USING THE PLANNING AND MANAGEMENT MODEL OF LAKES AND RESERVOIRS (PAMOLARE) AS A TOOL FOR PLANNING THE REHABILITATION OF LAKE CHIVERO

by

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A thesis submitted in partial fulfilment of the requirements for the degree of Master of Science in Tropical Resource Ecology

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Tropical Resources Ecology Programme

1 April 2011

ABSTRACT

The future condition of a lake ecosystem can be predicted through the interpretation of past and present responses to change. The objective of this study was to predict the changes in the eutrophic status of Lake Chivero using the Planning and Management Model of Lakes and Reservoirs (PAMOLARE) as a tool in planning its rehabilitation. The model estimated the effect of nutrient reduction through three management scenarios, which are the use of natural wetlands and use of efficient wastewater treatment systems against the existing management system. Modelling parameters were gathered through, experimental work, literature review and information from responsible authorities. The current eutrophic status of Lake Chivero was evaluated by analysing different physico-chemical variables from the lake's main and minor tributaries. Water samples were collected from eight sites, Marimba, Mukuvisi, Manyame, Kuwadzana, Budiriro, Glenview (rivers), lake midpoint and lake near wall. Sampling was conducted from the 29th of October 2010 to the 31st of January 2011. Physical parameters, dissolved oxygen (DO), turbidity, conductivity, total dissolved solids (TDS), pH and temperature were measured on site. Chemical analyses on composite samples were done for total nitrogen (TN), total phosphorus (TP) and chlorophyll-*a* using standard methods. Concentrations were determined by colorimetric methods, using a spectrophotometer. TN and TP concentrations were multiplied by river flow discharge over area, translating into nutrient loads. The results indicated that Lake Chivero is hypereutrophic, with mean phosphorus concentration of 2.77 mgL^{-1} and nitrogen 3.21 mgL^{-1}. The quality of the water varied within time and space, which was greatly influenced by the intensity and type of land use activities. Secchi depth was lowest from the rivers rarely exceeding 0.5 m and highest from the lake points reaching 1.9 m. The rivers recorded the least oxygen levels with Budiriro and Mukuvisi recording as low as 0.0 mgL^{-1}. Higher conductivity values were recorded from the rivers as compared to the lake points. Conductivity and TDS showed no relationship with the depth profile. DO, pH and temperature from the lake sites decreased with depth with a poor gradient. Mixing was experienced on some sampling days shown by absence of the thermocline. The multiple analysis of variance (MANOVA) for the physico-chemical parameters indicated that temperature, % oxygen saturation, DO, pH, salinity, TN and chlorophyll-*a* had some significant difference ($p \leq 0.05$) with site. Conductivity, ORP and TDS had significant difference ($p \leq 0.05$) to be about 493 tonnes per annum. The non-point phosphorus source competed closely with 634 tonnes per annum phosphorus from point sources. The estimated wetland area in the catchment has capacity to remove about 80 000 tonnes of phosphorus per annum and about $9.97*10^4$ tonnes of nitrogen per annum. Phosphorus in water would decrease from 2.77 to 0.22 mgL^{-1} in the next 6.5 years. Nitrogen levels in water will also decrease from 3.16 to 3.06 mgL^{-1} in the next 4 years. Results of the model scenario runs reveal that an 82% reduction of the current loadings would improve the water quality from hyper-eutrophic to eutrophic conditions. The modelling effort has yielded valuable information that can be used by decision makers for the evaluation of different management strategies on reducing point and non-point nutrient loadings into Lake Chivero.

ACKNOWLEDGEMENTS

I would like to thank my supervisor, Professor C.H.D Magadza for his unwavering technical support, guidance and encouragement throughout this project. I am truly grateful for the financial support given to me by Deutscher Akademischer Austausch Dienst (DAAD) German Academic Exchange Service without which I would not have reached this far. I am also truly thankful to the Research Grant received from the Japanese under the International Lake Environment Committee Foundation (ILEC).

Many thanks go to Dr. T Nhiwatiwa for all the services offered by the Biological Science Hydrobiology Laboratory, without which the project would have been impossible. I am grateful for the technical advice on Geographic Information Systems (GIS) by Dr. A Murwira and Mr Mutowo. I am also thankful for the support given by Dr. S Kativu. I am also grateful to the offices and personalities that gave me data and support for my study. These included the Zimbabwe National Water Authorities (ZINWA) Research and Data Offices, Harare City Council and National Park authorities. I am grateful for the support and encouragement by Sydney Moyo and all my colleagues (2010/2011 TREP class) throughout the academic year.

My sincere gratitude is extended to my in-laws, Mr and Mrs G.H Perekwa for being there for my family when I really needed support. I owe my deepest gratitude to my husband and sons, Masimba, Tawananyasha and Tapiwanashe for their love, support and patience. The support and encouragement from my parents Mr and Mrs T.A Nyarumbu and my brother Allen, which saw me through the tough times, is gratefully honoured. My final thanks go to the family that gave me a home during the study period. To Donald and Mellisa Chauke, I do not know what I would have done without you. THANK YOU.

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1. INTRODUCTION

1.1 Background

Fresh water is critical to the fulfilment of human needs for living although it represents the smallest percentage of the total water available on our planet. The establishment of any human community and the conservation of all land-based wild life is dependent on freshwater. Globally, lakes cover approximately 1% of land surface area with approximately 90% of this area accounted for by 250 of the world's largest lakes (Herdendorf, 1990). However, the smaller percentage is constituted by shallow lakes, which are the most abundant in the global landscape (Wetzel, 2001). Latest statistics by UNICEF and WHO (2008) reveal that 2.5 billion people lack access to improved sanitation facilities and 1.2 billion people live without any sanitation facilities. Humans throughout the world history have constructed artificial lakes primarily to address their water needs (ILEC and UNEP, 2003). However, the overgrowing population, increased demands, deterioration of existing water resources and the recent droughts have led to water scarcity in many parts of the world (UNEP, 2006; Jorgensen and Rast, 2007).

Accelerated eutrophication is a widespread and significant threat to lakes around the world (Ayres *et al*., 1996). Deevey (1984) defined eutrophication as a natural process, initially rapid in the early phase and then slows down to establish a trophic equilibrium. Today cases of eutrophication are mainly a result of anthropogenically driven enrichment with two nutrients, phosphorus and nitrogen (UNEP-IETC/ILEC, 2001).

Eutrophication stimulates an array of symptomatic changes, which include the increased production of algae and macrophytes, deterioration of water quality and other symptomatic changes, which are undesirable and interfere with water uses (OECD, 1982).

Previously known point sources of pollution were the major challenge in managing wastewater until in the early 1970s' when research revealed additional sources of non-point pollution also known as diffuse pollution (Novotny, 1995). Scientific evidence from studies by Novonty (1995) also pointed out that diffuse sources of pollution are difficult to identify and quantify, making implementation of effluent limitations almost impossible. Novonty (1999) further argued that, point-source discharge are easy to control because they can be monitored, quantified and treated before they are discharged into surface water bodies.

The estimated contribution of non-point sources of nitrogen and phosphorus into Lake Chivero, Zimbabwe is sufficient to maintain eutrophy (Thornton, 1982 and Magadza, 2003). Estimated results by Magadza (2003) on phosphorus and nitrogen export through surface runoff from Harare suburbs were about 272 tonnes of phosphorus per annum and 1000 tonnes of nitrogen per annum. Magadza pointed out that investing in high technology wastewater treatment plants alone, would no longer solve the pollution problems of Lake Chivero. In Zimbabwe, the control of non-point source pollution has lagged behind the control of nutrients from point sources, in terms of available technologies and the legal requirements for implementation.

Considering that the Worlds' water is threatened by pollution, it is important devise proper management tools that will help to protect the watersheds to maintain quality water in Lakes and Reservoirs. Mathematical models offer a platform for diagnosing and evaluating alternative solutions. This is because the models are derived from scientific theories and from observations of processes and responses in real lake ecosystems. In the light of these views, ecological modelling can be applied as an important management tool in the protection of watershed environments. This allows for the assessment of the feasibility of the different management plans in different contexts.

1.2 Problem statement

Numerous hydro-biological investigations carried out in Lake Chivero from as early as the seventies by distinguished scientists, Marshall and Falconer 1973; Thornton 1982; Marshal 1997; Magadza 1994; Moyo 1997; Jaravaza 1999; Nhapi *et al*., 2001 and Magadza 2004 have reported deteriorating water quality. Magadza (2004) confirmed that the lake was hypereutrophic. The expansion of urban populations coupled with an increase in urbanisation, industrial and agricultural land use have contributed significantly to greater quantities of wastewater. Municipal wastewater is highly contaminated with high organic and inorganic nutrients e.g. phosphorus and heavy metals respectively (Nhapi *et al*., 2001). Soluble nutrient concentrations have often been higher than permissible levels for drinking water in lakes of 0.3 mgL^{-1} total nitrogen (TN) and 0.01 mgL^{-1} total phosphorus (TP) (JICA, 1996). Extensive research has shown that nitrogen and phosphorus are the major nutrients increasing primary productivity in the lake resulting in deterioration of water clarity through increased phytoplankton biomass.

Because many residential suburbs lie on a higher elevation than the lake, generated wastewater will always drain into the water body. The overloading of treatment plants have resulted in the discharge of nutrient-rich raw sewage and industrial effluent into water bodies. The efficiency of the treatment plants has deteriorated over the years due to age and increased cost of maintenance. The proportion of households with access to safe means of excreta disposal for Harare show a decline by about 2.5% from 2002-2009 (ZIMDAT, 2010).

Health statistics from Harare and one of its satellite towns Chitungwiza show an increase in cases of water related illnesses such as diarrhoea, typhoid fever, hepatitis A, liver cancer and gastroenteritis. Figure.1.1 shows that in Chitungwiza, cases of diarrhoea increased from 26.1 to 3 420 per 100000 population from 2000-2002. In Harare between year 2000 and 2002, there was a decrease in the number of diarrhoea cases from 1270-520 per 100000 people. The cases have since doubled year 2000 statistics between the years 2005-2008. The increasing trends responds to findings by GESAMP (2001), who established a positive correlation between respiratory and intestinal diseases with increasing amounts of sewage pollution. Statistics for Harare in 2009 indicated that the overall percentage of households' drinking water appropriately treated in Zimbabwe was 34.8%. About 65.9% of Harare households had no access to appropriately treated drinking water.

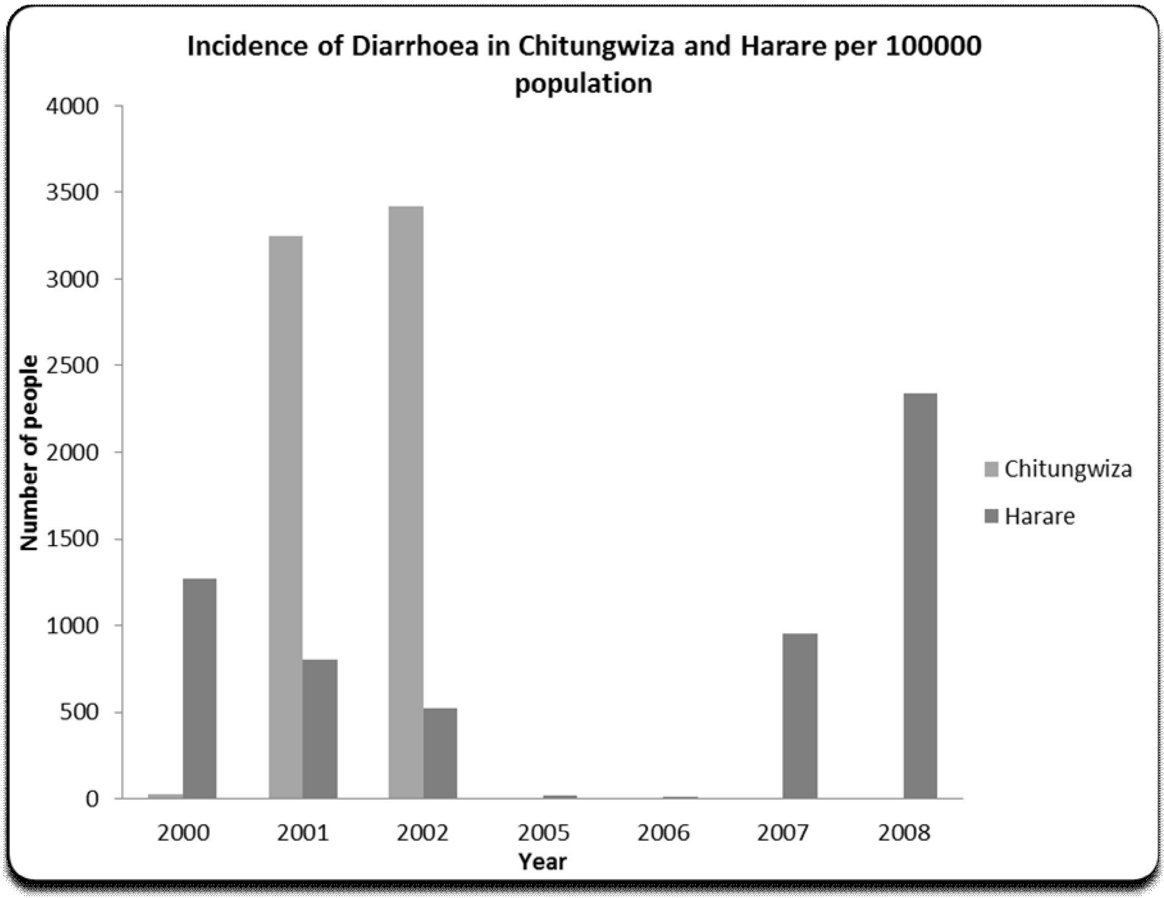


Figure 1.1. Total Incidence of Diarrhoea in Harare and Chitungwiza per 100 000 population from 2000-2008 (Source: **ZIMDAT, 2010)**
Ministry of Health and Child Welfare National Health Profile

Deductions made from lessons learnt from Lake Chivero (UNEP-IETC, 2000) showed that the management of water resources in Zimbabwe have too much bureaucracy. The paper cited that the potential of public participation is not utilised because of secrecy surrounding challenges faced by municipality in providing clean water. Magadza (2003) argued that if the public knew the impact of poor utilisation of the watershed, they would be conditioned to take remedial measures towards watershed management.

The assessment of the aquatic environment requires the development of proper tools because the physico-chemical and biological process linkages within are complex. Thus, many countries have engaged in lake-model development as a synthesis and overview tool, to develop management options to address such complex ecosystems (Jørgensen and Rast, 2007). Since models can be used to assess system sensitivity to certain natural or imposed impacts such as caused by climate and land use change (Rietnjes, 2007), they are also important as management tools.

1.3 Main objectives

The purpose of this ecological model was to predict the changes in the eutrophic status for Lake Chivero using the Planning and Management of Lakes and Reservoirs (PAMOLARE): Model for Eutrophication Management (Version 3.0), as a tool in planning the rehabilitation of Lake Chivero, assuming nutrient reduction through three management scenarios. The current trophic status of Lake Chivero in relation to current nutrient loadings was established. The current and projected trophic results were compared against each other to conclude if the lake can be rehabilitated.

1.3.1 Specific objectives

The specific objectives were to:

1. To determine the current physico-chemical status of Lake Chivero
2. To determine the current phosphorus and nitrogen loading into Lake Chivero
3. To estimate the wastewater purification potential of wetlands in Lake Chivero catchment area
4. To ascertain if the Planning and Management of Lakes and Reservoirs (PAMOLARE): Model for Eutrophication Management can be used as a tool in planning the rehabilitation of Lake Chivero

1.4 Justification

The project seeks to contribute to the importance of improved water supply and sanitation provision as emphasised in the Millennium Development Goals (United Nations, 2003). A significant number of people worldwide lack access to adequate water, sanitation, drainage, and solid waste disposal services. Lake Chivero serves directly as Harare's primary water supply reservoir for domestic use and irrigation purposes. In terms of its economic output, the lake has contributed significantly to the local tourism sector through revenue generation since it is one of the largest impoundments in Zimbabwe. Assuming the current unstable socio-economic situation in Zimbabwe, concepts of Integrated Lake Basin Management (ILBM) will help improve water quality in water bodies. Improved water quality will contribute towards the finance directed to water treatment. The integration of rehabilitated wastewater treatment works, preservation and utilisation of the natural purification processes through proper watershed management could reduce nutrient budget in lakes and reservoirs as argued by Vollenweider (1975). Because wetlands are a natural resource, they have minor costs attached with their preservation and utilisation. Since the major challenge in management approach of lake systems is the availability of sufficient knowledge or understanding of the state of the lake ecosystem, proven scientific evidence will go a long way in raising awareness. The on-going ILBM projects (ILEC, 2007) provide a management framework of good lake basin management. The lake governance pillars integrate institutions, technology, policy, information, finance, and stakeholder participation.

Although Lake Chivero is ranked among the most researched African reservoirs, it has a weak basin governance system. However, it has sufficient data on sources of increased nutrient loadings particularly from wastewater treatment plants, storm water drains and its catchment area. In view of the fact that the contribution of both point and non-point sources of pollution are equally fatal to freshwater ecosystems this study is important in that, it integrates both natural and mechanical control measures to abate pollution.

The use of ecological models in the management of Lakes and Reservoirs, although widely appraised (Jørgensen, 2000), still has to find credit in Zimbabwe. From a management point of view, the past and present state of Lake Chivero could be used to predict its future status in response to changes in the ecosystem, response to nutrient reduction and the potential role of other factors. The generated results will be important in policy formulation towards environmental management especially towards the preservation of water bodies. For Lake Chivero, the study is important in that it can be used as a reference point of whether it is still worthwhile to invest into its future.

1.5 Research questions

Specific questions addressed were:

1. What is the current physico-chemical status of Lake Chivero?
2. What are the current nutrient loadings for nitrogen and phosphorus into the Lake?
3. Do the existing wetlands in the catchment area of Lake Chivero have the potential to improve water quality?
4. Can the Planning and Management of Lakes and Reservoirs: Model for Eutrophication Management, be used as a tool in the abatement of eutrophication of Lake Chivero?

1.6 Working hypothesis

H_0: Reducing the current nutrient loadings into Lake Chivero does not have an effect on its projected trophic status (**$P_1=P_2$**)

H_1: Reducing the current nutrient loadings into Lake Chivero has an effect on its projected trophic status **($P_1 \neq P_2$)**

1.7 The study site

Lake Chivero is a manmade lake and the fourth-largest impoundment in Zimbabwe. The lake is situated on the Manyame River at latitude 17° 54′ S and longitude 30° 48′ E. It is elevated at an altitude of 1363 m above sea level, about 37 km southwest of Harare, the capital city of Zimbabwe. Like other major urban areas in southern Africa, the city of Harare is situated on a higher elevation upstream of its main water source. The only outlet from Lake Chivero is the Manyame River, which flows into Lake Manyame. Several seasonal rivers flow into these water bodies, restricting direct use of river water to the rainy season. All the major rivers and tributaries discharging into Lake Chivero pass through the city and its suburbs thus creating an obvious problem of water pollution. Mukuvisi, Marimba, and Manyame Rivers are the main tributaries to the lake. Of these main tributaries, Manyame River constitutes the largest catchment area of 474km^2 followed by Mukuvisi with 230km^2 and Marimba with 215 km^2.

City of Harare constitutes the main catchment area of Mukuvisi and Marimba Rivers covering a total area of ±89km^2. Other rapidly growing cities in the catchment include Chitungwiza, Epworth, Ruwa and parts of Seke and Chiota communal lands. Chitungwiza city covers an approximate area of about ±42km^2. Nyatsime River drains Chitungwiza suburbs and discharges into Manyame River. Ruwa River, drains directly into Manyame River also carrying nutrient loadings from Mabvuku and Epworth. However, some small rivers from suburbs in the catchment flow straight into the lake. Land use in the catchment area includes cattle grazing and crop cultivation. It was estimated that the city of Harare has about ±46 km^2 of open spaces, which are not yet formally utilised, and are under urban agriculture (Scientific and Industrial Research and Development Centre, 2010 -unpublished).

The catchment has spatially distributed wetlands with some parts of the river channels having dense growth of *Typha capensis, Hydrocotyl spp* and *Phragmites australis.* The greater part of Manyame River is under invasion by *Hydrocotyl* spp as shown in Plate 3. The most prominent wetland under National protection is the Monavale Vlei, which approximates an area of ±35 hectares.

The morphometric features of the Lake after Burke and Thornton, 1982 are as represented in Table 1.1. The deepest part with a maximum depth of 27.4 m occurs near the lake spillway (Munro, 1966) but because of siltation, a maximum depth recorded lately was 20 m (Mhlanga *et al*., 2006). The average precipitation in the catchment is 830 mm/year, but most of the rain falls as high-intensity storms from mid-November to April (JICA, 1996). However, changes in weather patterns linked to climate change have seen reduced precipitation and dry weather flow during August-October constituting largely sewage effluent.

Table 1.1. Hydrological and morphometric features of Lake Chivero

Characteristic	
Full supply volume	250 x $10^6 m^3$
Full supply surface area	26.30 km^2
Catchment area	2227 km^2
Shoreline length	74 km
Maximum depth	27.43 m
Mean depth	9.4 m
Maximum breadth	8.0 km
Mean breadth	1.68 km
Length	15.7 km
Renewal time	0.82 years

Source: (Burke and Thornton, 1982)

2. LITERATURE REVIEW

2.1 Modelling: An Overview

The need for prediction of water quality has arisen largely because of increased eutrophication of lakes throughout the world (Canfield. Jr. and Hoyer, 1988). Models have been used as an effective tool to gain insight into changes in water quality in lakes and reservoirs by simulating the response to external and internal loadings. Jørgensen (1994) defined a model as a formal expression of the essential elements of a problem in mathematical terms. The preliminary level in modeling is the verbal idea, which culminates into a conceptual diagram linking the ideas together. Simulation models are powerful tools in investigation of natural systems, specifically in predictions of natural disasters and evaluation of sustainable management decisions of various scales. Eutrophication models rely heavily on the lake phosphorus budget (Vollenweider, 1975), which is simply an itemized accounting of the inputs and outputs of phosphorus to and from the lake water column over a period. On the other hand, models are used as management tools to provide the necessary background for decisions on the abatement of eutrophication problems. Models can also be used as research tools to establish the understanding of complex interactions between physical, chemical and biological processes. Models thus offer guidelines for fruitful laboratory and field experiments.

Models in environmental sciences have five interrelated components namely; external variables, state variables, mathematical equations, parameters and universal constants. The external variables are forces from outside the ecosystem of concern having positive or negative impacts. These variables can be within and beyond control e.g. inputs of toxic substances to the ecosystems and climatic variables respectively.

External variables are important in that they give a reflection of the state of the ecosystem when certain forcing functions are varied over time. State variables represent quantitative characteristics describing ecosystem state. In eutrophication models, the state variables will be the concentrations of nutrients and phytoplankton. State variables can be determined through experimental research work predicted by changing external functions. The relationship between the external functions and state variables is linked by mathematical equations, which are used to represent the biological, chemical and physical processes. The same equations can be used in different models because the later processes are similar in the environmental context. Parameters are coefficients in the mathematical representation of processes. These coefficients are either constant for specific ecosystems or part of the ecosystem. Parameters are the major limitation in environmental modeling because they are represented as a range. Universal constants such as the gas constants and atomic weights are the same in environmental modeling.

The PAMOLARE model is divided into different loading models depending on the amount of information present and technical knowhow of the modeler. Jørgensen (2000) argued that a more complex model should account more accurately for the reactions of a real system. However, it was concluded that a more complex model contains more parameters and increases the level of uncertainty, because parameters have to be estimated by more observations through laboratory experiments and calibrations, which again are based on field measurements. Parameter estimations have intrinsic errors within them, which contributes significantly to their uncertainty.

2.1.1 Limitations in ecological modeling

Ecological models are limited in their scope despite the fact that models have been used as management tools across the globe (Jørgensen, 2000). Ecological models are uncertain because they never contain all the characteristics of a real ecosystem. Uncertainty is a result of intrinsic model features and human limited scope of knowledge. Jørgensen (2000) argued that models are stationary because they cannot take yearly variations of loadings and parameter values into account. Secondly, in many cases the models do not account for biological variables and their influence of biological processes on the model parameters. In eutrophication models, important interactions between several phytoplankton-limiting factors (light, phosphorus and nitrogen) are not taken into account.

2.2 Eutrophication in freshwater bodies

Earlier studies on nitrogen and phosphorus enrichment are a confirmation of studies by (Schindler, 1977), that these nutrients limit algal growth. This was supported by (Moss, 1998) who argued that massive blooms of cyanobacteria are accompanied by few submerged macrophytes, which also affect fish communities thus affecting biodiversity. Studies by Thornton (1980) in Lake Chivero also confirmed the impacts of nitrogen and phosphorus in Zimbabwean lakes and reservoirs. Total phosphorus concentration of 50–60 μgL^{-1} has been suggested as the boundary between mesotrophic and eutrophic for Lake Chivero in Zimbabwe (Thornton and Nduku, 1982). In many instances nitrogen plays an important role in net primary production, especially in lakes and streams with low nitrogen to phosphorus (N: P) loading ratios (Elser *et al*., 1990; Harper, 1992; Allan, 1995).

Ammonium (NH_4^{+}), nitrite (NO_2^{-}) and nitrate (NO_3^{-}) are the most common reactive forms of dissolved inorganic nitrogen in aquatic ecosystems (Kinne, 1984; Howarth, 1988; Wetzel, 2001). Inorganic nitrogen loading in lake systems can be through atmospheric deposition, surface and groundwater runoff, dissolution of nitrogen-rich geological deposits, nitrogen fixation by certain prokaryotes and biological degradation of organic matter. The natural source of phosphorus is the weathering of phosphorus-containing rocks such as apatite (Harper, 1992). Phosphorus therefore enters the lake from the catchment via sediment release. Phosphorus from domestic waste is largely contributed by detergents. Macrophytes, algae and microbes all utilize phosphorus as an essential nutrient, and contain P in their tissues. Fathi *et al.* (2001) also argues that the supply of P and N is considered to be one of the main factors determining the magnitude of the primary production

Garmaeva (2001) argued that most of the lakes threatened by eutrophication are those located in or near urban settlements. Results from studies on tropical lakes including Lake Victoria in Tanzania, Lake Yaounde in Cameron and Lake Chivero in Zimbabwe validate arguments by Garnaeva (2001). Pollution, man-made erosion, and draining of wetlands for intensive commercial, residential, and agricultural uses has resulted in risks to rivers, streams, and wetlands, making some freshwater ecosystems among the most endangered habitats (EPA, 2007).

2.3 Historical Background of Lake Chivero

Van der Lingen (1960) reported eutrophication related problems in Lake Chivero, Zimbabwe as early as 1959. Recent studies by Magadza (2003) pointed out that by mid-late 1960s the lake was in a hypereutrophic state. Conclusions reached from several studies and observations on the lakes physical, chemical and biological changes confirm the high level of eutrophy. The appearance of dense algal blooms *(Microsystis spp* and *Anabaena spp)* and the proliferation of the water hyacinth (*Eichhornia crassipes)* was the immediate indicator of eutrophication. Marshal (1981) argues that the increased accumulation of nutrients positively increased the proliferation of water hyacinth and incidences of dense algal blooms. This overabundance in algal biomass have caused water quality problems such as oxygen depletion in the bottom waters, filter clogging in water treatment plants, taste and odour in water supplies (Marshal, 1981). *Microcystis* produce dangerous toxins (microcystin), which also have detrimental effects on human health (Zilberg, 1966; Ndebele and Magadza, 2006). Results from the study by Ndebele and Magadza (2006) showed that the microsystin levels in Lake Chivero were 19.9 μgL^{-1}, which exceeded the recommended levels of microcystin in potable water of 1 μgL^{-1}. However, the blue green algae have been responsible for the increase in fish populations especially the Green-headed Tilapia (*Oreochromis macrochir*) (Minshull, 1978). Ironically, the *Oreochromis spp* is susceptible to deoxygenation thus; it dies when deoxygenation occurs and at turnover (Marshal, 1981; Moyo, 1997). Magadza (1997) also found out that excessive nutrient inputs in previous decades has resulted in regularly anoxic hypolimnion related to fish kills (Magadza, 1997).

Massive algal blooms coincide with fish kills in Lake Chivero (Mhlanga *et al.*, 2006). The paper reported that mild chlorophyll-a levels between 18.5±7.8µgL^{-1} and massive algal blooms up to 42.2 ±2.4µgL^{-1} recorded from February 2003- November 2004 resulted in fish kills.

The Water Pollution Control Act of 1975 that stipulated that wastewaters must contain less than 1 mgL^{-1} helped to improve the condition of the lake from the late seventies to early eighties (Thornton, 1980). Since the Municipality could not meet the stringent requirements of the Act, they resorted to the diversion of effluent to pasture land. Through effluent diversion and the installation of the Biological Nutrient Removal (BNR) system in 1974, the lake reverted to a meso-eutrophic state as reported by Thornton (1980). This move also triggered a decrease in conductivity to 126µScm^{-1}, soluble reactive phosphorus to 0.04mgL^{-1} and ammonia to 0.04mgL^{-1}. Nitrogen concentrations greater than 0.2 mgL^{-1} are critical for African lake systems (Thornton, 1980). In 1979, researchers noted an increased secchi depth from less than 0.5m to over two meters. Thornton (1981) found out that a reduction in phosphorus loadings in the lake by 94% reduced phosphorus loadings from 685 tonnes per annum to 39.6 tonnes. Magadza (1997) summarised the historical changes in phosphorus loading in the lake from 1967-1996. The summary reflects the three phases of the Lake history from the eutrophic condition at its inception, the eutrophication phase, the recovery phase and the post recovery phase.

The summary shows that phosphorus loading from sewage works dropped from 288 tonnes in 1967 to a mean of 86.7 tonnes per annum in 1976/78 season. Between 1978- 1996, nutrient loadings observed were in the excess of 350 tonnes per annum, which was attributed to increased poor sewage effluent being discharged into the water bodies. Magadza (1994) argued that such rates of nutrient build up could lead to a hypereutrophic state. However, by 1996, the phosphorus concentrations had risen to $1840 \mu gL^{-1}$ for studies done in Manyame River (Magadza, 1997).

Such responses supported arguments by Magadza (1994) that during the Thornton study the lake had rehabilitated to a metastable state in which it would revert to a eutrophic state if there were an increase in phosphorus loadings. The nutrient concentrations were higher than any time in the past with mean phosphorus concentrations in the lake in the range 1.98 mgL^{-1} to 2.99mgL^{-1} (Ndebele and Magadza, 2006). Such levels were concluded to be about three orders of magnitude from 1967 value of 0.04 mgL^{-1} when the lake was already in hypereutrophy. Apart from external nutrient loading, Jensen and Andersen (1992) argued that Fe-bound P, when present in significant proportions in the sediment, might also be a major source for internal P loading in water bodies. Although point sources of nutrients are the primary cause of excessive loadings in most lakes, nonpoint sources form urban and agricultural runoff have increased nutrient levels beyond limits upstream of wastewater discharge points (Nhapi *et al.*, 2004). Studies by Thornton (1982) estimated about 18 tonnes per annum phosphorus loads from other sources into water bodies.

Studies on riverine nutrient loadings by Marshal and Falconer (1973), Thornton (1980) showed that of the main tributaries into the lake, Mukuvisi contributed the bulk of the loadings and Manyame River contributed the least. Between 1973 and 1974, studies in Manyame River showed high phosphorus loadings of 3.9 m^2a^{-1} and phosphorus concentration of 6.6 μgL^{-1}. Recent studies by Nhapi *et al.* (2001) attributed eutrophication to continued input of nutrients and inorganic ions derived largely from treated sewage effluent.

Nutrient export were done by Mukwashi (2001) from the main tributaries (Mukuvisi, Manyame, and Marimba), streams emanating from high-density suburbs (Budiriro, Glenview, Kuwadzana, and Epworth), and low-density suburbs (Umswindale) and almost pristine streams (Gwebi). Total phosphorus was highest at Glenview between 5.081±0.59mgL^{-1}. The results also showed very high values of nitrogen in the range 23.06±1.49mgL^{-1}. The concentrations surpassed nitrogen levels of 0.51mgL^{-1} reported by JICA (1996) on Lake Chivero. The temperature in Marimba River wet season ranged between 21-25°C (Nhapi *et al.*, 2001).

Results by Mukwashi (2001) showed that Budiriro had the lowest value of dissolved oxygen, 1.69±0.67mgL^{-1} followed by Glenview with 3.83±0.54 mg L^{-1}. Oxygen levels below 5 mgL^{-1} have been argued not suitable for aquatic life (USEPA, 2000). Rios-Arana *et al.* (2003) pointed out temporal factors influencing the oxygen concentration in the water. It was found out that, oxygen increases during the day due to increased rate of photosynthesis. Neal *et al.* (2000) argues that biological productivity in lake systems cause elevated pH values. Studies by Billings *et al*. (1984) indicated that high pH is a result of high levels of photosynthetic.

The acceptable guidelines for pH in drinking water are in the range of 6.5–8.5 (WHO, 2001). Studies by Mukwashi (2001) from Budiriro recorded acidic pH (6.66±0.67 units) which is related to less productivity.

The deteriorating water quality of Lake Chivero has meant increased dosage of treatment chemicals such as flocculating agents (aluminium sulphate) as well as pH adjusting lime. A report by JICA (1999) indicated an increase in the levels of chloride, calcium and the nitrate ions. The calcium ions reported was 20 mgL^{-1}. Chloride values ranged between 3.0-10 mgL^{-1} and nitrate ranged between 2-6 mgL^{-1}. Studies in 2000 by Magadza (2003) indicated that the chloride levels in natural streams in Lake Chivero catchment are undetectable, as the geological underlying rocks are granitic. The study concluded that the chloride depth profile was therefore due to waste return rather than natural stream flows.

2.4 Hydrological issues

Apart from human influence, the trophic level of lakes as noted by Vollenweider and Kerekes (1982) is also affected by the water-mixing pattern within a reservoir, the interactions of climate, geology and hydrological systems. These interactions have an effect on nutrient concentrations, which is affected by fluctuations in water level and water retention time. Shallow lakes are particularly sensitive to any rapid change in water level and input. Water level fluctuations may have an overriding effect on the water chemistry and in turn, the ecology of shallow lakes, especially on the submerged plant development (Talling, 2001; Tan and Beklioglu, 2006).

Studies by Magadza (2003) on the water residence time in Lake Chivero showed that during the pre-1980 era the flushing rate was once per annum. However, due to reduced and unevenly distributed precipitation, which is largely attributed to the effects of climate change, the post-1980 era flushing rate per annum has decreased to almost once every two years. Magadza (2003) showed that during 1990-1996, the lake failed to spill. Fluctuations in water levels have emerged as the major factor affecting aquatic ecosystems. Concentrations of nutrients become concentrated during drought periods when water levels fall (Marshal and Falconer, 1973).

2.5 Population distribution and service delivery in the catchment

The expansion of urban populations (Table 2.1) has increased the coverage of domestic water supply and sewerage giving rise to greater quantities of municipal wastewater. Although the table shows an increasing trend in population growth, the figures are not a true reflection of the actual populations on the ground. It is argued that Chitungwiza alone houses over two million people and Harare urban almost five million people (Magadza, 2010, Pers. Comm). Unfortunately, rapid urbanisation is not matching, with employment creation and infrastructure development. Furthermore, in many urban areas of developing countries, less than 50% of the municipal solid wastes are collected and only an insignificant fraction is disposed of appropriately. Similar studies in Minneapolis/St. Paul metropolitan area, showed a positive correlation between percentage urban land-use with total phosphorus export (Walker, 1987).

Table 2.1. Population Distribution in some parts of Manyame catchment

District	2005	2006	2007	2008	2009
Harare Rural	23 332	23 530	23 746	23 963	24 180
Harare Urban	1 460 101	1 472 444	1 486 020	1 499 597	1 513 173
Chitungwiza	328 773	331 553	334 610	337 667	340 724
Epworth	116 083	117 064	118 144	119 223	120 302

Source: Register General (2009)

Studies by Bakker *et al*. (2000) showed that the majority of formally employed residents in the high-density suburbs earn below the poverty datum line. The practise of urban agriculture has expanded over the years and has gained momentum lately due to economic hardships as a means of supplementing livelihoods. The cultivation of open spaces, stream bank cultivation and wetland cultivation have resulted in destruction of vegetation, stream bank erosion causing siltation and depletion of water bodies respectively. The needs of agriculture for flat, fertile land with a ready supply of water means that wetlands are often a potential valuable agricultural resource. The cultivation of wetlands is a widespread and long-established land-use practice in many arid and semi-arid regions of Africa, due to their capacity to retain moisture for long periods, and sometimes throughout the year (Frenken and Mharapara, 2001). Most of the cultivated lands in Lake Chivero catchment consist of wetlands previously set aside for environmental protection (Magadza, 1997). The paper also mentions that the practice has been aggravated by the lack of enforcement of statutory regulations protecting the natural ecosystems. Agriculture especially on the stream bank increases the nutrient load into rivers due to siltation (Thornton and Nduku, 1982). They argued that industrialised and urban development resulted in significant increases in levels of nitrogen and phosphorus as compared to undeveloped areas. The untimely collection and illegal dumping of waste has also been a major source to the increased loading of biodegradable organic matter into water bodies.

Wastewater management in Lake Chivero catchment is mainly through wastewater treatment plants and the septic tank system. To date there are five major plants servicing the city (Table 2.2).

The sewage treatment plant for Chitungwiza, based in Zengeza has a design capacity of 21 750 m^3/day. By 1995, the Chitungwiza plant was already overloaded discharging greater than 16 000 m^3/day of raw effluent into Nyatsime River, which drains into Manyame then finally into Chivero. Nhapi *et al*. (2006) found out that the treatment plants have a combined nutrient removal efficiency of 24% for total nitrogen (TN) and 8% for total phosphorus (TP). Nhapi *et al*. (2006) also pointed out that during that time Crowbrough wastewater treatment works was performing within limits with nutrient concentrations of 4.6 ±3.0 mgL^{-1} TN and, 0.7±0.6 mgL^{-1} TP. The results showed that the Biological Nutrient Removal (BNR) effluent from Firle WTP was poor with nutrient concentrations of 13.7±10.7 mgL^{-1} TN and 1.9±3.4 mgL^{-1} TP. Apart from population pressure, Nhapi partly attributed these high concentrations to plant breakdowns and poor maintenance. The effluent concentrations exceeded applicable guidelines for phosphorus in water systems of 5 μgL^{-1} and 10 mgL^{-1} NO_3-N (WHO, 1984). The study noted that such high concentrations increased the likelihood of algal and other plant growth in water bodies as with Lake Chivero. Apart from urban agriculture, there are heavy and light formal and informal industries for example fertilizer manufacturing, soft drink manufacturing, car assembly and servicing industries and effluent from storm water drains.

Table 2.2. Sewage treatment plants servicing the city of Harare

Wastewater treatment plant	Design Capacity ML/day	Current Capacity ML/day	Received flows ML/day	Capacity utilization (%)
Firle	144	60	150	42
Crowborough	54	5	120	9
Hatcliffe	2.5	1	3	45
Donnybrook	12	3	7	30
Marlborough	7	3	7	45
Total	219.5	72	287	

Source: Harare Water 2010

2.6 Wetland components and processes

The Ramsar Convention (1971) defined wetlands as areas of marsh, fen, peat land or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salt, including areas of marine water the depth of which at low tide does not exceed six metres. The Environmental Protection Agency (Federal Register, 1980) defines wetlands as “areas that are inundated or saturated by surface or ground water at a frequency and duration sufficient to support, and that under normal circumstances do support, a prevalence of vegetation typically adapted for life in saturated soil conditions.” Mitsch and Gosselink (1986) argues that freshwater wetlands include a broad range of ecosystems that differ not only in their vegetation composition, but also in their hydrology, pH, soil organic content, organic matter mineralization rates, and inputs of anthropogenic nitrogen.

For the purposes of this study, wetlands will have one or more of the above attributes. However, in Zimbabwe extensive swamps and floodplains are lacking because most river valleys are steep and narrow.

Ouyang (2005) points out that the contribution of wetlands to hydrology and water quality through reducing the severity of flooding and erosion or improving water quality by filtering out contaminants has been masked by their well-known function of being habitat to wildlife. Wetlands provide habitat to a diversity of microbes, plants, insects, amphibians, reptiles, birds, fish, and mammals. Despite being areas of high ecological value particularly for the rural poor, wetlands are often over-exploited and degraded (Turner *et al*., 2000). It is estimated that in eastern South Africa, approximately 50% of wetlands have been lost or degraded, most commonly a result of modification by commercial or subsistence agriculture (Kotze *et al*., 1995). On a world scale since 1900, more than half of the world's wetlands had been destroyed for other land uses (Barbier, 1993). However, wetland budgets by Costanza *et al*. (1997) indicated an immense value of goods and services provided by wetlands on a World scale. The value of World's natural systems was estimated to be over thirty trillion United States dollars per year. Of this estimated value, freshwater wetlands constituted 10%, which as a whole constituted over a quarter of the budget.

2.6.1 Self-purification in wetlands

A number of biogeochemical processes occur in wetlands due to their saturation and high primary productivity. The removal of organic matter and nutrients in wetland systems is dependent on the microbiota and their metabolism (Wetzel, 1993; Hatano *et al*., 1993; Kadlec and Knight, 1996). Wetland processes transport and transform nutrients through settling, absorption, adsorption, microbial processes and plant uptake. Many scholars have argued that the efficiency of different wetland types in water purification depends on many factors, including the magnitude and frequency of flow (Bayley *et al*., 1985), water retention time (Walker, 1987), the degree of water-sediment contact (Bowden, 1987), the magnitude and nature of inputs (Richardson and Nichols, 1985) and the composition of wetland sediments (Richardson, 1985). Water flow dynamics by Howard-Williams and Gaudet (1985) show that upon entering a tropical swamp, water will follow the path of least resistance either streaming over, through or under the floating vegetation. The study concluded that the capacity of wetlands to attenuate wastewater flow into receiving water bodies is high when the degree of interaction between vegetation and the influent is high.

Studies by Gardner and Brooks (1980) highlighted the potential of aquatic systems to purify themselves of pollution. Wuhrmann (1991) also discussed the effectiveness of natural wetlands in processing wastewater among other functions of controlling floods and recharging surface water. The wetland potential has also been discussed under concepts of Integrated Lake Basin Management (ILEC, 2007). From lessons learnt and lessons not learnt, it was found out that wetlands alone cannot solve all eutrophication problems.

The publications supported earlier limitations in wetland use discussed by (Gardner and Brooks, 1980; Kotze, 2000), that every wetland has a limited capacity to assimilate nutrients and that overloading it will reduce its ability to perform this and other functions. The former study however, concluded that the shortcomings of wetlands in water quality management are outweighed by their benefits.

Spellman (1996) argues that the watershed area has an intrinsic self-purification potential, which can sustain and reduce downstream water quality deterioration. This self-purification process is very efficient in controlling diffuse pollution. However, the character of the stream and quality and quantity of the pollutant also determines the degree of purification. The self-purification ability of wetlands has found wide application in wastewater treatment in several developing countries e.g. China, Philipines, Burma, India and Thailand (Jørgensen, 2000). Studies by Machena (1997) and Tendaupenyu (2002) on the Mukuvisi River showed that the river has some self-purification potential. Tendaupenyu found out that a wetland in extend of 20969.52m^2 and spanning a mere 1500m (2.0970 Ha) was able to improve water quality by approximately 50%. It was approximated that the same wetland had a phosphorus removal capacity between 3 to 48 gs^{-1}. Tendaupenyu (2002) pointed out that this could be achieved by constructing larger wetlands throughout the course of the rivers and building weirs to ensure a constant water velocity. Similar studies on self-purification were done on Upper Chinyika River below Hatcliffe sewage treatment works (Bere, 2005). The results showed that the physico-chemical parameters deteriorated just below sewage outflow and then improving with increasing distance downstream because of self-purification, except for conductivity.

Results from experimental work by Anusa (2004) on artificial wetlands showed that a wetland as big as 5.85 m^2 has the potential to reduce turbidity, nitrates, ammonia, total phosphate and BOD_5 to acceptable limits. Nitrogen levels were reduced from 0.60±0.03 to 0.40±0.06 mgL^1 and total phosphorus values from 1.24±0.02 to 0.46±0.06 mgL^1. From the experimental results, it was found out that the percentage mean reduction of turbidity after passing through the same wetland was 92%, nitrate was 39%, phosphorus 80% and BOD_5 82%.

Several studies have also shown that freshwater wetlands are a "sink" for natural and anthropogenic nitrogen inputs (Tilton and Kadlek, 1979) with nitrogen removal efficiencies ranging from 20%-70% (Nixon and Lee, 1986). Vegetative growth, immobilization by microbes and burial in sediments is known to retain nitrogen for various periods of time (Bowden, 1987). However, denitrification potential is the major ecological process by which nitrogen is removed permanently from wetlands and downstream ecosystems. Jørgensen (1994) argues that as much as 100 kg nitrate-N per hectare may be found in drainage water from intensive agriculture. As much 2 000-3 000 kg of nitrates can be denitrified per hectare of wetlands per year (Jørgensen, 1994; UNEP-IETC, 2000). However, some lakes respond rapidly to an external loading reduction by an immediate or a delayed decline in lake concentrations following the changes in loadings (Welch and Cooke, 1995). Further studies by Welch and Cooke (1999) showed that internal phosphorus loading might be persistent and endure at least 10 years after an external loading reduction.

Since both organic and inorganic phosphorus occurs in a closed cycle, the removal and storage of phosphorus from wastewater can only occur within a wetland system. Phosphorus in wetlands can be removed through binding with organic matter. Macrophytes, algae and microbes all utilize phosphorus as an essential nutrient, and contain P in their tissues. Microorganisms will decompose the organic matter either aerobically or anaerobically. Insoluble phosphates can be precipitated with ion, calcium and aluminium ions.

3. MATERIALS AND METHODS

3.1 Modelling

The Planning and Management model of Lakes and Reservoirs: Model for Eutrophication Management (PAMOLARE version 3.0) was applied to project the future trophic status of Lake Chivero. The model simulated the water quality response of the Lake in 10 years due to nutrient reduction through the application of two management scenarios. The model also simulated the future of Chivero under the prevailing conditions when there is high nutrient loading due to poor wastewater treatment and uncontrolled non-point sources of pollution. The compilation of data required for the PAMOLARE lake model was developed through experimental work, literature review and consultations with the responsible authorities. Default values of the model were used where no information was available for state variables.

The 1-layer model was selected because there is little information on lake stratification distinguishing between the epilimnion and the hypolimnion since this lake does not permanently stratify (Thornton and Nduku, 1982). The writer also has a limited background in lake modeling and wishes to learn the basics of modeling.

The input data needed to build the model include:

- The initial nitrogen and phosphorus concentrations (mgL^{-1})
- Current nitrogen and phosphorus loadings (gm^2)
- Nitrogen and phosphorus bound
- Nitrogen and phosphorus released
- Lake morphometry [mean depth (m), sedimentation rate (m/year) and water residence time (years)]

3.1.1 External (forcing) variables

The main forcing functions for Lake Chivero are the nutrient loadings from wastewater treatment plants, residential areas, formal and informal industries, agriculture practises through the three main tributaries. The mean flow rates from October 2010 - January 2011 for Manyame, Mukuvisi and Marimba Rivers were obtained from Zimbabwe National Water Authority (ZINWA) Research and Data Division. The flow rates were mean daily recordings from gauging stations CR21, CR22 and CR24 respectively.

Nitrogen and phosphorus loading from the catchment were estimated using the formulae below:

$$L = Q * \frac{C}{A}$$

Where: L = nutrient loading (gm^2)

Q = flow rate in (m^3s^{-1})

C = nutrient concentration (mgL^{-1})

A = surface area of the Lake (m^2)

3.1.2 State variables

The initial state variables representing the condition of the lake at a given time include the physical, chemical and biological condition of the water. Chemical concentrations of nitrogen and phosphorus determined from field samples through laboratory analysis were used for modeling. The physical status of the water was monitored onsite using different probes. Standard mathematical equations extracted from PAMOLARE version 3.0 were applied to make estimations of relevant current information that could not be gathered (Vollenweider, 1975).

3.1.3 Phosphorus and Nitrogen (loading, bound and release)

Phosphorus and nitrogen input from the catchment was calculated for both point and non-point source pollution. Non-point estimations on loadings are based on principles by Ryding and Rast (1989), that under average hydrologic conditions and land use for specific purposes e.g. agriculture, nutrient loading per annum is constant. The input was expressed as loading per unit area of the lake surface area. Phosphorus bound is usually 15-25% of the total P in the sediment. Estimates from studies by Nduku (1976) for phosphorus in sediment were used. The anaerobic release of phosphorus from Lake Chivero was estimated to be between 0.03-0.13 mg $m^{-2}d^{-1}$ (Thornton, 1980). Nitrogen bound is slightly smaller, only 10-20% of nitrogen is sediment. However, default values were used for the denitrification of nitrogen.

3.2 Construction of Scenarios

Two management scenarios for Lake Chivero were assumed. The scenarios were mainly focused on nutrient reduction systems. It was assumed that the two scenarios would have a positive impact in improving the state variables of the lake ecosystem.

Scenario A: The utilisation of wetlands in Lake Chivero catchment

Scenario A incorporated the use of natural wetlands in Lake Chivero catchment area through preservation and application of regulatory statutes on sustainable use of the wetlands. The wetlands in Lake Chivero catchment were identified using Google Earth Pro 4.2 Satellite Imaging. A wetland inventory was created using area polygons by selecting the different wetlands and storing them in a database. The wetland area captured extended from City of Harare, Chitungwiza, Ruwa, Epworth, Mabvuku and Seke Communal lands.

The wetland database created in Google Earth was imported to the Integrated Land and Water Information Systems Model version 3.3 (ILWIS) for data editing and analysis. Arc View 3.2 Geographic Information System (GIS) was run to estimate the size of the wetlands spatially distributed in the Upper Manyame catchment. Human population and environmental weather conditions were treated as constants during modelling. Wetland efficiencies were extracted from past studies (Mukwashi, 2001; Tendaupenyu, 2002; Anusa, 2004). The extrapolated purification potential of the wetlands (Anusa, 2004) in Appendix 6 indicates that the reduction efficiency of phosphorus in a wetland $5.85m^2$ was 80% and for nitrogen, it was 37%. Results from studies by Tendaupenyu (2002) estimated that an area of 2.1 hectares spanning 1500m could remove between 3 and 48g of phosphorus per second.

Scenario B: Efficient wastewater treatment plants

Scenario B incorporated the efficient functioning of the existing mechanical wastewater treatment plants. It was assumed that effluent would be treated within acceptable limits. If the Biological Nutrient Removal (BNR) and wastewater ponds are fully functional, efficiency was estimated to be 85% (Water Environment Federation and American Society of Civil Engineers, 1998). The existing wastewater treatment plants could be rehabilitated through maintenance and upgrading of existing structures, which is currently in progress (Eng. Muserere, 2011, personal communication).

3.2.1 Model outputs

The parameters that are most related to the eutrophication problem were selected for in the PAMOLARE model. These included nitrogen and phosphorus in water (mgL^{-1}), phosphorus and nitrogen in sediments (gm^2), chlorophyll-*a* (mgL^{-1}) and secchi depth (m). The progression trends of the effect of nutrient reduction were shown over time. The model showed the period required by the lake for an improvement in water quality. It also showed the expected range of the trophic status of Lake Chivero over several years. Given a water management goal and an array of feasible control techniques, the probability that rehabilitation efforts will be successful was determined.

3.3 The sampling sites

Eight sampling sites (Figure 3.1.) were selected based on their contribution to the nutrient loading in the Lake. Samples from sites (1-3) (Table 3.1 and Fig 3.1.) collected downstream of sewage-effluent discharge points to capture the contributions of point sources of pollution into the lake. The contribution of diffuse source pollution was captured from sites 4-6 before any water treatment processes. Sites 4-6 are largely comprised of residential areas and agricultural lands under maize cultivation.

Sites 7-8 were the reference points to show the present status of the lake from the contributions of both point and non-point sources of pollution. The major wastewater treatment plants (WTP) servicing Manyame catchment area are Crowborough, Firle, Marlborough, Donnybrook, Zengeza and Hatcliffe (Table 2.2). Effluent from the treatment plants is directly discharged into river systems as shown in Figure 3.1 below. The exact coordinates of the sampling sites shown in Table 3.1 were located using a Garmin Etrex Summit 12 Channel Global Positioning System (GPS).

Table 3.1. Description of sampling sites

Site	Name	Designation	Coordinates
1	Marimba River	At the mouth to Lake Chivero	17°54,521´´S 030°50,450´´E
2	Mukuvisi River	After Firle treatment works	17°58,471´´S 030°50,450´´E
3	Manyame River	At skyline bridge	17°55,374´´S 030°58,020´´E
4	Kuwadzana	High density residential area	17°49,609´´S 030°54,355´´E
5	Budirio	High density residential area	17°54,096´´S 030°54,980´´E
6	Glenview	High density residential area	17°55,161´´S 030°56,140´´E
7	Mid Lake*	Middle section of lake	17°54,094´´S 030°48,038´´E
8	Near the dam *	Close to the watch tower	17°53,392´´S 030°47,177´´E

Notes: Sampling sites were adopted from past studies (Mukwashi, 2001 and Ndebele, 2003*)

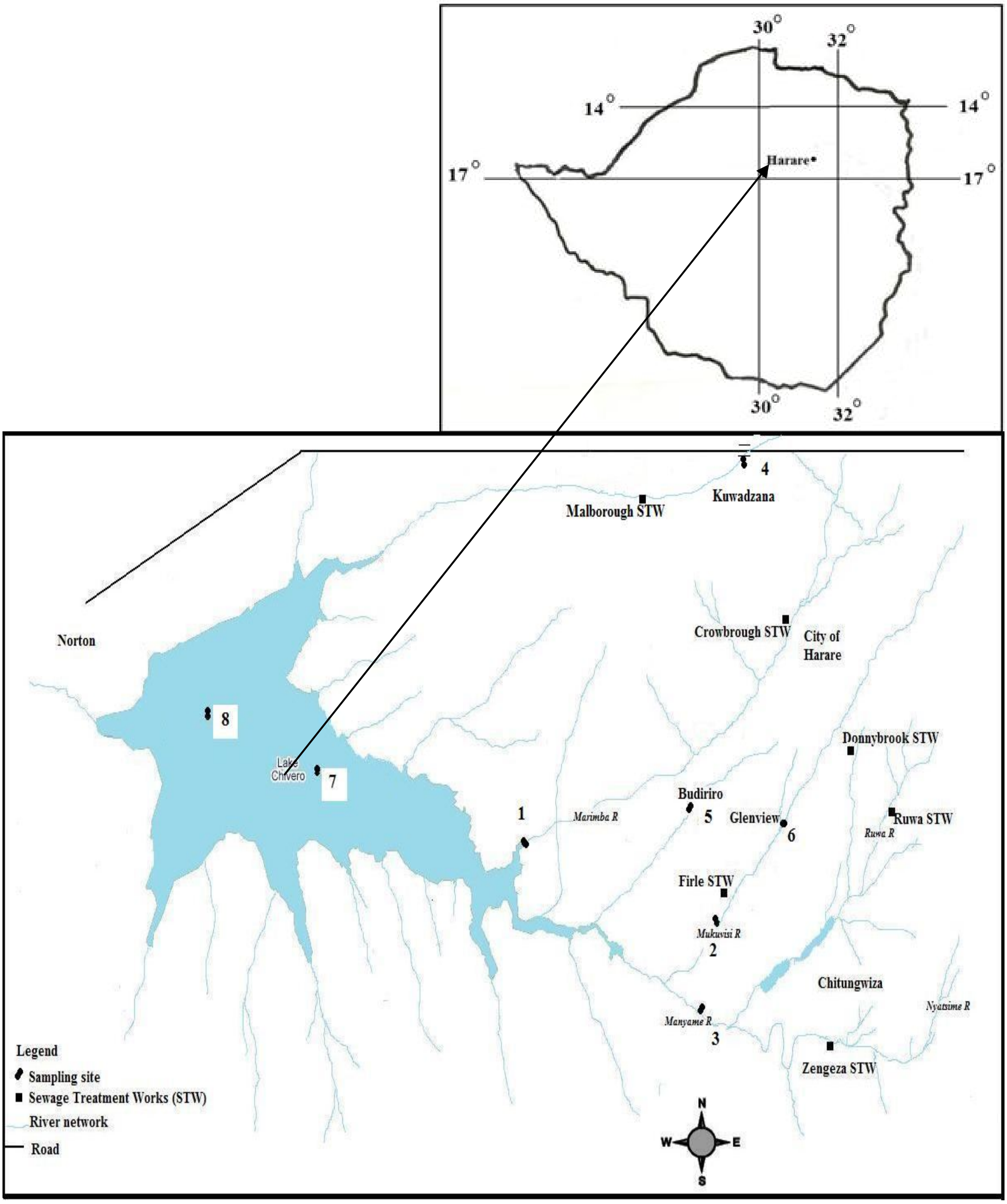


Figure 3.1. Site map showing numbered sampling locations

3.4 Data collection

Data were collected over a period of 3 months from 29 October 2010 to 31 January 2011. Surface water samples were collected from site 1-6 because the river systems are flowing. Vertical profiles at 2-meter interval for the physical parameters were taken from the two lake points (site 7 and site 8). Onsite temperature (°C), hydrogen ions concentration (pH), percentage oxygen saturation and dissolved oxygen (DO) (mgL^{-1}) were measured on site using a pH/mV/ DO meter (HACH HQ20). Conductivity (μScm^{-1}), oxidation-reduction potential (mV) and % salinity, were measured using a conductivity meter (WTW pH 330i)

Water transparency from the lake was measured with a standard 20 cm diameter secchi disk according to standard methods (Wetzel, 1983). A 1 cm graduated secchi disk was used to measure transparency from the rivers.

The recorded secchi depth was converted to Nephelometric Turbidity Units (NTU) using the formulae below:

$$\text{Depth (cm)} = 244.13 * (\text{Turbidity in NTU})^{-0.662}$$ (University of Wisconsin, 2003).

Where: 244.13 and -0.662 are constants

Composite water samples from the depth profile were collected in polythene bottles for chemical analysis. Prior to use the polythene bottles were soaked overnight in 0.1 molar hydrochloric acid solution, thoroughly rinsed with distilled water and left to dry. Onsite, the sample bottles were rinsed with the sample water before collecting the sample. A Ruttner sampler was used to collect the water samples. The water samples were stored on ice to reduce further chemical reactions until they were transported to the laboratory. The samples were kept frozen until analysis.

3.5 Laboratory Analysis

Chemical analysis of the water samples was conducted at the University of Zimbabwe in the Hydrobiology Laboratory. Total phosphorus (TP mgL^{-1}) and total nitrogen (TN mgL^{-1}) concentrations were determined from composite water samples by colourimetric methods. A spectrophotometer (HACH DR/2010) was used to convert the observed colours into actual concentrations. Prior to spectrophotometer measurement, samples were subjected to a mineralization process, using the persulphate digestion technique according to Murphy and Riley (1962). The total nitrogenous compounds in water are oxidised to nitrates by heating with the alkaline persulphate (Korololeff, 1969). The digested sample was passed through a copperised cadmium column were the nitrates are reduced to nitrites. To avoid under estimating the absorption range the nitrogen samples were diluted from 2 ml to 100 ml with distilled water. The concentrations were multiplied by the dilution factor of 50 to get the actual values.

Chlorophyll (*a*) as a measure of phytoplankton biomass was determined using the absolute alcohol extraction method (Bronmark and Hansson, 1998). The water samples were filtered using the Whatman Glass Filter (WGF). The filter paper was fully covered with absolute alcohol in a vial. The samples were placed in darkness at room temperature for 20 hours. After 20 hours, the samples were centrifuged for 10 minutes at 3000 revolutions per second. Biomass was calculated from absorbencies of the extract using the HACH DR/2010 spectrophotometer at 665 nm and 750 nm.

The chlorophyll-a concentration was determined using the formulae below:

$$\text{Chl } a \ \mu g/l = \frac{\text{Abs } 665 - \text{Abs } 750) * e * 10000}{83.4 * v * L}$$

Where: e = volume of extract (7 ml)

L= length of cuvette (10 cm)

V = filtered sample (0.1 liters)

83.4= the absorption coefficient for ethanol ($g^{-1}cm^{-1}$)

3.6 Statistical Analysis

Data were analyzed using STATISTICA version 5.0 Statistical package. A normality test was done using normal probability plots in STATISTICA. Multivariate Analysis of Variance (MANOVA) was run to test statistically the comparison of means for the physico-chemical characteristics for the different sampling sites and dates. Principal Component Analysis (PCA) was carried out to identify any underlying relationships between the physico-chemical variables. Site ordination was also done in PAST statistical package to identify the relationship between the different sites. Eigen values greater than one was taken as a criterion for the extraction of the principal components required to explain the source of variance in the data set. Correlation analysis in STATISTICA was run to test for significant relationships between the parameters. Cluster analysis was used to classify the variables into groups based on their similarity coefficients. The clusters join the most similar observations and successively the next most similar observations. The levels of similarity at which observations are merged were used to construct a dendrogram. Depth profile curves for the lake mid-point and lake wall were created in Microsoft Excel 2010.

4. RESULTS

4.1 Physicochemical status of the eight sampling sites

The averaged results for the whole study period for eight sites from October 2010- January 2011 are as shown in Table 4.1.

Table 4.1. Mean physico-chemical records for the composite water samples from eight sampling sites

Site	Temperature (°C)	Oxygen saturation (%)	Dissolved Oxygen (mg/l)	pH (units)	Conductivity (µS/cm)	Salinity (%)	Total Dissolved Solids (g)	Oxidation Reduction Potential (mV)	Total P (mg/l)	Total N (mg/l)	Chlorophyll a (µg/L)	Secchi depth (m)
Marimba	23.84±0.4	17.65±8.4	1.54±0.6	7.32±0.2	665.9±90.5	0.075±0.3	385.25±62.9	-82.06±48.5	3.99±0.24	6.66±1.47	34.27±4.5	0.14±0.2
Mukuvisi	24.85±0.5	34.48±8.9	2.53±0.7	7.34±0.1	742.3±106.7	0.900±0.2	427.25±76.7	-93.33±52.8	5.56±0.49	6.31±0.72	25.73±3.1	0.12±0.2
Manyame	21.62±0.9	15.70±8.2	1.21±0.7	7.14±0.2	581.0±177.6	0.063±0.48	260.26±49.6	-76.83±52.5	1.69±0.28	2.73±0.38	37.95±7.4	0.16±0.2
Kuwadzana	23.58±0.7	34.65±6.6	2.62±0.5	7.66±0.1	612.8±89.0	0.038±0.2	359.25±58.4	-36.19±11.7	1.21±0.44	4.08±1.20	18.41±2.8	0.28±0.1
Budiriro	24.43±0.3	12.19±8.8	1.05±0.8	7.22±0.1	854.7±103.8	0.188±0.4	509.75±82.9	-80.64±51.2	8.98±1.97	4.30±1.30	29.06±10.9	0.09±0.1
Glenview	24.67±0.5	27.24±6.0	2.04±0.4	7.57±0.1	693.1±105.8	0.063±0.2	386.13±62.6	-40.25±8.5	1.63±0.12	5.50±1.75	22.49±3.4	0.20±0.1
Lake mid	24.46±0.3	72.52±6.7	5.39±0.5	8.26±0.2	577.9±29.9	0.009±0.1	319.70±66.4	-70.28±2.9	3.69±0.35	3.70±0.35	85.68±21.0	1.1±0.2
Lake wall	24.66±0.3	79.44±7.8	5.82±0.5	8.32±0.1	580.3±30.0	0.009±0.1	305.57±60.7	-68.12±7.5	3.06±0.19	2.73±0.38	118.93±28.5	1.0±0.2

Simple descriptive statistics showed that temperature had variations from one sampling site to another. Mean temperature was highest for site 2 (24.85±0.51°C) and least for site 3 (21.62±0.86°C) as shown in Table 4.1. The temperature for the sampling period from all the sites was in the range of 17.6-28.2°C. MANOVA confirmed that the variation in temperature was significantly different with site (Table.4.2). The mean dissolved oxygen (DO) concentration was highest for site 8 (5.82±0.5 mgL^{-1}) and least for site 5 (1.05±0.8 mgL^{-1}). The DO concentration from the eight sites ranged between 0.0 - 14.6 mgL^{-1}. The pH values for the different water samples varied between 6.15 units to 9.54 units. The mean pH values from the river systems were slightly acidic with Manyame recording the least mean of (7.14±0.17 units) followed by Budiriro (7.22±0.12 units). The lake sites were slightly alkaline with the lake wall (site 8) recording the highest mean value of 8.32±0.13 units. The electrical conductivity of the water from the rivers and the lake was in the range of 145.7- 1450.0 µS cm^{-1}(Appendix 1). The mean conductivity was highest at Budiriro (854.69 μScm^{-1}) site followed by Mukuvisi (742.26 μScm^{-1}) and the least was recorded from the lake midpoint (577.93 μScm^{-1}). The total phosphorus (TP) concentration for Lake Chivero for the sampling period averaged to 2.77 mgL^{-1}. The mean total nitrogen concentration from the lake for the sampling period was 3.21 mgL^{-1}. The mean total N concentrations ranged between 2.73±0.38 mgL^{-1}(lake wall) to 6.66±1.47 mgL^{-1}(Marimba). The mean total P concentrations ranged between 1.21±0.44 mgL^{-1} (Kuwadzana) to 8.98±1.97 mgL^{-1}(Budiriro) (Table 4.1). Highest values of salinity were recorded from the rivers with Mukuvisi recording the highest value 0.9±0.2% and the lake points the least 0.009±0.1%. Manyame River recorded the highest calcium levels (Appendix 4) 1.04 gL^{-1} followed by the lake near the dam. Marimba recorded the least calcium of 0.21 gL^{-1}.

The measured mean chlorophyll (*a*) was highest from the lake sites as compared to the rivers. Highest mean values of 118.93±28.5 μgL^{-1} were recorded near the dam wall. The least chlorophyll levels of 18.41±2.8 μgL^{-1} were recorded from Kuwadzana site. The mean secchi depth was low for all the rives with levels below 0.50 m. Budiriro (site 5) recorded the lowest mean secchi depth of 0.086 m and highest mean depth of 1.11 m was recorded from the lake mid-point. The turbidity values for the whole period varied from 1.46 to 769.04 Nephelometric Turbidity Units (NTU).

Multivariate Analysis of Variance (MANOVA) for the comparison of means of the physico-chemical parameters indicated that temperature, oxygen saturation, DO, pH, salinity, TN and chlorophyll (*a*) had some significant difference with site (Table 4.2). Conductivity, ORP and TDS had significant difference with the sampling date. Table 4.2 represents probability levels from MANOVA.

Table 4.2. MANOVA probability values of the physico-chemical components with site and sampling date

Parameter	Temperature (°C)	Oxygen saturation (%)	DO (mg/l)	pH (units)	Conductivity (µS/cm)	Salinity (%)	TDS (g)	ORP (mV)	Total P (mg/l)	Total N (mg/l)	Chlorophyll a (µg/L)
Site	**0.001**	**0.00**	**0.00**	**0.00**	0.49	**0.00**	0.23	0.95	0.60	**0.00**	**0.00**
Date	0.68	0.29	0.10	0.20	**0.00**	0.18	**0.00**	**0.00**	0.72	0.93	0.45

*Values of $p \leq 0.05$ are statistically significant. Statistically significant values are represented in bold.

The principal components results showed that four factors with Eigen values greater than 1 explained for 73% of the variance in the data (Table 4.3). However, 50% of the variation was explained by only two factors. Factor 1 accounted for 34% of the total variance and Factor 2 accounted for 16%. Figure 4.1 show the principal components ordination formed by the different physico-chemical parameters. Oxygen saturation, dissolved oxygen, turbidity, salinity, chlorophyll-*a* and pH contributed to the first principal component (PCI). Conductivity and ORP contributed to PC2 with conductivity indicating a strong positive loading. PC3 was loaded with TN, temperature and TDS with TN contributing positively. PC4 was positively loaded with TP. The principal components showed that total phosphorus, temperature and salinity were independent of any group. However, from visual assessment TDS, TN, TP and conductivity seemed to belong to the same principal component as much as DO, oxygen saturation, turbidity, pH and chlorophyll -a. The principal components are as shown (Figure 4.1.).

The relationship within the components was further explained by a correlation analysis between physico-chemical parameters (Appendix.7). Results indicated that for components in PC1; DO, pH and chlorophyll-*a* are positively and significantly correlated to turbidity at ($p \leq 0.01$) (turbidity and pH r^2= 0.67), oxygen and turbidity (r^2= 0.63); chlorophyll-*a* and turbidity (r^2= 0.44). Salinity was negatively correlated with the parameters in PC1 (r^2 =-0.39). The correlation matrix (Appendix.7) confirmed a positive correlation between salinity, TDS and TN with conductivity. The correlation coefficient for conductivity and salinity was (r^2= 0.55).

However, conductivity and ORP had a negative correlation. It was also deduced from the correlation matrix that temperature and TDS had a positive correlation (r^2= 0.34) and temperature with TN had a negative correlation (r^2= -0.46).

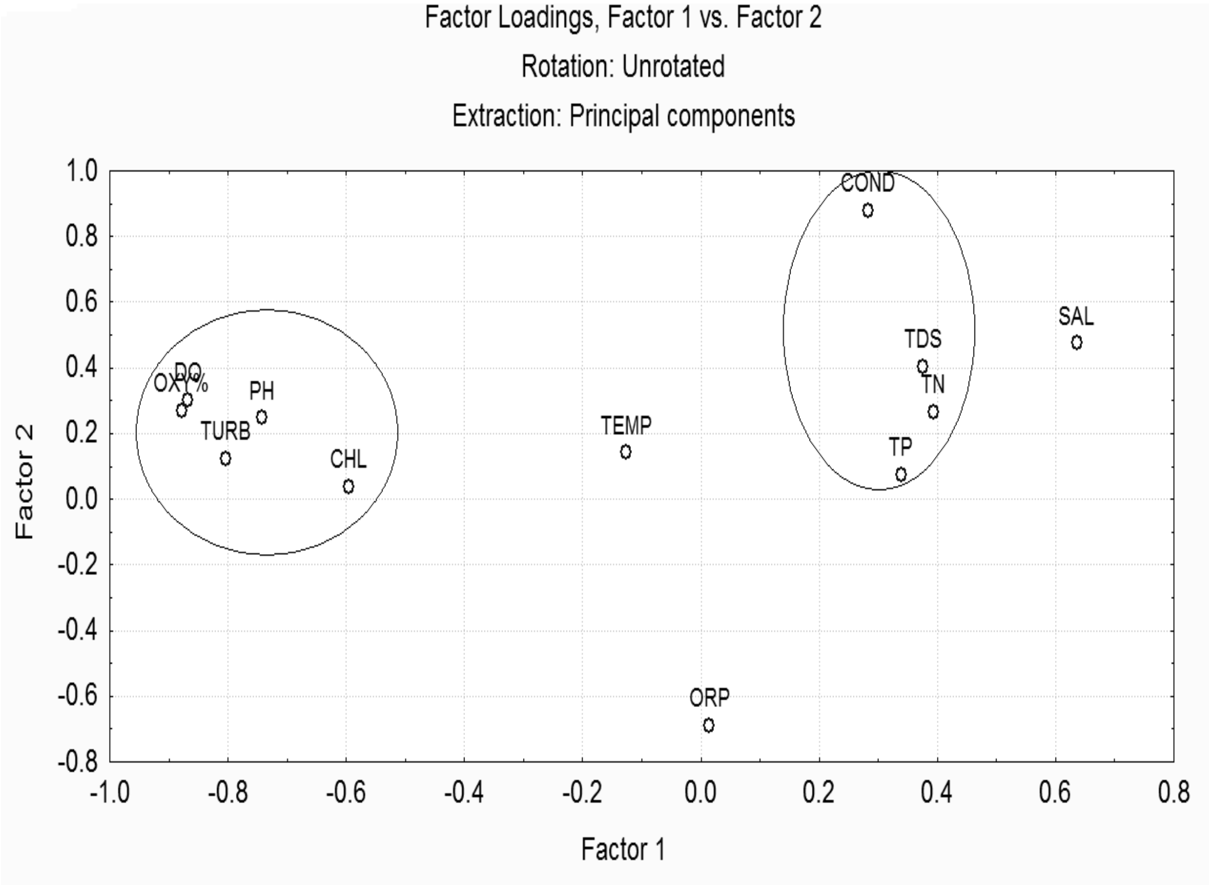


Figure 4.1. Principal component analysis performed on physico-chemical parameters from Lake Chivero and its feeder rivers.

Environmental variables: DO (Dissolved Oxygen); % OXY (Oxygen Saturation); TURB (Turbidity); CHL (Chlorophyll-a); ORP (Oxidation Reduction Potential); TEMP (Temperature); TDS (Total Dissolved Solids); TP (Total Phosphorus); TN (Total Nitrogen); SAL (Salinity); COND (Conductivity). Encircled Principal Components are related.

Table 4.3. Weight of the variables along the main principal components axis

VARIABLE	FACTOR1	FACTOR 2	FACTOR 3	FACTOR 4
TURB	**-0.803009**	0.123181	-0.050643	-0.006020
TEMP	-0.125878	0.142196	**-0.892324**	-0.032741
OXY%	**-0.878480**	0.270434	0.112151	-0.022973
DO	**-0.867748**	0.302082	0.131209	-0.000480
PH	**-0.741530**	0.247130	-0.215283	-0.191429
COND	0.283251	**0.878995**	0.016605	-0.019549
SAL	**0.635937**	0.474927	-0.182366	0.151639
TDS	0.376187	0.404888	**-0.474138**	-0.460121
ORP	0.014753	**-0.689569**	-0.352022	-0.290480
TN	0.393559	0.266041	**0.594936**	-0.282857
TP	0.338533	0.074398	-0.240821	**0.695414**
CHL	**-0.595094**	0.039083	-0.070510	0.351412
Eigen value	3.985262	1.976323	1.674122	1.044848
% Total variance	33.985262	16.4694	13.9510	8.7071
Cumulative Eigen value	3.985262	5.961585	7.635707	8.680555
Cumulative %	33.985262	50.454662	64.405662	73.112762

Extracted from Statistica-Principal Components Analysis

Notes: Numbers in bold print under the same column represent weights of the important variables contributing to the different factors.

The results from Cluster analysis confirmed the relationship between conductivity and TDS (Figure.4.2.). A close relationship between the two parameters was displayed due to their smaller linkage distance. However, the long linkage distance between the first cluster (conductivity and TDS) with ORP shows some dissimilarity. ORP shows a closer relationship with chlorophyll (a), which has a close relationship with percentage oxygen saturation. Oxygen saturation has a very close relationship with temperature and pH. This former cluster was closely related to TP, turbidity, DO and salinity.

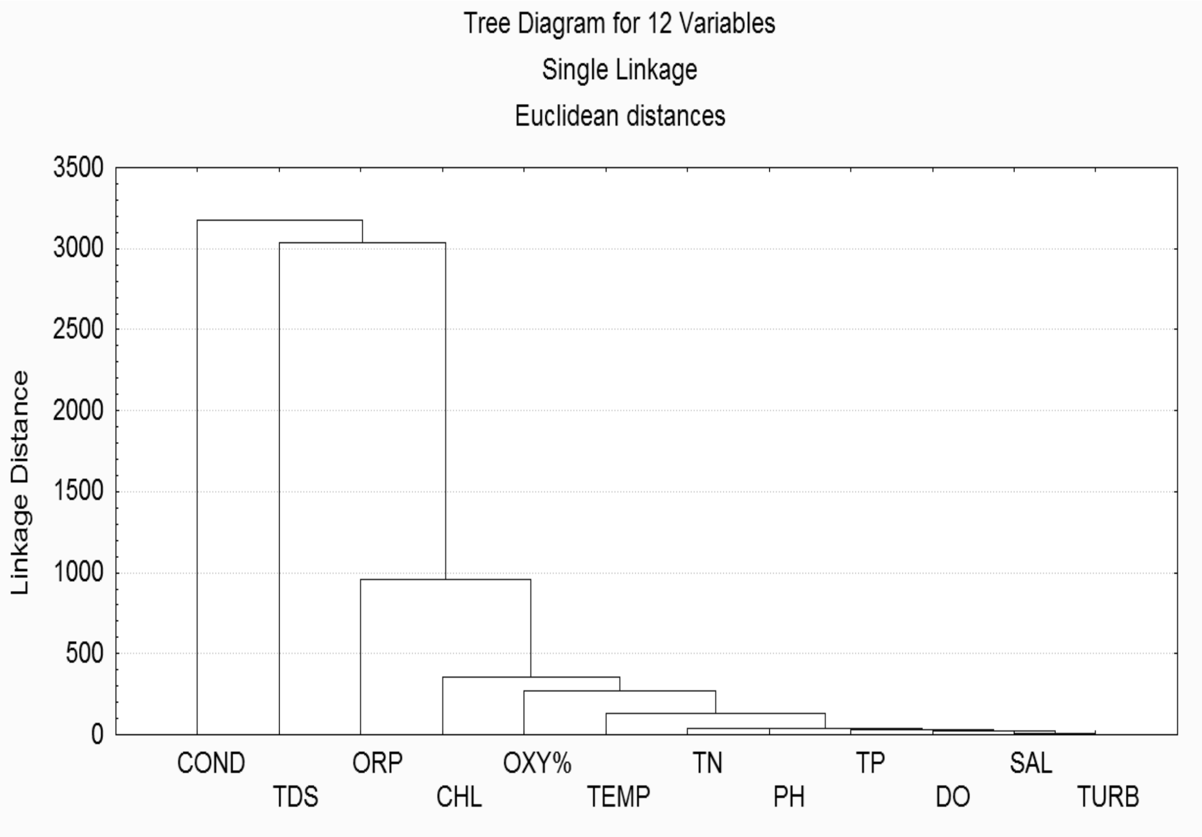


Figure 4.2. Dendrogram of the physico-chemical parameters using linkage distances

The rivers (site 1-6) caused much of the variability for physic-chemical records as shown by the positive loading in (Figure 4.3.). This same trend was observed in the cluster analysis in Appendix 7. Budirio site showed high dissimilarity levels compared to the other rivers as displayed by the long linkage distance. However, Marimba and Glenview site showed a very close relationship which was also closely related to Mukuvisi. The two lake points were closely related as displayed by the same linkage distance (Appendix 7.).

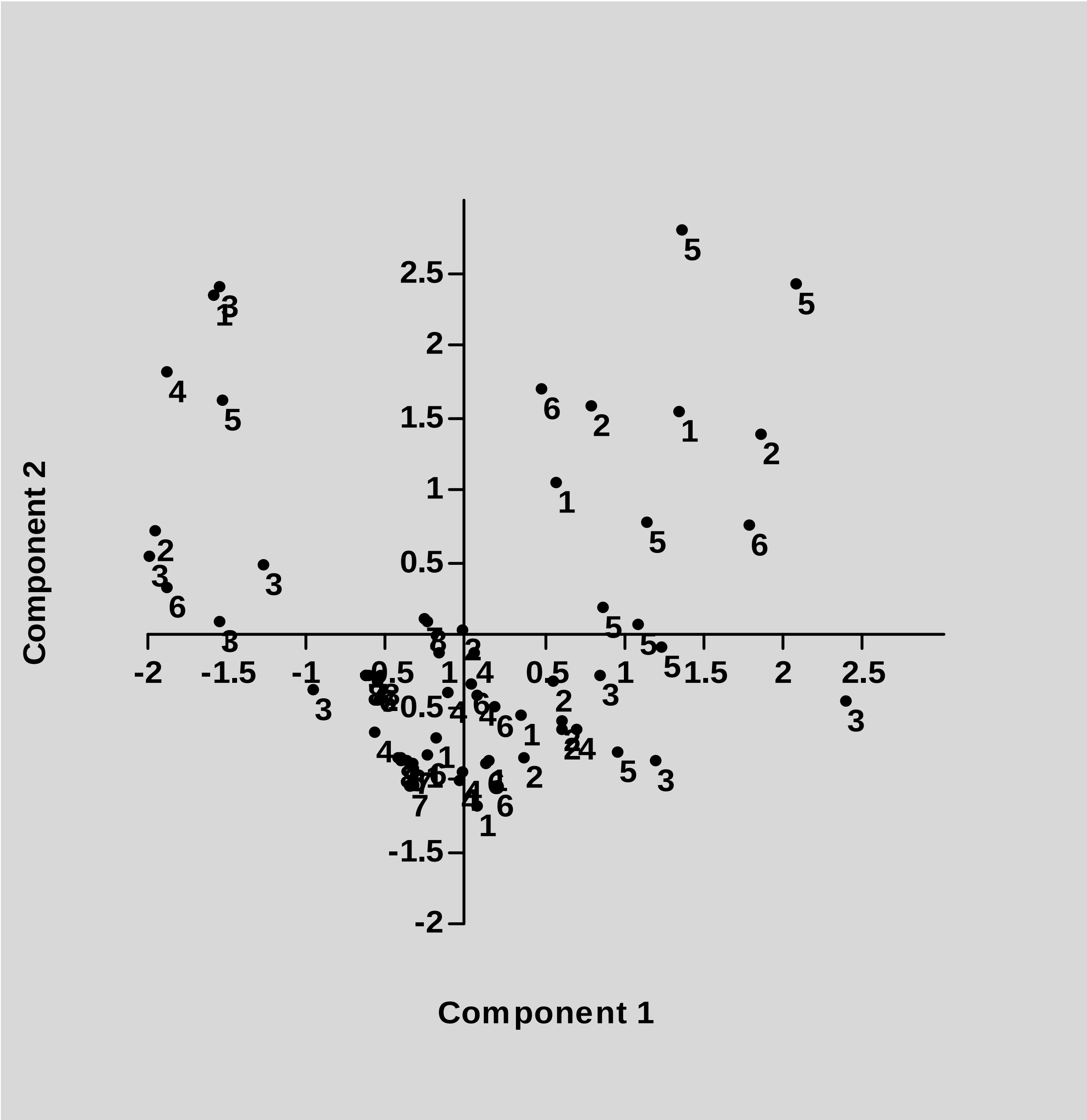
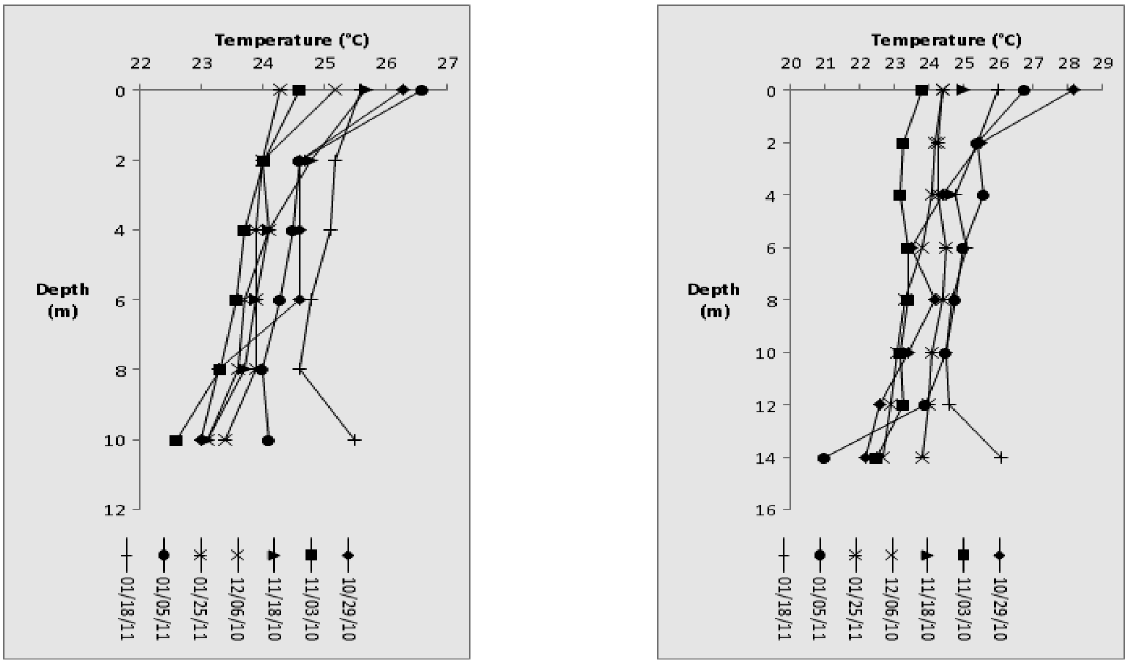


Figure 2.3. Principal Component plot for the sampling sites

SITES: 1 (Marimba); 2 (Mukuvisi); 3 (Manyame); 4 (Kuwadzana); 5 (Budiriro); 6 (Glenview); 7 (Lake Midpoint); 8 (Lake near the dam)

4.2 Physical parameter depth profiles for Lake Chivero

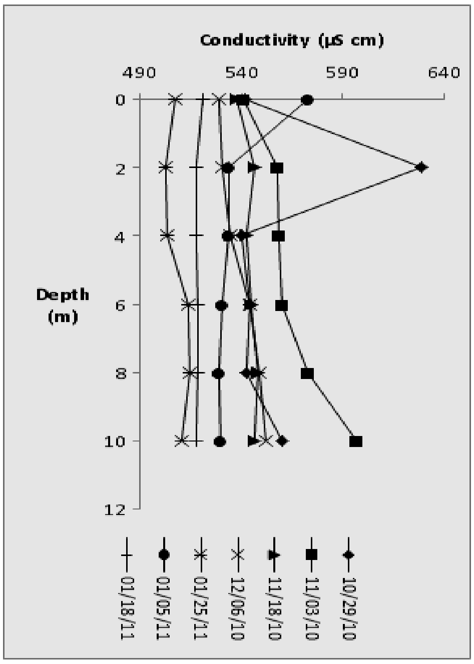
Figure 4.4 to Figure 4.9 show the depth profiles for the different physico-chemical parameters for Lake Chivero, lake mid-point (site 7) and lake near the wall (site 8).



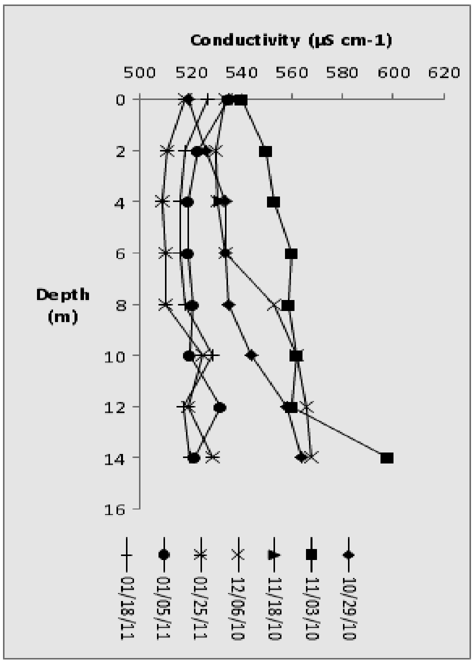
a) Site 7 b) Site 8

Figure 4.4. Temperature depth profile for different sampling dates at site 7 and 8

The temperature depth profile for the two lake points showed no convincing thermocline on all sampling days (Figure.4.4.). Temperature decreased with depth for both site 7 and site 8. At the lake midpoint, the mean temperature decreased at a rate of 0.25°C m^{-1}. Near the dam wall, the mean temperature decreased at a rate of 0.20°C m^{-1}. The maximum temperature at site 7 was 26.6°C and the minimum was 22.1°C. Near the dam wall (site 8), the maximum temperature was 28.2 °C and the minimum was 21.0°C.



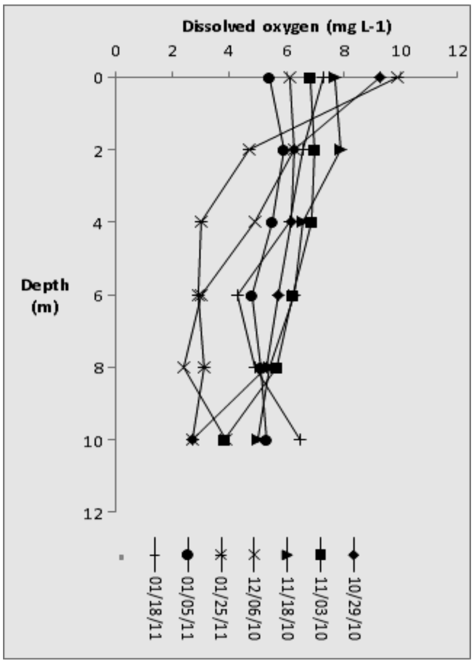
a) Site 7



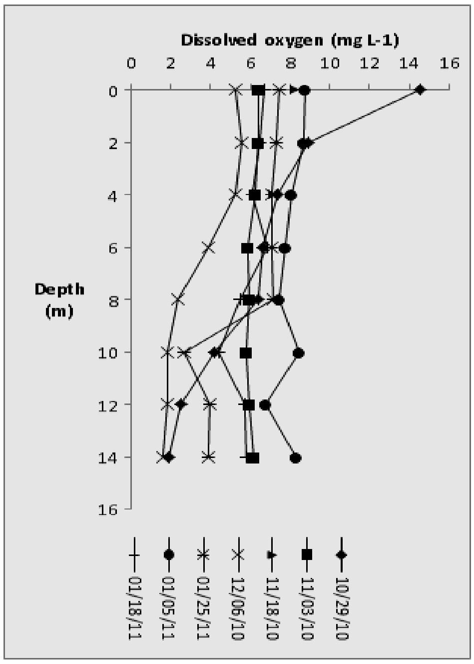
b) Site 8

Figure 4.5. Conductivity depth profile for different sampling dates at site 7 and 8

The conductivity depth profile did not follow a remarkable trend (Figure 4.5.). The mean conductivity for the lake mid-point (site 7) was 539.36 µS cm^{-1} ranging between 503 - 629 µS cm^{-1}. Conductivity near the dam wall recorded minimum value of 509 µS cm^{-1} and a maximum value of 598 µS cm^{-1}. Conductivity was high during the dry period as compared to the wet period as shown on the profile. Samples collected from October 2010 had comparatively higher conductivity than samples collected in January 2011. The highest conductivity was recorded from site 7 on 10-29-10.



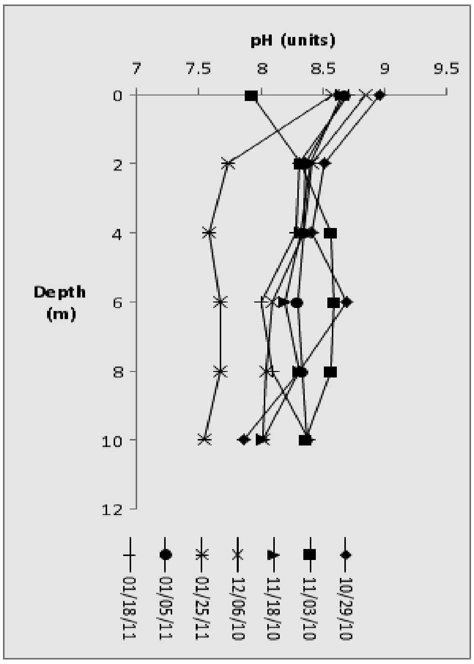
a) Site 7

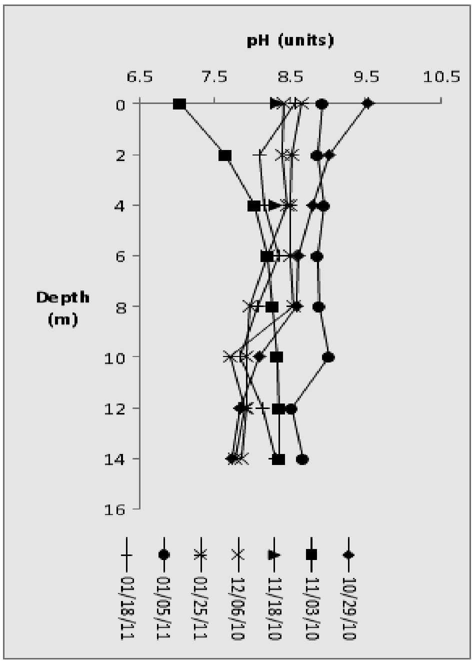


b) Site 8

Figure 4.6. Dissolved oxygen depth profile for different sampling dates at site 7 and 8

The lake (site 7 and 8) appeared partly stratified on some of the sampling days although with a weak thermocline. DO depth profile was gradually decreasing with depth as illustrated in Figure 4.6 resulting to a near oxygen deficit near the bottom. Site 7 recorded minimum oxygen concentration of 2.40 mg L^{-1} with site 8 recording even lower values of 1.60 mg L^{-1}. Evidence of mixing is as shown on the sampling date 01-05-11.

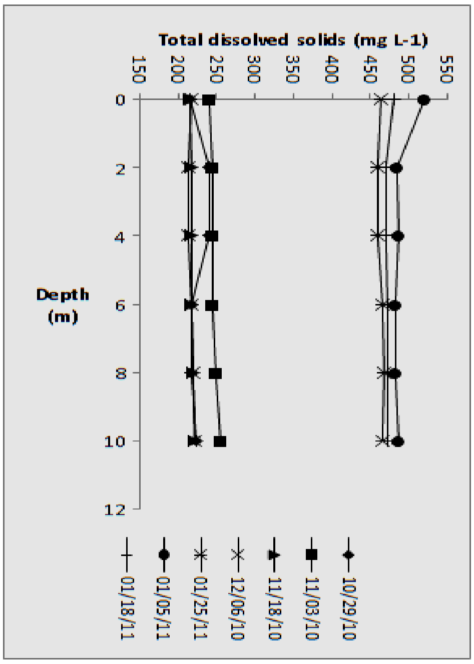




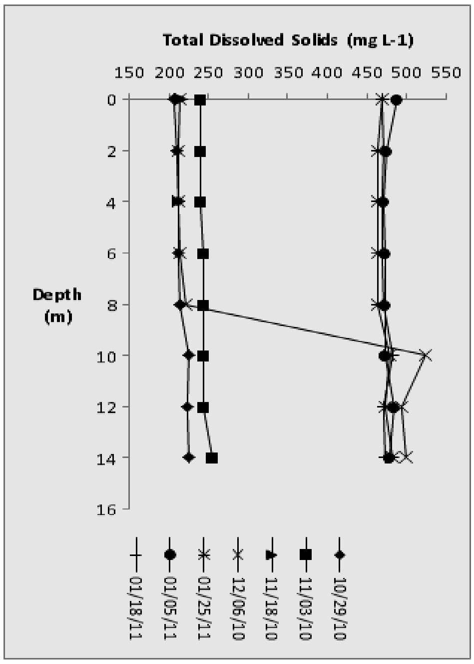
a) Site 7 b) Site 8

Figure 4.7. pH depth profile for different sampling dates at site 7 and 8

The pH generally decreased with depth for sites 7 and 8 (Figure 4.7.) on most sampling days except 11-03-10 where the pH was increasing with depth. The surface layers had more alkaline pH values. The mean pH for site 7 and 8 were slightly alkaline 8.28 units and 8.33 units respectively.



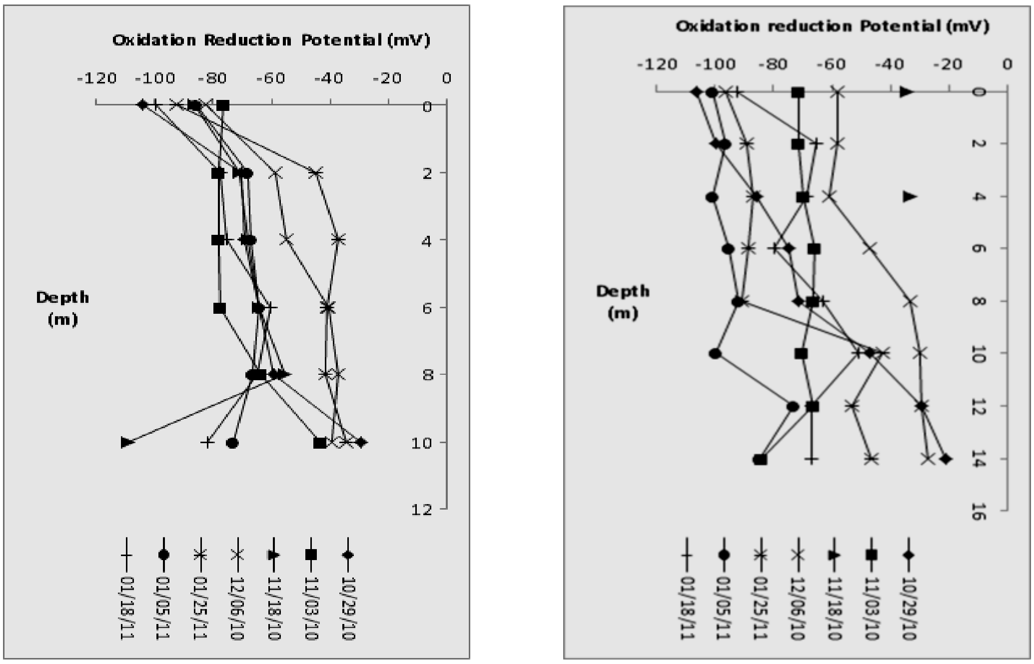
a) Site 7



b) Site 8

Figure 4.8. Total dissolved solids depth profile for different sampling dates at site 7 and 8

The TDS depth profile showed almost a straight line. TDS values increased as the months progressed from October- January. The data recorded on 01/05/11 were highest than any other sampling day for site 7 and 8. The mean values of TDS were highest at lake near wall with 361.44 mgL^{-1} and least at lake midpoint 333.86 mgL^{-1}. The minimum TDS from site 7 was 521 mg L^{-1} and the maximum was 629 mgL^{-1}. From site 8, the maximum TDS value was 525 mg L^{-1} and the least was 207 mg L^{-1}. On 12-06-10, TDS sharply increased with depth between (8m-14m) from 221-525 mgL^{-1}.



a) Site 7 b) Site 8

Figure 4.9. Oxidation Reduction Potential depth profile for different sampling dates at site 7 and 8

The oxidation-reduction potential depth profile was increasing with depth on some of the sampling days except 11-03-10 (site 7 and 8). The lake midpoint recorded maximum ORP of -29.0 mV and a minimum of -108.90 mV. Near the wall, the maximum ORP was -21.00 mV and the minimum value was -106 mV. The mean ORP value was highest for lake mid with -65.9 mV slightly more than the lake wall with -67.99 mV. ORP increased from the mild wet periods (October) to the wet period (January) as shown on the profile.

4.3 Current nutrient loadings

The total phosphorus and nitrogen loadings into Lake Chivero from the three main feeder rivers and three minor sub catchment rivers is as shown in Table 4.4. The estimated loading for Marimba, Mukuvisi and Manyame gave an indication of the contribution of point source pollution. Kuwadzana, Glenview and Budiriro gave an indication of the contribution of non-point sources of pollution.

Table 4.4. Current phosphorus and nitrogen loadings (g m^{-2}) from the Lake Chivero sub catchment area for 2010

Site	Total Nitrogen	Total Phosphorus
Marimba	12.20	7.31
Mukuvisi	16.42	14.47
Manyame	20.28	3.61
Total	**48.9**	**25.39**
Kuwadzana*	1.42	0.42
Glenview*	9.99	2.95
Budiriro*	7.82	16.33
Total	**19.24**	**19.70**

*Non-point source pollution

The estimated total phosphorus loading into Lake Chivero per annum is as shown in (Table 4.4). The mean point and non-point source of P loadings were used to estimate the total tonnage of phosphorus per annum. From the estimated phosphorus loading for 2010 (Table 4.5), it was derived that 492.5 tonnes per annum is from non-point source contribution and 634 tonnes per annum is from point source pollution.

4.4 Wetland map of Lake Chivero catchment

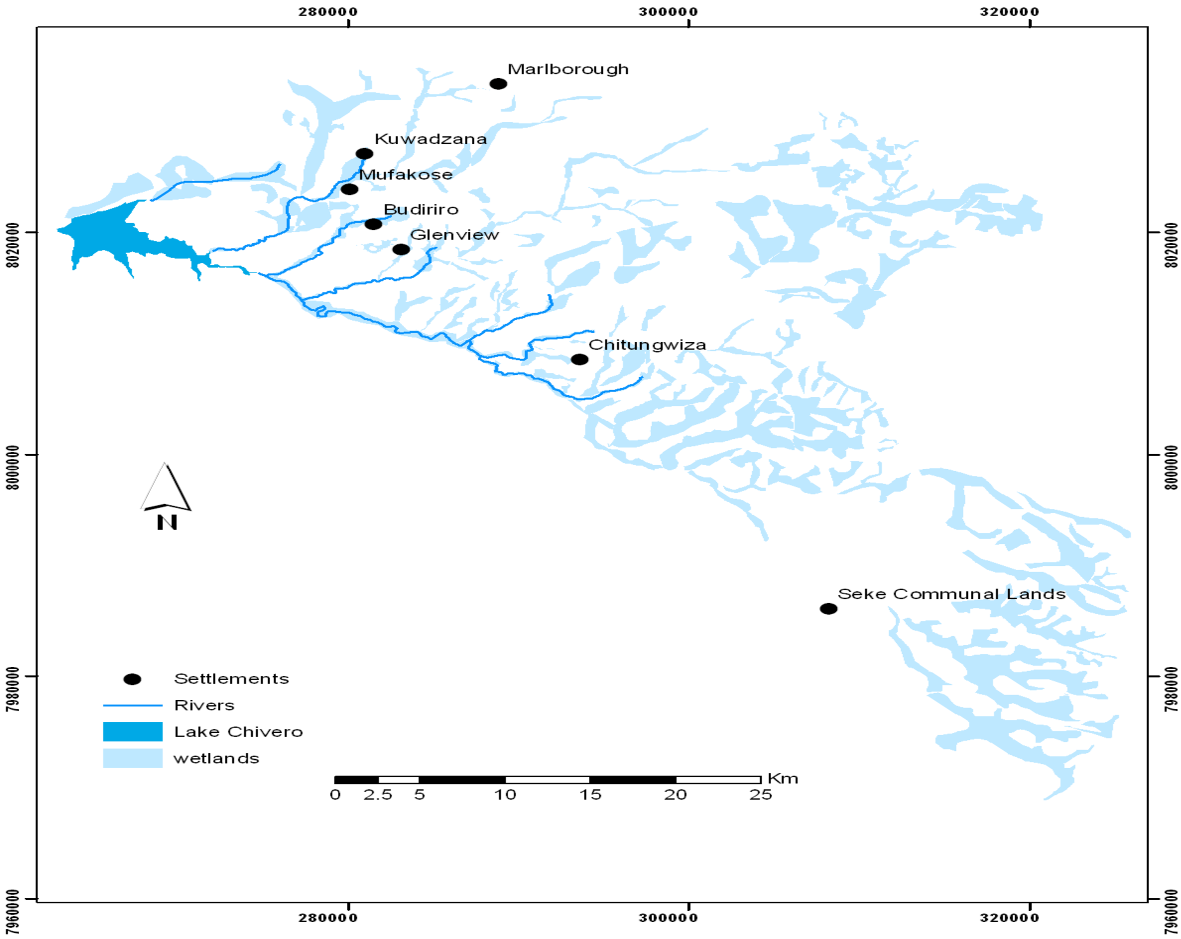


Figure 4.10. Map of wetlands in Lake Chivero catchment

The total wetland area in the catchment was approximated to be 39 869 hectares. The wetlands in Figure 4.10 could denitrify as much as 9.97 $*10^4$ tonnes of nitrogen per annum based on UNEP-IETC (2000) guidelines. It was approximated that the wetlands in Lake Chivero catchment can remove about 80 000 tonnes of phosphorus per annum using findings from Anusa (2004).

4.5 PAMOLARE Results

Figures 4.11 - 4.13 show the projected trends in water quality if the current wastewater management system is not improved.

4.5.1 Projected trends on the effect of the current wastewater management system on water quality in Lake Chivero

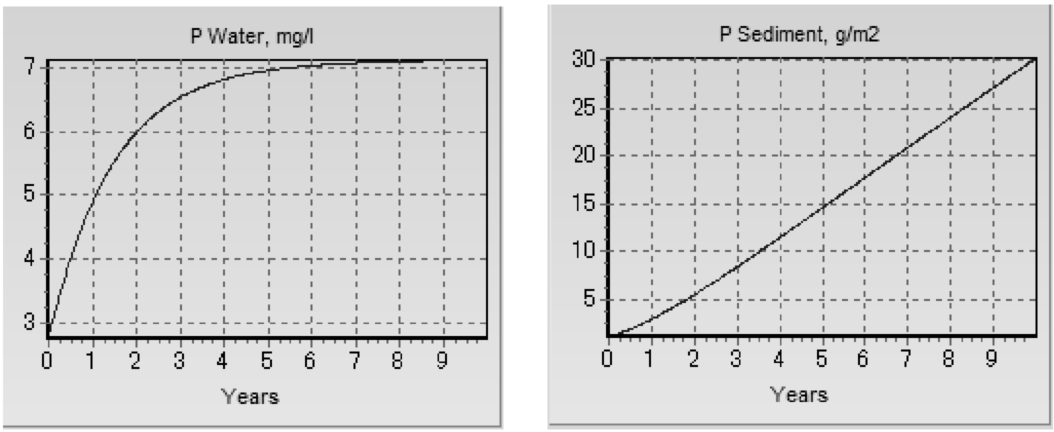


Figure 4.11. Projected trend for phosphorus in water and sediments in Lake Chivero under the current wastewater treatment system and land use

If the current wastewater treatment systems are not upgraded P levels in water will continue increase from 2.77 mgL^{-1} to 7.11 mgL^{-1} in the next eight years (Appendix 12.). An increase in nutrient loading after the next 5 years will not cause any significant difference in P concentration. The P in sediment will increase linearly with time to about 30.28 gm^2 in the next 10 years.

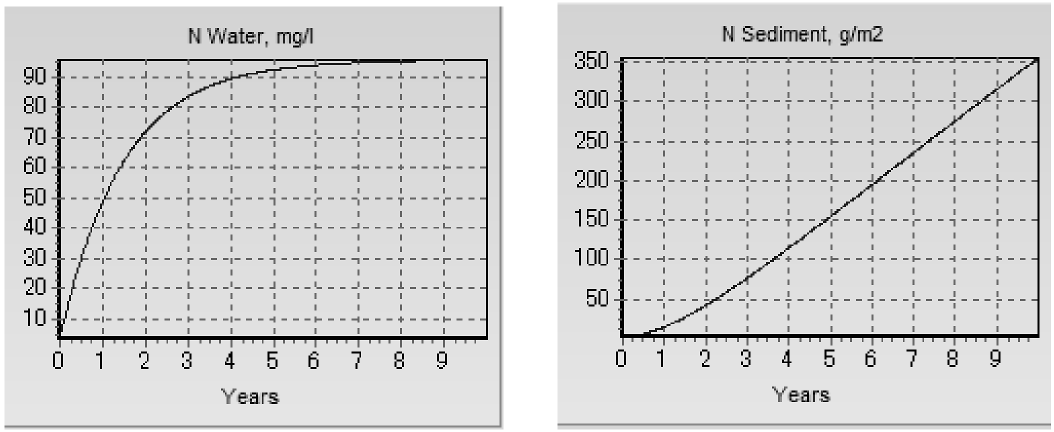


Figure 4.12. Projected trend for nitrogen in water and sediments in Lake Chivero under the current wastewater treatment system and land use

N in water will increase to from 3.21 mgL^{-1} to almost 90.5 mgL^{-1} in the next 10 years before becoming constant. Beyond 90.5 mgL^{-1} no amount of nutrient loading will influence nitrogen concentration. Nitrogen in sediments will increase linearly with time from 0.5 mgL^{-1} to about 351 gm^2 in the next 10 years.

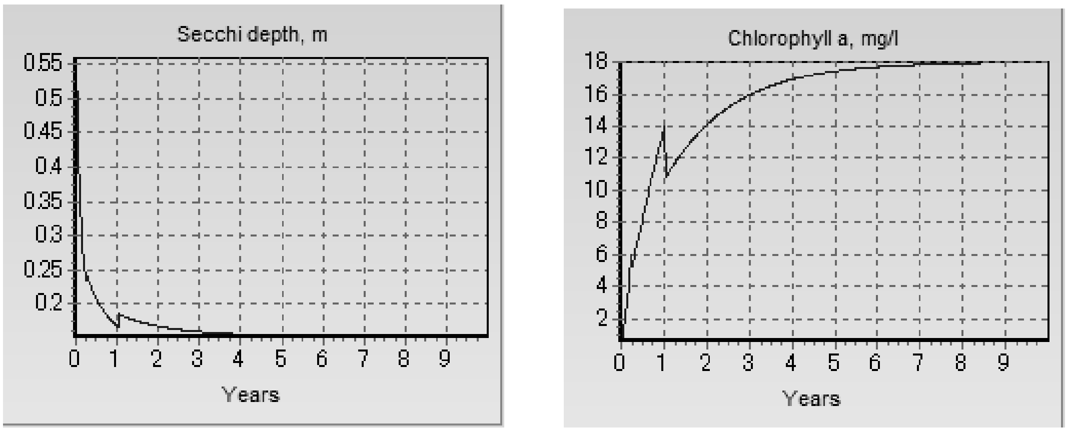


Figure 4.13. Projected trend for secchi depth and chlorophyll- a levels in Lake Chivero under the current wastewater treatment system and land use

Secchi depth will decrease from about 0.52m to 0.14m in the first year. However, the depth will slightly increase in the same year to about 0.16m before further decreasing to 0.15 m in 10 years. Chlorophyll-a will increase to 14 mgL^{-1} within the first year and then falls to about 10.4 m in that same year. The chlorophyll level will increase to 18 mgL^{-1} in the next 7 years and remain constant.

The projected trends below show the effect of subsequent nutrient reduction under two management scenarios, through use of wetland followed by use of an efficient Biological Nutrient Removal (BNR) system (Figures 4.14. - 4.19.).

4.5.2 Projected trends on the effect of wetland use in wastewater purification on water quality in Lake Chivero

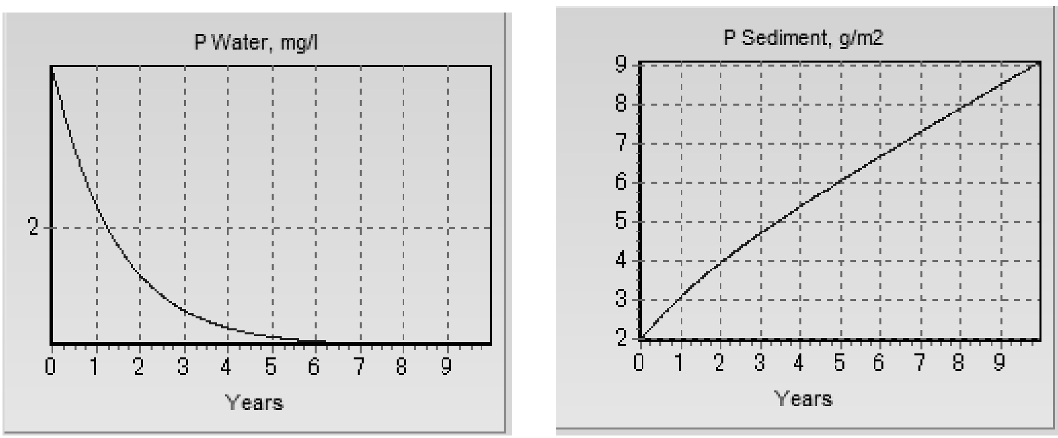


Figure 4.14. Projected trend for phosphorus in water and sediments in Lake Chivero under wetland use in wastewater purification

Wetland utilization will reduce the P in water to from 2.77 mgL^{-1} about 1.44 mgL^{-1} in the next 6 years. In ten years, the wetlands will reduce the current P concentration by almost 52%. The N in sediments will increase almost linearly at a slower rate to about 9.2 gm^{-2} in the next 10 years

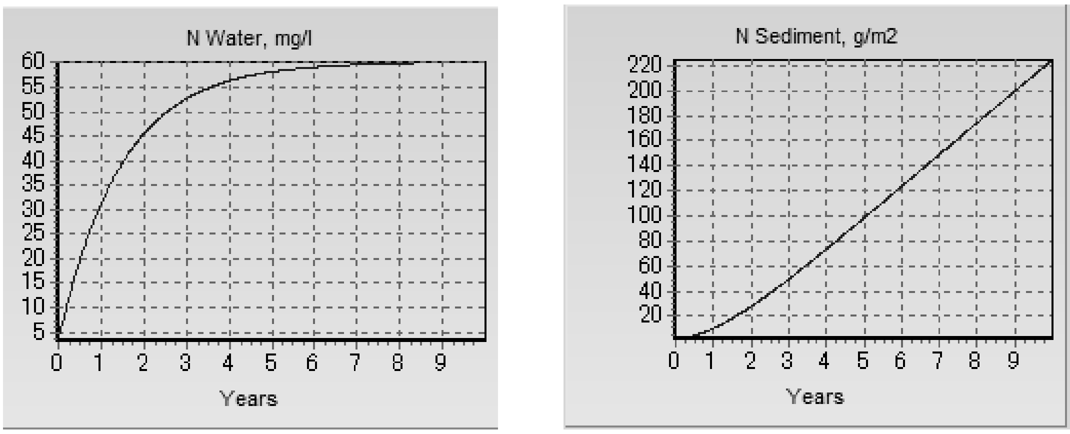


Figure 4.15. Projected nitrogen in water and sediments in Lake Chivero under wetland use in wastewater purification

The N in water will increase at a slower rate to 60 mgL^{-1} in the next 8 years. The N in sediments will increase almost linearly to about 221 gm^2 in the next 10 years

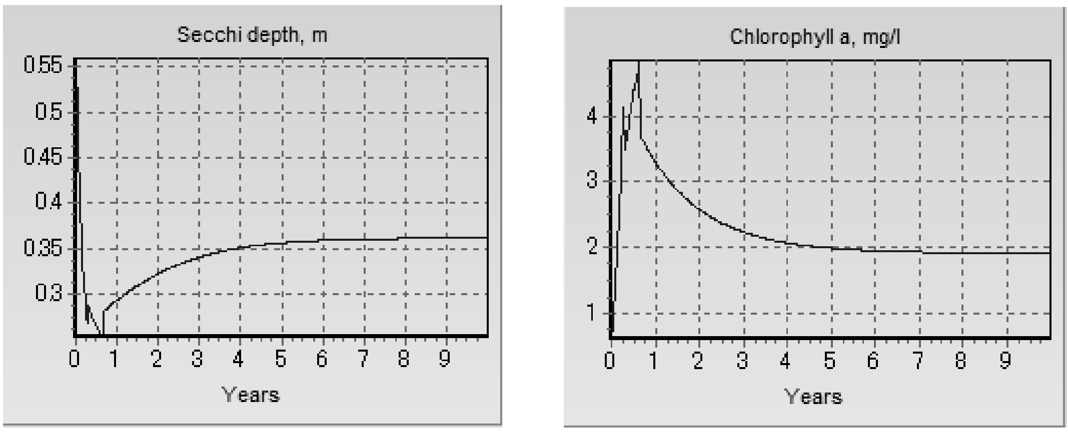


Figure 4.16. Projected secchi depth and chlorophyll- a levels in Lake Chivero under wetland use in wastewater purification

Chlorophyll-a will decrease to about 5 mgL^{-1} within the next year and decrease to about 1.92 mgL^{-1} l in the next 10 years. Secchi depth will decrease within the first year to about 0.2 m and thereafter start to increase to about 0.37 m in the next 10 years.

4.5.3 Projected trends on the combined effect wetland use and an efficient wastewater treatment system on water quality in Lake Chivero

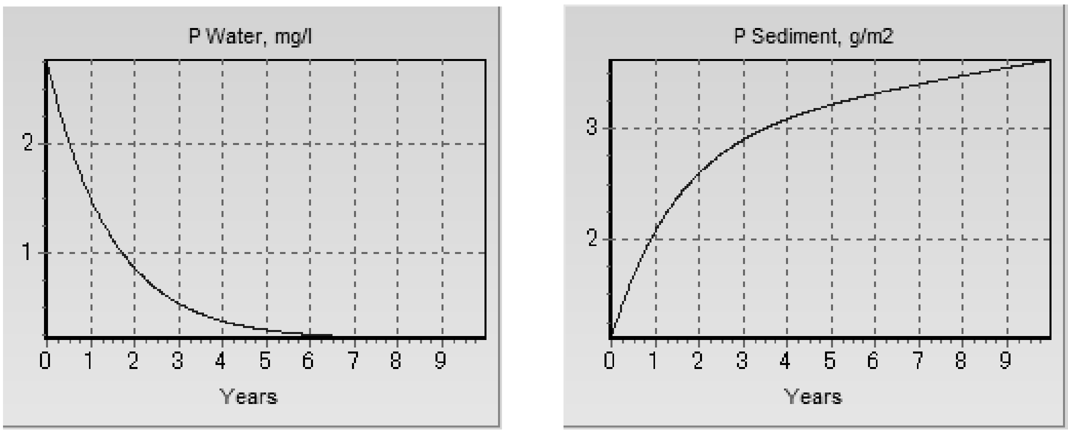


Figure 4.17. Projected phosphorus in water and sediments in Lake Chivero under wetland use and an efficient wastewater treatment system

P in water will decrease to 0.22 mgL^{-1} in the next 6.5 years. The combination of wetland removal and efficient treatment plants will reduce P loading by 82%. P in sediment will increase at a slower rate to about 3.62 gm^2 in the next 10 years. Phosphorus in sediments will increase sharply in the first 2 years after subsequent nutrient reduction.

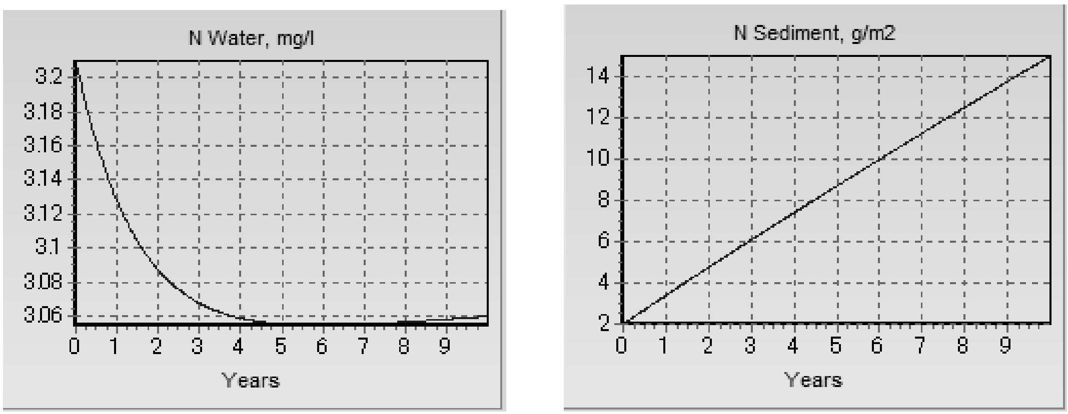


Figure 4.18. Projected nitrogen in water and sediments in Lake Chivero under wetland use and an efficient wastewater treatment system

Nitrogen levels in water will decrease from 3.16 to 3.06 mgL^{-1} in the next 4 years and there after continue to decrease. The nitrogen concentration in sediments will increase at a lower rate than previous conditions to about 14.98 gm^2 in 10 years.

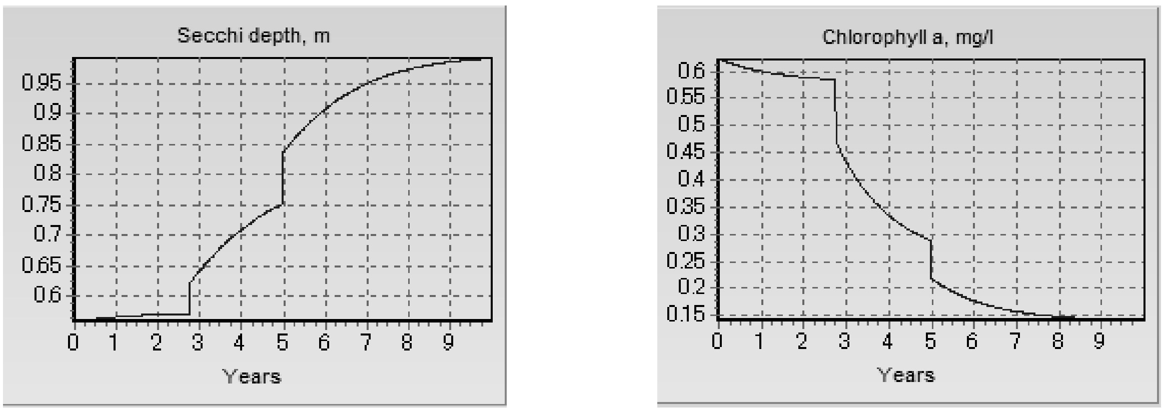


Figure 4.19. Projected secchi depth and chlorophyll- a levels in Lake Chivero under wetland use and an efficient wastewater treatment system

Secchi depth will slowly increase in the first 2.8 years to 0.52m. In 5 years, the levels will increase to between 0.75-0.88m. The secchi depth will further increase to about 1.0 m in 10 years. Chlorophyll-a level will decrease sharply in the first 2.8 years to about 0.58 mgL^{-1}. The chlorophyll level will decrease to about 0.46 mgL^{-1}within the same year. The level will further decrease to about 0.29 mgL^{-1} by year 5. By the end of 8 years, the chlorophyll- *a* levels will be 0.14 mgL^{-1}.

Table 4.5. Summary of the projected trends of the water quality in Lake Chivero under the current and two improved management scenarios

Parameter	Current treatment System	Utilization of wetlands	Combination of wetlands and BNR
Phosphorus in water (mgL^{-1})	7.11	1.44	0.22
Phosphorus in sediment ($g\ m^{-2}$)	30.28	9.2	4.39
Nitrogen in water(mgL^{-1})	90.6	60.2	3.06
Nitrogen in sediment ($g\ m^{-2}$)	351	221	4.5
Secchi depth (m)	0.15	0.36	1.00
Chlorophyll- a (mgL^{-1})	18.02	1.92	0.14

Source: Extracted from PAMOLARE version 3.0 (1 layer model)

4.5.4. Comparison of the historical, current and projected trophy status of Lake Chivero

The modelling results showed that an 82% decrease in nutrient loading would reduce the current phosphorus loadings from 564 tonnes per annum to 34.1 tonnes per annum. The current nutrient loadings and concentrations are closely related to 1967 data. The modelled results for nutrient reduction also compare closely with the recovery phase of Lake Chivero during the 1978 period (Table 4.6).

Table 4.6. Historical changes in phosphorus regime in Lake Chivero (after Thornton, 1982; Magadza, 1997*) in comparison with the present study (2010-11) and projected status (2020)

Parameter	1967	1978	1996*	2010-11	2020 (Projections)
P concentration (mgL^{-1})	2.8	0.13	1.8 (Manyame)	2.77	0.22
P load g (m^2)	27.4	1.5	14	22.56	1.36
P load (tonnes/pa)	685.0	39.6	350.0	564	34.1
Conductivity (μScm^{-1})	160	120	800	609	

Adopted from Magadza (2003)

5. DISCUSSION

5.1 Current physico-chemical status

The low dissolved oxygen content from most of the sampling sites is an indicator of high organic contamination. The mean oxygen values recorded from the rivers (site 1-6) were below the mean prescribed values for survival of aquatic life of 5.0 mg L^{-1} (USEPA, 2000). Although the deoxygenation of a river caused by organic waste is generally a slow process, the outcome is adverse to the ecosystem. The variation in DO from one site to another for the same data set could be due to differences in location and more significantly due to differences in the time of sampling. The DO concentration levels are known to fluctuate naturally throughout the day Rios-Arana *et al*. (2003). Suspended particles scatter sunlight, thus decreasing the photosynthetic activity of plants, and algae, which contributes to lowering the oxygen concentration as recorded in the rivers e.g. Budiriro and Mukuvisi. Budirio site is consistent with past studies by Mukwashi (2001) were the same site recorded the least oxygen concentration.

The relatively low levels of secchi depth recorded from the sampling sites, ranging from 0.03 m - 1.9 m are indicative of eutrophic lake (Wetzel, 1983). The range of eutrophic lakes lies between 0.8 - 7.0 m. The turbidity values had large variations from the rivers (site 1-6) and the lake points (site 7 and site 8). Because lotic ecosystems are considered as common pool resources, they are used as repositories for disposal of domestic sewage, industrial effluents and agricultural runoff. In the present study, the turbidity in the rivers was largely attributed to high sediments washed from adjacent cultivated slopes. The expanse of stream bank cultivation (Plate 1) and stream bank cultivation (Plate 2) conforms to lessons learnt by UNEP-IETC (2000) that the public are not aware of the consequences of poor watershed management. Plate 1 also supports arguments by Kotze *et al*. (1995) that about 50% land in Southern Africa has been lost to commercial or subsistence agriculture. However, for Budiriro, turbidity was largely attributed to domestic and sewage waste from an adjacent burst sewer system. Turbidity from the lake points could be largely attributed to algal scums due to increased productivity. The higher the turbidity, the harder it is to see through the water. This also have an effect on aquatic organisms, as some organisms cannot survive in turbid water. The turbidity units far exceed limits by the World Health Organization, which should be less than 1NTU for drinking water.

The mean pH for the sampling period was within the guideline range of 6.5–8.5 (WHO, 2001) for drinking water. The elevated pH values in the lake could be an indicator of leaching of soils rich in organic elements through run-off from the first precipitation events. Alkalinity in Lake Chivero is consistent with studies by Thornton and Nduku (1982). The significant positive correlation found between pH and turbidity further explains the effect of increased photosynthesis. Alkalinity was attributed to increased nutrient discharge into the lake, which influences increased phytoplankton growth. This supports arguments by Billings (1984) that photosynthesis elevates pH in proportion to the rate of removal of free carbon dioxide (the higher the removal rate, the higher the pH).

The ORP values recorded during the sampling period for all the sites are indicative of anoxic conditions. The anoxic range was classified according to Inniss (2005) who argued that ORP values less than -200 mV are indicative of anaerobic conditions and values between -200 and +200 mV are representative of anoxic conditions. Such conditions are undesirable because they trigger the release of iron (Fe) bound phosphorus in bottom sediments.

The process involves the reduction of Fe^{3+} to Fe^{2+}, which is responsible for increasing the P concentration in water. This conforms to arguments by Jensen and Andersen (1992) who found out that Fe-bound P, when present in significant proportions in the sediment, may be a major source for internal P loading in water bodies.

The mean conductivity values, which were higher in the rivers and low from the lake points, could be attributed to surface runoff from the catchment. This is because lotic systems are normally treated as wastewater discharge points by industries and household. High values of conductivity in the rivers could be due to the high pollution levels in water, resulting from the high nutrient loads of wastewater treatment plants (Nhapi, 2004), burst sewer pipes, salts from fertilisers, seepage from uncollected garbage and leachate from landfills. Conductivity increases in proportion to the ionic concentration, which is a result of dissolved solids. This relationship was indicated by the positive correlation between conductivity and salinity. However, the salinity recorded from the lake was almost undetectable which contrasts current research, which shows a chloride depth profile (Magadza, 2003). The depth profile is more realistic assuming that there is continued anthropogenic pollution from the catchment. The low salinity might imply that the probe could have been faulty. The mean conductivity within the lake was low as compared to the rivers probably because of dilution effect of the larger volume of water. Since conductivity determined by the amount of dissolved salts, the negative correlation between ORP and conductivity indicates that, there are large quantities of organic carbon, which is not decomposed.

The final water quality in Lake Chivero is affected by the significant quantities of nitrogen and phosphorus that drains from its main tributaries. The eutrophication of Lake Chivero supports arguments by Garmaeva (2001) who argued that most of the lakes threatened by eutrophication are those located in or near urban settlements. Nitrogen and phosphorus levels in the Marimba, Mukuvisi and Manyame Rivers show the significant influence of sewage discharge into water bodies. The current N status in Marimba compares closely with studies by Nhapi *et al.* (2006). However, from the same study (Nhapi *et al.*, 2006) the increase in P from 1.9 to the current 5.56 mgL^{-1} could be attributed to increased sediments washed from cultivated areas in the catchment. Current findings from experimental work by the International Lake Environment Committee (ILEC, 2010, unpublished) indicated that the dominant reactive form of N was the NH_4^+ ion. From ILEC results, it was deduced that the current TN in Marimba is dominated by the NH_4^+ ion, which is an indication of oxygen deficit. High phosphorus levels in the Mukuvisi stretch could be directly attributed to the Fertilizer Company ZIMPHOS, that is situated upstream of the river.

In the high-density suburbs e.g. Budiriro, the high phosphorus levels are mostly because of sediments carried from cultivated fields and overloading of treatment works. The lower phosphorus levels in Manyame River could be attributed to the invasive *Hydrocotyl spp* spreading along the stretch of the river (Plate.3). The low levels of P for Glenview and Kuwadzana show effects of self-purification by riverine wetlands supporting arguments by Spellman (1996). The signs of self-purification were evidenced by higher transparency of 0.20 m and 0.28 m for Glenview and Kuwadzana respectively as compared to other rivers. Self-purification from these two sites was also evidenced by the amount of phosphorus, which was less when compared to other sites. Higher P levels were expected from these same sites considering the amount of agricultural activities in the catchment. The effect of the rainy days was apparent as it coincided with low turbidity values from the streams probably from sediments being washed from adjacent fields e.g. Kuwadzana on 12-21-10 (Appendix 1).

The low turbidity from Budiriro unlike other sampling stations was closely attributed to the untreated raw effluent from an unmanaged sewerage upstream. Organic effluents frequently contain large quantities of suspended solids which reduce light availability to autotrophs. On settling down, organic matter alters the characteristics of the riverbed rendering it unsuitable habitat for many microorganisms. There is little productivity in the rivers as shown by the low chlorophyll-*a* values recorded as compared to the lake points. Wetzel (2001) argues that chlorophyll-*a* in rivers is mostly attached on rocks and other substrates (periphyton) and most is in the drifting form. There is therefore higher productivity from the lake, which is influenced by the mass accumulation of nutrients from catchment and the long water retention time. The recorded chlorophyll-*a* was higher than values recorded by Mhlanga *et al.* (2006) which is an indicator of increased nutrient levels.

The total phosphorus concentration (2.77 mgL^{-1}) in the lake exceeds the boundary between mesotrophic and eutrophic conditions for Lake Chivero in Zimbabwe as argued by Thornton and Nduku (1982). The current P concentration in water compares quite closely with 1967 values (Thornton, 1982). Higher values than 1967 data were expected assuming that conditions such as population growth and land under cultivation have increased over the years.

However, the installation of the BNR and diversion of effluent to agricultural land in 1978 helped improve the situation. The nitrogen from the lake also exceeds 0.2 mgL^{-1} which is critical for African lake systems as argued by Thornton (1980).

The high calcium levels conform to arguments by JICA (1999) who reported an increase in calcium ions due to increase in use of pH correcting agents. The results for the nutrient loadings, showing that Mukuvisi contributed most of the limiting nutrient (phosphorus) and Manyame the least, are consistent with past studies by Marshal and Falconer (1967); Thornton (1980). Since the collecting points for these sites was below the sewage treatment works, the high P could be a combination of fertilisers, domestic waste from human excreta and detergents.

The official population records for Chitungwiza and Harare (Register General, 2009) are misleading because they underestimate the real situation on the ground. Such oversights are a problem for town planners and city engineers because all water management systems depend on the population within a given area. The use of underestimates will always pose an inherent problem of misplanning thus prolonging the problem of poor water quality.

5.2 Depth profiles for physical parameters

Conductivity results from the depth profile supported arguments from studies by Marshal and Falconer (1973) that conductivity has no variation with depth. Findings from the study by Marshal and Falconer (1973) indicated that the salt concentration of nutrients become concentrated during drought periods when water levels fall out. The present conductivity trend is consistent with the observed trends of decreasing conductivity with the wet season. The non-conducting form of organic carbon in the water best explains the negative correlation between ORP and conductivity. ORP increases with an increase primary productivity, which is influenced by the wet spell. Thus, the accumulation of organic matter occurs during the rainy season, whereas it deteriorates during the dry season. Conductivity will therefore increase upon the action of microbes on organic matter.

Scientific evidence from studies by Marshal (1981) concluded that oxygen depletion was accelerated by overabundance and decay in algal biomass. This trend was observed by the oxygen depth profile showing a decrease with depth. The bottom of the lake is depleted of oxygen because the decomposition of dead organic matter takes place at the bottom. Studies by Marshal (1981) concluded that the decay of biomass result in water quality problems such as taste and odour in water supplies and clogging of filters in wastewater treatment plants. The lack of oxygen at the lake bottom was confirmed in recent experimental work by ILEC (2010 - unpublished) where they found out that the NH_4^+ ion was the dominant form of N at 10 m deep from the pelagic and dam site . Findings from the same work indicated that the NO_3-N was the dominant form of N at the surface waters from both pelagic and dam site.

The undefined temperature thermocline indicated that the lake was regularly mixing maybe due to wind and rain. The results were inconsistent with observations by Thornton and Nduku (1982) that the lake would stratify during August-March. The oxygen and temperature profile were closely related because the amount of DO depends on temperature – the warmer the water the less the dissolved oxygen. The oxygen profile also had an effect on the pH depth profile because photosynthesis plays an important role in oxygen production in lake ecosystems (Rios-Arana *et al*., 2003). Because the surface waters are directly exposed to sunlight they photosynthesise more than deep waters and are therefore highly alkaline. In deep waters, respiration is the dominant process, which results in less pH values as compared to the surface.

TDS was affected by the different sampling days rather than depth. The concentration of TDS was greatly influenced by the wet spell. The increase in TDS could be attributed to solids being washed away from the cultivated area in the catchment, sewage effluent and storm water drains. TDS on 12-06-10 show the effect of a rainy day, whereby cooler water from the streams flowed into the lake and by virtue of its high density, it was directed to the lake bottom. ORP was highest in deep waters as shown by the increasing trend with depth. The ORP depth profile conforms to observed trends by Magadza (2003). Magadza (2003) also observed anoxic ORP values as classified by Inniss (2005). This could be explained by the fact that dead organic matter tends to accumulate at the lake bottom and thus respiration is dominant in that zone.

5.3 Model Outcomes

The trend shown under the current loadings and management indicate that the concentration of N and P in both water and sediment will continue to increase in the next 8 years. Results of the model scenario runs reveal that an 80% and 85% reduction in the phosphorus loads in Lake Chivero would significantly improve the water quality from a hypereutrophic to a eutrophic state in the next 10 years. Since one of the pivotal steps in the recovery of Lake Chivero is the reduction of the nutrient loading from its catchment. The two scenarios in the ecological modeling of Lake Chivero show some significant improvement over its current ecological functioning. The resulting phosphorus concentration after nutrient reduction falls within the eutrophic range of 0.084-0.221 mgL^{-1} (Department of Water Affairs, 2001; Carin van Ginkel, 2002). However, from the ecological model, it is clear that Scenario A "Use of wetlands in the catchment" shows significant improvement in phosphorus over the current nutrient loading into the lake. However, within the context of this project, this improvement could be considered sufficient as a short-term measure because the Lake shows reversal from a hypereutrophic state to a eutrophic state. The high phosphorus even after nutrient reduction supports arguments by Welch and Cooke (1999) that internal phosphorus loading might be persistent and endure for at least 10 years even after an external loading reduction. The high phosphorus values could therefore be due to internal phosphorus loading from sediment re-suspension, and subsequent nutrient release.

The projected nitrogen after nutrient reduction did not show an immediate response to nutrient reduction. Scientific evidence suggest that unlike phosphorus, nitrogen is difficult to control because its sources vary widely ranging from fertiliser and animal wastes to failing treatment plants and septic systems (Howarth, 1988).

Arguments by (Kinne, 1984; Wetzel, 2001) indicated that nitrogen is present in different forms under different oxic conditions e.g. under anoxic conditions ammonium is decomposed from organic matter. It was concluded that in the presence of oxygen the ammonia is oxidised to nitrite and then to nitrates. Unlike P, N had lower reduction efficiency under wetland use, which could have affected the decreasing response. The decrease in nutrients (N and P) concentrations was directly related to a decrease in algae as characterized by chlorophyll-*a* in the model. Reductions in external nutrient loadings do not produce immediate reductions in chlorophyll a concentrations, but lag periods occur during which nutrient and chlorophyll a levels adjust to the reduced loading. This trend supports arguments by Fathi *et al.* (2001) that N and P are the main factors in determining the magnitude of the primary productivity. The decrease in primary productivity indicators and detritus is also associated with increased secchi depth. However, in the eutrophication model the secchi disk did not improve significantly as compared to Thornton (1980) when secchi depth increased to about 1.5 m - 2 m after nutrient reduction. Even though there is a projected decrease in chlorophyll-*a* values in 2020 due to nutrient reduction, the projected nutrient levels even after reduction are sufficient to maintain high productivity.

The projected status for 2020 when compared to the present status responds similarly to the recovery of Lake Chivero (Thornton, 1980) through the diversion of wastewater to fields and the installation of the BNR system in 1978. During the Thornton (1980) study, a 94% reduction in loadings reduced phosphorus from 685 to 39 tonnes per annum. The current study shows consistency with past studies on the effect of reducing phosphorus loadings.

An 82% reduction in phosphorus loadings was estimated to be able to reduce the current loadings of 564 to 34 tonnes per annum. The estimated contribution of non-point P pollution of 493 tonnes per annum was 27-fold the findings from Thornton (1982) and almost double estimates by Magadza (2003). Nutrient recycling from sediments would increase the time required to reach new equilibrium nutrient concentrations following remedial treatments. Increased or constant nutrient cycling may produce smaller changes in trophic state than predicted by the models. The slow response of nutrients in sediments could be attributed huge quantities of accumulated silt at the bottom of the lake. The impact of massive siltation have been explained by Mhlanga *et al*. (2006) who recorded a maximum depth of 20 m a deviation from Munro (1966) who recorded a maximum depth of 27.4 m near the lake spillway.

The estimated wetland area if fully utilised will improve significantly nutrient loading from surface runoff. However, it is important to note that the wetland area used for estimation of nutrient reduction was just an approximation. The approximation is subject to errors attributed to; when the satellite image was produced, individual preference on wetland selection and the quality of image. The estimated area could be an overestimation because there is significant wetland degradation as argued by Kotze *et al*. (1995). On the other hand, the area could be an under estimation because some wetlands due to size and position could not be accounted for. The nutrient removal efficiency is also subject to a number of factors argued by scholars such as magnitude and frequency of flow (Bayley *et al*., 1985), water retention time (Walker, 1987) and the magnitude and nature of inputs (Richardson and Nichols, 1985).

6. CONCLUSIONS AND RECOMMENDATIONS

It can be concluded that the ecological processes that occur in a lake are dependent on the physico-chemical (abiotic) and biotic factors and the interrelations between them. The current nutrient loading from both point and non-point sources are sufficient to increase eutrophication over the years. The study indicated that the sustainable utilisation of wetlands in combination with proper wastewater treatment plants has potential to reduce the current nutrient loading into Lake Chivero. The estimated nutrient reduction from the two management scenarios is enough to revert the lake from hypereutrophy to a eutrophic state. Therefore the Planning and Management of Lakes and Reservoirs (Model for Eutrophication Management) -PAMOLARE can be used as an ideal tool in planning the rehabilitation of Lake Chivero. This is because the modelling effort has yielded clear trends that can be used by decision makers for evaluating different management strategies in reversing eutrophication.

The issues of nutrient reduction into Lake Chivero cannot be over emphasised because a wide range of management options have been proven through scientific work by a number of scholars cited in the text. This study therefore echoes the same sentiments that the reduction of nutrient loadings into Lake Chivero can be achieved through Integrated Water Resource Management (IWRM), good management and sound governance. As long as pertinent issues on urban poverty, watershed management, public awareness and involvement in water related issues are not addressed, eutrophication of Lake Chivero will remain a problem. I therefore recommended that the lessons learnt and not learnt from Lake Chivero be put into perspective and at least feasible measures be implemented to safeguard our Lakes and Reservoirs.

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8. APPENDICIES

Appendix 1. Raw data on physical parameters measured from the eight sampling sites

Sample No	Site	Date	Depth (m)	Temperature (°C)	Oxygen (%)	Dissolved oxygen (mg l^{-1})	pH (units)	Conductivity (µS/ cm^{-1})	Salinity (%)	TDS (mg l^{-1})	ORP(mV)	Secchi depth (m)	Turbidity (NTU)
1	1	10/29/10	0	24.9	2.6	0.2	7.85	789	0.1	315	-4.4		
2	1	11/3/10	0	22.8	56.6	4.5	6.15	1030	0	320	-50.8	0.04	479.8
3	1	11/18/10	0	24.5	3.4	0.7	7.89	829	0.2	331	-28.2	0.05	355.5
4	1	12/6/10	0	23.7	53.7	3.8	7.58	671	0.1	268	-10.4	0.15	65.9
5	1	12/21/10	0	21.8	0.8	0.1	7.38	542	0	598	22.8	0.04	479.8
6	1	1/5/11	0	24.7	0.7	1.3	7.65	637	0.1	621	-28.3	0.12	94.7
7	1	1/18/11	0	25.2	5.8	0.4	7.09	657	0.1	596	-8.7	0.16	61.3
8	1	1/25/11	0	23.1	17.6	1.3	7.01	573	0	523	-4.7	0.17	56.0
9	2	10/29/10	0	26.2	3.4	0.2	7.23	862	0.02	344	-4.4		
10	2	11/3/10	0	24.1	64.9	5.1	7.30	1190	0.1	365	-57.2	0.04	479.8
11	2	11/18/10	0	25.7	20.3	1.5	7.67	869	0.2	348	-14	0.04	479.8
12	2	12/6/10	0	24.6	39.8	2.8	7.63	704	0.1	281	-13.8	0.11	108.0
13	2	12/21/10	0	22.1	65.5	4.8	7.28	523	0	454	-17.7	0.1	121.2
14	2	1/5/11	0	26.1	31.8	2.1	7.60	756	0.1	684	-26	0.08	174.8
15	2	1/18/11	0	26	0	0	6.87	739	0.1	666	3.9	0.07	213.8
16	2	1/25/11	0	24	50.1	3.7	7.22	710	0.1	648	-16	0.12	94.7
17	3	10/29/10	0	17.6	7.4	0.7	7.13	1046	0.3	417	-15.2		
18	3	11/3/10	0	19.8	72.1	5.8	7.43	1450	0.1	398	-64.8	0.1	121.2
19	3	11/18/10	0	19.7	4.9	0.3	7.47	967	0	388	-3	0.11	108.0
20	3	12/6/10	0	22.7	2.6	0.2	7.04	332	0	133	-21.2	0.11	108.0
21	3	12/21/10	0	21.2	11.5	0.8	6.50	595	0	476	23.7	0.13	81.7
22	3	1/5/11	0	23.2	3.5	0.3	7.13	380	0	345	-0.8	0.26	29.5
23	3	1/18/11	0	24.6	8.1	0.5	6.48	146	0.1	118	25.3	0.04	498
24	3	1/25/11	0	24.1	15.5	1.1	7.95	215	0	197	-56.6	0.18	51.3
25	4	10/29/10	0	23.5	22.8	1.6	8.09	685	0.1	273	-34.8		
26	4	11/3/10	0	22.8	65.1	5.2	7.88	933	0	378	-58.5	0.29	24.5
27	4	11/18/10	0	22.9	25.1	2.3	7.93	750	0.1	303	-29.3	0.31	22.6
28	4	12/6/10	0	24	34.7	2.4	7.35	736	0.1	296	3.1	0.13	81.7
29	4	12/21/10	0	20.1	58.4	4.4	7.50	551	0	349	-29.4	0.05	355.5
30	4	1/5/11	0	25.3	13.5	0.9	7.78	618	0	559	-34.4	0.43	13.8
31	4	1/18/11	0	26.3	19.3	1.4	7.35	621	0	564	-23.6	0.28	26.3
32	4	1/25/11	0	23.8	38.3	2.7	7.43	480	0	438	-27.9	0.38	16.6
34	5	10/29/10	0	23.3	5.3	0.4	7.16	972	0.3	392	-8.7	0.03	
35	5	11/3/10	0	24.3	73.3	6.3	7.56	1170	0.1	445	-70.5		739.0

36	5	11/18/10	0	25.5	6.3	0.9	7.40	982	0.3	393	1.4	0.03	769.0
37	5	12/6/10	0	25.3	2.9	0.2	7.55	1001	0.3	407	-8.7	0.05	355.5
38	5	12/21/10	0	23.1	5.6	0.4	6.61	824	0	759	17.8	0.05	355.5
39	5	1/5/11	0	24.9	1	0	7.49	888	0.2	808	-19.2	0.05	355.5
40	5	1/18/11	0	24.9	0	0	6.99	849	0.2	773	-3.3	0.05	355.5
41	5	1/25/11	0	24.1	3.1	0.2	7.04	789	0.1	723	-6.1	0.05	355.5
42	6	10/29/10	0	24.2	52.9	3.7	7.52	748	0	244	-80.5		
43	6	11/3/10	0	25.7	46.1	3.7	7.17	1230	0.1	374	-68	0.05	343.2
44	6	11/18/10	0	26.1	33.6	2.3	8.12	772	0.1	307	-39	0.04	479.8
45	6	12/6/10	0	24.8	5.9	0.6	7.94	770	0.1	346	-31.4	0.25	30.6
46	6	12/21/10	0	22.9	26.4	2	7.47	628	0	560	-27.3	0.19	46.2
47	6	1/5/11	0	26.4	20.4	1.4	7.93	668	0.1	613	-43.8	0.24	33.3
48	6	1/18/11	0	23.6	5.9	0.7	7.22	652	0.1	593	-16.1	0.17	56.0
49	6	1/25/11	0	23.6	26.7	1.9	7.19	563	0	511	-14.4	0.31	22.6
50	7	10/29/10	0	26.3	135.1	9.3	8.97	542	0	216	-104	1.9	1.5
51	7	10/29/10	2	24.6	89.2	6.3	8.52	629	0.1	241	-70.5	1.9	1.5
52	7	10/29/10	4	24.6	86.5	6.2	8.42	540	0	240	-69.4	1.9	1.5
53	7	10/29/10	6	24.6	81.4	5.7	8.69	544	0	217	-63.9	1.9	1.5
54													
55	7	10/29/10	8	23.3	73.9	5.3	8.31	543	0	218	-59	1.9	1.5
56	7	10/29/10	10	23	37.3	2.7	7.86	560	0	224	-29	1.9	1.5
57	7	11/3/10	0	24.6	93	6.8	7.93	541	0	240	-76.5	1	3.9
58	7	11/3/10	2	24.0	94.5	7.0	8.32	558	0	245	-78.2	1	3.9
59	7	11/3/10	4	23.7	95	6.9	8.57	559	0	245	-78	1	3.9
60	7	11/3/10	6	23.6	85.6	6.2	8.59	560	0	245	-77.4	1	3.9
61	7	11/3/10	8	23.3	78.4	5.7	8.57	573	0	250	-63.7	1	3.9
62	7	11/3/10	10	22.6	52.9	3.8	8.36	597	0	255	-42.9	1	3.9
63	7	11/18/10	0	25.7	119.1	7.7	8.65	538	0	215	-86.2	1.2	2.9
64	7	11/18/10	2	24.8	112.8	7.9	8.40	547	0	218	-70.7	1.2	2.9
65	7	11/18/10	4	24.1	93.5	6.6	8.32	543	0	217	-68	1.2	2.9
66	7	11/18/10	6	23.9	86.8	6.3	8.20	545	0	218	-64	1.2	2.9
67	7	11/18/10	8	23.7	75.4	5.4	8.31	548	0	220	-55.2	1.2	2.9

68	7	11/18/10	10	23.1	66.9	5	8.02	547	0	221	-108.9	1.2	2.9
69	7	12/6/10	0	25.2	88.5	6.1	8.84	529	0	217	-82.4	1	3.9
70	7	12/6/10	2	24	88.5	6.3	8.41	531	0	213	-58.4	1	3.9
71	7	12/6/10	4	24.1	69.9	4.9	8.35	535	0	214	-55	1	3.9
72	7	12/6/10	6	23.7	41.4	3	8.10	544	0	218	-40.4	1	3.9
73	7	12/6/10	8	23.6	34.4	2.4	8.04	549	0	220	-37	1	3.9
74	7	12/6/10	10	23.1	30	3.9	8.02	552	0	222	-39.5	1	3.9
75	7	12/21/10	0	26.6	79.2	5.4	8.68	573	0	521	-85.9	1.2	2.9
76	7	12/21/10	2	24.6	82.9	5.9	8.36	534	0	485	-67.9	1.2	2.9
77	7		4	24.5	77.2	5.5	8.35	534	0	487	-67.1	1.2	2.9
78	7	12/21/10	6	24.3	66.8	4.8	8.30	531	0	483	-64.2	1.2	2.9
79	7	12/21/10	8	24	69.8	5.1	8.34	529	0	483	-66.6	1.2	2.9
80	7	12/21/10	10	24.1	77.8	5.3	8.37	530	0	488	-73	1.2	2.9
81	7	1/18/11	0	25.6	104.5	7.3	8.71	521	0	481	-99.8	1.1	3.3
82	7	1/18/11	2	25.2	93.4	6.6	8.31	518	0	471	-77.3	1.1	3.3
83	7	1/18/11	4	25.1	86.3	6.1	8.28	518	0	471	-75.3	1.1	3.3
84	7	1/18/11	6	24.8	60.1	4.3	8.01	519	0	473	-60.1	1.1	3.3
85	7	1/18/11	8	24.6	67.7	4.9	8.09	519	0	473	-64.9	1.1	3.3
86	7	1/18/11	10	25.5	91.8	6.5	8.39	518	0	473	-81.8	1.1	3.3
87	7	1/25/11	0	24.3	142.3	9.9	8.58	508	0	464	-92.2	0.9	4.5
88	7	1/25/11	2	24	66.8	4.7	7.74	503	0	459	-44.7	0.9	4.5
89	7	1/25/11	4	23.9	41.5	3	7.59	504	0	459	-36.8	0.9	4.5
90	7	1/25/11	6	23.9	41.3	2.9	7.67	514	0	467	-41.1	0.9	4.5
91	7	1/25/11	8	23.9	43.4	3.1	7.68	515	0	469	-41.5	0.9	4.5
92	7	1/25/11	10	23.4	37.7	2.7	7.55	511	0	466	-34.4	0.9	4.5
93	8	10/29/10	0	28.2	200	14.6	9.54	519	0	207	-106	0.6	8.3
94	8	10/29/10	2	25.5	126.7	8.9	9.02	526	0	211	-99.6	0.6	8.3
95	8	10/29/10	4	24.4	103.6	7.4	8.80	534	0	213	-86	0.6	8.3
96	8	10/29/10	6	23.5	93.2	6.6	8.60	534	0	213	-74.5	0.6	8.3
97	8	10/29/10	8	24.2	89.8	6.4	8.58	535	0	214	-71.6	0.6	8.3
98	8	10/29/10	10	23.4	56.9	4.2	8.10	544	0	226	-47	0.6	8.3
99	8	10/29/10	12	22.6	34.2	2.5	7.84	558	0	223	-29	0.6	8.3
100	8	10/29/10	14	22.2	25.1	1.9	7.74	564	0	226	-21	0.6	8.3
101	8	11/3/10	0	23.8	87.9	6.4	7.04	540	0	240	-71.4	1.9	1.5
102	8	11/3/10	2	23.3	88	64	7.64	550	0	240	-71.5	1.9	1.5
103	8	11/3/10	4	23.2	84	6.2	8.02	553	0	240	-69.6	1.9	1.5
104	8	11/3/10	6	23.4	82.9	5.9	8.19	560	0	245	-65.6	1.9	1.5
105	8	11/3/10	8	23.4	90	5.9	8.27	559	0	245	-66.5	1.9	1.5
106	8	11/3/10	10	23.2	80	5.8	8.32	562	0	245	-70	1.9	1.5
107	8	11/3/10	12	23.3	81.7	5.9	8.35	560	0	245	-66.4	1.9	1.5

108	8	11/3/10	14	22.5	85.4	6.2	8.34	598	0	255	-84	1.9	1.5
109	8	11/18/10	0	25	118.5	8.2	8.33	538	0	215	-34.1	1.4	7.9
110	8	11/18/10	2										
111	8	11/18/10	4	24.7	98.5	7.2	8.31	532	0	213	-33	1.4	7.9
112	8	11/18/10	6										
113	8	11/18/10	8										
114	8	11/18/10	10										
115	8	11/18/10	12										
116	8	11/18/10	14										
117	8	12/6/10	0	24.4	76.6	5.3	8.41	534	0	214	-58.2	1.1	3.3
118	8	12/6/10	2	24.2	79.3	5.6	8.40	530	0	212	-58	1.1	3.3
119	8	12/6/10	4	24.1	74.7	5.3	8.45	531	0	212	-60.7	1.1	3.3
120	8	12/6/10	6	23.8	55.1	3.9	8.21	534	0	214	-47.1	1.1	3.3
121	8	12/6/10	8	23.3	33.1	2.4	7.97	553	0	221	-33	1.1	3.3
122	8	12/6/10	10	23.1	24.6	1.8	7.92	562	0	525	-29.8	1.1	3.3
123	8	12/6/10	12	22.9	22	1.8	7.91	566	0	495	-29.2	1.1	3.3
124	8	12/6/10	14	22.7	21.8	1.6	7.85	568	0	499	-27	1.1	3.3
125	8	12/6/10	2										
126	8	12/6/10	4										
127	8		6										
128	8	12/6/10	8										
129	8	12/6/10	10										
130	8	12/6/10	12										
131	8	12/6/10	14										
132	8	12/21/10	0	26.8	127.5	8.8	8.94	535	0	489	-100.6	1	3.9
133	8	12/21/10	2	25.4	121.8	8.7	8.87	523	0	475	-96.2	1	3.9
134	8	12/21/10	4	25.6	113.8	8.1	8.95	519	0	472	-100.8	1	3.9
135	8	12/21/10	6	25	108	7.8	8.86	519	0	474	-95.4	1	3.9
136	8	12/21/10	8	24.8	103.9	7.5	8.89	521	0	474	-91.9	1	3.9
137	8	12/21/10	10	24.5	116	8.5	9.02	520	0	473	-99.4	1	3.9
138	8	12/21/10	12	23.9	91.6	6.8	8.53	532	0	484	-72.9	1	3.9
139	8	12/21/10	14	21	105.4	8.3	8.67	522	0	479	-84.7	1	3.9

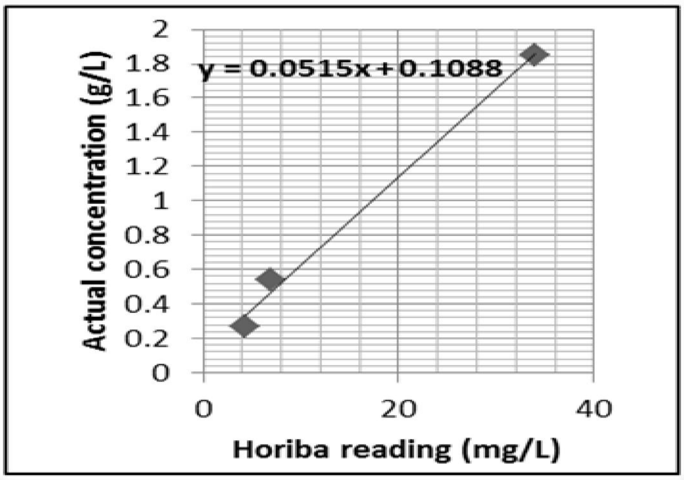
140	8	1/18/11	0	26	96.3	6.7	8.56	527	0	470	-92.2	1	3.9
141	8	1/18/11	2	25.4	90.3	6.5	8.09	518	0	472	-65.1	1	3.9
142	8	1/18/11	4	24.8	83.6	6.1	8.16	516	0	470	-68.8	1	3.9
143	8	1/18/11	6	25.1	95.2	6.9	8.35	516	0	470	-79.9	1	3.9
144	8	1/18/11	8	24.7	75.6	5.5	8.07	518	0	471	-63.3	1	3.9
145	8	1/18/11	12	24.6	78.1	5.7	8.14	517	0	471	-67.2	1	3.9
146	8	1/18/11	14	26.1	76.6	5.8	8.30	520	0	474	-67	1	3.9
147	8	1/25/11	0	24.4	106	7.5	8.66	518	0	470	-96.4	0.9	4.5
148	8	1/25/11	2	24.3	102.4	7.3	8.52	511	0	465	-88.9	0.9	4.5
149	8	1/25/11	4	24.3	99.4	7.1	8.49	509	0	465	-87	0.9	4.5
150	8	1/25/11	6	24.5	99	7.1	8.51	510	0	464	-88.3	0.9	4.5
151	8	1/25/11	8	24.4	99.8	7.2	8.55	510	0	464	-90.6	0.9	4.5
152	8	1/25/11	10	24.1	36.7	2.7	7.70	525	0	479	-42.5	0.9	4.5
153	8	1/25/11	12	24	55.5	4	7.89	519	0	474	-53.3	0.9	
154	8	1/25/11	14	23.8	53.5	3.9	7.77	529	0	482	-46.6		

Appendix 2. Laboratory results for composite water samples

Sample number	Name	Date	Total Nitrogen (mg L^{-1})	Total Phosphorus (mg L^{-1})	Chlorophyll *a* (μg L^{-1})
1	Marimba	10/29/10	3.47	1.97	31.89
2	Marimba	11/3/10	7.42	1.86	52.88
3	Marimba	11/18/10	9.49	2.58	20.14
4	Marimba	12/6/10	15.27	0.83	21.82
5	Marimba	12/21/10	4.19	0.84	26.86
6	Marimba	1/5/11	6.30	1.12	26.86
7	Marimba	1/18/11	4.76	1.37	47.00
8	Marimba	1/25/11	1.40	1.22	46.70
9	Mukuvisi	10/29/10	8.07	4.06	25.18
10	Mukuvisi	11/3/10	7.88	2.36	38.61
11	Mukuvisi	11/18/10	1.47	3.57	38.61
12	Mukuvisi	12/6/10	8.63	3.94	16.79
13	Mukuvisi	12/21/10	5.57	1.63	16.79
14	Mukuvisi	1/5/11	7.15	3.40	26.02
15	Mukuvisi	1/18/11	5.47	2.19	20.14
16	Mukuvisi	1/25/11	5.24	3.97	23.70
17	Manyame	10/29/10	20.14	3.06	5.88
18	Manyame	11/3/10	16.01	1.34	20.98
19	Manyame	11/18/10	19.09	1.68	47.84
20	Manyame	12/6/10	5.00	1.85	24.34
21	Manyame	12/21/10	7.67	2.19	26.86
22	Manyame	1/5/11	4.39	2.00	60.43
23	Manyame	1/18/11	2.51	0.60	61.47
24	Manyame	1/25/11	1.34	0.83	55.80
25	Kuwadzana	10/29/10	0.87	4.03	22.60
26	Kuwadzana	11/3/10	9.22	0.89	10.91
27	Kuwadzana	11/18/10	9.22	1.23	15.11
28	Kuwadzana	12/6/10	4.87	0.69	4.20
29	Kuwadzana	12/21/10	2.64	0.28	26.02
30	Kuwadzana	1/5/11	2.75	0.57	27.70
31	Kuwadzana	1/18/11	2.17	0.61	18.47
32	Kuwadzana	1/25/11	0.91	0.41	22.30
33	Budiriro	10/29/10	1.13	3.94	97.36
34	Budiriro	11/3/10	0.66	5.40	16.79
35	Budiriro	11/18/10	0.59	11.22	50.36
36	Budiriro	12/6/10	1.36	9.80	8.39

37	Budiriro	12/21/10	8.39	21.20	23.50
38	Budiriro	1/5/11	8.43	3.92	11.38
39	Budiriro	1/18/11	7.87	4.65	10.91
40	Budiriro	1/25/11	5.96	8.70	13.80
41	Glenview	10/29/10	1.57	1.87	5.88
42	Glenview	11/3/10	1.78	1.59	20.98
43	Glenview	11/18/10	10.57	2.18	27.70
44	Glenview	12/6/10	7.12	1.16	24.34
45	Glenview	12/21/10	0.89	1.86	15.11
46	Glenview	1/5/11	5.74	1.27	17.63
47	Glenview	1/18/11	14.43	1.55	33.57
48	Glenview	1/25/11	1.90	1.53	34.70
49	Lake mid p	10/29/10	3.16	3.55	65.47
50	Lake mid p	11/3/10	3.71	2.00	198.90
51	Lake mid p	11/18/10	4.28	2.53	37.77
52	Lake mid p	12/6/10	4.72	2.56	85.61
53	Lake mid p	12/21/10			
54	Lake mid p	1/5/11	3.76	2.26	31.89
55	Lake mid p	1/18/11	4.28	1.59	84.77
56	Lake mid p	1/25/11	1.97	2.12	95.33
57	Near wall	10/29/10	2.11	3.99	117.51
58	Near wall	11/3/10	3.84	2.39	220.74
59	Near wall	11/18/10	3.12	2.98	47.00
60	Near wall	12/6/10	4.13	3.28	55.20
61	Near wall	12/21/10			
62	Near wall	1/5/11	2.55	2.09	34.41
63	Near wall	1/18/11	1.75	3.13	170.38
64	Near wall	1/25/11	1.58	2.78	187.32

Appendix 3. Calibration curve for the Calcium ion (Ca^{2+}) on the Horiba U-23 multi-meter



Appendix 4. Mean concentrations for Ca^{2+} ions from the sampling sites

Site	Name	Calcium g/l
1	Marimba	0.21
2	Mukuvisi	0.31
3	Manyame	1.04
4	Kuwadzana	0.39
5	Budiriro	0.24
6	Glenview	0.49
7	Mid lake	0.39
8	Lake near wall	0.51

Appendix 5. Monthly flow rates (m^3/sec) into Lake Chivero from October 2010- January 2011

River	Oct-10	Nov-10	Dec-10	Jan-11	Mean
Manyame (C21)	0.208	0.531	1.899	5.204	1.777
Mukuvisi (C22)	1.158	1.014	2.556	4.425	2.17
Marimba (C24)	0.361	0.413	2.853	2.666	1.527

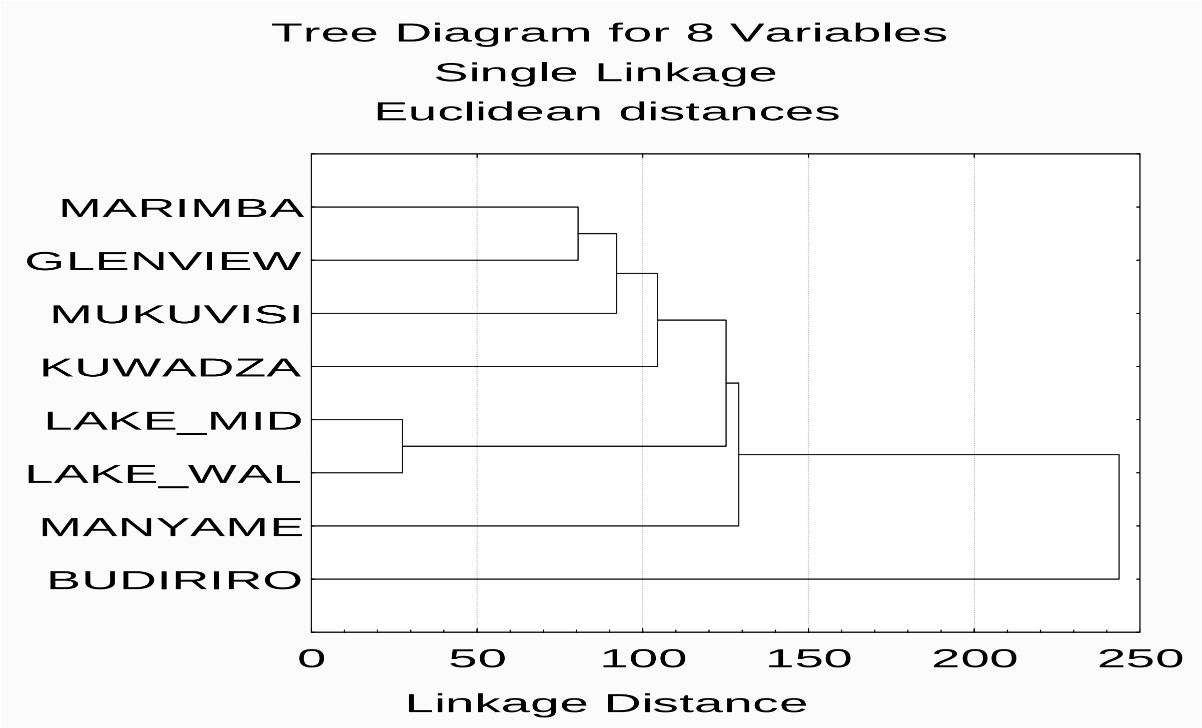
Source: (ZINWA Research and Data Division, 2010)

Appendix 6. Percentage reduction of turbidity, nitrate, total phosphate and BOD after passing through a 5.85 m^2 wetland

Variable	Chibuku wastewater	Kitchen wastewater	Mean %
Turbidity	86.70	96.64	91.67
Nitrate	42.50	33.30	37.9
Total phosphate	96.80	62.90	79.85
BOD	85.33	78.33	81.83

Source: (Anusa, 2004)

Appendix 7. Dendrogram of the different sampling sites using linkage distances



Appendix 8. Correlation Matrix of the different physico-chemical parameters

VAR	TURB	TEMP	OXY%	DO	PH	COND	SAL	TDS	ORP	TN	TP	CHL
TURB	1.00	0.11	**0.63**	0.62	0.67	-0.17	-0.39	-0.19	-0.08	-0.24	-0.19	0.44
TEMP	0.11	1.00	0.04	0.03	0.29	0.09	0.08	0.34	0.17	-0.46	0.12	0.12
OXY%	**0.63**	0.04	1.00	0.99	0.62	-0.01	-0.47	-0.23	-0.15	-0.20	-0.22	0.41
DO	**0.62**	0.03	**0.99**	1.00	0.61	0.03	-0.45	-0.23	-0.18	-0.19	-0.21	0.42
PH	**0.67**	0.29	**0.62**	**0.61**	1.00	-0.04	-0.23	-0.09	-0.01	-0.21	-0.24	0.34
COND	-0.17	0.09	-0.01	0.03	-0.04	1.00	0.55	0.40	-0.52	0.33	0.10	-0.10
SAL	**-0.39**	0.08	**-0.47**	**-0.45**	-0.23	**0.55**	1.00	0.34	-0.20	0.21	0.31	-0.27
TDS	-0.19	**0.34**	-0.23	-0.23	-0.09	**0.40**	**0.34**	1.00	0.01	0.11	0.06	-0.25
ORP	-0.08	0.17	-0.15	-0.18	-0.01	**-0.52**	-0.20	0.01	1.00	-0.14	-0.01	-0.06
TN	-0.24	**-0.46**	-0.20	-0.19	-0.21	**0.33**	0.21	0.11	-0.14	1.00	0.01	-0.27
TP	-0.19	0.12	-0.22	-0.21	-0.24	0.10	0.31	0.06	-0.01	0.01	1.00	-0.10
CHL	**0.44**	0.12	**0.41**	**0.42**	**0.34**	-0.10	-0.27	-0.25	-0.06	-0.27	-0.10	1.00

Correlations are significant at $p \leq 0.01$ and N = 62

Values in bold are statistically different at $p \leq 0.01$; a negative sign shows negative correlation between the parameters.

Appendix 9. PAMOLARE simulation of the effect of current wastewater management and land use on water quality

Simulated period	10.0 year(s)
Printing step	0.500 year
Integration step	0.020 year
Physical data	
Lake depth	9.40 m
Water residence time	1.60 years(s)
Sedimentation constant	0.50 m/year
Reduction of nutrient outflow due to thermocline	0.00
Nitrogen data	
Initial value of nitrogen in water	3.210 mg/l
Initial value of nitrogen in sediment	2.000 g/m^2
Nitrogen loading	68.140 g/m^2/year
Sediment release of nitrogen	0.010 /year
Fraction of nitrogen bound in sediment	0.100
Phosphorus data	
Initial value of phosphorus in water	2.770 mg/l
Initial value of phosphorus in sediment	1.094 g/m^2
Phosphorus loading	45.090 g/m^2/year
Sediment release of phosphorus	0.010 /year
Fraction of phosphorus bound in sediment	0.050

Appendix 10. PAMOLARE simulation of the effect of wetland use on wastewater purification

Simulated period	10.0 year(s)
Printing step	0.500 year
Integration step	0.020 year
Physical data	
Lake depth	9.40 m
Water residence time	1.60 years(s)
Sedimentation constant	0.50 m/year
Reduction of nutrient outflow	
due to thermocline	0.00
Nitrogen data	
Initial value of nitrogen in water	3.210 mg/l
Initial value of nitrogen in sediment	2.000 g/m^2
Nitrogen loading	42.798 g/m^2/year
Sediment release of nitrogen	0.010 /year
Fraction of nitrogen bound in sediment	0.100
Phosphorus data	
Initial value of phosphorus in water	2.770 mg/l
Initial value of phosphorus in sediment	1.094 g/m^2
Phosphorus loading	9.085 g/m^2/year
Sediment release of phosphorus	0.010 /year
Fraction of phosphorus bound in sediment	0.050

Appendix 11. PAMOLARE simulation of the effect of the combination of efficient wastewater treatment system and wetland use on wastewater purification

Simulated period	10.0 year(s)
Printing step	0.500 year
Integration step	0.020 year
Physical data	
Lake depth	9.40 m
Water residence time	1.60 years(s)
Sedimentation constant	0.50 m/year
Reduction of nutrient outflow	
due to thermocline	0.00
Nitrogen data	
Initial value of nitrogen in water	3.210 mg/l
Initial value of nitrogen in sediment	2.000 g/m^2
Nitrogen loading	2.170 g/m^2/year
Sediment release of nitrogen	0.010 /year
Fraction of nitrogen bound in sediment	0.100
Phosphorus data	
Initial value of phosphorus in water	2.770 mg/l
Initial value of phosphorus in sediment	1.094 g/m^2
Phosphorus loading	1.363 g/m^2/year
Sediment release of phosphorus	0.010 /year
Fraction of phosphorus bound in sediment	0.050

Appendix 12. The mathematical formulation of the nitrogen and phosphorus sub-model (Extracted from PAMOLARE version 3.0 Help section: 1 layer model)

The following are mathematical formulations of the nitrogen sub-model:

1)	Nload/z	(loading, mg/l/year)
2)	(1/Wres) * Nwat * a	(hydraulic outwash, mg/l/year)
3)	Denit/z	(denitrification, mg/l/year)
4)	NWat * SedRate /z	(sedimentation, mg/l/year)
5)	NSed * NRel/z	(sediment release, mg/l/year)
6)	(1-NBound) * Nsed	(demobilization from sediment, g/m^2/year)

These processes form the two differential equations:

- DNwat/dt = ((Nload-Denit) +Nrel*NSed)/z - (1/Wres) * Nwat * a-(1/z) * SedRate * Nwat

- DNSed/dt = SedRate * Nwat * (1-NBound)-Nrel * Nsed

Where:

NWat is total nitrogen (mg/l) in the water column.
Nsed is nitrogen (g/m^2) in sediment.
Nload is the nitrogen input (g/m^2/year) to the lake
Nrel is the sediment release rate (/year) of nitrogen.
Nbound is the ratio of immobilized sedimentated nitrogen.
z is mean depth (m) of the lake.
Wres is the mean residence time (year) of the water.
SedRate is the mean sedimentation rate. (m/year)
a is a correction factor of nutrient output due to thermocline formation.

- Denit = NLoad-0.34 * Wres$^{-0.16}$ * z$^{0.17}$ (Jensen *et al.*, 1990)

- DPwat/dt = (Pload+Prel * Psed) / z-1 / Wres * Pwat * a-1/z * SedRate * Pwat

- DPsed/dt = SedRate * Pwat * (1-PBound) - Prel * Psed

Where:

PWat is total nitrogen (mg/l) in the water column.

Psed is nitrogen (g/m^2) in sediment.

Pload is the nitrogen input (g/m^2/year) to the lake.

Prel is the sediment release rate (year) of nitrogen.

Pbound is the immobilized ratio of sedimentated phosphorus.

- Chlorophyll (mg/l) = 0.000073 * (TP * 1000)$^{1.4}$ (Edmondson, 1986).

NB: The nitrogen and the phosphorus sub-models are almost identical. The only difference is the denitrification process included in the nitrogen sub-model.

Appendix 13. PAMOLARE Output of the current wastewater management and land use on water quality

Time Years	Water N mg/l	Sediment N g/m2	Water P mg/l	Sediment P g/m2	Limiting nutrient	Chla mg/l	Secchi depth m	Zoopl. mg/l	Fish mg/l	Av. Prim. Prod. mg/l/day	Av max. prim prod mg/l/day	Av. Fish yield mg ww/m2/year
0.5	29.89	5.76	4.02	1.89	P & N	8.46	0.20	7.85	299.75	41.35	82.78	29.41
1.0	48.86	14.60	4.90	2.94	P & N	14.02	0.17	9.89	387.15	59.32	118.73	42.18
1.5	62.34	27.04	5.53	4.17	P	12.68	0.17	9.44	368.01	55.23	110.54	39.27
2.0	71.93	41.99	5.98	5.51	P	14.14	0.17	9.93	388.94	59.71	119.50	42.45
2.5	78.76	58.71	6.30	6.94	P	15.21	0.16	10.26	403.58	62.90	125.89	44.72
3.0	83.62	76.65	6.53	8.42	P	15.99	0.16	10.50	413.88	65.18	130.44	46.33
3.5	87.08	95.43	6.69	9.95	P	16.55	0.16	10.67	421.17	66.80	133.69	47.49
4.0	89.55	114.78	6.80	11.49	P	16.95	0.16	10.78	426.35	67.96	136.01	48.31
4.5	91.31	134.51	6.89	13.06	P	17.24	0.16	10.87	430.04	68.80	137.68	48.90
5.0	92.57	154.48	6.95	14.63	P	17.45	0.15	10.93	432.70	69.40	138.87	49.33
5.5	93.48	174.59	6.99	16.21	P	17.61	0.15	10.97	434.61	69.83	139.74	49.63
6.0	94.13	194.78	7.02	17.79	P	17.72	0.15	11.00	436.00	70.14	140.37	49.86
6.5	94.61	214.99	7.05	19.37	P	17.80	0.15	11.03	437.01	70.37	140.83	50.02
7.0	94.95	235.19	7.06	20.94	P	17.86	0.15	11.04	437.77	70.55	141.17	50.14
7.5	95.21	255.36	7.08	22.51	P	17.90	0.15	11.06	438.34	70.67	141.43	50.24
8.0	95.40	275.48	7.09	24.08	P	17.94	0.15	11.07	438.77	70.77	141.63	50.31
8.5	95.54	295.53	7.09	25.64	P	17.97	0.15	11.07	439.11	70.85	141.78	50.36
9.0	95.65	315.52	7.10	27.19	P	17.99	0.15	11.08	439.38	70.91	141.91	50.40
9.5	95.74	335.42	7.10	28.74	P	18.01	0.15	11.09	439.61	70.96	142.01	50.44
10.0	95.81	355.25	7.11	30.28	P	18.02	0.15	11.09	439.80	71.01	142.10	50.47

Appendix 14. PAMOLARE Output on the effect of wetland use on wastewater purification

Time Years	Water N mg/l	Sediment N g/m2	Water P mg/l	Sediment P g/m2	Limiting nutrient	Chla mg/l	Secchi depth m	Zoopl. mg/l	Fish mg/l	Av. Prim. Prod. mg/l/day	Av max. prim prod mg/l/day	Av. Fish yield mg ww/m2/year
0.5	19.62	4.58	2.38	1.70	P & N	4.39	0.26	5.82	214.89	25.85	51.77	18.41
1.0	31.29	10.30	2.11	2.22	P	3.28	0.29	5.09	185.40	20.98	42.04	14.95
1.5	39.59	18.22	1.91	2.68	P	2.86	0.31	4.78	172.99	19.02	38.12	13.56
2.0	45.49	27.69	1.77	3.11	P	2.58	0.32	4.56	163.96	17.63	35.35	12.57
2.5	49.69	38.24	1.67	3.50	P	2.38	0.33	4.39	157.43	16.65	33.37	11.88
3.0	52.67	49.54	1.60	3.87	P	2.24	0.34	4.27	152.73	15.95	31.98	11.38
3.5	54.80	61.36	1.55	4.22	P	2.14	0.35	4.19	149.36	15.45	30.99	11.03
4.0	56.32	73.53	1.52	4.57	P	2.08	0.35	4.13	146.96	15.10	30.28	10.78
4.5	57.41	85.93	1.49	4.90	P	2.03	0.35	4.09	145.26	14.85	29.79	10.60
5.0	58.19	98.47	1.48	5.23	P	2.00	0.36	4.05	144.05	14.68	29.44	10.48
5.5	58.74	111.11	1.46	5.55	P	1.97	0.36	4.03	143.20	14.56	29.20	10.39
6.0	59.15	123.78	1.46	5.87	P	1.96	0.36	4.02	142.61	14.47	29.02	10.33
6.5	59.44	136.48	1.45	6.18	P	1.94	0.36	4.01	142.19	14.41	28.91	10.29
7.0	59.65	149.16	1.45	6.50	P	1.94	0.36	4.00	141.91	14.37	28.82	10.26
7.5	59.81	161.82	1.44	6.80	P	1.93	0.36	4.00	141.72	14.34	28.77	10.24
8.0	59.93	174.46	1.44	7.11	P	1.93	0.36	3.99	141.59	14.33	28.73	10.23
8.5	60.02	187.05	1.44	7.42	P	1.93	0.36	3.99	141.51	14.31	28.71	10.22
9.0	60.08	199.59	1.44	7.72	P	1.93	0.36	3.99	141.46	14.31	28.70	10.21
9.5	60.14	212.09	1.44	8.02	P	1.92	0.36	3.99	141.44	14.30	28.69	10.21
10.0	60.18	224.54	1.44	8.33	P	1.92	0.36	3.99	141.43	14.30	28.69	10.21

Appendix 15. PAMOLARE Output on the combination of efficient wastewater treatment system and wetland use on wastewater purification

Time Years	Water N mg/l	Sediment N g/m2	Water P mg/l	Sediment P g/m2	Limiting nutrient	Chla mg/l	Secchi depth m	Zoopl. mg/l	Fish mg/l	Av. Prim. Prod. mg/l/day	Av max. prim prod mg/l/day	Av. Fish yield mg ww/m2/year
0.5	2.75	2.66	2.03	1.66	N	0.50	0.61	2.15	71.39	5.41	10.90	3.90
1.0	2.42	3.22	1.51	2.07	N	0.42	0.65	1.98	65.18	4.75	9.58	3.43
1.5	2.18	3.72	1.13	2.37	N	0.36	0.69	1.86	60.63	4.28	8.65	3.10
2.0	2.01	4.17	0.87	2.59	N	0.32	0.72	1.77	57.31	3.95	7.98	2.86
2.5	1.90	4.59	0.68	2.76	N	0.30	0.74	1.70	54.90	3.71	7.51	2.69
3.0	1.81	4.99	0.55	2.89	N	0.28	0.76	1.65	53.17	3.55	7.18	2.57
3.5	1.75	5.36	0.45	3.00	N	0.27	0.77	1.62	51.93	3.43	6.94	2.49
4.0	1.71	5.72	0.38	3.08	N	0.26	0.78	1.59	51.05	3.34	6.77	2.43
4.5	1.68	6.07	0.34	3.15	N	0.25	0.79	1.57	50.42	3.29	6.65	2.39
5.0	1.66	6.42	0.30	3.21	P & N	0.18	0.89	1.37	43.11	2.62	5.32	1.92
5.5	1.65	6.76	0.28	3.26	P & N	0.17	0.92	1.32	41.61	2.49	5.06	1.82
6.0	1.64	7.09	0.26	3.31	P & N	0.16	0.94	1.29	40.53	2.40	4.87	1.76
6.5	1.63	7.42	0.25	3.36	P & N	0.16	0.95	1.27	39.76	2.33	4.74	1.71
7.0	1.62	7.75	0.24	3.40	P & N	0.15	0.96	1.25	39.21	2.28	4.65	1.68
7.5	1.62	8.08	0.23	3.44	P & N	0.15	0.97	1.24	38.82	2.25	4.58	1.65
8.0	1.62	8.40	0.23	3.47	P & N	0.15	0.97	1.24	38.55	2.23	4.53	1.64
8.5	1.62	8.72	0.23	3.51	P & N	0.15	0.98	1.23	38.35	2.21	4.50	1.63
9.0	1.62	9.04	0.22	3.55	P & N	0.15	0.98	1.23	38.22	2.20	4.48	1.62
9.5	1.62	9.36	0.22	3.58	P & N	0.15	0.98	1.22	38.12	2.19	4.46	1.61
10.0	1.62	9.68	0.22	3.62	P & N	0.14	0.98	1.22	38.06	2.19	4.45	1.61

Appendix 16. Google Image, showing sampling sites, land use and the physical overlay of Lake Chivero catchment (Downloaded, 11-11-10)

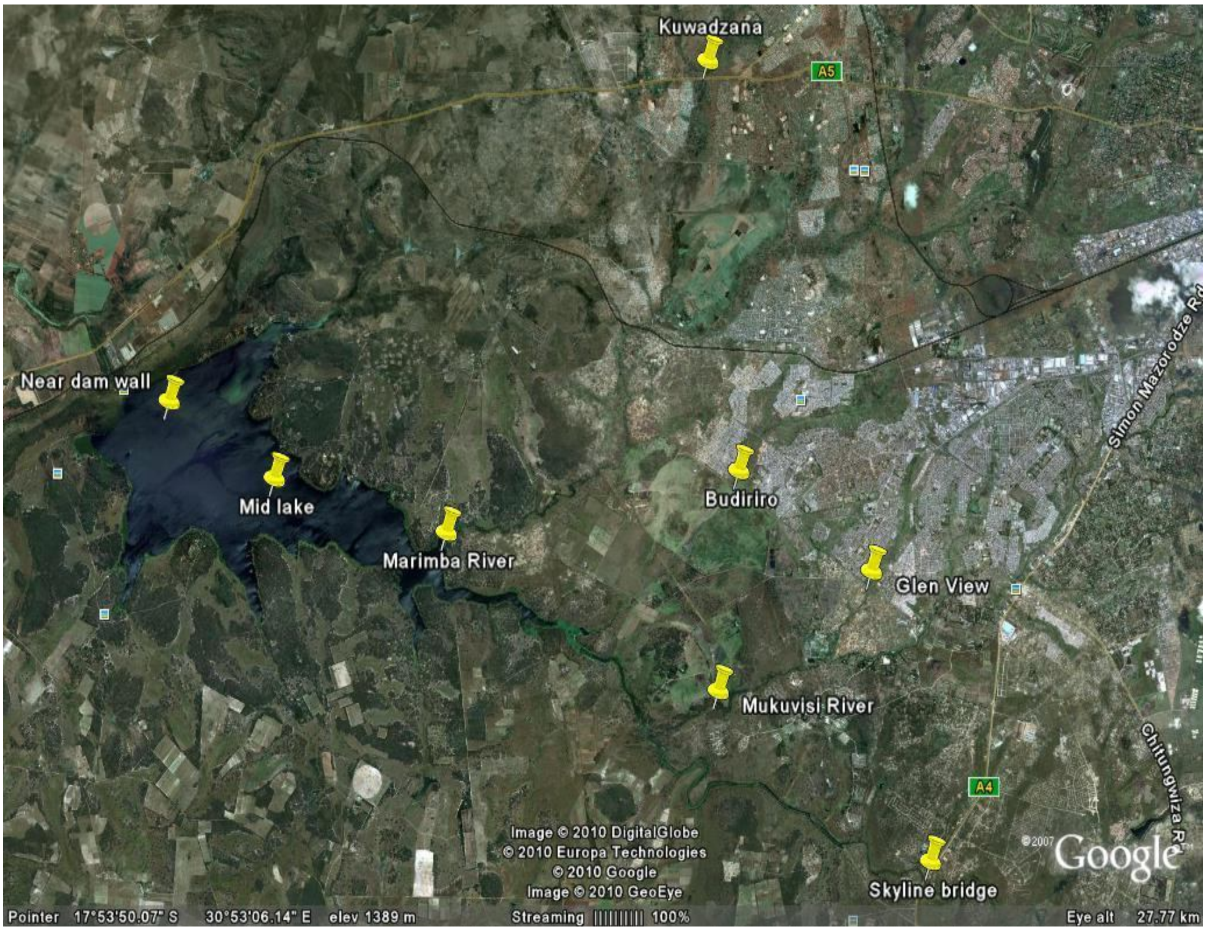


Plate 1. Glenview – The expanse of urban agriculture in Lake Chivero catchment

Plate 2. Kuwadzana – Uncontrolled stream bank cultivation

Plate 3. Manyame - River stretch highly infested by *Hydrocotyl spp*