Limnochemistry and Biological Characteristics of Small High Altitude Reservoirs in a Sub-Tropical Region, Nyanga, Zimbabwe

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A B S T R A C T

The ecological characteristics of ten small reservoirs in the high-altitude Eastern Highlands region of Zimbabwe, were studied. Water quality and sediment quality for a range of parameters and also the phytoplankton, zooplankton, macrophyte communities were described. The water quality of the reservoirs was in near pristine condition and their trophic status was oligotrophic and ultra-oligotrophic. In contrast, the sediments especially of the Connemara reservoirs had unusually high levels of phosphorus. Given the high levels of dissolved oxygen in the reservoirs, most phosphorus is likely to be bound to the sediment but its present source was not immediately clear. Phytoplankton densities were very low indicative of low productivity. The major phytoplankton taxa identified included Cyanophyta, Euglenophyta, Chrysophyta, Bacillariophyceae, Pyrrophyta and Chlorophyta. The least abundant taxa were the Euglenophyta while the most abundant was the Chlorophyta. Zooplankton taxa comprised of Daphniidae, Chydoridae, Bosminidae, Sididae, Macrothricidae, Cyclopoida and Calanoida. The daphniids were the most abundant species, while the rotifers were not identified further in this study. Several macrophyte species were identified but the reservoirs showed low similarity in macrophytes composition. There were no clear environmental gradients to explain the patterns. The results of this study provide an important baseline from which future studies especially on the impact of climate change and landuse can be assessed.

Keywords: Small dams, montane, limnology, phytoplankton, zooplankton

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Introduction

Lakes and reservoirs are important habitats providing valuable ecosystem services throughout the world. However, increasing human populations have result in an accelerated demand on water supplies for domestic, industrial and agricultural use (Brönmark and Hansson 2002). The predicted global human population increase which is linked with rapid economic development will in the near future result in the limited availability of freshwater resources. The lack of enough of water resources is therefore predicted as one of humankind greatest problem to resolve in this century (Johnson et al. 2001). Furthermore, freshwater systems have been severely affected by a many other anthropogenic disturbances, which have led to serious negative effects on the structure and function of these ecosystems (Brönmark and Hansson 2002). Hence, there is a

need to fully understand how these ecosystems function before they are irreversibly degraded.

The small reservoirs in Nyanga (Eastern Highlands region) are located at high altitude and have relatively cool, ultra-oligotrophic waters. Some investigations have been carried out in the reservoirs in Nyanga but they all tend to be superficial in their approach. The most detailed study was that of Nduku and Robarts (1977) who investigated water chemistry in the Connemara reservoirs. The sediments of Connemara 3 dam were very rich in nutrients (nitrogen & phosphorus) and comparable to those of highly eutrophic systems like Lake Chivero (Nduku and Robarts 1977) but the water was oligotrophic despite receiving effluent via underground streams from septic tanks built for cottages dotting the lake. This paradox was attributed to the geochemistry of the area which consists of mainly dark dolerite rock

(Nduku and Robarts 1977) which leads to the release of large amounts of iron and manganese when it weathers. These cations complex the reactive phosphorus in the water and 'lock' it in the sediments in an insoluble form thus making it unavailable for use by the algae. The lake was also fully oxygenated at all times and phosphorus was locked to the sediments in an insoluble form. It is believed that this phenomenon had prevented eutrophication of these lakes by septic tanks of the cottages that surround them (Nduku and Robarts 1977).

Thornton and Cotterill (1978) also gave some details on the water chemistry and aspects of the plankton populations in a general limnological survey of the reservoirs in the national Park. Green (1990) sampled nine Nyanga reservoirs as part of a general survey of the zooplankton of some reservoirs along the Eastern watershed of Zimbabwe and the effect of altitude on the species composition. This survey found that zooplankton in the Connemara and Troutbeck reservoirs was significantly different from that of the other reservoirs. No explanation was given for this and it is not clear if these differences were caused by high altitude or the fact that they are on a different river system or because of differences in water chemistry. High altitude lakes are very diverse and examples of studies elsewhere include Andean lakes in South (Mühlhauser et al. 1995; Jorge et al. 2009); high altitude regions of Africa such as Kenya (Mwaura et al. 2002) and Ethiopia (Elizabeth et al. 1992); and alpine lakes (Mosello 1984); and even including lakes in the Himalayas (Tartari et al. 1998). The local differences among high latitude lakes make it difficult to make generalisations, and therefore each system has to be studied.

In Zimbabwe, thousands of reservoirs have been constructed to supply the water demands of industry, agriculture and the rapidly growing human urban population. National statistics estimate that there are about 12 000 small (<10ha or 106 m^3) reservoirs covering an area about 126 089ha (Ersal 1994). About 80% of the 10 747 listed reservoirs in Zimbabwe are <5ha in area. The majority of these reservoirs (61 %) are situated in the former commercial farming areas, with 25% in communal lands and 14% in resettlement areas (Ersal 1994). This distribution reflects the high demand for water for large-scale agriculture (Ersal 1994). However, until recently very little was known about the limnology of small reservoirs (Nhiwatiwa and Marshall 2006, 2007).

This study aims to increase our understanding of limnological characteristics of high altitude waterbodies, which have not yet been studied in much detail. The results will also form an important baseline against which to measure future changes that might take place in them. When this study was done, issues around climate change were not so topical then compared to the present, and for these sensitive systems it is important to have on record their ecological status to monitor for future changes. The main objective was therefore to investigate a number of reservoirs in order to determine the relationships between water chemistry, phytoplankton and zooplankton. Sediments were also analysed to explore the relationship between catchment geology and sediment chemistry.

Study area
Nyanga in situated in Zimbabwe's Eastern highlands with the highest altitude of all the regions of this country (> 1500m a.s.l.). It has a montane climate with high annual rainfall > 800mm annually and very cold winters (10-16ºC). Ten small montane reservoirs in the Nyanga area were chosen for this study. Reservoirs on the Nyangombe River were located in the Rhodes Nyanga National Park while those on the Tsanga River were situated in community areas (Figure 1). Some morphometric characteristics of the reservoirs are presented in Table 1. The reservoirs are mainly used for recreation, irrigation and domestic water supply.

Materials and Methods
Water quality
The study was done in July 2003 for a two week period. Six sampling sites were randomly selected in each reservoir: 3 in the pelagic and 3 in the littoral zones. A 3-litre van Dorn sampler was used to collect water samples at 0.5m depth intervals to produce a depth integrated sample of 18L per sampling site. The samples were mixed (vertical series) and subsamples taken for field and laboratory analyses. Conductivity & total dissolved solids, pH, and transparency were measured with a conductivity meter (WTW LF330), a pH/mv meter (WTW pH 330) and a 20-cm diameter Secchi disc, respectively.

Water quality chemical variables were measured with a HACH water analysis kit (DR/2010 portable data logging spectrophotometer) using filtered water samples (Whatman GF 47mm filters) except for total nitrogen and total phosphorus. The summary of each method is given but they are described in detail in Farber et al. (1960): Chemical oxygen demand, determined by the reactor digestion method (No.8000); Nitrate-nitrogen by the chromotropic acid method (No. 10020); nitrite by the diazotization (chromotropic acid) method (No. 8507); ammonia by the salicylate method (Method 10023), and total nitrogen by persulfate digestion (No. 10071); Reactive and total phosphorus were determined by the Phos Ver 3 (No. 8048) and the PhosVer 3 with
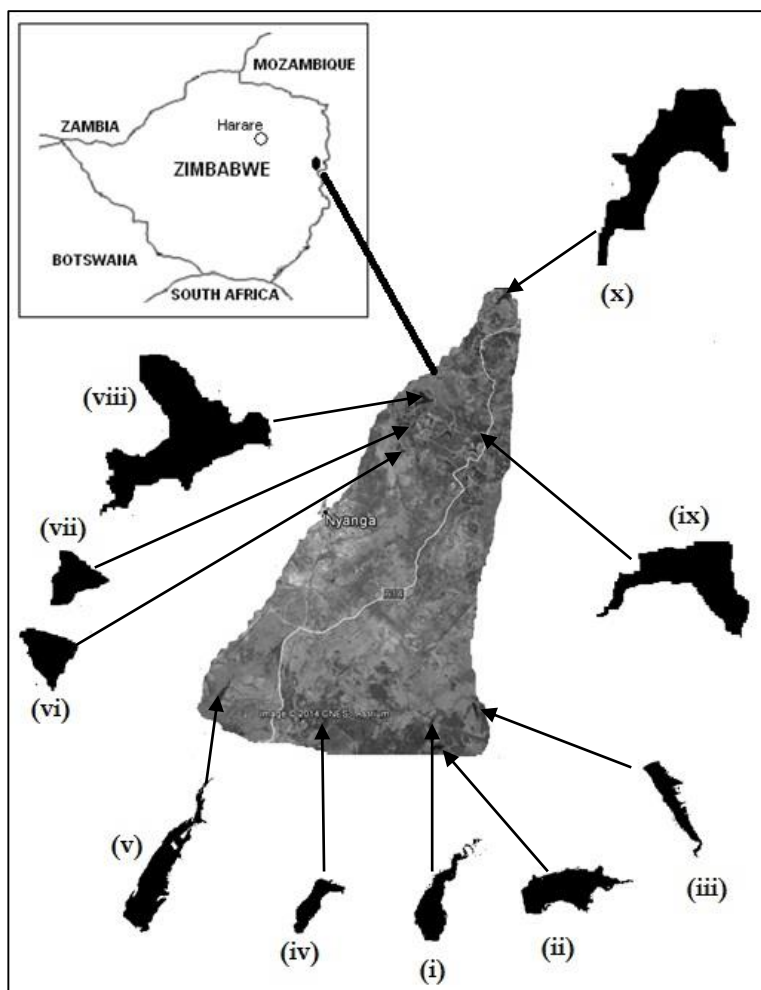
Figure 1. Map of Nyanga and the ten small montane reservoirs that were sampled in this study. (Insert: Map of Zimbabwe). . (Gul = Gulliver (i); Mar = Mare (ii); Pur = Purdon; Rho = Rhodes (iv); Udu = Udu (v); Con I, 2, 3 = Connemara I, 2, 3 (vi, vii & viii); Tro = Troutbeck (ix); Sto I = Storer I (x).

acid persulfate digestion methods (No. 8190) respectively.

Sediment

Sediment analysis was done at Institute of Environmental Soil Science laboratory at the University of Zimbabwe. The variables analysed in units of ($\mu g\ g^{-1}$ of sediment) include soil pH, ammonium-N, nitrate-N, total available nitrogen, total organic carbon, total nitrogen, total phosphorus, available phosphorus, calcium (Ca), magnesium (Mg), potassium (K), sodium (Na), iron (Fe) and manganese (Mn). Metal concentrations in water were analysed in the laboratory using Flame Atomic Absorption Spectrophotometry (FAAS) (Greenberg 1980). The water samples were first filtered through Whatman G/F filters and then acidified with nitric acid to pH less than 2. The water sample was then aspirated into a flame and atomized.

Metals in the sediments were also analysed using the Flame Atomic Absorption Spectrophotometry method (FAAS) (Greenberg 1980). The acid digestion method was used to extract the metals from

the sediments for quantification by the FAAS. This procedure consisted of two parts: I. Digestion: the sediments were oven dried at 180º C in a muffle furnace and large aggregates were broken up. Then 20ml of nitric acid and 5ml of perchloric acid were added to 5g of the oven dried sample. The mixture was then heated on a hot plate until fumes were produced and allowed to cool to room temperature. 2. Acidification: 20ml of 50% hydrochloric acid was added to the mixture from the first digestion. The acidified mixture was heated until boiling and then was cooled to room temperature. The acidified mixture was filtered and distilled water was added to the filtrate in a volumetric flask up to the 100 millimetre mark. The digested sediments were then analysed for metal amounts in an Atomic Absorption Spectrometer (Greenberg 1980).

Quality control was assured by the use of procedural blanks and standards. A known concentration of the standard solution was assayed after every ten samples to verify the analytical quality of the result since there was no standard reference material available. In all the cases for sediments and

Table 1. Morphometric and water quality (mean) characteristics of the ten small montane reservoirs, Nyanga, Zimbabwe (2003).

	Nyangombe River reservoirs				Tsanga River reservoirs					
	Gul	Mar	Pur	Rho	Udu	Con 1	Con 2	Con 3	Tro	Sto 1
GPS Coordinates: LAT	18.295295°	18.302565°	18.295997°	18.288663°	18.279148°	18.167202°	18.163870°	18.157591°	18.184954°	18.091835°
LONG	32.769960°	32.770550°	32.790618°	32.725622°	32.697361°	32.778085°	32.779917°	32.788673°	32.806045°	32.839444°
Altitude (m a.s.l.)	1951	1951	1920	1707	1676	2270	2263	2255	2134	1840
Surface area (x 10^4 m^2)	5.67	9.19	8.38	4.25	14.50	4.57	5.42	44.31	4.12	39.00
Perimeter (km)	1.48	1.51	1.50	1.02	2.62	1.13	1.10	3.70	1.45	3.63
Max. depth (m)	9.1	7.3	12.5	10.1	14	9.14	6.61	9.14	6	-
pH	6.4	7.1	7.3	7.1	6.8	7.9	7.3	7.0	6.6	6.1
Conductivity (μScm^{-1})	10.1	10.8	8.3	8.3	34.8	8.5	10.1	7.4	22.1	13.6
Temperature (°C)	14.2	14.3	14.0	14.0	14.5	13.5	14.0	12.1	13.0	14.0
D.O. (% sat.)	99.3	102.3	99.0	99.0	105.3	110.7	108.3	86.0	104.3	109.3
Secchi (m)	3.3	3.8	3.7	3.7	3.4	1.5	2.0	2.8	3.7	5.7
Ammonia (NH4-N) (mg l^{-1})	0	0.04	0	0	0.04	0.13	0.05	0.05	0.04	0.01
Nitrates (NO3-N) (mg l^{-1})	0.3	0.4	0.1	0.1	0.3	0.20	0.5	0.3	0.0	0
Nitrite (NO2-N) (mg l^{-1})	0.07	0.09	0.095	0.095	0.075	0.02	0.01	0.02	0.001	0.003
Chl *a* (μg l^{-1})	0.0002	0.0002	0.0005	0.0005	0.002	0.0018	0.0005	0.0020	0.0003	0.0001
Tot. Chl (μg l^{-1})	0.0002	0.0003	0.0006	0.0006	0.002	0.0021	0.0005	0.002	0.0003	0.0001
TDS (mg l^{-1})	0.004	0.003	0.003	0.003	0.005	0.006	0.003	0.004	0.003	0.003
COD (mg l^{-1})	25.3	10.0	6.7	6.7	31.7	92.3	71.3	68.7	4.0	0.0
Calcium (mg l^{-1})	0.02	0.02	0.02	0.02	0.06	0.02	0.03	0.04	0.07	0.06
Potassium (mg l^{-1})	1.2	1.0	1.2	1.2	0.9	1.00	1.0	0.3	0.8	0.3
Magnesium (mg l^{-1})	0.3	0.3	0.2	0.2	0.6	0.2	0.4	0.41	0.70	0.67
Reac. phosphorus (mg l^{-1})	0.04	0.03	0.1	0.1	0.0	0.002	0.01	0.001	0.02	0.03
Tot. phosphorus (mg l^{-1})	0.09	0.03	0.1	0.1	0.1	0.002	0.01	0.03	0.03	0.03
Sulphate (mg l^{-1})	0.30	0.4	0.4	0.4	0.3	0.5	0.5	0.4	0.3	0.4

**N.B. (Gul = Gulliver; Mar = Mare; Pur = Purdon; Rho = Rhodes; Con I, 2, 3 = Connemara I, 2, 3; Tro = Troutbeck; Sto I = Storer I).

water, a preparation / reagent blank was prepared for every 20 samples and all the concentrations were below the detection limits. Each sample was analyzed in triplicate for repeatability with a relative standard deviation < 5 % for all the metals analyzed.

Concentrations of nickel copper, cadmium lead, iron zinc and chromium were then determined using FAAS (Greenberg 1980).

Plankton

A subsample of 5L was taken from the well mixed depth integrated sample and passed through a net of mesh size 64μm. In addition, qualitative horizontal and vertical net hauls were taken at littoral and limnetic region in each reservoir. The zooplankton samples were preserved in 10% formaldehyde. These samples were taken to the laboratory were identification and enumeration were done under the microscope. Cladocerans were identified to species using keys in Rey and Saint-Jean (1980), Seaman et al. (1999) and Fernando (2002). Unfortunately it was not possible to identify copepods to species level and rotifers were not included in the analysis. Total chlorophyll and Chlorophyll *a* were analysed as an indication of phytoplankton biomass in each of the reservoirs. Subsamples of 300ml were collected in plastic bottles and these were later filtered using Whatman GF 47mm filter paper. Analysis was done by the method described by Bronmark and Hansson (1998). Identification of phytoplankton was only done to Class level using keys in Prescott (1970), Elenbass (1994) and Canter-Lund and Lund (1995).

Macrophytes

The detailed macrophyte flora of each reservoir was surveyed by wading in the shallows and by boats for the deep water. Wading was done in a zigzag manner across the littoral zone length, frequently investigating all the habitat types present. At sites where the water was too deep to wade, a boat was used. Samples were collected and those that could not be identified on site were preserved in plant pressed for future processing and verification. Identification of the macrophytes was taken to species level where possible, using field identification guides by Sainty and Jacobs (1988). Preserved samples were alos later verified using identification guides by Gerber et al. (2004) and Cook (2004).

Data analysis

Principal Component Analysis (PCA) in the program CANOCO (version 3.12) was used to determine correlative relationships among the ten reservoirs for water and sediment quality and sediment chemical variables were examined using. To reduce skewness because of different measuring units, all the variables were log transformed. Principal Component Analysis analysis was done in two stages: for the water quality variables and then the sediment variables. The analysis for water quality was done for 17 physico-chemical variables and these were conductivity, pH, total dissolved solids, Secchi disc transparency, chemical oxygen demand, reactive phosphorus, total chlorophyll, nitrate-N, ammonia-N, nitrite-N, total phosphorus, water temperature, dissolved oxygen, calcium, potassium, magnesium and sulphate. Principal Component Analysis (PCA) for the sediment quality was done for 14 variables which were pH, ammonium-N, nitrate, total available nitrogen, total organic carbon, total nitrogen, total phosphorus, available phosphorus and the cations iron, manganese, calcium, magnesium, potassium and sodium.

Significant differences between the reservoirs in water and sediment quality were first tested with Kruskal-Wallis Anova at 5% significance level. Then pairwise comparisons were done using Mann-Whitney tests at 5% significance level, with Bonferonni corrected and uncorrected measures. The programme STATISTICA (ver 10) was used for the analysis. Cluster analysis was done for water quality, sediment quality and macrophyte species composition using the PRIMER statistical package (PRIMER-E, 2000) based on a similarity matrix of normalized Euclidean distances.

Results

Water quality

The results of the water quality assessments for the ten reservoirs are presented in Table 1. The pH did not vary much across the reservoirs being near neutral ranging from 6.1 in Storers I to 7.9 in Connemara 3. Since sampling was done in winter, temperatures were very low being less than 15°C while dissolved oxygen showed conditions close to super saturation (>100%) for most of the reservoirs, typical of oligotrophic systems. Water clarity measured by the Secchi disc was in most reservoirs < 4 but was uncharacteristically low in Connemara I dam (1.5m). Conductivity was exceptionally low with most reservoirs about 10 μS cm^{-1} or less which is near distilled water, while the highest conductivity was measured in Udu dam (34.8 μScm^{-1}). Similarly total dissolved solids were extremely low (< 0.001 mgl^{-1}) and the pattern across reservoirs matched that of conductivity. Chemical oxygen demand was rather variable among the reservoirs with some reservoirs recording 0 mgl^{-1} while the Connemara reservoirs recorded the highest values > 65 mgl^{-1}.

Cations and anions were also measured in the reservoirs. Calcium (Ca) ranged from 0.02 to 0.09 mgl^{-1} while potassium (K) was in most reservoirs around 1 mgl^{-1} and about 2 magnitudes greater than calcium. Magnesium concentrations were about a magnitude lower than potassium with most values in the range of 0.3-0.5 mgl^{-1} and higher values were above 0.6 mgl^{-1}. Sulphates did not vary much among the reservoirs ranging between 0.3–0.5 mgl^{-1}. Nutrients comprising nitrogen and phosphorus fractions were also measured in the reservoirs. Reactive phosphorus concentrations were highest in the Nyangombe reservoirs Purdon, Rhodes and Udu reservoirs while the lowest values were measured in the Connemara reservoirs. A similar pattern was observed for total phosphorus concentrations with sometimes very small differences between reactive and total phosphorus concentrations. Ammonia-nitrogen concentrations were highest in the Connemara reservoirs but were undetectable in some of the reservoirs such as Purdon and Rhodes. Total chlorophyll and chlorophyll *a* were of very low concentrations suggesting low algal biomass in the reservoirs. Overall, there were no significant differences in water quality among the reservoirs (Kruskal-Wallis Anova, p > 0.05) and none of the pairwise comparisons were significantly different (Mann-Whitney, p > 0.05).

Principal Components Analysis (PCA) results showed that the first two axes (axis 1 & 2) accounted for 59% of the patterns in the environmental factors for the ten small reservoirs (Figure 2). The first axis explained 34.5% while the second axis explained for 24.5% of the variation. The factor loadings indicated that the first PC axis was characterised by a larger number of environmental parameters (with factor loading > |0.50|) than the second PC axis. The parameters with positive factor loadings on PC axis 1 were pH, ammonia-nitrogen, nitrate-nitrogen, total chlorophyll, TDS, COD and sulphates. Negative factor loadings on PC axis 1 were recorded for Secchi disk transparency and calcium. On PC axis 2, positive factor loadings were recorded for nitrite-nitrogen and magnesium, while negative factor loadings were recorded for ammonium, total organic carbon and total phosphorus. Only iron had factor loading > |0.50| on PC axes 3 & 4.

The plot of the first and second PCs showed patterns which linked the different site characteristics to sediment parameters measured. In the first upper right quadrat, there was Gulliver and Rhodes dams which were characterized by increasing ionic content of metal ions Na, Mg and Ca (Figure 3). Connemara 1 & 3 dams were in the right lower quadrat and were characterized by higher nutrient concentrations of ammonium, total nitrogen, total phosphorus and total

organic matter (Figure 2). The lower left quadrat had all the remaining sites which suggested that they were all similar in their overall water quality characteristics (Figure 2).

Sediment

Sediments were assessed for several soil parameters and the results are presented in Table 2. Sediment pH was generally acidic in the reservoirs. Ammonium-nitrogen and total available nitrogen concentrations differed slightly and the trends that emerged among the reservoirs showed that Connemara 1 & 3, and Troutbeck reservoirs (all Tsanga River reservoirs) had the highest concentrations, while the least concentration was in Mare dam. Nitrate concentrations were generally low ranging from undetectable (0 ppm) to 0.97 ppm in Mare dam. Total nitrogen was highest in the sediments of Connemara 3 (8.43 ppm) and Gulliver (9.37 ppm) reservoirs. Available phosphorus concentrations were relatively low in all the reservoirs (0.09-0.22 ppm) which was in contrast to the total phosphorus concentrations. Total phosphorus concentrations were several magnitudes higher than those of available phosphorus were measured ranging from 120 – 896 ppm. The highest sediment phosphorus concentrations were recorded in Connemara 3 and the least concentration in Udu dam. Connemara 2 had total phosphorus concentrations of 522 ppm and 550 ppm, respectively.

Calcium (Ca) had relatively higher concentrations compared to the others cations. The lowest concentrations were recorded in Connemara I & 2 and Purdon reservoirs (≈ 50 ppm) and the highest in Gulliver dam (198 ppm). Iron (Fe) and Manganese (Mn) were all less than 0.25 ppm with higher concentrations of Fe in Rhodes reservoirs while Mn concentrations were comparable among the reservoirs (Table 2). Magnesium (Mg) concentrations varied widely among the reservoirs ranging from undetectable (0 ppm) to as high as 55 ppm. The highest value was in Gulliver dam while the least values were in Troutbeck. Potassium (K) concentrations ranged from 2 -13.4ppm with highest concentrations in Gulliver dam. Sodium (Na) concentrations in the reservoirs ranged from 12.7 – 36 ppm, and again Gulliver dam had the highest concentrations while the least were in Storers I dam, a pattern similar to that of K and Mg.

Ordination analysis results

Principal Components Analysis (PCA) showed that the first two axes cumulatively explained 64.4% of the variation among the reservoirs in sediment characteristics Figure 3. Axis 1 accounted for the

most variation with 34.8% while the second axis accounted for 29.6% of the variation. The factor loadings indicated that the first PC axis was defined by a larger number of environmental parameters (with factor loading > |0.50|) than the second PC axis. The parameters with positive factor loadings on PC axis 1 were total organic carbon, total nitrogen, calcium, magnesium, potassium and sodium. Negative factor loadings on PC axis 1 were recorded for available phosphorus and pH. On PC axis 2,

positive factor loadings were recorded for nitrate and magnesium, while negative factor loadings were recorded for ammonium, total organic carbon and total phosphorus. Only iron had factor loading > |0.50| on PC axes 3 & 4.

The plot of the first and second PCs shows patterns which linked the different site characteristics to sediment parameters measured. In the first upper right quadrat, there was Gulliver and Rhodes dams which were closely related to increasing ionic content
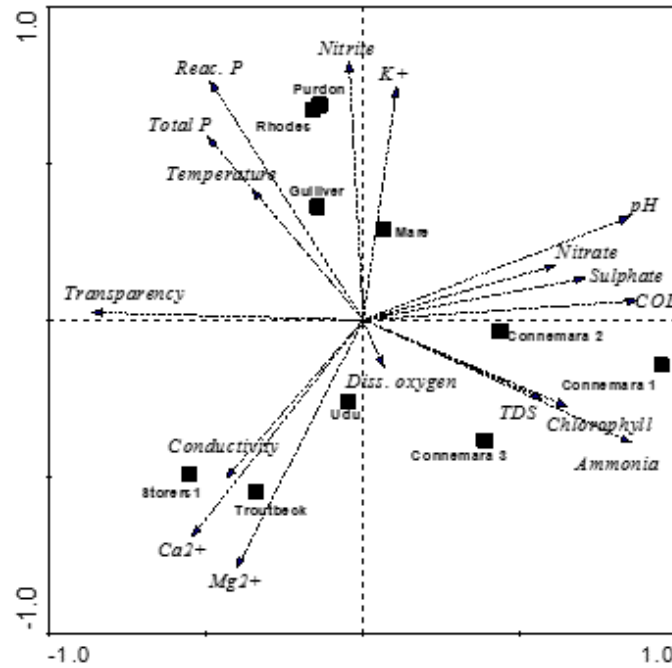

Figure 2. Principal Components Analysis (PCA) ordination plot of environmental variables in ten small montane reservoirs, Nyanga, Zimbabwe (2003).
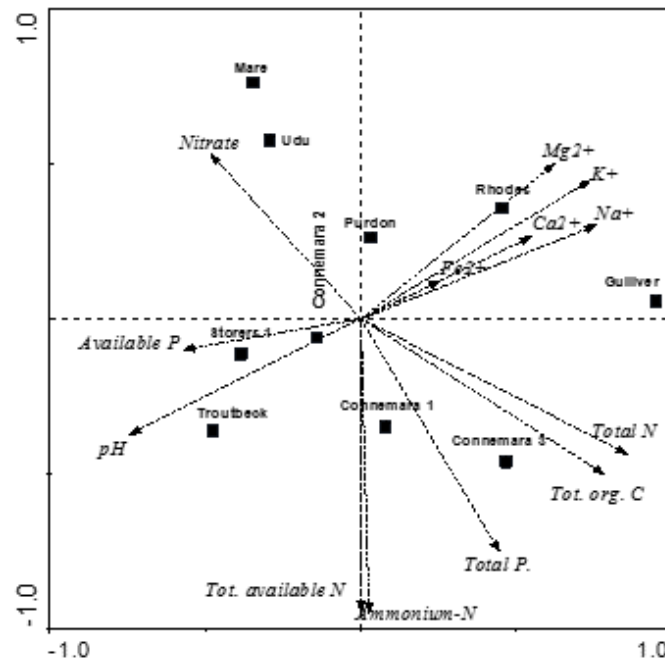

Figure 3. Principal Components Analysis (PCA) ordination plot showing the sediment characteristics of ten small montane reservoirs, Nyanga, Zimbabwe (2003).

Table 2. Sediment characteristics of the ten small montane reservoirs, Nyanga, Zimbabwe (2003).

	Nyangombe River reservoirs					Tsanga River reservoirs				
Variable	Gul	Mar	Pur	Rho	Udu	Con 1	Con 2	Con 3	Tro	Sto 1
pH	4.8	5.5	4.6	4.8	5.5	4.9	5.5	5.2	6.1	6.1
Ammonium N (µg/g)	17.47	9.57	12.50	12.40	12.43	28.23	14.63	28.68	26.83	17.87
Nitrate (µg/g)	0.01	0.97	0.37	0.01	0.43	0.01	0.30	0.38	0.27	0.43
Total available nitrogen (µg/g)	17.47	10.50	12.80	12.40	12.87	28.23	14.90	29.06	27.07	18.23
Total organic carbon (mg/g)	106.17	28.33	46.33	45.10	24.80	45.20	48.20	90.31	40.33	46.37
Total nitrogen (mg/g)	9.37	1.40	3.00	3.13	1.37	4.47	3.42	8.43	1.80	2.50
Total phosphorus (µg/g)	456.67	176.67	336.67	440.00	120.00	383.33	521.67	896.67	336.67	413.33
Available P (µg/g))	0.09	0.18	0.09	0.12	0.09	0.12	0.13	0.12	0.22	0.20
Iron (Fe) (µg/g)	ND	0.02	ND	0.44	0.01	ND	0.12	0.14	ND	0.19
Manganese (Mn) (µg/g)	0.09	0.18	0.09	0.12	0.09	0.12	0.13	0.12	0.22	0.2
Calcium (Ca) (µg/g)	198.40	109.55	50.77	128.26	106.88	52.10	49.77	112.22	71.48	82.83
Magnesium (Mg) (µg/g)	54.78	24.05	2.00	20.71	16.70	9.35	2.67	24.22	ND	11.36
Potassium (K) (µg/g)	13.36	8.02	8.02	6.68	3.34	6.01	3.67	5.34	3.34	2.67
Sodium (Na) (µg/g)	36.07	16.70	19.37	34.07	22.04	16.70	19.04	21.54	22.04	12.69

*ND = not detectable, **N.B. (Gul = Gulliver; Mar = Mare; Pur = Purdon; Rho = Rhodes; Con 1, 2, 3 = Connemara I, 2, 3; Tro = Troutbeck; Sto 1 = Storer 1)

Table 3. Phytoplankton taxa density (ind. m^{-3}) recorded in the ten small montane reservoirs, Nyanga, Zimbabwe (2003).

	Nyangombe River reservoirs					Tsanga River reservoirs				
Taxa	Udu	Rho	Mar	Pur	Gul	Con 1	Con 2	Con 3	Tro	Sto 1
Cyanophyta	2510	24	265	41	1024	245	23	13313	491	199
Euglenophyta	0	0	267	0	16	6.5	0	0	1.5	3.1
Chrysophyta-Chrysophyceae	1972	26 891	2134	1642	1719	173	22 728	80	798	1988
Chrysophyta-Bacillariophyceae	8290	1537	2131	678	2205	1387	1602	469	643	992
Pyrrophyta	1297	1462	556	1216	720	1103	503	1163	81	148
Chlorophyta	11468	1524	12580	6756	6523	335520	45160	69920	7245	9539
Total density (ind. m^{-3})	25537	31438	17692	10332	11285	338434	70226	84946	9258	12870

**N.B. (Gul = Gulliver; Mar = Mare; Pur = Purdon; Rho = Rhodes; Con 1, 2, 3 = Connemara 1, 2, 3; Tro = Troutbeck; Sto 1 = Storer 1)

of metal ions Na, Mg and Ca (Figure 3). Connemara I & 3 dams were in the right lower quadrat and were characterized by higher nutrient concentrations of ammonium, total nitrogen, total phosphorus and total organic matter (Figure 3). The upper left quadrat had only site JUN P2 which was positioned close to the origin, thereby showing that it was not strongly associated with high pH and dissolved oxygen (Figure 3). The lower left quadrat had all the remaining sites which suggested that they were all similar in their overall water quality characteristics (Figure 3).

Phytoplankton communities

The phytoplankton community was not examined to species level but only the major groups were identified (Table 3). The major taxa identified included Cyanophyta, Euglenophyta, Chryospshaceae (Chrysophyta), Bacillariophyceae (Chrysophyta), Pyrrophyta and Chlorophyta. The least abundant taxa were the Euglenophyta being absent in reservoirs such as Udu, Rhodes, Purdon, Connemara 2 & 3. In the reservoirs it occurred its densities were extremely low (0.9-267 ind.m^{-3}). Overall the Chlorophyta were the dominant taxa and were generally more abundant in the Tsanga River reservoirs. Highest overall densities were recorded in Connemara 1 (> 300 000 ind.m^{-3}), followed by Connemara 3 (≈ 85 000 ind.m^{-3}) and 2 (≈ 70 000 ind.m^{-3}). Densities were least in Troutbeck (≈ 9200 ind./m3), Purdon (≈10 300 ind.m^{-3}) and Gulliver (≈ 11 000 ind.m^{-3}) reservoirs.

Macrophyte communities

A comprehensive assessment of the macrophyte communities of the 10 Nyanga reservoirs found 25 species of macrophytes (Table 4). Rhodes, Troutbeck and Storers 1 reservoirs had the highest number of species with 12 species each; and followed by Udu dam with 10 species while Mare and Purdon reservoirs had nine species each (Table 4). The three Connemara reservoirs had the least number of macrophyte species. The species diversity of macrophytes in the reservoirs followed a similar trend to that of species richness, where reservoirs having the highest number of species also have the most diverse plant community (Table 4). The reservoirs differed a lot in their aquatic vegetation characteristics. The most frequently encountered macrophyte species were *Juncus effuses* (80%)*, Lagarosiphon major* (60%)*, Eleocharis* sp. (50%)*, and Cyperus maculates, Nymphaea caerulea, Potamogeton thunbergii Potamogeton octandrus* all with a frequency of occurrence of (50%). Rarely encountered macrophyte species with an occurrence of 10% included *Wolffia arrhizam*, *Utricularia* sp., *Scirpus costatus, Nymphoides forbesiana, Isoetes aequinoctalis, Elatine triandra, Cyperus dichrostachys* and *Carex drakenbergensis*.

Table 4. Macrophyte species occurring in ten small montane reservoirs, Nyanga, Zimbabwe (2003).

Species	Nyangombe River reservoirs					Tsanga River reservoirs				
	Gul	Mar	Pur	Rho	Udu	Con 1	Con 2	Con 3	Tro	Sto 1
Carex cognata var. drakensbergensis				+		+			+	
Cyperus dichrostachys									+	
Cyperus maculatus	+		+						+	+
Elatine triandra				+						
Eleocharis sp.	+	+	+						+	+
Eriocaulon schweickerdtii		+		+						+
Hiomanthera sp.										+
Isoetes aequinoctalis						+				
Juncus effuses	+	+	+	+		+	+	+	+	
Lagarosiphon major	+		+	+	+			+	+	
Najas sp.					+					
Nitella sp.		+				+		+		+
Nymphaea caerulea	+	+	+	+	+					
Nymphoides forbesiana			+							
Phragmites australis				+	+					+
Polygonum sp.				+	+				+	+
Potamogeton octandrus		+	+	+	+					+
Potamogeton thunbergii		+	+	+	+					+
Ranunculus meyeri	+	+			+	+				
Scirpus costatus									+	
Scirpus fluitans		+							+	+
Scirpus inclinatus			+						+	+
Typha latifolia				+	+				+	+
Utricularia sp.					+					
Wolffia arrhiza				+						
Species richness	6	9	9	12	10	5	1	3	12	12
Shannon-W (H)	1.792	2.197	2.197	2.485	2.303	1.609	0	1.099	2.485	2.485
Simpson (1-D)	0.8333	0.8889	0.8889	0.9167	0.9	0.8	0	0.6667	0.9167	0.9167

**N.B. (Gul = Gulliver; Mar = Mare; Pur = Purdon; Rho = Rhodes; Con I, 2, 3 = Connemara 1, 2, 3; Tro = Troutbeck; Sto 1 = Storer 1)

Zooplankton communities

Twelve zooplankton species were identified as well as three taxonomic groups (Macrothricidae, Cyclopoida, and Calanoida) (Table 5). The Daphniidae had 8 species, Chydoridae had 2 species and Bosminidae and Sididae were each represented by one species each (Table 5). The number of species ranged from 4-7 species in the reservoirs hence no reservoir contained more than half the possible number of species. There was a single record of a Macrothricidae species, *Macrothrix* sp., only found in Udu dam. *Ceriodaphnia reticulata*, *C. quadrangula*, and *Sinocephalus serrulatus* only occurred in two reservoirs while *Daphnia rosea* and *Diaphanosoma excisum* occurred only in three reservoirs (Table 5). Strangely, there were no Calanoida sampled in the Nyangombe River reservoirs while the Cyclopoida were recorded in all the reservoirs as one of the most abundant taxa groups particularly in the reservoirs Gulliver, Mare, Rhodes, Udu and Connemara I.

Discussion

The water quality of the high altitude Nyanga reservoirs was of very good quality with some having conductivity close to that of distilled water. Nutrient concentrations were generally very low range and as a result the Nyanga reservoirs can be classified as oligotrophic and ultra-oligotrophic systems. The lack of significant urban developments around the reservoirs has helped significantly maintain near pristine water quality. The sediments were rather unusual with regards to the high levels of total phosphorus. In an earlier study, (Nduku and Robarts 1977) alluded to the same problem of high phosphorus content in the sediment of only one dam, Connemara No. 3. In this study done nearly 25 years later, the same situation still prevails. Processes that influence the binding of phosphorus are mediated by the iron-exchange process which is influenced by dissolved oxygen concentrations in the water.

Table 5. Zooplankton species densities (ind. m^{-3}) in ten small montane reservoirs, Nyanga, Zimbabwe (2003).

	Nyangombe River reservoirs					Tsanga River reservoirs				
Taxa	Gul	Mar	Pur	Rho	Udu	Con 1	Con 2	Con 3	Tro	Sto 1
Daphniidae										
Daphnia longispina	270	400	230	700	-	40	430	-	530	230
D. laevis	70	1370	270	1730	-	10	-	-	-	-
D. laevis gehelmd	230	70	1000	930	130	10	1730	-	1500	600
D. rosea	-	-	-	-	-	-	-	270	-	70
D. pulex	130	130	30	370	-	30	300	600	330	970
Ceriodaphnia reticulata	-	-	-	-	70	-	-	-	-	-
C. quadrangula	30	-	-	70	-	-	-	-	-	-
Sinocephalus serrulatus	-	-	-	-	70	-	130	-	-	-
Chydoridae										
Alona sp.	-	70	-	-	330	10	70	30	-	30
Chydrous sp.	30	-	-	30	1330	-	30	70	100	1270
Bosminidae										
Bosmina longirostris	70	2330	-	-	1200	40	-	30	-	4070
Sididae										
Diaphanosoma excisum	-	-	-	30	70	-	-	-	-	-
Macrothricidae	-	-	-	-	370	-	-	-	-	-
Cyclopoida	2830	3730	130	1370	6200	250	300	130	170	1300
Calanoida	-	-	-	-	-	-	270	-	-	70
No. of species	7	6	4	7	7	6	6	5	4	7
Total density (ind. m^{-3})	3660	8100	1660	5230	9770	390	3260	1130	2630	8610

**N.B. (Gul = Gulliver; Mar = Mare; Pur = Purdon; Rho = Rhodes; Con 1, 2, 3 = Connemara 1, 2, 3; Tro = Troutbeck; Sto 1 = Storer 1)

Typically the high dissolved oxygen levels in these reservoirs would evidently promote the binding of phosphorus to the $FePO_4^{3-}$ complex that can be easily trapped in the sediments. However what explains this high level of phosphorus in the sediments is still not clear. The construction of cottages around Connemara 3 and the subsequent construction of septic tanks was the main source of increased phosphorus loading in the reservoir. It was clearly a logical explanation for the discrepancy observed between the high phosphorus content of the sediments and the oligotrophic status of the water column. Little Connemara Dam (No. 3) is situated in a small dolerite catchment and when the dolerite rocks are weathered, there is release of large amounts of iron and manganese, but not a lot of calcium or carbonate (Nduku and Robarts 1977). The available phosphorus in the water then forms complexes with iron and also manganese and are then sequestrated to the bottom sediments.

Catchment characteristics have an important role in the limnological features of these reservoirs. In comparison with a similar studies carried out in Kenya on eight small high altitude lakes (Mwaura et al. 2002) and in Chile (Mühlhauser et al. 1995), the Nyanga reservoirs have lower nutrient loads, and significantly higher water transparency and lower turbidity. Temperatures in Kenya ranged from $15 - 21^{\circ}C$ while the temperatures measured in Nyanga during sampling were all below $15^{\circ}C$. Dissolved oxygen levels were at 100% saturation in the Nyanga reservoirs but much lower oxygen levels ranging from $23.4 - 33.6\%$ were measured in the Kenya reservoirs with even periods of oxygen depletion. Conductivity and Total dissolved solids were much higher in the Kenya reservoirs ranging from $37–101\mu S/cm$ and $29 - 82mg/l$, respectively. The Chile lake is a moderately saline lake and is an endorheic system (Mühlhauser et al. 1995), Evidently, differences in catchment characteristics also clearly define the limnology of these high altitude reservoirs in Kenya, Chile and Nyanga. Most of the Nyanga reservoirs were under the protection of the State, while the remaining were under the management of different estates and this ensured that detrimental environmental activities were curbed.

The high altitude Nyanga reservoirs supported a fairly large diversity of macrophytes, with a fairly large divergence among the reservoirs. It is obvious that the high water clarity enabled the structured development of macrophytes communities, even at the deepest parts of some reservoirs like Connemara 3. This was supported by Secchi disc readings ranging from 1.5m to 5.7m, which is indicative of high light penetration. Light limitation is a major factor limiting the distribution of submerged macrophytes in lentic systems (Wetzel 2001).

The phytoplankton was only identified to order so significant taxonomic resolution was lost. However an impression of the phytoplankton community was shown by the results obtained with the dominance of the Chlorophyta and Chrysophyta. This phytoplankton composition was consistent with systems of good water quality, low nutrient loading and pH that is not in the extremes of alkalinity or acidity (Wetzel 2001). Algal densities were also very low in all reservoirs when compared to other studies on small reservoirs that were more productive (Nhiwatiwa and Marshall 2007; Dalu et al. 2013). Measurements of algal biomass using chlorophyll *a* concentrations showed results of less than 0.001 mg/l for nearly all the reservoirs. This is magnitudes lower than chlorophyll *a* measurements from the Cleveland dam in Harare which is somewhat considered oligotrophic (Ndebele 2009). Our results were therefore consistent with the low nutrient status and productivity of all the Nyanga reservoirs.

Zooplankton densities were low (mostly < 1 ind./L) and comparable to other oligo-mesotrophic systems such as Cleveland dam (Elenbaas and Grundel 1994). Small reservoirs on the Munwahuku River had much higher densities than the Nyanga reservoirs although species richness was actually comparable (Nhiwatiwa and Marshall 2007). The shallow Nyanga reservoirs and their prolific macrophyte vegetation have ideal littoral environment that perhaps contributes to the abundance of chydorid species in the reservoirs. The absence of Calanoida taxa from most reservoirs was intriguing as they typically occur in Zimbabwean reservoirs. The reasons for this were not clear but it could be that at time of sampling, the Calanoida populations were at their lowest or they are under severe predation pressure in these very clear waters.

It might be useful for a study that investigates the diet of the rainbow trout (*Oncorhynchus mykiss*) in these lakes especially the juvenile that are zooplanktivorous. Water clarity is very high. The diversity of the zooplankton occurring in 18 impoundments (altitudes range 1200 m - 2270 m) in Zimbabwe were assessed in 1983 (Green 1990). The species richness of crustaceans in the Nyanga reservoirs ranged from $4 - 7+$ (to include Calanoida and Macrothricidae not identified to species. Green (1990) carried out a zooplankton survey of small reservoirs at a range of altitudes and found 30 species of Rotifera and 20 species of Crustacea, and the mean numbers of species per lake were 5·7 rotifers and 4·5 crustaceans. According to the survey by Green (1990), *Daphnia laevis* was the most widespread and frequently dominant crustacean, while among the

rotifers *Keratella cochlearis* was most frequently dominant, particularly in the lakes located at higher altitudes. The results of this study again confirm the dominance of *D. laevis* in concurrence with the findings of Green (1990).

High altitude reservoirs differ a lot in different regions of the world and there are also not many studies on small water reservoirs. In comparison with small farm reservoirs of comparable size in Zimbabwe (Nhiwatiwa and Marshall, 2007) in which over 40 zooplankton species were identified, zooplankton species richness is very low in Nyanga high altitude reservoirs. A study in Kenya on eight small montane reservoirs (Mwuara et al. 2002) revealed a zooplankton community that was composed mainly of crustaceans, rotifers and protozoa in. The zooplankton community of 21 montane water bodies were also studied in Brazil (Santos-Wisniewski et al. 2002). Like the Nyanga reservoirs, these waterbodies were densely colonized by macrophytes and were dominated by the Chydoridae, which typically inhabit the littoral zone living in association with macrophyte vegetation. The results was evidence of the importance of the littoral zone as favourable habitats Chydoridae species and thereby contributing to the overall diversity of cladocerans (Santos-Wisniewski et al. 2002).

Results of the cluster analysis (PCA) revealed groups of reservoirs with closely interrelated similarities which could be attributed to their being situated on the same river systems. The ordination analysis also identified the lowest locality (Udu) as the most divergent from the Nyangombe River system reservoirs and with the most typical tropical zooplankton community. Although all the Nyanga reservoirs are situated within the tropics, the high altitude of their location appeared to have excluded some of the most ubiquitous tropical African zooplankton species.

The reservoirs in Nyanga are located at high altitude and have relatively cool, ultra-oligotrophic waters. There are few indigenous fish species and the reservoirs are dominated by exotic rainbow trout (*Oncorhynchus mykiss*), which is the major angling species of a thriving tourist fishing activity. The rainbow trout mainly feeds on aquatic insects, crabs, frogs and other fish (Marshall 2011). A few specimens of the green-headed bream *Oreochromis macrochir* were seen in Udu dam during this study but they were struggling to survive in these freezing waters (pers. obs.). It is possible that an introduction of the fish into these waters but tilapia do not thrive at such low temperatures. The river sardine *Mesobola brevianalis* species was also introduced into the reservoirs in the 1970s from Lake Mutirikwe to

provide food for the predatory trout but it appears the introduction was not a success since none were caught in this campaign.

The results of this study have given important insights into changes in some of the reservoirs that had been previously studied whilst new information was presented in other important ecosystems previously not studied. This work paves the way for a more detailed, seasonal sampling so that time-linked processes such as thermal stratification, can be fully understood for such reservoirs. Ecosystems such as the Nyanga reservoirs could provide useful indicators of change due to rising global temperatures through changes in their fauna and flora. It is also likely that these ecosystems are highly vulnerable and also responsive to climate change effects with serious consequences for their ecological integrity. Similarly, these pristine systems are also vulnerable to anthropogenic activities. The results of the study of Lake Hayq in the Ethiopian Highlands (Elizabeth et al. 1992), concluded that once was an exceptionally clear water lake with very low phytoplankton biomass was facing accelerated eutrophication because of human activity.

Acknowledgements

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