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Using the Planning and Management Model of Lakes and Reservoirs (PAMOLARE) as a tool for planning the rehabilitation of Lake Chivero, Zimbabwe

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ABSTRACT

The objective was to determine the applicability of the Planning and Management Model of Lakes and Reservoirs (PAMOLARE) as a tool in predicting and managing changes in Lake trophic status, using Lake Chivero (Zimbabwe) as a case study. The model was used to estimate the effect of nutrient reduction under three management scenarios, which were: the use of the existing management system (used as the baseline scenario), the use of natural wetlands and the combination of efficient wastewater treatment systems and wetlands. Modelling parameters were gathered through, 2010 field data, literature review and information acquired from responsible authorities. The current trophic status of Lake Chivero was evaluated by analyzing different physico-chemical variables from the lake's major and minor tributaries. Physico-chemical parameters measured were dissolved oxygen, turbidity, conductivity, total dissolved solids, pH, temperature, total nitrogen, total phosphorus and chlorophyll-a. The results indicated that Lake Chivero was hypereutrophic, with a mean phosphorus concentration of 2.77 mg L^{-1} and a mean nitrogen concentration of 3.21 mg L^{-1}. Most physico-chemical parameters differed significantly with ($P \leq 0.05$) with sampling site. The phosphorus contribution from non-point sources was estimated to be about 493 tonnes per annum compared to 634 tonnes per annum from point sources. About 40,000 ha of wetlands would have the capacity to remove up to 80,000 tonnes of phosphorus and about 99,700 tonnes of nitrogen per annum. The results of the model scenario runs revealed that phosphorus in the lake water could decrease from 2.77 to 0.22 mg L^{-1} over 6.5 years. Nitrogen levels in the lake water also could decrease from 3.16 to 3.06 mg L^{-1} over 4 years. The notable trends indicated that the model could be used as a tool for planning the management of Lake Chivero.

1. Introduction

Fresh water is critical to the fulfillment of human needs although it represents the smallest percentage of the total water available on our planet. Globally, lakes cover approximately 1% of land surface area with 250 of the world's largest lakes accounting for approximately 90% of this area (Herdendorf, 1990). In contrast, the smaller percentage is constituted by shallow lakes, which are the most abundant in the global landscape (Wetzel, 2001). Increased worldwide cases of eutrophication mainly because of anthropogenically driven enrichment of waters with phosphorus and nitrogen were reported by Ayres et al., (1996), UNEP-IETC/ILEC (2001) and JICA (1996). However, earlier studies on aquatic ecosystems by Kinne (1984), identified ammonium (NH_{4+}), nitrite (NO_{2-}) and nitrate (NO_{3-})as the most common reactive forms of dissolved inorganic nitrogen. In sub-Saharan Africa, Nyenje et al. (2010) noted accelerated eutrophication and nutrient release in water ecosystems specifically in urban areas.

Consequently, recent studies on Lake Chivero in Zimbabwe have shown an increasing trend in eutrophication. The Lake sits on the watershed from which it extracts its water and provides for a growing population (Magadza, 2003). Effluent from the city is therefore discharged upstream of the water supply reservoir therefore posing water quality management problems. Point source pollution in the city is of major concern in terms of wastewater management. However, the estimated contribution of non-point sources of nitrogen

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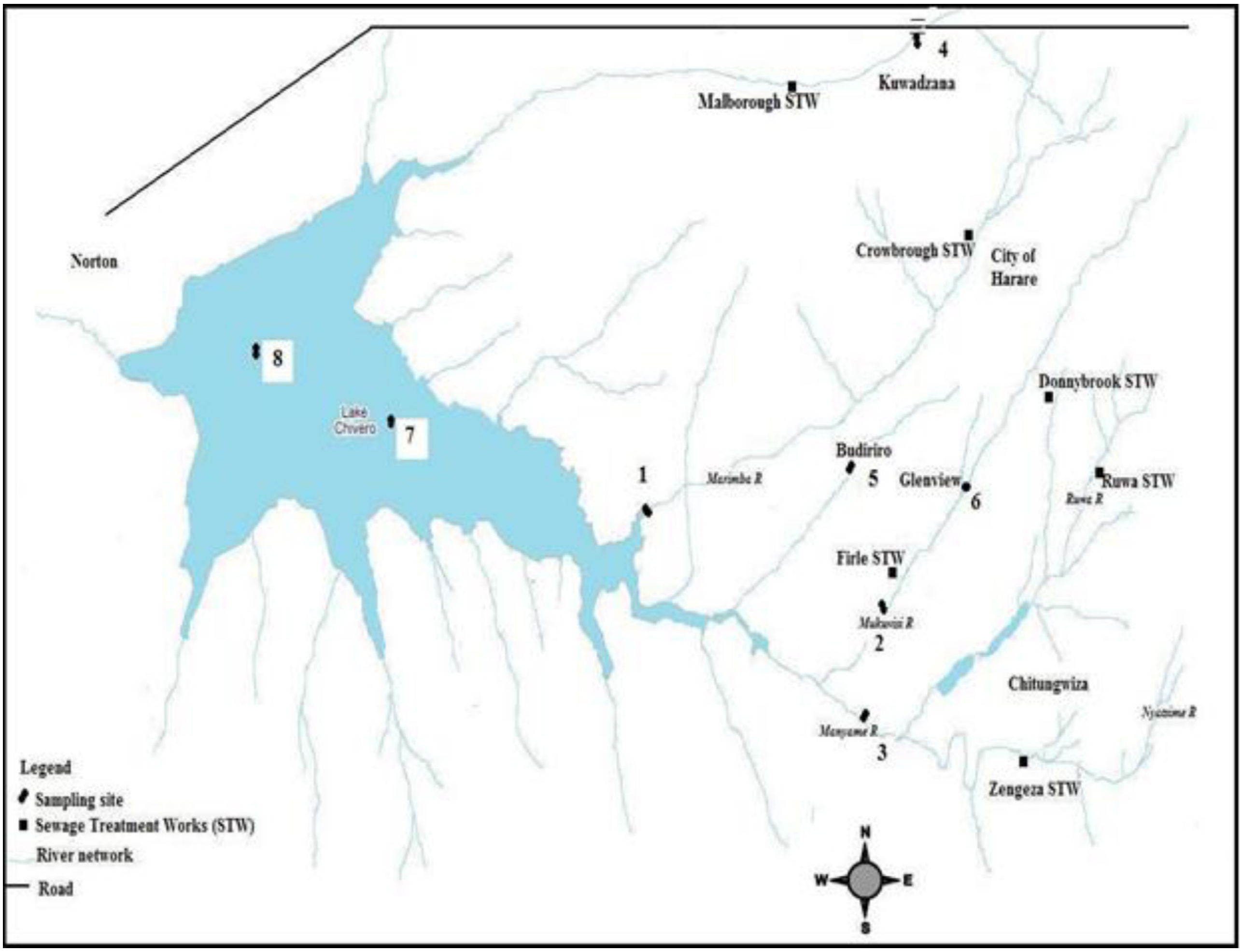

Fig. 1. Site map showing numbered sampling locations.

and phosphorus to Lake Chivero is sufficient to maintain eutrophy (Marshal, 1981; Thornton and Nduku, 1982; Magadza, 2003). 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.

With the increasing dimension of effluent sources from point source to non-point source, the implementation of pollution control through effluent limitations alone is almost impossible Magadza (2003). Results from this study pointed out that investing in high technology wastewater treatment plants alone, would not solve the pollution problems of Lake Chivero. Earlier studies by Spellman (1996) in managing water pollution indicated that the watershed area has an intrinsic self-purification potential, which can improve downstream water quality. These arguments are supported by recent initiatives on Lake Basin Management Nakamura and Rast (2011) who are promoting an integrated approach to Lake Basin governance for sustainable water resource management.

Mathematical models offer a platform for diagnosing problems and evaluating alternative solutions for maintaining water quality. The models are derived from scientific theories and from observations of the processes and responses of lake ecosystems. Ecological modelling allows for the assessment of the feasibility of the different management actions in different contexts before major investments in infrastructure are considered. Jørgensen (2010) reported use of multiple lake models developed for environmental management, highlighting a wide spectrum of complexity within the models. Application of different models therefore is based on the processes accounted for and the available data set.

The Planning and Management Model of Lakes and Reservoirs (PAMOLARE)—Version 3.0, was developed for use by decision-makers and engineers engaged in lake and reservoir management in developing countries and countries with economies in transition. The PAMOLARE tool has been used successfully as a tool in the prediction of eutrophication response in hypereutrophic lakes e.g., Lake Fure in Denmark (Gürkan et al., 2013) and Zarivar wetland in Iran (Hamidian and Hasanzaden, 2011). The following four models are available in the PAMOLARE package; namely, (i) the Vollenweider plot, (ii) 1-layer lake model (low complexity), (iii) 2-layer lake model (moderate complexity) and (iv) structurally dynamic 2-layer lake model (moderate complexity using energy to model the structural dynamics of phytoplankton and zooplankton). The PAMOLARE model is one of the models that have been developed to describe eutrophication processes in water bodies for environmental management.

2. Materials and methods

2.1. Modelling

The PAMOLARE Version 3.0 model was applied to project the future trophic status of Lake Chivero. The one layer model was selected taking into consideration the model requirements and the relevant information available. The one layer model was appropriate because this Lake does not permanently stratify (Thornton and Nduku, 1982).

The input data used to build the model included:

- The current nitrogen and phosphorus concentrations in water ($mg\,L^{-1}$).
- Current nitrogen and phosphorus loadings ($g\,m^{-2}/y^{-1}$).
- Nitrogen and phosphorus bound to sediment particles.
- Nitrogen and phosphorus released into the water from sediment particles.
- Lake morphometry [mean depth (m), sedimentation rate (m/y^{-1}) and water residence time (years)].

The compilation of data required for running the PAMOLARE lake model was developed through experimental work, consultations with the responsible authorities and literature review.

2.2. Monitoring and assumptions

Eight sampling sites (Fig. 1) were selected based on their contributions to the nutrient loading of the Lake. Sites 1–6 were rivers flowing into the lake and sites 7 and 8 were lake points. Samples from the Manyame, Mukuvisi and Marimba Rivers were collected downstream of sewage-effluent discharge points and were used to capture the contributions of the point sources of pollution to the Lake. The contribution of diffuse source pollution was captured from Kuwadzana, Glenview and Budiriro sites upstream of any water treatment plant discharges. Sites 4–6 were largely comprised of residential areas and agricultural lands under maize cultivation. Sites 7–8 were the reference points to document 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. Effluent from the treatment plants is directly discharged into the river systems. The exact coordinates of the sampling sites shown in Table 1 were located using a Garmin Etrex Summit 12 Channel Global Positioning System (GPS). The mean point and non-point sources of P loadings were used to estimate the total tonnage of phosphorus per annum delivered to the Lake.

Data were collected over a period of 3 months from 29 October 2010 to 31 January 2011, which coincides with the summer season in Zimbabwe. Composite water samples were collected from all the sites in polythene bottles for chemical analysis. Composite samples from the Lake sites were taken by depth profile at 2 m interval from surface water (0 m) to 14 m and surface water from the rivers. Prior to use the polythene bottles were soaked overnight in a 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. Temperature (°C), hydrogen ions concentration (pH), percentage oxygen saturation and dissolved oxygen concentration (DO) ($mg\,L^{-1}$) were measured on site using a pH/mV/DO meter (HACH HQ20). Conductivity ($\mu S\,cm^{-1}$), oxidation-reduction potential (mV) and percentage salinity were measured using a conductivity meter (WTW pH 330i). Water transparency was measured with a standard Secchi disk according to standard methods (Wetzel, 1983).

Chemical analysis of the water samples was conducted at the University of Zimbabwe Hydrobiology Laboratory. Total phosphorus (TP $mg\,L^{-1}$) and total nitrogen (TN $mg\,L^{-1}$) concentrations were determined by colorimetric 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 where the nitrate was reduced to nitrite. 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 et al., 1998).

From the experiments and observations made on the catchment it was concluded that the main external variables negatively affecting Lake Chivero ecosystem were the nutrient loadings from the wastewater treatment plants, residential areas, formal and informal industries, and agriculture along the three main tributaries; the Manyame, Mukuvisi and Marimba rivers. To estimate the nutrient loadings from the tributaries, the mean flow rates from October 2010 to January 2011 were obtained from the Zimbabwe National Water Authority (ZINWA) Research and Data Division. The flow rates were mean daily record from gauging stations CR21, CR22 and CR24 respectively.

Nitrogen and phosphorus loadings from the catchment were estimated using Eq. (1) below:

$$L = Q \times \frac{C}{A} \tag{1}$$

where: L = nutrient loading ($g\,m^{-2}/year^{-1}$),
Q = flow rate in ($m^3\,s^{-1}$),
C = nutrient concentration ($mg\,L^{-1}$),
A = surface area of the Lake (m^2).

Default values of the model were used where no information was available. Standard mathematical equations extracted from PAMOLARE Version 3.0 were applied to estimate relevant information that could not be gathered directly by observation (Vollenweider, 1975).

Phosphorus and nitrogen inputs from the catchment were calculated for both point and non-point sources of pollution. Non-point estimations of loadings were based on the principles articulated 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 annual input was expressed as loading per unit area of the lake surface area. Phosphorus bound to sediment particles is usually 15–25% of the total P in the sediment. Results by Nduku (1976) of the phosphorus in the lake sediment were used in estimating the nutrients bound. The anaerobic release of phosphorus from Lake Chivero was estimated to be between 0.03–0.13 $mg\,m^{-2}\,d^{-1}$ (Thornton, 1980). The mass of nitrogen bound to sediment particles is slightly smaller, only 10–20% of nitrogen contained in the sediment. Default values were used for denitrification.

2.3. Scenario generation

Three management scenarios to reduce nutrient loading into Lake Chivero were evaluated. The scenarios were based on measures already in place and/or likely to be considered. It was assumed that the three scenarios would have a positive impact on improving the state variables of the lake ecosystem. Scenario A was a conceptualization of the existing wastewater management system, which was used as the baseline. Scenario B incorporated the use of natural wetland purification potentials in the Lake Chivero catchment area through preservation and application of regula-

Table 1
Description of sampling sites; the sampling sites were adopted from past studies (Mukwashi, 2001 and Ndebele, 2003[a]).

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[a]	Middle section of lake	17°54,094"S 030°48,038"E
8	Near the dam[a]	Close to the watch tower	17°53,392"S 030°47,177"E

[a] Represents the two lake sites.

tory statutes governing the sustainable use of wetlands. Scenario C incorporated the use of wetlands and the efficient functioning of the existing mechanical wastewater treatment plants. It was assumed that wastewater treatment plant effluents would be treated within acceptable limits. If the Biological Nutrient Removal (BNR) practices and wastewater ponds are fully functional, their 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). The model simulated the water quality response of the Lake over 10 years in response to the various nutrient reduction scenarios.

The wetlands in Lake Chivero catchment extending from the City of Harare to Chitungwiza, Ruwa, Epworth, Mabvuku and the Seke Communal lands were identified using Google Earth Pro 4.2 Satellite Imaging accessed on 24-11-2010. A wetland inventory was created using area polygons by selecting the different wetlands and storing them in a database. The wetland database created in Google Earth was imported into the Integrated Land and Water Information Systems Model (ILWIS) version 3.3 for data editing and analysis. Arc View 3.2. A Geographic Information System (GIS) was used to estimate the size of the wetlands spatially distributed in the Upper Manyame River catchment. Wetland efficiencies were extrapolated from past studies (Tendaupenyu, 2002; Anusa, 2004). The extrapolated purification potential of the wetlands (Anusa, 2004) indicated that the reduction efficiency for phosphorus in a wetland of 5.85 m^2 was 80% and for nitrogen, it was 37%. Results from studies by Tendaupenyu (2002) estimated that an area of 2.1 hectares, spanning a longitudinal distance of 1500 m could remove between 3 and 48 g of phosphorus per second.

The output model estimated nitrogen and phosphorus concentrations in the lake water ($mg\,L^{-1}$), phosphorus and nitrogen in sediments ($g\,m^{-2}$), chlorophyll-a ($mg\,L^{-1}$) and Secchi depth (m). The model showed the period required by the Lake for an improvement in water quality. It also showed the expected range in 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 would be successful was determined.

2.4. Statistical analysis

Data were analysed using the STATISTICA version 5.0 Statistical package. Multivariate Analysis of Variance (MANOVA) was run to statistically test the comparison of means for the physico-chemical characteristics at the different sampling sites and dates. Principal Component Analysis (PCA) was used to identify any underlying relationships between the physico-chemical variables and sites. 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.

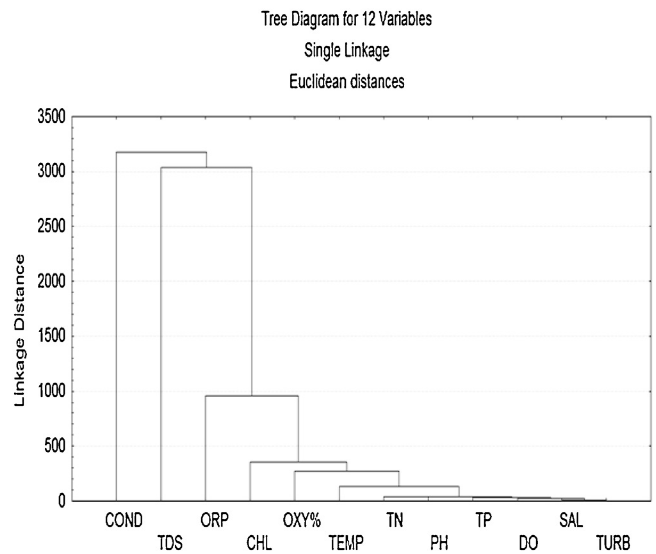

Fig. 2. Cluster analysis performed on physico-chemical parameters from Lake Chivero and its feeder rivers.

3. Results

3.1. Current physico-chemical status of sampling sites

The mean physical and chemical parameters are shown in Table 2. Temperature varied from one sampling site to another. Mean temperature was highest for Mukivisi River (24.85 ± 0.51 °C) and lowest for Manyame River (21.62 ± 0.86 °C). The DO concentrations from the eight sites ranged between 1.05–5.82 $mg\,L^{-1}$. The pH values for the different water samples varied between 7.14 units to 8.32 units. The mean pH values recorded from the river systems were slightly acidic with the Manyame River having the lowest mean of 7.14 ± 0.17 units. The lake sites were slightly alkaline with the dam wall (site 8) having 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 577.9–854.7 $\mu S\,cm^{-1}$. The mean conductivity was highest at Budiriro (854.69 $\mu S\,cm^{-1}$) and the lowest at the lake midpoint (577.93 $\mu S\,cm^{-1}$). The total phosphorus (TP) concentration in Lake Chivero for the sampling period averaged 2.77 $mg\,L^{-1}$. The mean total nitrogen concentration in the Lake for the sampling period was 3.21 $mg\,L^{-1}$.

The mean chlorophyll-a concentration was highest at the lake sites compared with the rivers. The highest mean value of 118.93 ± 28.5 $\mu g\,L^{-1}$ was recorded near the dam wall. The mean Secchi depth was low in all the rivers with levels below 0.50 m. Budiriro site had the lowest mean Secchi depth of 0.09 m and highest mean depth of 1.11 m was recorded from the lake mid-point. Multivariate Analysis of Variance (MANOVA) for the comparison of the means of the physico-chemical parameters indicated that temperature, oxygen saturation, DO, pH, conductivity, TN and

Table 2
Mean physico-chemical records for the composite water samples from eight sampling sites recorded from October 2010–January 2011.

Site	Temperature (°C)	Oxygen saturation (%)	Dissolved Oxygen (mg/L)	pH (units)	Conductivity (µS/cm)	Total dissolved solids (mg/L)	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	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	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	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	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	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	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	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	305.57 ± 60.7	−68.12 ± 7.5	3.06 ± 0.19	2.73 ± 0.38	118.93 ± 28.5	1.0 ± 0.2

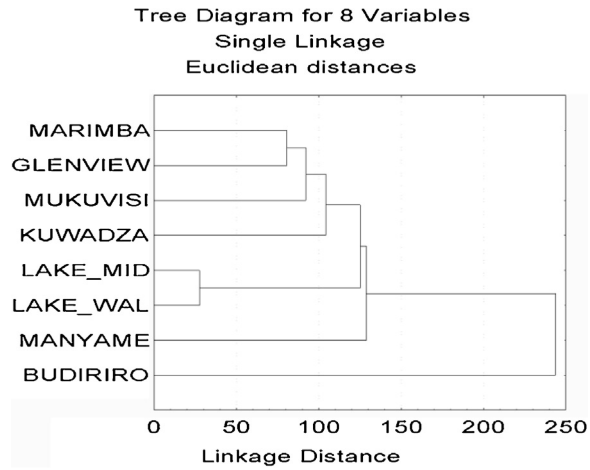

Fig. 3. Dendrogram of the eight different sampling sites using linkage distances.

Table 3
Current phosphorus and nitrogen loadings (g m^{-2}) from the Lake Chivero sub catchment area for 2010.

Site	Total nitrogen (g m^{-2})	Total phosphorus (g m^{-2})
Marimba	12.20	7.31
Mukuvisi	16.42	14.47
Manyame	20.28	3.61
Total	48.9	25.39
Kuwadzana[a]	1.42	0.42
Glenview[a]	9.99	2.95
Budiriro[a]	7.82	16.33
Total[a]	19.24	19.70

[a] Non-point source pollution.

chlorophyll-a differed significantly ($p \leq 0.05$) with sampling sites. Conductivity, ORP and TDS differed significantly ($p \leq 0.05$) with sampling dates.

The results of the Cluster analysis (Fig. 2) showed a close relationship between conductivity and TDS. The relationship between the two parameters is indicated by their smaller linkage distance. However, the long linkage distance between the first cluster (conductivity and TDS) and that including ORP indicates some dissimilarity. ORP showed a closer relationship with chlorophyll-a, which also had a close relationship with percentage oxygen saturation. Oxygen saturation had a very close relationship with temperature and pH. This former cluster was closely related to TP, turbidity and DO.

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).

The rivers (sites 1–6) caused much of the variability in the physico-chemical records as shown in Fig. 3. The Budirio site showed high levels of dissimilarity compared to the other rivers as displayed by the long linkage distances. However, the Marimba and Glenview sites showed a very close relationship which was also closely related to the Mukuvisi. The two lake points were closely related as displayed by the same linkage distance (Fig. 3).

3.2. Nutrient loadings into Lake Chivero

The total phosphorus and nitrogen loadings into Lake Chivero from the three main feeder rivers and three minor sub catchment rivers are shown in Table 3. From the estimated phosphorus loading for 2010 in Table 3, it was estimated that 492.5 tonnes per

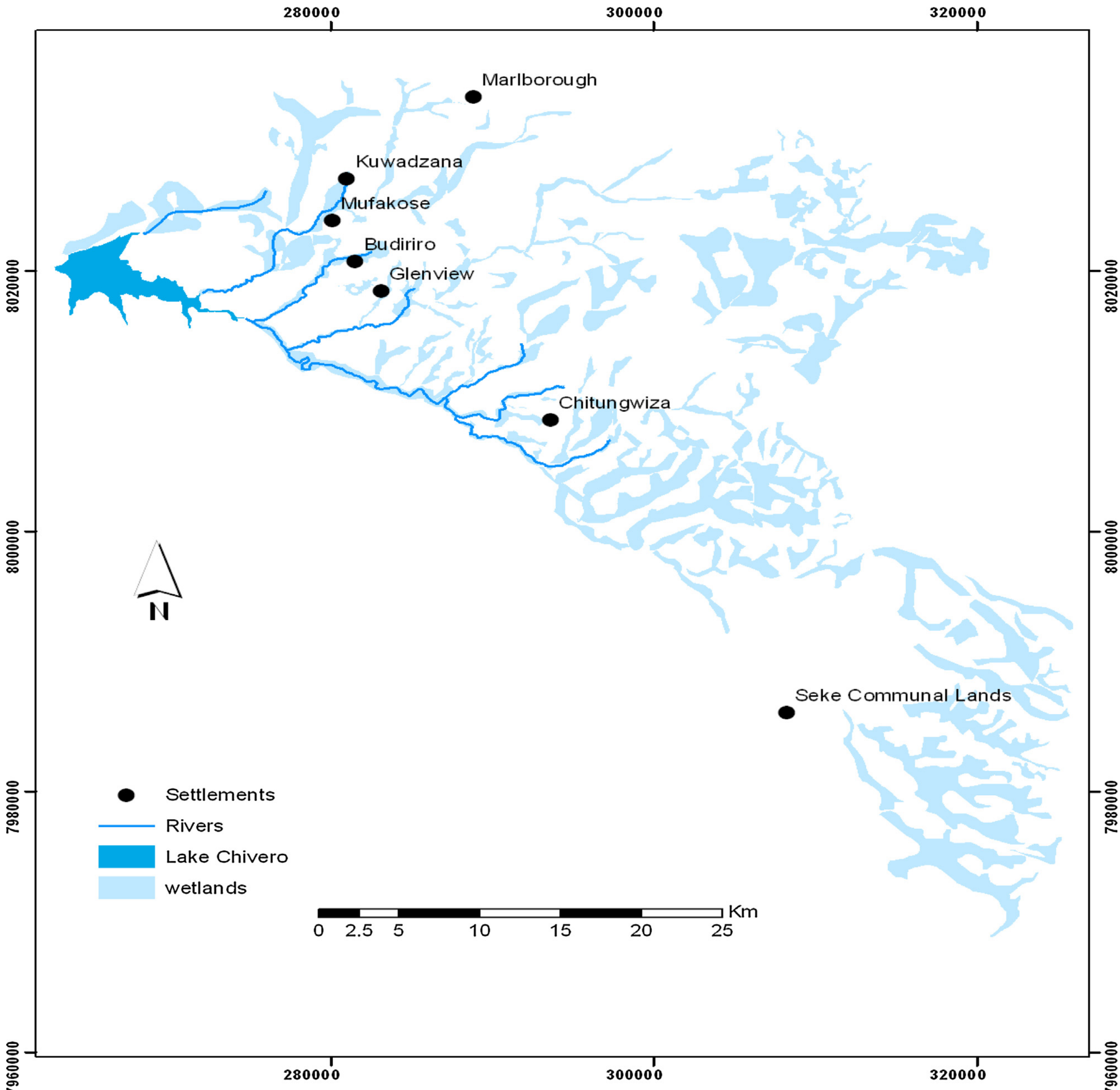

Fig. 4. Map of wetlands in Lake Chivero catchment.

Table 4
Historical changes in phosphorus regime in Lake Chivero (after Thornton and Nduku (1982) and Magadza (1997)[a]) in comparison with the present study (2010–11) and projected status (2020).

Parameter	1967	1978	1996[a]	2010–11	2020 (Projections)
P concentration (mg L^{-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 ($\mu S\ cm^{-1}$)	160	120	800	609	

Adopted from Magadza (2003).

[a] 1996 data is from Magadza and 1967 and 1978 from Thornton and Nduku.

annum were from non-point source contribution and 634 tonnes per annum were from point sources of pollution. The mean seasonal phosphorus loading for 2010 was 564 tonnes per annum (Table 4).

3.3. *Wetland contributions to nutrient reduction into Lake Chivero*

The total wetland area in the catchment was approximated as 39,900 ha (Fig. 4). The wetlands could denitrify as much as 99,700 tonnes of nitrogen per annum based on UNEP-IETC (2001) guidelines. It was estimated that the wetlands in the Lake Chivero catchment could remove about 80 000 tonnes of phosphorus per annum based on the findings of Anusa (2004).

3.4. Model outputs

The model outputs from the three scenarios are as shown on Fig. 5. Fig. 5a shows that if the current wastewater treatment systems are not upgraded (Scenario A), P levels in the lake water would continue to increase from 2.77 mg L^{-1} to 7.11 mg L^{-1} over the next eight years. An increase in nutrient loading after the next five years, however, would not cause any significant difference in P concentration. The P in the sediment would increase linearly with time to about 30.28 g m^{-2} over the next 10 years. N in the water would increase from 3.21 mg L^{-1} to almost 90.5 mg L^{-1} during the next 10 years before becoming constant. Beyond 90.5 mg L^{-1} no amount of nutrient loading would influence the inlake nitrogen concentration. Nitrogen in the sediments would increase linearly with time from 0.5 gm^2 to about 351 gm^2 over the next 10 years. Secchi depth would decrease from about 0.52 m to 0.14 m in the first year. However, the depth would increase slightly in the same year to about 0.16 m before further decreasing to 0.15 m over the 10 years. Chlorophyll-a would increase to 14 mg L^{-1} within the first year and then falls to about 10.4 mg L^{-1} in that same year. The chlorophyll-a level then would increase to 18 mg L^{-1} in the next seven years and remain constant.

Nutrient removal through the use of wetlands (Scenario B, Fig. 5b) followed by the use of an efficient Biological Nutrient Removal (BNR) system (Scenario C, Fig. 5c) would result in a decrease in nutrient concentrations. P in the water would decrease to 0.22 mg L^{-1} over the next 6.5 years. The combination of wetland removal and efficient treatment plants would reduce P loading by 82%. P in the sediments would increase at a slower rate to about 3.62 g m^{-2} over the next 10 years. Phosphorus in the sediments would increase sharply in the first two years after the application of nutrient reduction measures. Nitrogen levels in the water would decrease from 3.16 to 3.06 mg L^{-1} over the next four years and there after continue to decrease.

The nitrogen concentration in the sediments would increase at a lower rate than under previous conditions to about 14.98 g m^{-2} in 10 years (Fig. 5c). The Secchi depth would slowly increase in the first 2.8 years to 0.52 m. In the following five years, the levels would increase to between 0.75–0.88 m. The Secchi depth would further increase to about 1.0 m in 10 years. Chlorophyll-a levels would decrease sharply in the first 2.8 years to about 0.58 mg L^{-1}. The chlorophyll-a levels would decrease to about 0.46 mg L^{-1} within the same year and further decrease to about 0.29 mg L^{-1} by year 5.

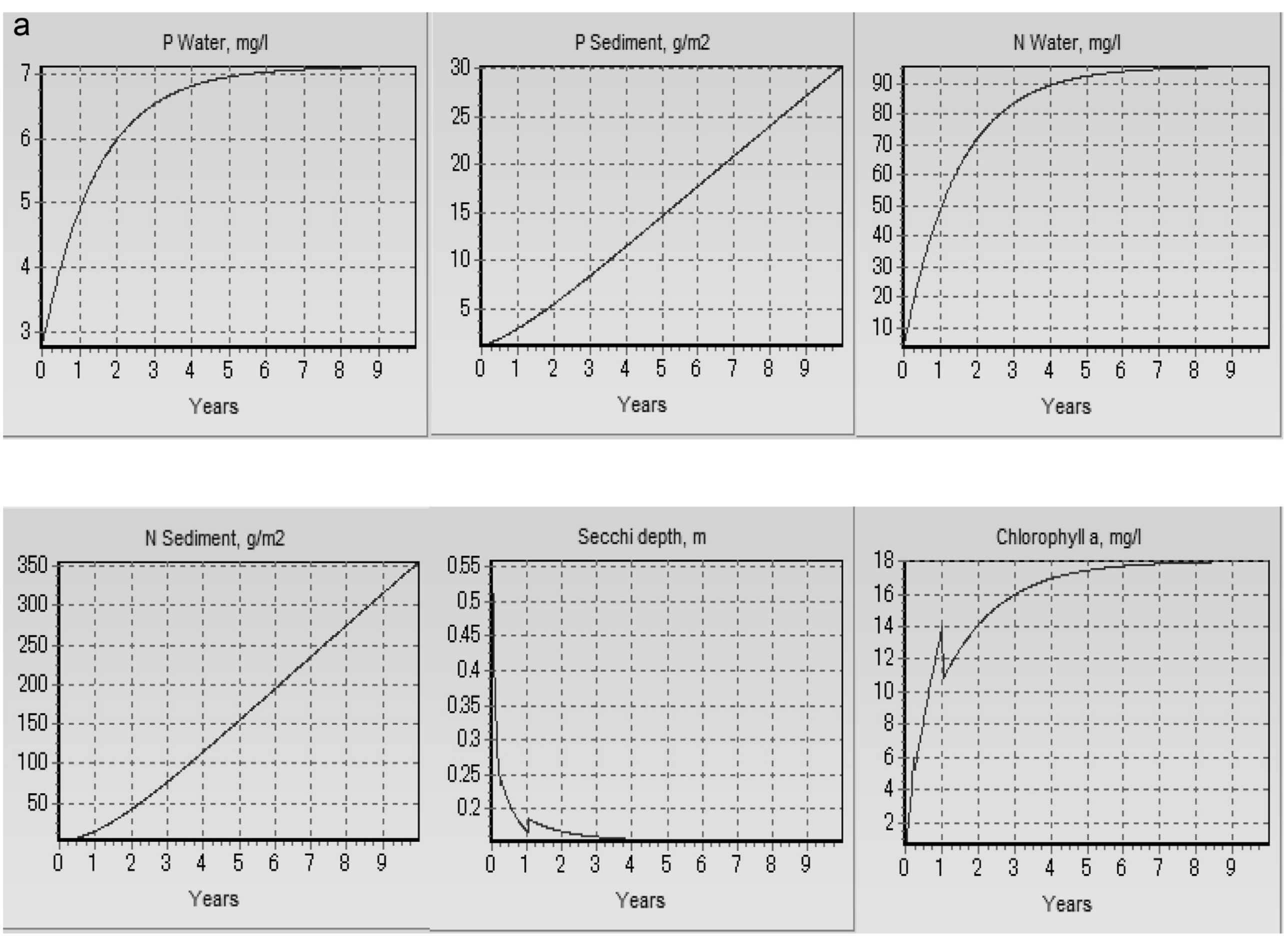

Fig. 5. PAMOLARE outputs showing the projected trends in water quality for phosphorus in water and sediments; nitrogen in water and sediments; Secchi depth and chlorophyll-levels of Lake Chivero under three management scenarios over ten years. (a) Projected trend for phosphorus in water and sediments; nitrogen in water and sediments; Secchi depth and chlorophyll-a levels in Lake Chivero under the current wastewater management system and land use. (b) Projected trend for phosphorus in water and sediments; nitrogen in water and sediments; Secchi depth and chlorophyll-a levels in Lake Chivero under wetland use in wastewater management. (c) Projected trend for phosphorus in water and sediments; nitrogen in water and sediments; Secchi depth and chlorophyll-a levels in Lake Chivero under wetland use and an efficient wastewater management system.

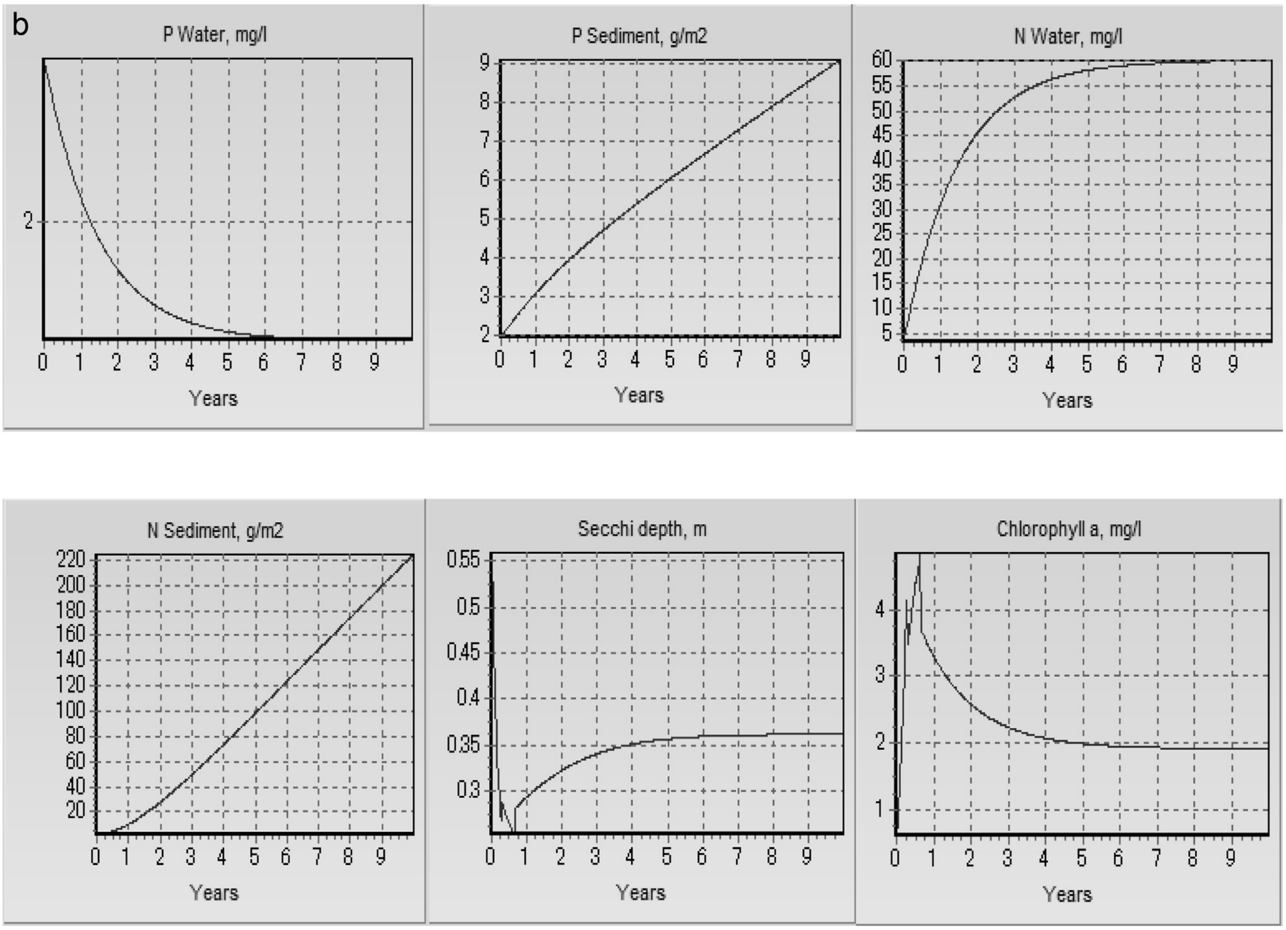

Fig. 5. (*Continued*)

4. Discussion

4.1. Current physico-chemical status of sampling sites

The low dissolved oxygen content at most of the sampling sites is an indicator of high levels of organic contamination. The mean oxygen values recorded from the rivers were below the mean value generally accepted as the minimum required for the 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 invariably adverse to the ecosystem. The variation in DO from one site to another in the same data set could be due to differences in location and more significantly due to differences in the time of sampling. The DO concentrations are known to fluctuate naturally throughout the day (Rios-Arana et al., 2003). The DO concentrations at Budirio site are consistent with past studies by Mukwashi (2001) where the same site had the lowest oxygen concentrations.

The relatively low Secchi depths recorded at the sampling sites, ranging from 0.03 m to 1.1 m are indicative of eutrophic lakes (Wetzel, 1983) which lies in a range between 0.8 and 7.0 m. The rivers seem more eutrophic as compared to the lake points because the rivers are used as repositories for the disposal of domestic sewage, industrial effluents and agricultural runoff. Rivers can be considered as common pool resources and thus are bound to abuse due to the lack of individual ownership (Harding, 1969). In the present study, the turbidity in the rivers was attributed to the sediments washed from cultivated slopes adjacent to the rivers.

The low turbidity at the Budiriro site unlike at the other sampling stations was attributed to the discharge of untreated raw effluent from an adjacent burst sewer system. Organic effluents frequently contain large quantities of suspended solids which reduce light availability to autotrophs. On settling, the organic matter alters the characteristics of the riverbed rendering it an unsuitable habitat for many microorganisms. The low productivity in the rivers is shown by the low chlorophyll-a values recorded from the streams as compared to the Lake. Wetzel (2001) argues that chlorophyll-a in rivers is mostly in the form of periphyton attached on rocks and other substrates and not in the drifting phytoplanktonic form. The chlorophyll-a value recorded during this study was higher than the values recorded by Mhlanga et al. (2006) which is suggests increased nutrient levels in the Lake catchment.

The extent of stream bank cultivation (Appendix B) suggests that the public is not aware of the consequences of poor watershed management. This also supports arguments by Kotze et al. (1995) that about 50% of the wetlands in Southern Africa have been lost to commercial or subsistence agriculture.

The elevated pH values in the lake could be an indication of leaching of soils rich in organic elements as a result of run-off from the first precipitation events. However, the alkaline lake conditions could also be attributed to the photosynthesis of proliferating algae and water hyacinth. Alkalinity in Lake Chivero is consistent with the studies by Thornton and Nduku (1982) who argued that increased nutrient discharge into the lake further influences increased phytoplankton growth. The ORP values recorded during the sampling period for all the sites were indicative of anoxic conditions. The anoxic range was classified according to Inniss (2005)

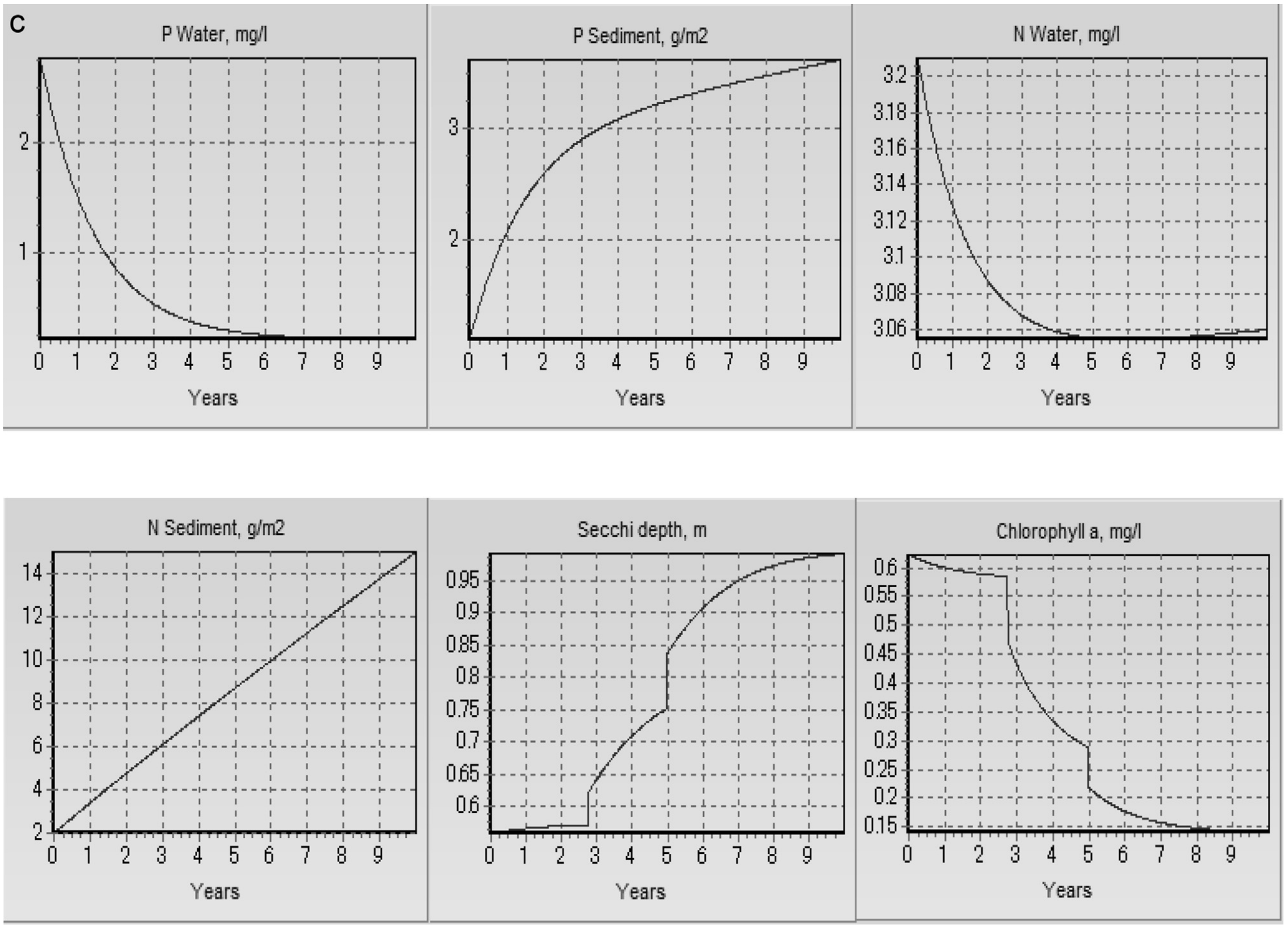

Fig. 5. (*Continued*).

who argued that ORP values of less than −200 mV are indicative of anaerobic conditions and values between −200 and +200 mV are representative of anoxic conditions. Anoxic 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 lower at the lake points, could be attributed to surface runoff from the catchment. High values of conductivity in the rivers could be due to the high pollution levels in the water, resulting from the high nutrient loads from wastewater treatment plants (Nhapi, 2004), burst sewer pipes, salts from fertilisers, seepage from uncollected garbage and leachate from landfills. Lotic systems are normally treated as wastewater discharge points by industries and households. Conductivity increased in proportion to the ionic concentration of dissolved solids. The mean conductivity within the lake was low when compared to the rivers probably because of dilution effect of the larger volume of water. Since conductivity is determined by the amount of dissolved salts, the negative correlation between ORP and conductivity would indicate that, there are large quantities of organic carbon present in the water, which is not decomposed.

The in-lake 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 discharged into water bodies. The current N status in the Marimba River compares closely with that found in the study of Nhapi et al. (2006). However, the increase in P since the same study from Nhapi et al. (2006), from 1.9 to the current 5.56 mg L^{-1} could be attributed to increased sediments washed from the cultivated areas in the catchment. Current findings from experimental work by the International Lake Environment Committee Foundation (ILEC, 2010, unpublished) indicate that the dominant reactive form of N was the NH_4^+ ion. From the ILEC results, it was deduced that the current TN content in the Marimba River is likely to be dominated by the NH_4^+ ion, which is an indication of an oxygen deficit. High phosphorus levels in the Mukuvisi River could be directly attributed to the fertilizer company ZIMPHOS, that is situated upstream of the river.

In the high-density suburbs of Budiriro, the high phosphorus levels are most likely to be associated with of sediments carried from cultivated fields and the overloading of the treatment works. The lower phosphorus levels in the Manyame River could be attributed to uptake by the invasive macrophyte, *Hydrocotyl* spp. which is spreading along the banks of the river. The low levels of P at the Glenview and Kuwadzana sites are likely to show the effects of self-purification by riverine wetlands. Self-purification was evidenced by the higher transparencies of 0.20 m and 0.28 m at the Glenview and Kuwadzana sites respectively as compared to the other rivers. Self-purification at these two sites was also evidenced by the amount of phosphorus, which was less when compared to other sites. Higher P levels were expected at these sites considering the amount of agricultural activity in the catchments. The effects of the rainy days were apparent as they coincided with high turbidity values in the streams, probably due to sediments being washed from adjacent fields.

The total phosphorus concentration (2.77 mg L^{-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 and Nduku, 1982). Higher values than 1967 were expected assuming that conditions such as population growth and land under cultivation had increased over the intervening years. However, the installation of the BNR and diversion of effluent to agricultural land in 1978 helped improve the situation. The nitrogen concentration in the lake also exceeded 0.2 mg L^{-1}, which is a critical value for African lake systems as argued by Thornton (1980).

The results for the nutrient loading analyses, showing that the Mukuvisi River contributed most of the limiting nutrient (phosphorus) and the Manyame River the least, are consistent with past studies by Thornton (1980). Since the collecting points for these sites were below the sewage treatment works, the high P loads could be a combination of fertilizers, domestic wastes 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 for planning thus prolonging the problem of poor water quality.

4.2. Model outputs

The trend shown under the current loadings and management approach indicates that the concentrations of N and P in both water and sediment will continue to increase in the next eight years. Results of the model scenario runs revealed that an 80–85% reduction in the phosphorus loads in Lake Chivero could significantly improve the water quality from a hypereutrophic to a eutrophic state over the next 10 years. Consequently, one of the pivotal steps in the recovery of Lake Chivero is the reduction of nutrient loading from its catchment. The three scenarios in the ecological modelling of Lake Chivero show some significant improvements over its current ecological functioning. The resulting phosphorus concentration after nutrient reduction falls within the eutrophic range of 0.084–0.221 mg L^{-1} (Department of Water Affairs, 2001). However, from the ecological model, it is clear that Scenario B, "use of wetlands in the catchment", shows significant improvements in phosphorus load reduction over the current nutrient loadings into the lake. However, within the context of this project, these improvements could be considered sufficient as a short-term measure because the Lake would show a reversal from a hypereutrophic state to a eutrophic state. Higher phosphorus concentrations even after nutrient load reduction could be possible due to internal phosphorus loading from sediment re-suspension and subsequent nutrient release. Welch and Cooke (1999) note that that internal phosphorus loading might be persistent and endure for at least 10 years even after an external loading reduction.

The projected nitrogen concentrations after nutrient reduction did not show an immediate response to nutrient reduction. Scientific evidence suggests 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 to the atmosphere (Howarth 1988). Wetzel (2001) notes that nitrogen is present in different forms under different oxic conditions; e.g., under anoxic conditions ammonium is likely to dominate due to decomposition of organic matter, while in the presence of oxygen, the ammonia would be oxidized to nitrite and then to nitrate. Unlike P, N had a lower reduction efficiency after wetland treatment, which could affect the decreased response.

The decreases in nutrient (N and P) concentrations were directly related to a decrease in algae as characterized in the model by a decrease in chlorophyll-a concentration. Reductions in external nutrient loadings do not produce immediate reductions in chlorophyll-a concentration, 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 the primary productivity indicator (and subsequent reduction in detritus produced) is also associated with increased Secchi depth. However, in the eutrophication model, the Secchi disk transparency did not improve significantly as compared to the improvements noted by Thornton (1980) who reported that Secchi depth increased to about 1.5–2 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 likely to be sufficient to maintain high productivity.

The projected status for 2020 when compared to the present status is forecast to be similar to that documented during the recovery of Lake Chivero that occurred as a result of the diversion of wastewater to fields and the installation of the BNR system in 1978 (Thornton, 1980). During the Thornton (1980) study, a 94% reduction in loadings reduced phosphorus loads from 685 to 39 tonnes per annum. The current study shows consistency with these past studies with respect to the effect of reducing phosphorus loadings.

An 82% reduction in phosphorus loadings was estimated to be able to reduce the current loadings of 564–34 tonnes per annum. The estimated contribution of non-point P pollution of 493 tonnes per annum was 27-fold higher than the findings from Thornton and Nduku (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 released from sediments could be attributed to the huge quantities of accumulated silt at the bottom of the lake. The impacts of massive siltation have been explained by Mhlanga et al. (2006) who recorded a maximum water depth of 20 m, a deviation from the data presented by Munro (1966) who recorded a maximum depth of 27.4 m near the lake spillway.

4.3. Wetland contributions to nutrient reduction into Lake Chivero

The estimated wetland area if fully utilized could improve significantly nutrient loading from surface runoff. However, it is important to note that the wetland area used for estimating nutrient reduction is just an approximation. The approximation is subject to errors attributed to: when the satellite image was produced, the individual preferences in wetland selection by the photo- interpreters and the quality of image. The estimated area could be an overestimation because there has been significant wetland degradation as argued by Kotze et al. (1995). On the other hand, the area could be an under estimation because some wetlands might not have been accounted for due to their size and position. Their nutrient removal efficiency is also subject to a number of factors such as magnitude and frequency of flows (Bayley et al., 1985), water retention time (Walker, 1987) and the magnitude and the nature of inputs (Richardson and Nichols, 1985).

4.4. 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 compared closely with the recovery phase of Lake Chivero during the 1978 period.

5. Conclusions and recommendations

Ecological processes that occur in a lake are dependent on the physico-chemical (abiotic) and biotic factors of the system and the interrelations between them. It can be concluded that the current nutrient loadings in Lake Chivero from both point and non-point sources are sufficient to cause increased eutrophication over the years. The study indicated that the sustainable utilisation of wetlands in combination with proper wastewater treatment plants has the potential to reduce the current nutrient loadings into Lake Chivero. The estimated nutrient reductions that could be achieved from the two management scenarios would be enough to revert the lake from hypereutrophy to a eutrophic state. The Planning and Management of Lakes and Reservoirs Model for Eutrophication Management (PAMOLARE) could be used as a tool in planning the rehabilitation of Lake Chivero. The reduction of nutrient loadings into Lake Chivero could be achieved through the practise of Integrated Water Resource Management (IWRM), through good management and sound governance. However, as long as pertinent issues of urban poverty, watershed management and public awareness and involvement in water related issues are not addressed, eutrophication in Lake Chivero will remain a problem.

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Appendix A. Summary of the projected trends of the water quality in Lake Chivero under the three management scenarios.

Parameter	Current treatment system	Utilization of wetlands	Combination of wetlands and BNR
Phosphorus in water ($mg\,L^{-1}$)	7.11	1.44	0.22
Phosphorus in sediment ($g\,m^{-2}$)	30.28	9.2	4.39
Nitrogen in water($mg\,L^{-1}$)	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 ($mg\,L^{-1}$)	18.02	1.92	0.14

Output from PAMOLARE version 3.0 (1 layer model).

Appendix B. Agricultural activities taking place in Lake Chivero catchment area (2010).

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