation (Chiou et al., 2000).

Nitrogen oxides (NO, NO_2) and sulphur dioxide (SO_2) from mining activities (Hill, 2010), and automobile exhaust (and machines powered by fossils fuels) are converted into nitric acid (HNO_3) and sulphuric acid (H_2SO_4) in the atmosphere. These acids can affect the pH of streams by combining with moisture in the air and falling to the earth as acid rain.

Surface waters can sometimes act as weak buffer solutions depending on the concentrations of carbonates and bicarbonates (Exploring the Environmental Water Quality, 2004).

The pH values of natural surface waters usually range from 5.5 to 8.5. Extremely high (≥9.6) or low (≤4.5) values are unsuitable for most aquatic organisms. Fledgling fish and immature stages of aquatic insects are extremely sensitive to pH levels below 5. Most aquatic species prefer pH near neutral but can withstand a pH in a range of about 6 (7 for nitrifiers) to 8.5 (Novotny, 2002).

Changes in pH can also affect aquatic life indirectly by altering other aspects of water chemistry. Low pH levels accelerate the release of heavy metals from sediments on the stream bottom. The heavy metals can reduce the chance of survival of most aquatic organisms (Exploring the Environment Water Quality, 2004). Overall the seasonal pH was in the alkaline range with ERS (September to December) registering the most alkaline water condition. There were significant differences between the seasons as revealed by the statistical analysis with EDS registering the highest pH.

3.4.3 Electroconductivity (EC)

A one-way between-groups analysis of variance was conducted to explore the impact of season on EC, as measured over a period of the four seasons. There was no statistically significant difference at the $p < .05$ level in EC for the four seasons: F (3, 182) = 1.50, p = .22.

Salty water conducts electricity more readily than purer water. Therefore, electrical conductivity is routinely used to measure salinity. The types of salts (ions) causing salinity usually are chlorides, sulphates, carbonates, sodium, magnesium, calcium and potassium.

While an appropriate concentration of salts is vital for aquatic plants and animals, salinity that is beyond the normal range for any species of organism will cause stress or even death to that organism. Salinity also affects the availability of nutrients to plant roots (Water for Life & Greening Australia, n.d.).

Depending on the type of salts present, salinity can increase water clarity. At very high concentrations, salts make water denser, causing salinity gradations within an unmixed water column and slightly increasing the depth necessary to reach the water table in groundwater bores.

Electrical conductivity in waterways is affected by: geology and soils; land use, such as agriculture (irrigation), urban development (removal of vegetation, sewage and effluent discharges), industrial development (industrial discharges); flow (electrical conductivity is generally lowest during high flows and increases as flows decrease, with extreme levels occurring during droughts); run-off; groundwater inflows; temperature; evaporation and dilution (Waterwatch Australia, 2002).

Contaminated discharges can change the water's electrical conductivity in various ways. For example, a failing sewage system raises the conductivity because of its chloride, phosphate, and nitrate content, but an oil spill would lower the conductivity. The discharge of heavy metals into a water body can raise the conductivity as metallic ions are introduced into the waterway (ibid). Despite the wide variations observed in the EC values and several outliers as revealed by the boxplots, there was no significant difference across the seasons.

3.4.4 Dissolved Oxygen (DO)

A one-way between-groups analysis of variance was conducted to explore the impact of season on DO, as measured over a period of twelve months. As in the previous cases, the seasons were divided into four. There was a statistically significant difference at the $p < .05$ level in DO for the four seasons: F (3, 182) = 5.10, $p = .00$. Despite reaching statistical significance, the actual difference in mean scores between the groups was rather minor. The effect size, calculated using eta squared, was .08. Post-hoc comparisons using the Tukey HSD test indicated that the mean score for ERS ($M = 10.00$, $SD = 2.40$) was significantly different from LRS ($M = 8.60$, $SD = 1.40$), EDS ($M = 8.90$, $SD = 1.70$) and LDS ($M = 9.00$, $SD = 1.80$).

Adequate DO is necessary for good water quality. Its depletion in water is associated with microorganisms decomposing much of the organic matter in a water body (Hill, 2010). Oxygen is a necessary element to all forms of life. Natural stream purification processes require adequate oxygen levels in order to support aerobic life forms. Ahluwalia and Malhotra (2007) argue that if the amount of DO is high, the degree of self-purification of water is high; in such cases, milder water treatment is required. As DO levels in water drop below 5.0 ppm, aquatic life is put under stress; the lower the concentration, the greater the stress. Novotny (2002) contends that water quality investigations and toxicities studies indicate that the DO content is the most important parameter for protecting fish and aquatic biota. Oxygen dissolves in water at very low concentrations. The atmosphere is 20% oxygen or 200,000 ppm and can reach concentration of up to 10.0 ppm oxygen dissolved in its water (Wright, 2005). ERS differed significantly from the other seasons; it had the highest amount of DO, implying that the water is most oxygenated during this season. Despite some monthly outliers below the recommended 5 ppm, all the seasonal averages indicated healthy water conditions along the Zambezi River watershed.

3.4.5 Total Suspended Solids (TSS)

A one-way between-groups analysis of variance was conducted to explore the impact of season on TSS, as measured over a period of twelve months. There was no statistically significant difference at the $p < .05$ level in TSS for the four seasons: F (3, 182) = 2.20, $p = .09$.

Total suspended solids (TSS) include all particles suspended in water which will not pass through a filter. Suspended solids are present in sanitary wastewater and many types of industrial wastewater. There are also nonpoint sources of suspended solids, such as soil erosion from agricultural and construction sites.

As levels of TSS increase, a water body begins to lose its ability to support a diversity of aquatic life. Suspended solids absorb heat from the sun, which increases water temperature and subsequently decreases levels of DO (warmer water holds less oxygen than cooler water). Photosynthesis also decreases, since less light penetrates the water (Hill, 2010). As less oxygen is produced by plants and algae, there is a further drop in DO levels.

High TSS levels can also destroy fish habitat because suspended solids settle to the bottom and can eventually blanket the river bed. Suspended solids can smother the eggs of fish and aquatic insects, and can suffocate newly-hatched insect larvae. Suspended solids can also harm fish directly by clogging gills, reducing growth rates, and lowering resistance to disease. As revealed by the HSD test, there was no significant difference in the TSS values across the seasons. The *PV* as set by ZBS was not exceeded across the four seasons.

3.4.6 Total Dissolved Solids (TDS)

A one-way between-groups analysis of variance was conducted to explore the impact of season on TDS, as measured over a period of twelve months. There was no statistically significant difference at the $p < .05$ level in TSS for the four seasons: $F\ (3, 182) = 1.50, p = .22$.

TDS in drinking water may come from natural sources, sewage, urban run-off, industrial wastewater, (WHO, 1996) and chemicals used in the water treatment process, or the material from the piping or hardware used to convey the water. Elevated TDS have resulted from natural environmental features such as: mineral springs, carbonate deposits, salt deposits, and sea water intrusion. Other sources may include: drinking water treatment chemicals, stormwater and agricultural runoff, and point/non-point wastewater discharges (Oram, 2007). As was the case with TSS, there was no significant difference in TDS across the seasons and its *PV* was not exceeded.

3.4.7 Alkalinity as $CaCO_3$

A one-way between-groups analysis of variance was conducted to explore the impact of season on alkalinity, as measured over a period of twelve months. There was no statistically significant difference at the $p < .05$ level in alkalinity as $CaCO_3$ for the four seasons: $F\ (3, 182) = .4, p = .74$.

The ability of surface waters to neutralize acidic inputs depends on carbonate (CO_3^{2-}) and bicarbonate (HCO_3^-) expressed as alkalinity (Novotny, 2002). In natural water, alkalinity is due to the presence of HCO_3^-, SiO_3^{2-}, $HSiO_3^-$, CO_3^{2-} and OH^-. Sometimes, the presence of salts of weak organic acids bind H^+ and thus results in increasing the concentration of OH^- ions (Ahluwalia & Malhotra, 2007). Most alkalinity in surface water comes from $CaCO_3$, being leached from rocks and soil. This process is enhanced if the rocks and soil have been broken up for any reason, such as mining or urban development. Limestone contains especially high levels of $CaCO_3$. Alkalinity is significant in the treatment of wastewater and drinking water because it will influence treatment processes such as anaerobic digestion. Baird and Cann (2008, p. 594) have pointed out that "the alkalinity value for a lake is sometimes used by biologist as a measure of its ability to support aquatic plant life, a high value indicating a high potential fertility." Water may also be unsuitable for use in irrigation if the alkalinity level in the water is higher than the natural level of alkalinity in the soil (APECwater, n.d.). This study did not find any significant difference across the four seasons in alkalinity as $CaCO_3$. However, the boxplots reveal that several locations exceeded the recommendable values of alkalinity; several outliers were observed as revealed by Figure 7, and Figure 11 to Figure14.

3.4.8 Turbidity (TB)

A one-way between-groups analysis of variance was conducted to explore the impact of season on turbidity, as measured over a period of twelve months. There was no statistically significant difference at the $p < .05$ level in turbidity for the four seasons: $F\ (3, 182) = 2.60, p = .053$.

Unfiltered storm water runoff in streams, lakes, ponds, and oceans can have a significant impact on water quality. As storm water flows over the land surface, it picks up pollutants like sediments, nutrients, pathogens, debris, toxins and various other chemicals.

Polluted storm water runoff not only lowers water quality but can harm or kill fish and other wildlife. For example, excessive amounts of sediment in water can destroy aquatic habitats.

Nonpoint source pollution comes, primarily, from rainwater which runs over lawns, parking lots, city streets, forest, and construction sites. There was no significant difference in TB across the four seasons although the boxplot revealed skewed distribution and several outliers towards higher levels in the ERS and LRS.

3.4.9 Total Phosphorus (TP)

A one-way between-groups analysis of variance was conducted to explore the impact of season on TP, as measured over a period of twelve months. There was a statistically significant difference at the $p < .05$ level in TP for the four seasons: $F\ (3, 182) = 3.10, p = .03$. The effect size, calculated using eta squared, was .05. Post-hoc comparisons using the Tukey HSD test indicated that the mean score for ERS ($M = 269.8$, $SD = 254.07$) was significantly different from LDS ($M = 175.10$, $SD = 62.80$). LRS ($M = 237.30$, $SD = 204.56$), and EDS ($M = 186.50$, $SD = 71.78$) did not differ significantly from any other season.

Phosphorus, a nutrient essential to the growth of organisms, and is commonly the limiting factor in the primary productivity of surface water bodies. TP includes the amount of phosphorus in solution (reactive) and in particle form. Agricultural drainage, wastewater, and certain industrial discharges are typical sources of phosphorus and can contribute to the eutrophication of surface water bodies (Baird & Cann, 2008). Phosphorus can lead to population explosion of photosynthetic bacteria and blue-green algae (Ahluwalia & Malhotra, 2007).

Concentrations of phosphorus in water, air, and soil are measured to assess the present situation. With traditional measuring methods, it is only possible to determine environmental problems caused in the past. Early recognition of future loading, as well as the identification of the effective measures, enables the potential decrease of later loading. Both are possible only with measures for environmental protection on the whole system, which is the integration of water, land, and air, and will be based solely on prevention. For sustainable river basin management, there is a strong need to evaluate different option strategies. Only thus will the available resources be applied in the most advantageous, sustainable way (Drolc et al., 2002). As for TP, HSD revealed that ERS was significantly different from LDS, and all the other seasons did not differ significantly. ERS registered the highest TP loadings followed by LRS. The results show that the water is particularly worse during the rainy season, a consequence of stormy water from farms, unsewered onsite sanitation infrastructure and industries.

3.4.10 Ammonia-Nitrogen (NH_3-N)

A one-way between-groups analysis of variance was conducted to explore the impact of season on NH_3-N, as measured over a period of twelve months. There was a statistically significant difference at the $p < .05$ level in NH_3-N for the four seasons: F (3, 179) = 14.70, $p = .00$. Despite reaching statistical significance, the actual difference in mean scores between the groups was quite small. The effect size, calculated using eta squared, was .2. Post-hoc comparisons using the Tukey HSD test indicated that the mean score for ERS ($M = .00$, $SD = .00$) was significantly different from LRS ($M = 60.10$, $SD = 83.64$), EDS ($M = 36.50$, $SD = 10.93$) and LDS ($M = 42.30$, $SD = 12.53$). In addition, LRS differed significantly from EDS.

At pH of 7.00 or below, most of the ammoniacal nitrogen will be ionized as ammonium. At pH levels greater than 9.00 the proportions of nonionised ammonia will increase. The nonionized ammonia is toxic to fish, while the ionized ammonia is a nutrient to algae and aquatic plants and also exerts dissolved oxygen demand (Novotny, 2002). Ammonia (NH_3) is mainly generated from agricultural sources, with major point sources found particularly near intensive livestock and poultry farms. Ammonia pollution causes both acidification of soils and a decrease in the richness of plant species (European Commission, 2006). NH_3-N is a constituent in raw domestic wastewater. The findings of this study show that ERS differed significantly from all seasons. This is partly because there was no water flow in some sampled locations (for example Kalomo and Quayi are ephemeral rivers) and hence no parameters were analysed. LRS and EDS differed significantly, with the former registering higher NH_3-N loading compared to the latter.

4. Discussion on pollution with Water Pollution Index

4.1 Season Comparison of Parameters exceeding their *PVs* and *WPI*

In the proceeding section, the ten parameters considered in this study are compared relative to what is expected to be found in

Table 5. The Averages and Standard Deviation (SDs) of the Ten Parameters in the Four Seasons and the Corresponding PVs

	Unit	PVs	Min ERS	Max ERS	Mean ERS	SD	Min LRS	Max LRS	Mean LRS	SD	Min EDS	Max EDS	Mean EDS	SD	Min LDS	Max LDS	Mean LDS	SD
T	°C	40	23.90	32.10	27.37	1.86	22.00	30.90	27.33	2.19	17.50	30.80	25.58	2.80	15.10	26.60	23.02	2.17
pH		6 - 9	6.93	9.20	8.29	.48	7.08	8.66	7.91	.42	6.33	8.45	7.57	.42	6.46	8.41	7.76	.49
EC	µs/cm	2300	42.00	775.00	127.96	129.95	36.00	645.00	124.56	118.12	35.00	841.00	173.08	212.49	63.00	1098.00	197.25	274.20
DO	mg/L	>5	6.22	16.69	10.03	2.31	4.32	11.15	8.76	1.38	3.96	12.60	8.90	1.69	6.56	12.00	9.01	1.42
TSS	mg/L	100	1.00	1278.00	65.35	232.76	2.00	1073.00	59.72	165.99	1.00	278.00	13.82	39.27	1.00	45.00	5.16	6.89
TDS	mg/L	3000	28.14	519.25	85.76	87.06	24.12	432.20	83.46	79.15	23.45	563.47	115.96	142.37	42.21	735.66	132.16	183.72
Alkanility as $CaCO_3$	mg/L	120	24.20	214.30	64.53	38.80	19.10	239.30	58.73	40.60	20.10	238.40	62.56	46.11	28.00	249.20	68.40	47.17
Turbidity	NTU	10	1.70	1308.00	69.29	244.63	1.00	1250.00	84.07	222.09	1.00	333.00	15.62	47.13	.78	39.80	4.47	5.97
TotalP	µg/L	1000	64.00	1120.00	259.98	248.87	32.00	1200.00	237.33	204.56	44.80	352.00	186.47	71.78	64.00	336.00	175.11	62.80
Ammonia-Nitrogen	µg/L	1250	nd	nd	nd	nd	4.05	488.11	60.06	83.64	12.85	69.19	36.52	10.93	20.43	77.73	42.26	12.53

nd, not determined; NTU, Nephelometric Turbidity Unit

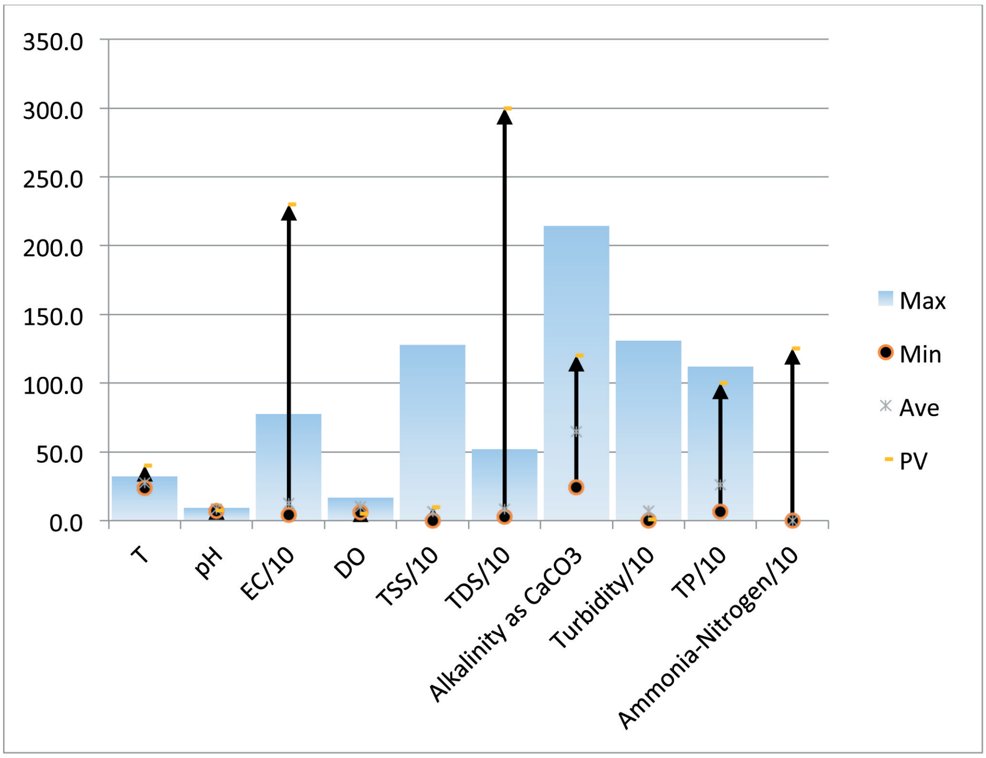

Figure 11. Early Rain Season (ERS) comparison of parameters exceeding their *PVs*

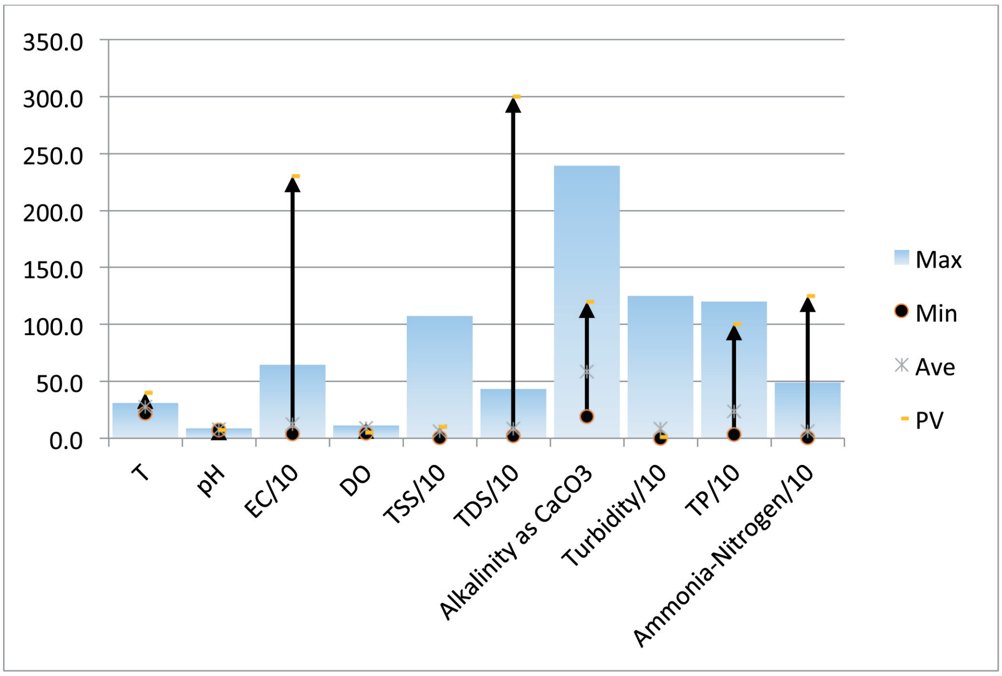

Figure 12. Late Rain Season (LRS) comparison of parameters exceeding their *PVs*

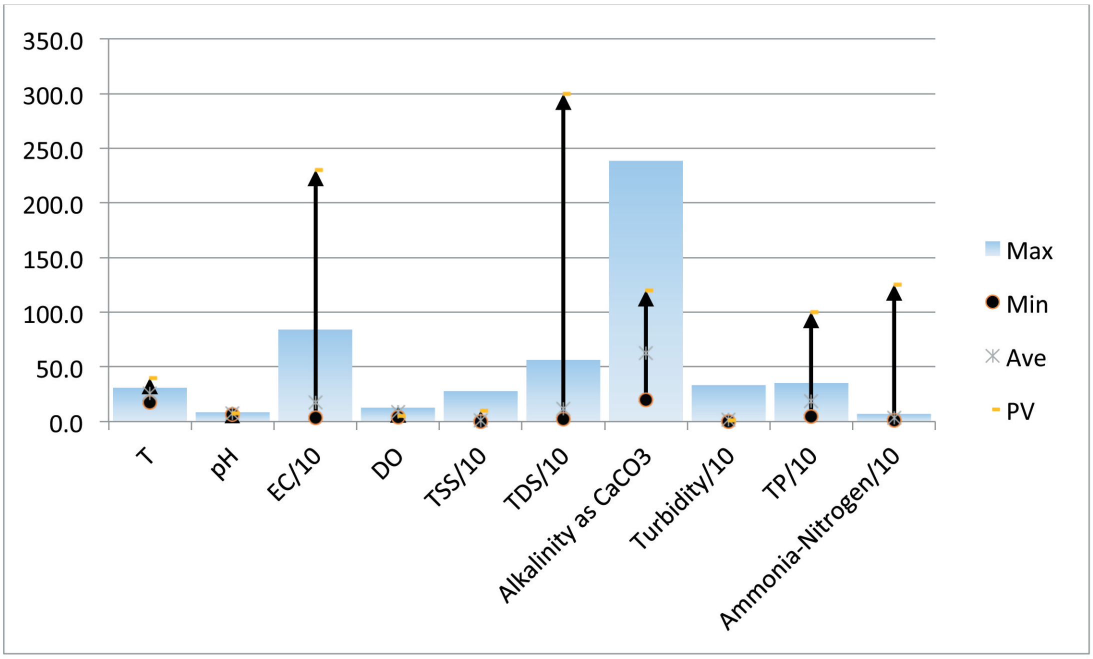

Figure 13. Early Dry Season (EDS) comparison of parameters exceeding their *PVs*

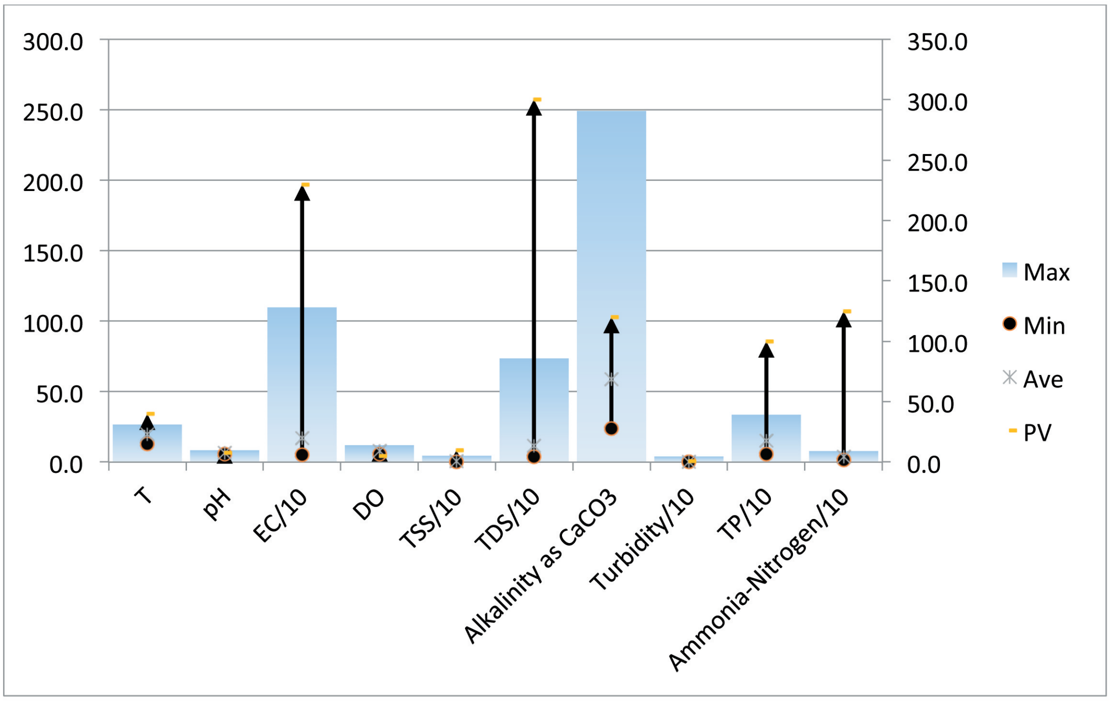

Figure 14. Late Dry Season (LDS) comparison of parameters exceeding their *PVs*

unpolluted water samples. The minimum, maximum and the mean values of the parameters are compared to their *PVs*. In-depth analyses of the parameters are hereby presented by season as depicted from Figure 11 to Figure 14.

Of the ten parameters, TSS, turbidity, and TP exceeded their *PVs* in some seasons in contrast to alkalinity as $CaCO_3$ which exceeded its *PV* in all the seasons as depicted by Figure 11 to Figure 14.

4.2 Local Characteristics of Pollution

Figure 15 and Figure 16 (using the water pollution index) show an important pattern that the most compromised water samples came from tributaries that feed the Zambezi River. Amongst the outstanding locations which were most polluted are Quayi river (*WPI*= 6.40), Kariba at Sanyati-further (*WPI*= 5.28), Kalomo River (*WPI* = 4.76) and Deka river (*WPI* = 4.65), Kanzinze River (*WP* = 1.95), and Kariba at Gatche Gatche (*WPI* = 1.47).

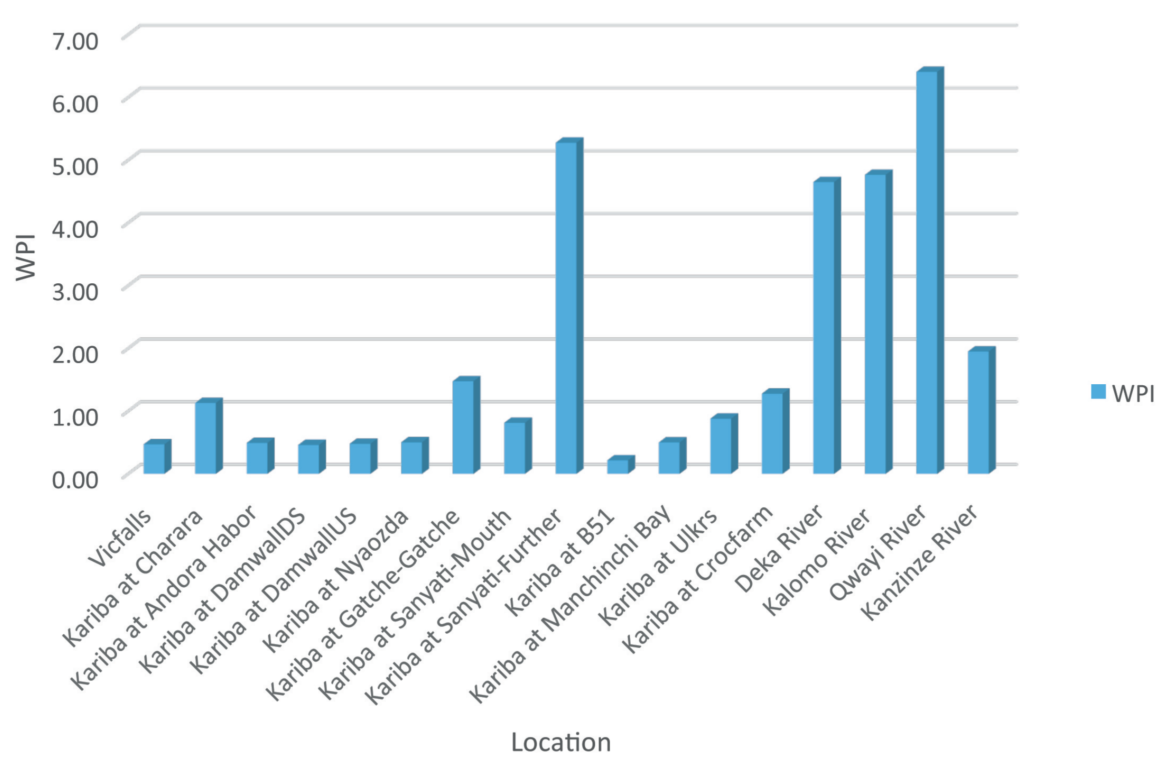

Figure 15. Comparison of Pollution by Location using the *WPI*

4.3 Seasonal Characteristics of Pollution

Furthermore, the data obtained using the *WPI* as presented in Figure 17 shows which season(s) have notable pollution problems and the data clearly shows that LDS is characterised by very safe water with reference to the ten parameters that were the focus of this study. When the 17 locations are further compared for their overall contribution to water quality, it was found that tributaries discharging the water into the Kariba/ Zambezi River had the most compromised water as shown by the *WPI* values of Quayi River, Kariba at Sanyati-further, Kalomo and Deka Rivers.

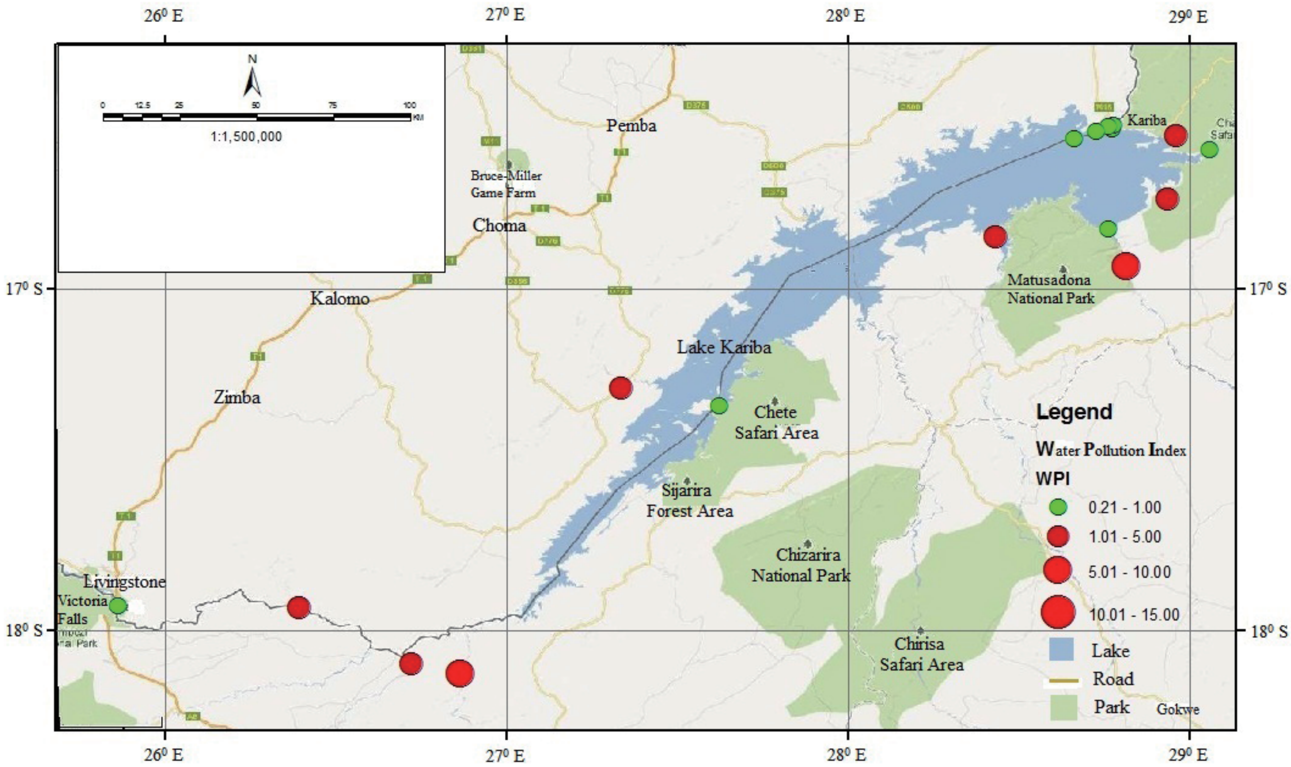

Figure 16. Spatial Distribution of Pollution by Location using the *WPI* on the Lake Kariba, Zambezi River and its tributaries
Source: Map data ©2012 Google

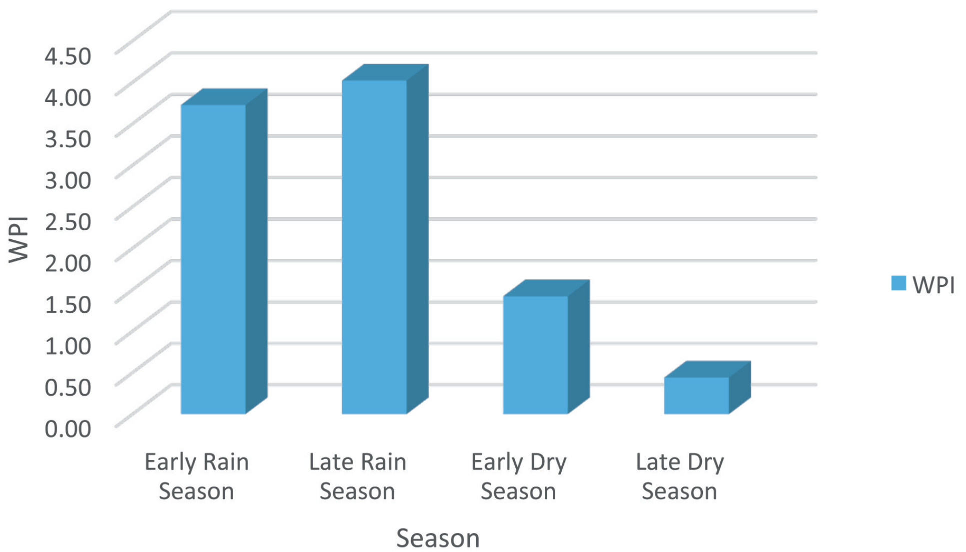

Figure 17. Comparison of pollution by season using the *WPI*

In addition it can be argued, as shown in Figure 17, that deterioration in water quality climaxes in the LRS and quality gradually improves towards the EDS until it attains its best level in the LDS before the quality tumbles again in the ERS. The pattern is consistent with onset of the rain season in October indicating that pollutants are washed to the river banks from further inland close to and inside the human settlements.

5. Conclusion

The findings of this study reveal that the water quality deterioration along Lake Kariba, Zambezi River and its tributaries is particularly in a critical condition during the rainy reason. ERS had a *WPI* of 3.72 and LRS had a *WPI* of 4.02 and hence more care is particularly needed when using the water from the watershed (shown in Figure 16) during these seasons. Furthermore, using principal factor analysis, the ten parameters yielded four factors and the most predominant (as evidenced from factor loadings) factors controlling water quality along the watershed are: factor 1 dominated by turbidity, factor 2 dominated by TDS, factor 3 dominated by DO and factor 4 by temperature. These parameters were found to be very momentous, as reviewed by factor loadings, in explaining water quality across the seasons. By far the biggest problems (frequently exceeding their *PVs*) were caused by turbidity followed by alkalinity as $CaCO_3$, then TSS and to a less extent by total phosphorus. It is also important to note that the tributaries feeding Lake Kariba are the most polluted. Furthermore, the watershed waters (after traversing between Zambia and Zimbabwe) flows into the neighbouring Mozambique and the results show that the water exiting Lake Kariba is generally free of any significant pollution, across all seasons, probably a consequence of the diluting effect of the vast water resources of the Lake. However, it is vitally important to alert the users of the water by the banks and further downstream of some of the hazards found in the water with changing seasons and especially during the late rainy season.

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