

Nutrient Limitation of Phytoplankton in Five Impoundments on the Manyame River, Zimbabwe

by

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Abstract

Nutrient limitation was investigated in the Manyame lakes during 2004-05, namely, Harava Dam, Seke Dam, Lake Chivero, Lake Manyame and Bhiri Dam. *Selenestrum capricornutum* was used as the test organism in one group of bioassays and on the other the lakes natural phytoplankton population. Nitrogen was indicated to be the primary limiting nutrient in Harava Dam, Seke Dam and Lake Manyame. Phosphorus was found to be the primary limiting nutrient in Bhiri Dam while no nutrient indicated to be limiting the growth of phytoplankton in Lake Chivero instead, light was suggested to be limiting the growth of phytoplankton. Since Robarts and Southall (1977), Harava Dam and Seke Dam showed signs of getting enriched owing to the sewage discharge from expanding urban settlements in Ruwa and surrounding areas. Lake Chivero has remained much the same in the last 30 years and was indicated to be acting as a nutrient trap since the dams downstream of it were not found to as eutrophic as itself. Therefore Lake Manyame, Seke Dam and Harava Dam were concluded to be mesotrophic, Bhiri Dam – oligotrophic and Lake Chivero, eutrophic.

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Introduction

The availability of nutrients is a major limitation to aquatic primary productivity, especially of surface waters (Schindler, 1977). Phytoplankton plays an important part in material circulation and energy flow in aquatic ecosystems and they also control the growth, reproductive capacity and population dynamics of other aquatic organisms such as zooplankton and fish (Kuang *et al.*, 2004). The ability to identify the factors that limit algal growth is of considerable importance to an understanding of the ecology of aquatic plants and to the development of effective water management practices (Beardall *et al.*, 2001).

Most aquatic ecosystems around the world, especially rivers, lakes and reservoirs have been polluted by untreated domestic sewage, domestic waste water, industrial waste water, agricultural waste, and other pollutants (Kuang *et al.*, 2004). The addition of nutrients from these sources increases the biomass of aquatic plants, benthic invertebrates, and fish as well as changing the taxonomic composition of these communities (Schindler *et al.*, 1971). A reduction in habitat complexity and biodiversity has been observed in such water bodies (Vollenweider, 1992).

In general, throughout the world, phosphorus is the primary limiting nutrient in inland waters (Guildford *et al.*, 2003) and this is the case in most Zimbabwean reservoirs except for those that have been artificially enriched. Robarts and Southall (1977) noted that phytoplankton growth in Zimbabwean man made lakes was controlled by phosphorus and nitrogen on the degree of cultural eutrophication. Increasing the levels of phosphorus and nitrogen lead to an increased growth rates of phytoplankton and in cases where a continued increase in these nutrients did not increase phytoplankton growth rates, light was found to be the limiting factor limiting. A similar observation was made in South Africa by Haarhoff *et al.* (1992) who reported that, phosphorus was

usually limiting in oligotrophic to mesotrophic systems while nitrogen is only limiting in eutrophic systems, where effluents are a major source of nutrient load. Thornton (1980) reported that nitrogen and phosphorus were the most important limiting nutrients in Zimbabwean waters. Nutrient enrichment studies done in Lake Victoria and Lake Malawi showed that phytoplankton was limited by nitrogen, provided there was adequate light, in both Lakes (Guildford *et al.*, 2003). Studies on nutrient limitation in tropical areas are of importance as they determine the factors that control algal growth and the ones which threaten lakes that are still in a relatively unpolluted state.

The role of nutrients in the eutrophication of temperate lakes in the southern hemisphere has been evaluated by a variety of lakes and reservoirs in New Zealand, Australia and South Africa. In general, the lakes in New Zealand have low total nitrogen to total phosphorus and have about half the nitrogen concentration of comparable lakes in North America and Europe (UNEP, 2000). Lakes and reservoirs located in the semi-arid regions of South Africa and Australia tend to be phosphorus limited to a greater extent than lakes and reservoirs located in the semi-arid south-west United States. Impoundments with low nutrient concentrations were usually phosphorus limited, and, as phosphorus loading increased, nitrogen became more pronounced (UNEP, 2000).

Systematic evaluation of the role of nutrient limitation in tropical lakes is not possible because too few of the wide variety of tropical lakes were examined. East African lakes have relatively more attention than the other lakes. Nitrogen limitation may be widespread because of the low nitrate concentration and moderate to high phosphate concentration common in eastern African lakes (UNEP, 2003). In southern American tropical floodplain lakes, seasonal and regional differences in the relative importance of the nitrogen or phosphorus occur. Concentrations of both total nitrogen and total phosphorus in South American reservoirs correlate with chlorophyll (UNEP, 2000).

The purpose of this investigation was to determine the limiting nutrients in five impoundments on the Manyame River in Zimbabwe. Harava Dam, Seke Dam and Lake Chivero were investigated previously by Robarts and Southall (1977) and are subject to increasing nutrient enrichment from the city of Harare, In the study by Robarts and Southall (1977), phosphorus was found to be limiting in Harava and Seke Dams while no nutrient was found to be limiting the growth of phytoplankton in Lake Chivero, hence, light was concluded to be the limiting factor. This study will provide an opportunity to determine whether or not phytoplankton is still limited by the same nutrients as it was almost thirty years ago in the three dams previously studied by Robarts and Southall (1977) and provide elementary information on nutrient limitation in Lake Manyame and Bhiri Dam where not much work has been done.

Some approaches for determining phytoplankton nutrient limitation.

Chemical analyses of water do not necessarily indicate the potentially limiting nutrients since aquatic ecosystems are dynamic (Moss, 1969). When determining the limiting nutrients in a water body it is necessary to take into account the physiology of the organisms as well as the chemistry of the water (Robarts and Southall, 1977). Methods used to identify limiting nutrients in the past have included (a) the analysis of nutrient availability, (b) elemental composition and cell quotas for various nutrients, (c) bioassays monitoring the growth of test species or of natural populations following nutrient enrichment and (d) measurements of various physiological parameters, such as the enhancement of respiration and dark carbon fixation rates or the perturbation of the photosynthetic rate following a re-supply of nutrient (Beardall *et al.*, 2001).

Methods for identifying limiting nutrients

Bioassays with test organisms

Bioassay experiments use the growth of microalgal cells as a measure of the capacity of a water sample to support their growth (Beardall *et al.*, 2001). Water taken from a given site is filtered and inoculated with a test organism such as *Selenastrum capricornutum*, which has been used in fresh waters (Miller *et al.*, 1978), or *Thalassiosira pseudonana*, used in marine samples (Hayes *et al.*, 1984). Growth of the test organism is measured in the presence of specific added nutrients and if the addition of a particular nutrient leads to increased growth, it is deduced that it was limiting in the original sample. The growth of the test organism can also be measured in the absence of a particular nutrient with all other nutrients being present and if growth is reduced it is deduced that the missing nutrient was limiting in the original sample (Robarts and Southall, 1977).

This type of assay is simple and easy to set up hence it is favoured by laboratories with few resources but it has some drawbacks problems that come with it. Firstly, growth rate is the measured parameter and since these bioassays rely on final biomass attained after a period of days they are essentially measures of Liebig limitation (Beardall *et al.*, 2001). These assays simply provide information about the maximum biomass the water body could sustain and which nutrient will first become limiting as the population increases. Secondly, bioassays of this type tend to reflect the nutrient requirements of the test organism, which may bear little resemblance to those of the species found in the water body under investigation (Beardall *et al.*, 2001) Thirdly, filtration of the water sample prior to inoculation with the test organism may also remove colloids and organic complexes that are a source of nutrients, especially phosphorus (Wood and Oliver, 1995).

In spite of these drawbacks this method was chosen for this project because it was the method used by Robarts and Southall (1977) and it would therefore be possible

to assess changes in nutrient limitation over 30 years. Data obtained by other methods might not have allowed for a realistic comparison between the two time periods.

Enrichment experiments with natural populations

Enrichment experiments have been carried out using the natural population of phytoplankton as an inoculum. A sample with the natural population is spiked with a mix lacking a particular nutrient or with various nutrients (Beardall *et al.*, 2001) and growth (Cullen *et al.*, 1992) or carbon assimilation (Boyd *et al.*, 1998) is determined over a period of time. If growth (measured as changes in biomass from chlorophyll concentration or cell numbers) or productivity (^{14}C fixation or photosynthetic O_2 evolution) in samples without a particular nutrient is similar to that in a control with all nutrient additions, it is usually deduced that the nutrient is not limiting. On the other hand, if a particular nutrient addition stimulates production and/or growth, then that nutrient is considered to be a limiting nutrient in the original water sample (Beardall *et al.*, 2001).

These experiments also have drawbacks. Firstly, the natural species composition of the water sample can influence the outcome of an enrichment experiment so that the addition of one nutrient can induce limitation of other nutrients (Boyd *et al.*, 1998). Secondly, the physical enclosure of a natural population can affect its physiological performance and cause the species composition to change, and the population can be isolated from important nutrient sources such as sediments, particulate matter or recycling (Healey, 1979). Thirdly, the removal of zooplankton can bring relief from grazing pressure resulting in significant stimulation of growth even in the controls (Cullen *et al.*, 1992). Fourthly, if samples are incubated at a higher photon flux than they might experience in situ, populations that were originally light-limited will be exposed to conditions where that limitation is removed. This can allow a potentially limiting nutrient to express itself and the results from such experiments may the factors that truly limit the

plankton assemblage (Beardall *et al.*, 2001). Lastly, in enrichment bioassays based on short term ^{14}C fixation or O_2 exchange, the addition of the limiting nutrient can cause short term decreases in the rate of photosynthesis because of interactions between nutrient uptake and other metabolic processes (Elrifi and Turpin, 1987).

Elemental ratios and macromolecular composition

The elemental composition of phytoplankton and the composition of the water in which it is growing, has been used as a potential index of nutrient limitation using a method devised by Redfield (1958). Carbon nitrogen and phosphorus are assimilated by phytoplankton at an average ratio of 106: 16: 1 (the Redfield ratio) and so the growth of phytoplankton in a water body with an N: P ratio of 5 would most probably be limited by nitrogen whereas a water body with an N: P ratio of 30 is likely to be phosphorus-limited.

The principal disadvantage of this method is that while elemental ratios of a water body can provide evidence for possible Liebig limitation of algal populations they are less useful for ascertaining whether a phytoplankton population is nutrient limited at a given point in time (Beardall *et al.*, 2001). Falkowski (2000) argued that the Redfield ratio is not constant and has been embraced by aquatic ecologists as conveying more information than is warranted. This is worsened by the difficulties of determining the availability of nutrients for algal growth in the water sample, especially in turbid waters with high levels of particulates (White and Payne, 1980).

Measurements of physiological parameters

Physiological analyses offer the possibility of estimating the nutrient status of a water body because algae respond to nutrient limitation by increasing their uptake capacity and/or efficiency for the specific nutrient (Beardall *et al.*, 2001). Gotham and Rhee (1981) showed that the maximal rate of phosphate uptake, in a range of fresh

water cyanobacteria and microalgae, was enhanced as the phosphorus-limited growth rate decreased. Nitrogen or phosphorus deficient algal cells rapidly take up the limiting nutrient immediately after it is re-supplied (Goldman and Gilbert, 1983), and the rate of uptake under these conditions is significantly greater than the rate required to maintain the growth of the algae at its maximal rate (Parslow, *et al.*, 1984a). Transient uptake rates vary with species (Parslow, *et al.*, 1984b) and the determination of uptake rates is complicated by a range of other factors including incubation conditions and time, non-stable substrates, recent presence of alternative nitrogen sources (e.g. NO_3^- and NH_4^+) and different cellular nitrogen status (Flynn, 1998).

Many physiological parameters used as indices of nutrient status are based on the changes in cell function that occur during nutrient limitation (Beardall *et al.*, 2001). The ATP content of phytoplankton cells decreases during the onset of P or N deficiency and increases over the period following the re-supply of the limiting nutrient (Healey, 1979). Consequently, the uptake of the limiting nutrient is increased and ATP derived from the light reactions of photosynthesis can be used for rapid uptake of the nutrient at the expense of C assimilation (Parslow, *et al.*, 1984b). If ATP is derived from enhanced cyclic photophosphorylation, rather than from linear electron transport, then the evolution of photosynthetic O_2 will be diminished while the cell is taking up nutrient (Healey, 1979). This combination of enhanced nutrient uptake by nutrient-limited cells, reduced O_2 evolution and C assimilation rates, and enhanced CO_2 evolution rate following nutrient supply led Lean and Pick (1981) to use a ratio of C fixation (O_2 evolution) to nutrient uptake rate as an index of limitation for natural populations of lake phytoplankton (Table 1).

Table 1: The scale of P-limitation derived from the ratio of carbon assimilation to phosphate uptake capacity (mol mol^{-1}) in natural populations of phytoplankton from North American lakes (Lean and Pick, 1981).

Nutrient Status	Molar ratio of carbon assimilation/phosphate uptake capacity.
Replete	>100
Low deficiency	30-100
Moderate deficiency	10-30
Extreme nutrient stress	<10

Photosynthesis and nutrient uptake in phytoplankton

Phytoplankton, which are usually the most important primary producers in lake ecosystems, require three primary inorganic macronutrients, nitrogen (usually supplied as ammonia or nitrate), phosphorus and silica, and five micronutrients, iron, copper, zinc, manganese and molybdenum) to fix carbon during photosynthesis. The rate of assimilation of nutrients is a function of its concentration and increases hyperbolically (Figure 1).

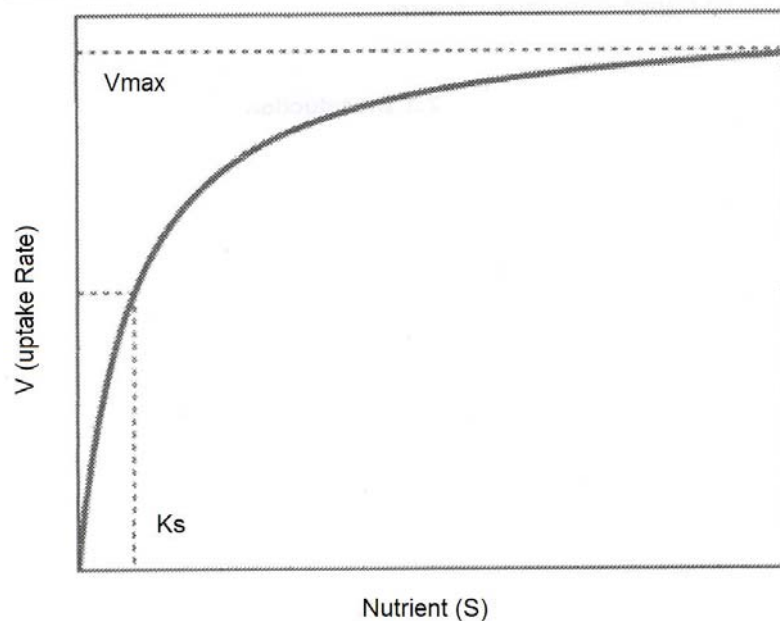


Figure 1: The hyperbolic relationship between the uptake of a nutrient (V) and its concentration (S). From Smayda (1997).

The two important kinetic characteristics of the nutrient uptake curve are the maximum velocity of cellular uptake (V_{max}) and the concentration of nutrient (K_s) at which uptake is half V_{max} . These parameters vary among species and influence their response to nutrient enrichment or limitation in competition with other species (Smayda, 1997). The half-saturation constant, K_s , determines the efficiency with which species take up nutrients at low concentrations and a species with a high K_s value will be less able to assimilate nutrients at low concentrations. It might therefore be expected that eutrophication would favour species with a less efficient nutrient uptake (Smayda, 1997). At increased rates of nutrient uptake, cellular growth is stimulated and leads to an increase in the population that, as in the nutrient uptake curve (Figure 1) increase to an asymptotic level and remains relatively constant irrespective of further increases in nutrient concentration (Panosso and Granèli, 2000). The population at this upper level, in the absence of grazing by animals, corresponds to the carrying capacity for that particular species determined by the nutrient being supplied. The carrying capacity varies with nutrient type, nutrient concentration, the influence of accompanying growth factors, and among species.

Very high nutrient concentrations, particularly of ammonia, can be inhibitory (Thomas *et al.*, 1980) while light intensity also influences the effect of nutrients on photosynthesis at a cellular (individual) level (Cloern, 2001). Photosynthesis ceases in the absence of light and also when nutrients are in short supply. Under these conditions, respiration is favoured and if this respiration pathway is prolonged so that the ratio of photosynthetic oxygen production to respiration drops below 1.0, the oxygen concentrations will decrease and push the water body towards hypoxia or, in extreme cases, to anoxia. Thus, nutrient loading can oxygenate or deoxygenate a nutrient-enriched water body (Rabalais and Turner, 2001). The complexity of the relationships between nutrients and photosynthesis and the nine major macro- and micro-nutrients

that regulate phytoplankton growth and the differences in the nutritional physiology and kinetics of different species makes it difficult to analyse the influence of eutrophication on phytoplankton (Cloern, 2001).

The research questions being addressed in this investigation were: (i) what is the limiting nutrient in each dam, (ii) what is the phytoplankton composition and biomass in each dam, (iii) is there any evidence that the previously oligotrophic impoundments have become enriched as a result of urban growth in their catchments?

The study area

The Manyame River, which rises near the town of Marondera about 65 km east of Harare, flows in an east-west direction until reaching the Great Dyke after which it flows in a northerly direction until it reaches Lake Cahora Bassa on the Zambezi River in Mozambique. The upper Manyame is of great importance because it supplies water to Harare and Chitungwiza, and some smaller centres such as Norton and Ruwa, which together have a population of about two million people or 18% of Zimbabwe's population (Magadza, 1997). Four dams have been constructed on the river to meet these needs, while another dam has recently been built on the Manyame about 100 km from Harare near the town of Chinhoyi (Figure 2). These impoundments range in size from 215-8100 ha (Table 2) and all are susceptible to some degree to pollution emanating from the Harare urban area.

Table 2: Physical characteristics of the five impoundments on the Manyame River. Data from Marshall (1994) and Zimbabwe National Water Authority.

	Date of construction	Area (ha)	Volume (m ³ x 10 ⁶)	Mean depth (m)	Catchment area (km ²)
Harava	1973	215	9	4.3	149
Seke	1929	109	4	3.3	748
Chivero	1952	2630	250	9.5	2227
Manyame	1976	8100	480	6.0	3790
Bhiri	2000	112	172	3.2	5362

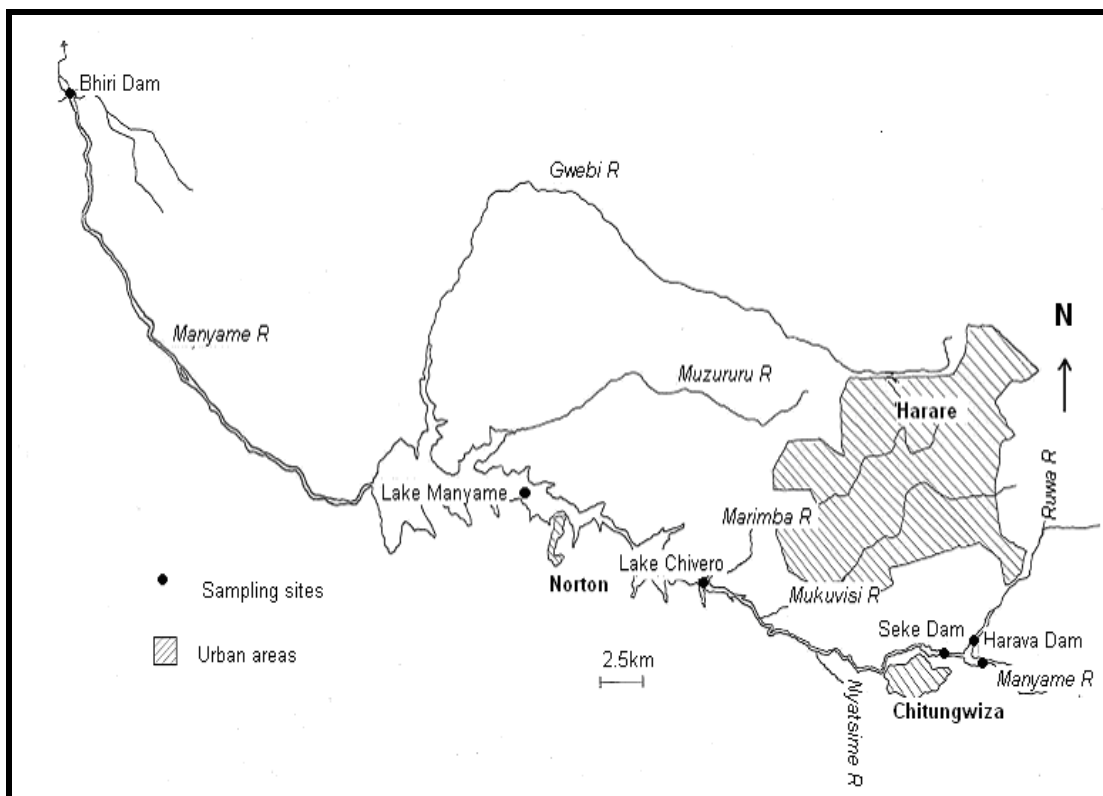


Figure 2: The location of the Manyame lakes in relation to urban centres of Harare and Chitungwiza, and the location of the sampling stations.

Harava (formerly Henry Hallam) Dam is located 15 km south of Harare at the junction of the Manyame and Ruwa Rivers. When Robarts and Southall (1977) examined nutrient limitation in this impoundment, its catchment area was predominantly rural and there was no evidence of nutrient enrichment. Since then, the population has

grown rapidly with an expansion of the semi-formal settlement of Epworth and the townships of Mabvuku and Ruwa and there may now be a much higher levels of nutrient enrichment in the dam. Evidence that this may be occurring can be seen in the extensive growth of *Eichhornia natans* on the dam, although it does not form mats because its water level fluctuates extensively and it is exposed to the wind.

Seke (formerly Prince Edward) Dam is located immediately below Harava Dam, which spills almost directly into its upper end. There was no evidence of nutrient enrichment in the 1970s (Robarts and Southall, 1977) but this could have changed since all of its water comes from Harava Dam and it may also have been affected by population growth in the catchment area. This is supported by the fact that much of its water surface is now covered by macrophytes, principally *Eichhornia natans*, *Hydrocotyle ranunculoides*, *Nymphaea* sp. and *Azolla filiculoides*.

Lake Chivero is the next downstream impoundment, located about 35km south west of the city of Harare. It was created as the principal water supply for the city and has a long history of water quality problems caused by the discharge of sewage effluent from Harare and Chitungwiza into its tributaries, which have been most evident in algal blooms and problems with floating macrophytes such as the water hyacinth *Eichhornia crassipes* (Marshall, 2005). The lake has been enriched to the extent that phosphorus is no longer a limiting nutrient and the phytoplankton may now be self-limiting through reduced light penetration caused by its dense population (Robarts 1981, Robarts and Southall, 1975, 1977; Robarts *et al.*, 1982). Its water quality improved briefly in the 1970s following a programme to divert sewage effluent onto the land for irrigation but this was insufficient to deal with the increasing quantities of effluent and the water quality continued to deteriorate from the mid-1980s onwards

Lake Manyame was created in 1976 with the construction of the Darwendale Dam about 15 km below Lake Chivero. Although most of its inflow comes from Lake

Chivero it is not yet exhibiting the effects of eutrophication although there is some evidence of elevated phosphorus concentrations (Marshall, 1994) and the dense growth of *Lagarosiphon ilicifolius* that occur in shallow areas may be an early symptom of enrichment. The growth of the town of Norton, situated on the south bank, has been rapid in recent years and may cause problems in future. Little research has been done on this lake, apart from a description of temperature and oxygen stratification in its formative years (Cotterill and Thornton, 1985).

Bhiri Dam, the most recent dam in the catchment, was constructed for irrigation purposes although it has not been fully utilized for this purpose. Like other dams in the area it was probably eutrophic during its filling phase owing to the release of nutrients from the drowned land and vegetation (Coche, 1974; Mitchell and Marshall, 1974; Masundire, 1992). Its nutrient status is presently unknown but the presence of extensive beds of *Lagarosiphon ilicifolius* suggests that it may still be enriched.

Methods

The six sites in the five impoundments were sampled from November, 2004 to February, 2005. Sampling sites in Harava Dam, Seke dam and Lake Chivero were the same as those used in 1975-76 (Robarts and Southall, 1977). In Harava Dam, samples were taken from each of the arms of the impoundment formed by the two inflowing rivers, the Manyame (sampling station located at 17° 60'S 31° 03'E) and the Ruwa (17° 58'S 31° 02'E). The sampling point in Seke Dam was located about 150 m from the dam wall (17° 59'S 31° 03'E) mid-lake. The sampling sites in Lake Chivero and Manyame, and Bhiri Dam were located in deep waters in the main part of the dams at 17° 55'S 30° 49'E, 20° 13'S 32° 11'E and 17° 49'S 30° 31'E, respectively.

The following physico-chemical variables were measured with a Horiba U23 water quality monitor: dissolved oxygen, conductivity, pH, chloride, and calcium with readings being taken from the surface to the bottom at 0.5 m intervals. Transparency was determined with a Secchi disc. A Nansen water sampler was used to collect water samples at depths of 5m and these samples were mixed to give an integrated sample, which was taken to the laboratory for analysis. The concentrations of ammonia, total nitrogen and total phosphorus were determined in the laboratory by using a HACH ER/04 water testing kit. A twenty-litre sample of surface water was collected in a plastic container at each dam and transported to the laboratory for bioassay cultures.

Phytoplankton samples were collected by filtering 50L of lake water through 25 μ m plankton net and after preservation in Lugol's solution; the species present were identified in the laboratory under an inverted microscope with the help of identification keys in Lund and Lund (1998) and Elenbaas (1994). The density of phytoplankton was determined by counting the numbers present in five 1-ml sub samples from each site and the mean value was recorded. An estimate of phytoplankton biomass was obtained by measuring chlorophyll *a* and phytophytein using methods given in Bartram and Balance (1995).

Nutrient limitation in each impoundment was determined from bioassays with *Selenestrum capricornutum* as the test organism as well as by enrichment experiments using natural populations of phytoplankton. For the bioassays with *Selenestrum capricornutum*, surface water samples were filtered under reduced pressure through 1.2 μ m and 0.45 μ m membrane filters. Forty-five 100-ml conical flasks were autoclaved and numbered permanently, then washed with filtered water from the samples after which 60 ml of filtered water were introduced into each flask and nutrients added. Nutrient solutions were made up with various macro- and micronutrients (Table 3), some of which were left out so that bioassays were done on solutions with lacking certain nutrients

(Table 4). A 1-ml aliquot from a one-week-old pure culture of *Selenestrum capricornutum* was added to each flask, which was then plugged loosely with cotton wool and covered with aluminium foil paper. The cultures were grown at room temperature. Growth was measured every three days over a period of nine days by the change in absorbance at 600 nm using a DR/2010 spectrophotometer. Absorbance was then converted to biomass (mg l^{-1} dry weight) of *Selenestrum capricornutum* by the equation

$$B = 31.97 + 152.25 A_{600}, r^2 = 0.71$$

Where B = biomass and A_{600} = absorbance at 600 nm. This equation was obtained by growing *Selenestrum capricornutum* in cultures, measuring the absorbance and then filtering the culture through previously weighed filter paper, drying the filter paper and residue in an oven at 105° C. The dry weight of *Selenastrum* on the filter paper was then determined by subtraction.

Water for enrichment experiments was collected by filtering 20 L of dam water through a 20- μm mesh plankton net to remove the zooplankton. The water was taken to the laboratory in a plastic container where the following treatments were prepared in triplicate in transparent bottles of about 1L volume: (i) all nutrients supplied except K_2PO_4 , (ii) all nutrients except NaNO_3 , (iii) all nutrients except micronutrients, (iv) all nutrients and (v) no nutrients. A 5 ml aliquot of phytoplankton collected by filtering 20 L of lake water through a 25- μm plankton net was added in each bottle. The treatments were incubated at 21°C using natural light and the growth of the phytoplankton community was determined by measuring the chlorophyll a concentration after 1, 2 and 3 days according to the method given in Bartram and Balance (1995). Each experiment was replicated 3 times.

Table 3: Nutrient solutions and final enrichments of bioassay cultures. All micronutrients were added as one solution with a total volume of 0.1 ml. From Robarts and Southall (1977).

	Molarity of stock solution	Volume (ml) of stock solution added to 60ml cultures	Final enrichment concentration (mg l ⁻¹)	
(a)Macronutrients				
NaNO ₃	0.300	0.1	N	6.80
			Na	11.70
K ₂ HPO ₄	0.006	0.1	K	0.76
			P	0.30
MgCl ₂ . 6H ₂ O	0.028	0.1	Mg	1.10
			Cl	3.21
MgSO ₄ . 7H ₂ O	0.055	0.1	Mg	2.16
			S	2.86
CaCl ₂ . 2H ₂ O	0.030	0.1	Ca	1.95
			Cl	3.44
NaHCO ₃	0.179	0.1	Na	6.67
			C	3.48
(b) Micronutrients				
H ₃ BO ₃	0.003	0.1	B	0.053
MnCl ₂ . 4H ₂ O	0.001		Mn	0.119
ZnCl ₂	0.0002		Zn	0.025
Na ₂ EDTA . 2H ₂ O	0.00003		Mo	0.005
FeCl ₃ . 6H ₂ O	0.00036		Fe	0.032
Na ₂ EDTA . 2H ₂ O	0.0008		EDTA	0.376
CoCl ₂ . 6H ₂ O	0.00003		Co	0.003
CuCl ₂	0.0000007		Cu	0.00007

Table 4: The growth cultures used in the bioassays. From Robarts and Southall (1977).

Culture	
1	All nutrients added except NaNO_3
2	All nutrients added except K_2HPO_4
3	All nutrients added except $\text{MgCl}_2 \cdot 6\text{H}_2\text{O}$
4	All nutrients added except $\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$
5	All nutrients added except $\text{CaCl}_2 \cdot 2\text{H}_2\text{O}$
6	All nutrients added except NaHCO_3
7	All nutrients added except micronutrients
8	No nutrient enrichment

Data Analysis

A one-way analysis of variance (ANOVA) was used to test variation in the physico-chemical variables and phytoplankton biomass among the dams. T-tests were used to ascertain if there was a change in the pattern of nutrient limitation since 1974-75 in the impoundments studied by Robarts and Southall (1977). The t-test was also used to determine if the physico-chemical variables the two arms of Harava Dam were significantly different. The Brillouin index of diversity was used to measure the diversity of phytoplankton in each dam using the equation:

$$HB = \frac{\ln N! - \sum \ln n_i!}{N_i}$$

Where HB = index of species diversity, N = total number of individuals in a sample and n_i = number of individuals of i th species Cluster analysis was carried out on physico-chemical variables and algal composition to group dams with similar water quality.

Results

Trophic status of the five impoundments

All variables, except for dissolved oxygen, followed a similar trend of increasing in concentration from Harava Dam to Lake Chivero and then decreasing from Lake Chivero to Bhiri Dam. This reflects the eutrophic status of Lake Chivero and the generally mesotrophic status of the other water bodies.

The mean pH ranged from 5.1 in Bhiri Dam to 8.9 in Lake Chivero and although it was higher in Harava and Seke dams (6.8 and 7.1) respectively it was much lower in Lake Manyame and Bhiri Dam (5.6 and 5.1, respectively) although the differences between these impoundments were no significant (Figure 3a). The pH (mean = 8.9) was significantly higher in Lake Chivero than in the other impoundments, which reflects its eutrophic state. Conductivity ranged from 229-331 $\mu\text{S cm}^{-1}$ with the lowest values in Harava and Seke Dams. It rose sharply in Lake Chivero and remained relatively high in the two downstream impoundments, with all three being significantly higher than the upper two (Figure 3b). The concentrations of calcium (Figure 3c) and chloride (Figure 3d) followed a similar pattern being low in Harava and Seke Dams, rising sharply in Lake Chivero then declining sequentially in Lake Manyame and Bhiri Dam.

The Harava and Seke Dams were too shallow to develop an oxycline, although the concentration of dissolved oxygen decreased below the depth of the photic zone, which was indicated by the Secchi disc transparency (Table 5). Oxygen concentrations were very high in the first metre of Lake Chivero and they decreased continuously below the photic zone, falling to 4.7 mg l⁻¹ at 14 m but without a marked oxycline. Oxygen concentrations were not as high in Lake Manyame, which had a transparency of 2.5 m, and only began to decline from 3m downwards but there was no oxycline because the lake was too shallow. Transparency was highest in Bhiri Dam (5 m) and dissolved

oxygen concentrations were $> 7.0 \text{ mg l}^{-1}$ down to 4 m depth which marked the beginning of a pronounced oxycline with the concentration of dissolved oxygen falling to 0.3 mg l^{-1} at 8 m depth.

Table 5: The concentrations of dissolved oxygen (mg l^{-1}) in relation to depth and transparency (m).

Depth (m)	Harava (Ruwa)	Harava (Manyame)	Seke	Chivero	Manyame	Bhiri
0	5.1	6.3	6.9	9.1	6.8	7.7
1	5.0	5.7	5.8	9.1	7.0	7.8
2	4.6	4.7	4.9	7.0	7.0	7.9
3	4.0	4.9	5.0	6.5	6.9	7.6
4				5.4	6.5	5.8
6				5.2	6.5	0.8
8				5.2		0.3
10				4.8		
12				4.7		
14				4.7		
Transparency (m)	0.9	1.1	1.5	0.7	2.5	5.0

The eutrophic state of Lake Chivero was most clearly demonstrated in the concentrations of ammonia (Figure 4a), total nitrogen (Figure 4b) and total phosphorus (Figure 4c), which were much higher than in any of the other impoundments. The concentrations of these nutrients were significantly lower in these impoundments than in Lake Chivero, but they were not significantly different from each other.

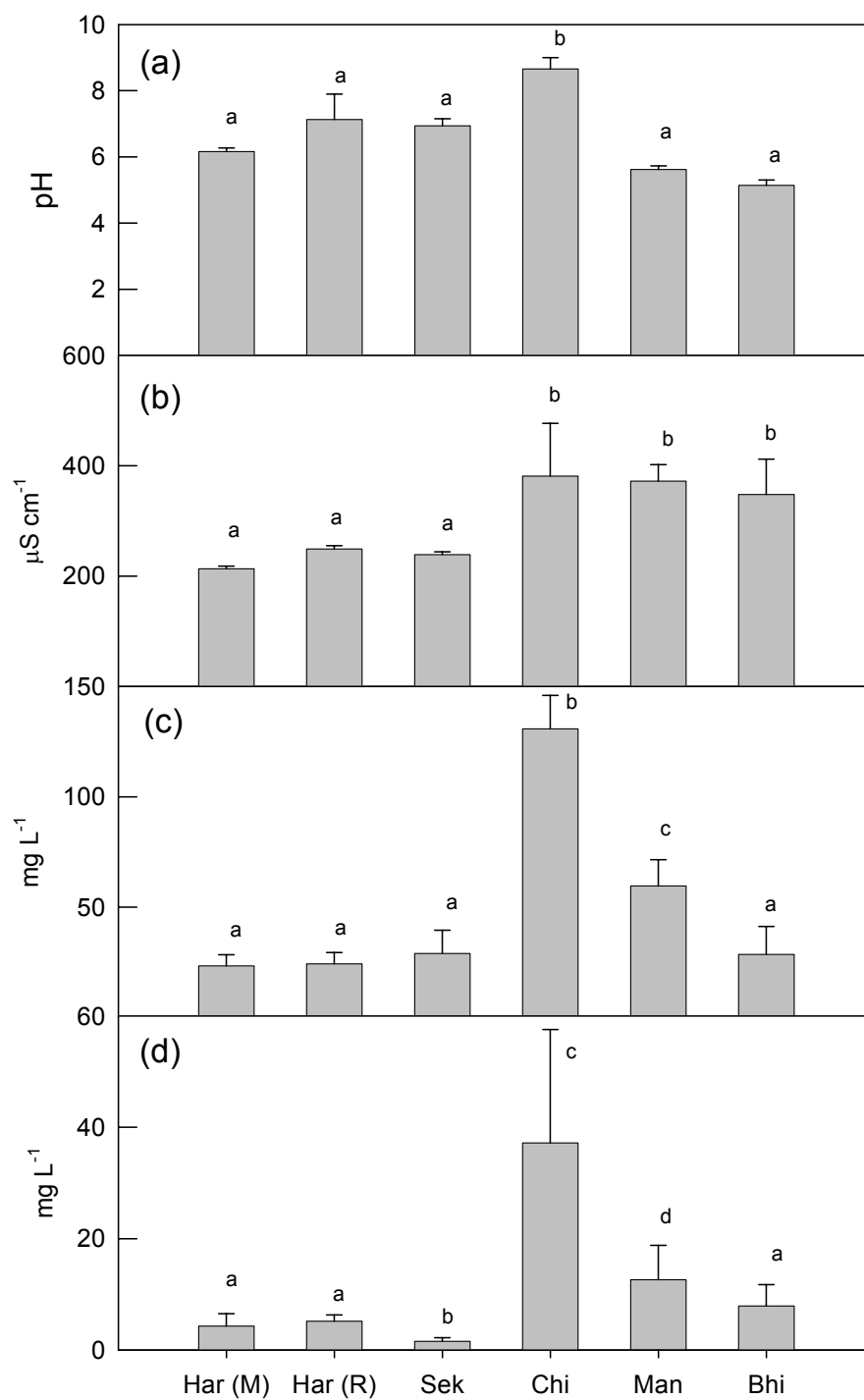


Figure 3: The mean values of (a) pH, (b) conductivity, (c) calcium and (d) chloride in the five impoundments. Values with the same superscripts are not significantly different, $p > 0.05$: ANOVA (Appendix 2).

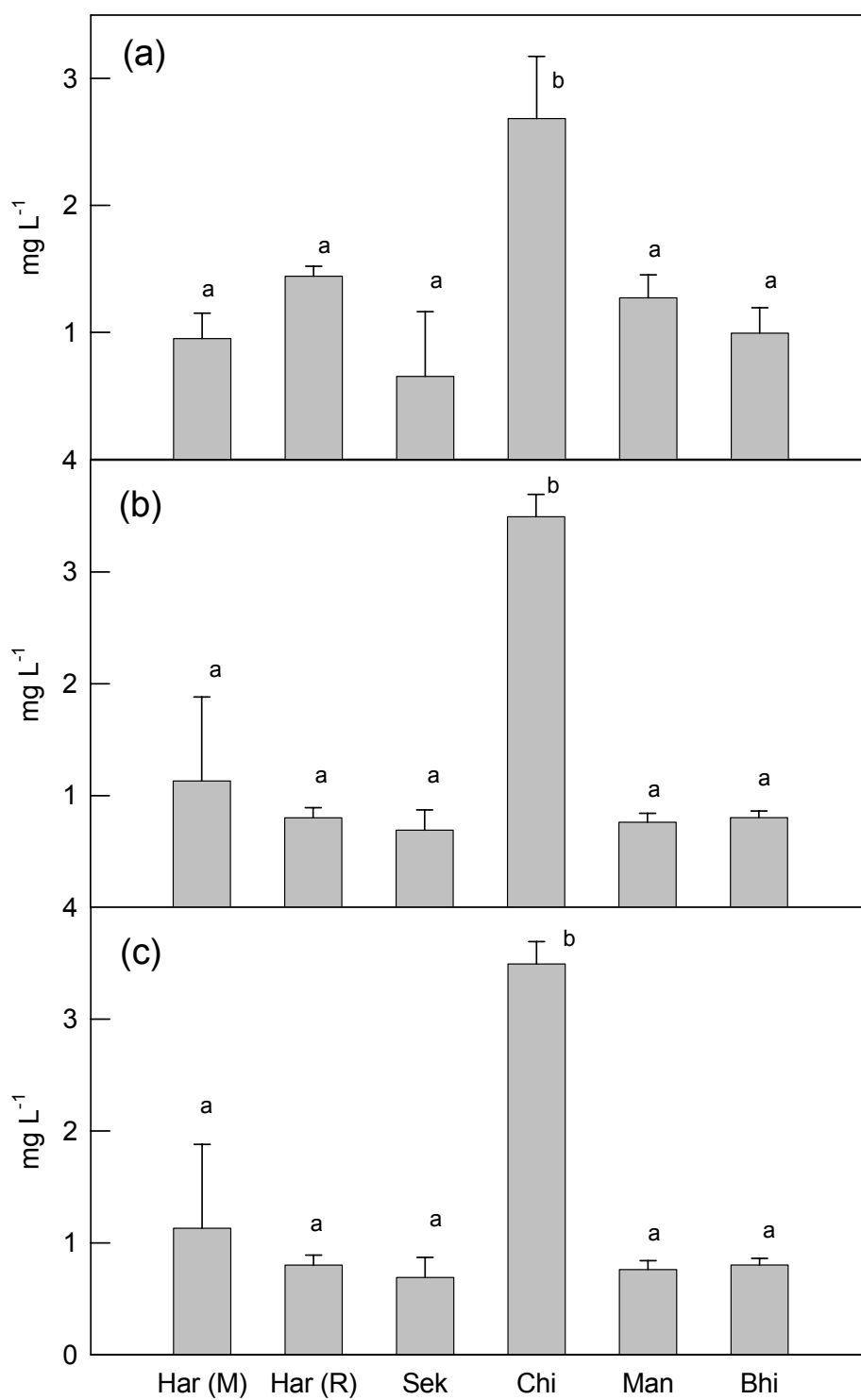


Figure 4: The mean values of (a) ammonia, (b) nitrogen and (c) phosphorus in the five impoundments. Values with the same superscripts are not significantly different, $p > 0.05$: ANOVA (Appendix 2).

Nutrient limitation

According to the bioassays with *Selenastrum capricornutum*, nitrogen is the primary limiting nutrient in both arms of the Harava Dam, Lake Manyame and Seke Dam, phosphorus was the limiting nutrient in Bhiri Dam and no nutrient was limiting in Lake Chivero (Figure 5). Sulphur is the secondary limiting nutrient in both arms of Harava and Seke Dams while phosphorus and nitrogen were the secondary limiting nutrients in Lake Manyame and Bhiri Dam respectively.

The results of the bioassay with the lake's phytoplankton community are less obvious (Figure 6). In both arms of the Harava Dam nitrogen seemed to be the main limiting nutrient, while in Seke Dam phosphorus was rather more limiting. There was no nutrient limitation in Lake Chivero but both nitrogen and phosphorus limited growth to some extent in Lake Manyame. Phosphorus is the primary limiting nutrient in the Bhiri Dam.

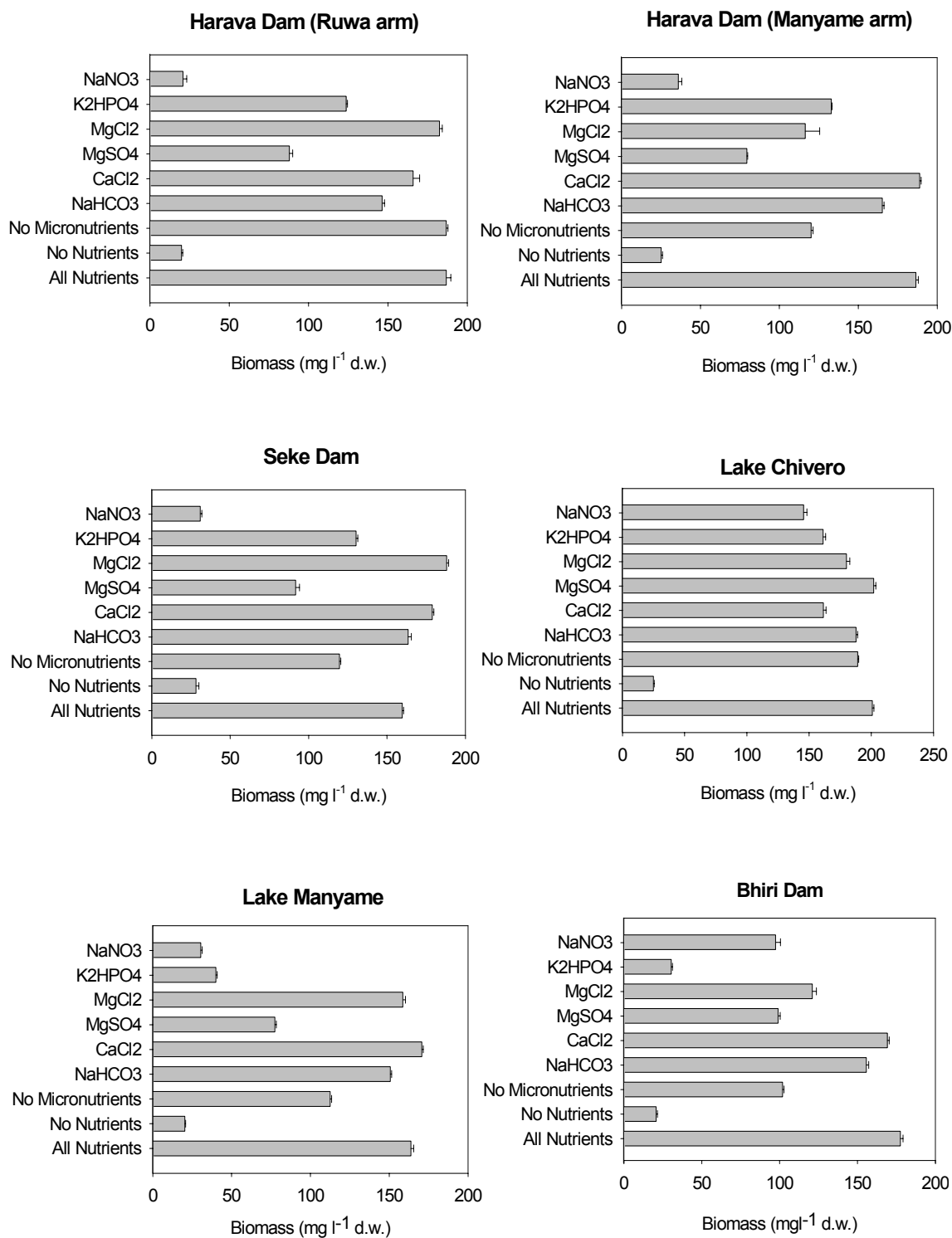


Figure 5: The mean maximum growth response (mg l^{-1} dry weight) of *Selenestrum capricornutum* after nine days of incubation in membrane filtered lake water with different nutrient enrichments.

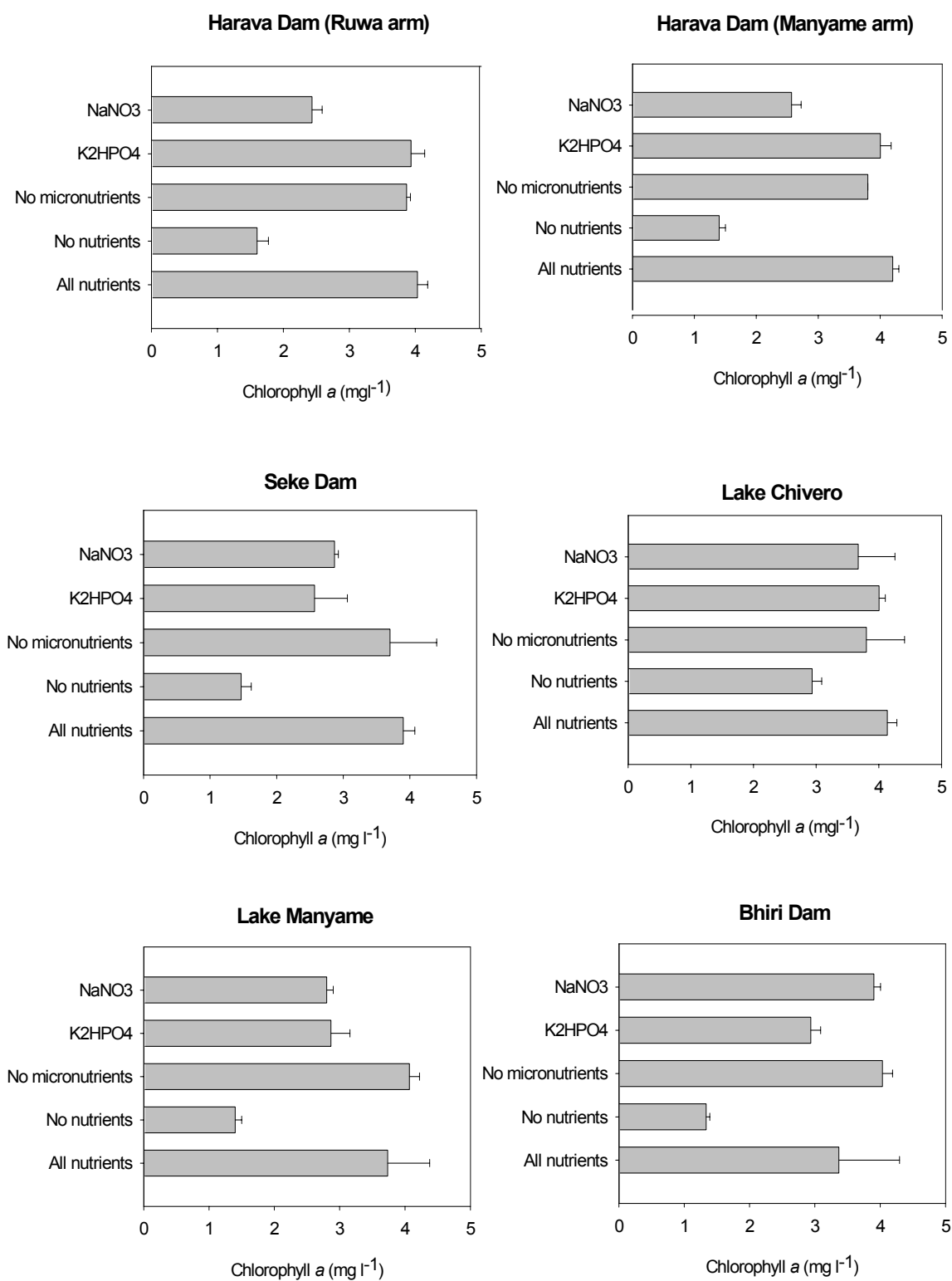


Figure 6: Mean maximum growth response of phytoplankton community after three days of incubation in filtered lake water with different nutrient enrichments.

Phytoplankton biomass and generic composition

The biomass of phytoplankton was not significantly different in the impoundments (12-17 mg m⁻³ dry weight), except for Lake Chivero where it was much higher (38 mg m⁻³) than in the others, which is a reflection of its eutrophic state (Figure 7).

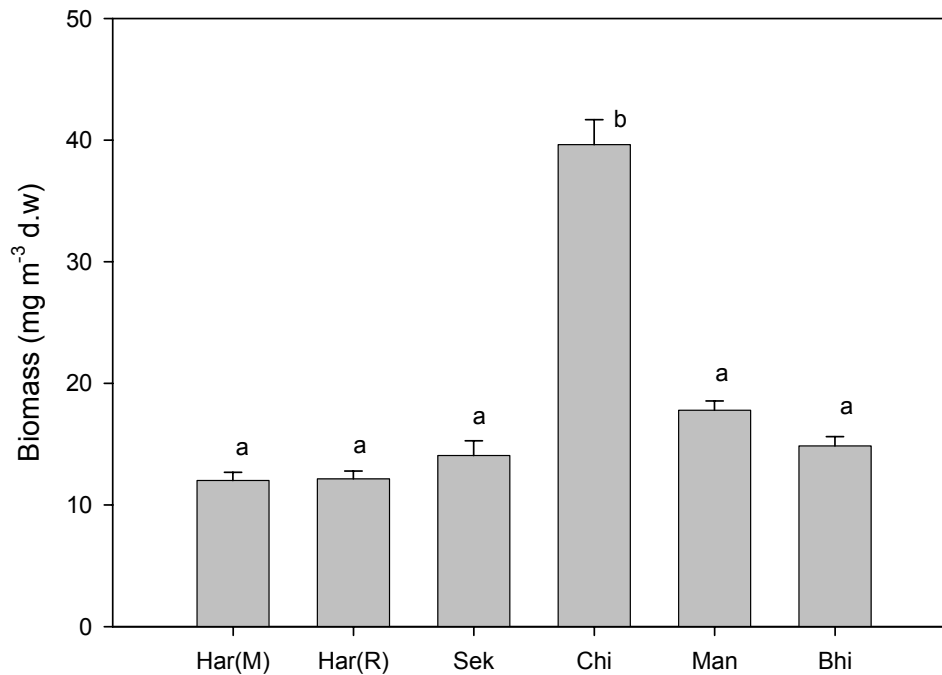


Figure 7: The mean biomass (mg m⁻³ d.w.) of phytoplankton in the five impoundments. Values with the same superscript are not significantly different, $p > 0.05$; ANOVA (Appendix 4).

A total of 41 genera were identified from the phytoplankton samples with the largest number (38) being recorded in Lake Chivero, followed by Bhiri Dam, with 29 genera (Table 6). Blue-green algae were the dominant type of algae, making up from 61% of the total in the Manyame arm of Harava Dam to 89% in Lake Manyame (Figure

8). *Microcystis* was the most abundant form constituting 61% (Manyame arm of Harava Dam) to 80% in Lake Manyame. Blue-greens were the second most numerous forms in the Ruwa arm of Harava Dam and Lake Manyame (*Oscillatoria*), and Lake Chivero and Seke dam (*Anabaena*). Bhiri Dam differed slightly in having green algae, *Pediastrum* as the second most numerous form, while the Manyame arm of Harava Dam differed further in having the dinoflagellate *Ceratium* as the second most numerous form (24% of the total). The Brillouin diversity index differed little amongst the impoundments, ranging from 1.06 (Lake Manyame) to 1.47 (Seke Dam).

Table 6: The composition of the phytoplankton in the five impoundments (abundance per 1 ml sample)

	Genera	Harava (Ruwa)	Harava (Manyame)	Seke Dam	Lake Chivero	Lake Manyame	Bhiri Dam
Date of collection		10-11-04	11-11-04	17-11-04	30-11-04	27-01-05	09-02-05
Chlorophyta	<i>Pediastrum</i>	18	8	10	35	31	28
	<i>Scenedesmus</i>	5	0	0	21	0	3
	<i>Volvox</i>	18	4	12	19	18	21
	<i>Chlamydomonas</i>	6	0	0	44	19	23
	<i>Eudorina</i>	0	0	0	11	0	2
	<i>Ankistrodesmus</i>	0	0	0	12	0	0
	<i>Spirogyra</i>	41	24	4	27	23	5
	<i>Straurastrum</i>	0	28	60	71	12	3
	<i>Zygnema</i>	0	0	0	3	1	5
	<i>Chlorella</i>	8	0	0	16	0	0
	<i>Coelastrum</i>	0	0	0	1	0	0
	<i>Pandorina</i>	108	0	0	2	3	0
	<i>Gonium</i>	3	17	29	8	0	0
	<i>Selanastrum</i>	9	0	0	7	2	3
	<i>Amscottia</i>	7	0	0	0	0	0
	<i>Asterococcus</i>	20	92	0	41	0	0
	Unidentified	5	0	1	0	0	0
Bacillariophyta	<i>Asterionella</i>	19	18	21	2	17	5
	<i>Melosira</i>	82	0	0	47	7	2
	<i>Navicula</i>	0	0	47	19	0	1
	<i>Pinnularia</i>	2	0	80	75	8	2
	<i>Cyclotella</i>	3	22	19	55	4	12
	<i>Tabellaria</i>	11	40	0	2	14	21
	<i>Gyrosigma</i>	0	0	81	0	0	1
	<i>Surirella</i>	0	0	78	80	0	1
	<i>Synedra</i>	0	0	0	1	1	2
Cyanophyta	<i>Microcystis</i>	1675	962	1264	2985	1288	524
	<i>Anabaena</i>	13	9	89	93	24	12
	<i>Spirulina</i>	0	3	0	7	19	13
	<i>Nostoc</i>	0	0	0	3	0	2
	<i>Oscillatoria</i>	158	51	47	43	38	21
	Unidentified	0	0	2	1	0	1
	<i>Chroococcus</i>	0	0	0	1	29	11
	<i>Merismopedia</i>	0	0	4	56	26	10
Euglenophyta	<i>Phacus</i>	1	0	0	2	5	1
	<i>Euglena</i> sp	2	0	0	23	3	2
	<i>Trachelomonas</i>	0	0	0	1	0	0
Dinophyta	<i>Ceratium</i>	0	411	39	2	12	3
Haptophyta	<i>Rhodomonas</i>	0	0	0	1	0	0
	<i>Gonyostomum</i>	0	0	71	0	0	0
	Rotifera	1	1	0	0	2	0
Total		2215	1690	1958	3817	1606	740
No of genera		23	15	18	36	24	29
Brillouin diversity Index		1.10	1.32	1.47	1.31	1.06	1.43

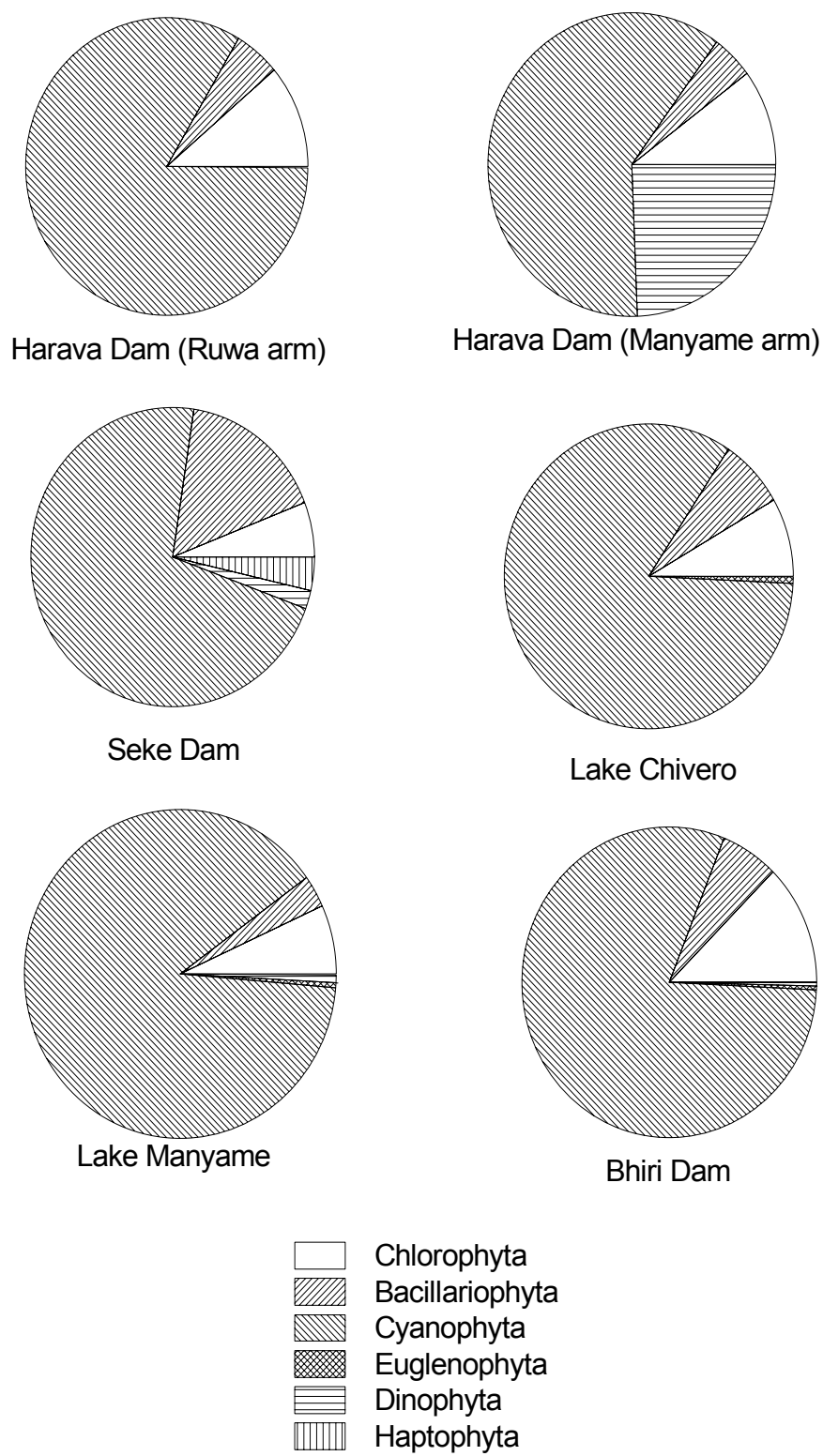


Figure 8: Phytoplankton in the five impoundments. (% proportion in 1ml sample)



Plate 1: Some of the phytoplankton from the impoundments, *Scenedesmus*.

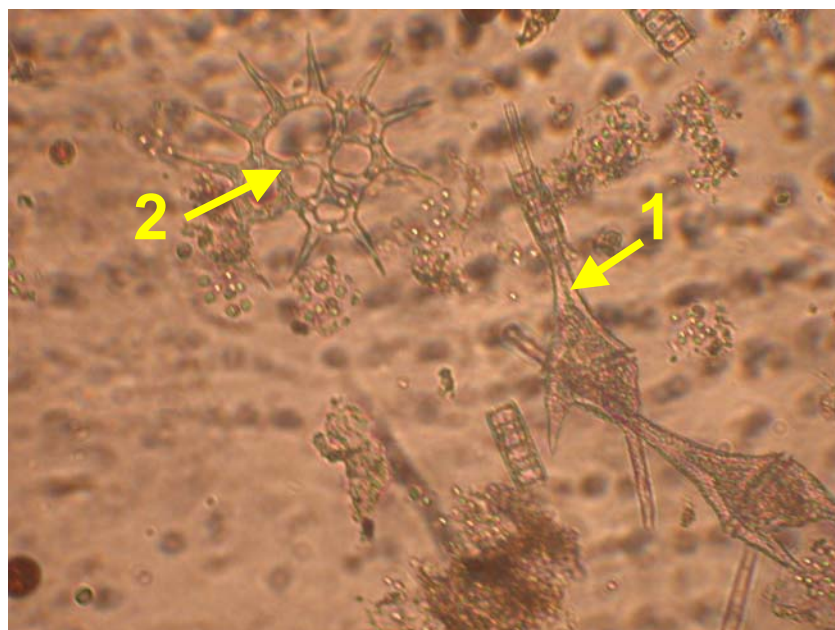


Plate 2: Some of the phytoplankton from the impoundments, (1) *Ceratium*, (2) *Staurastrum*.

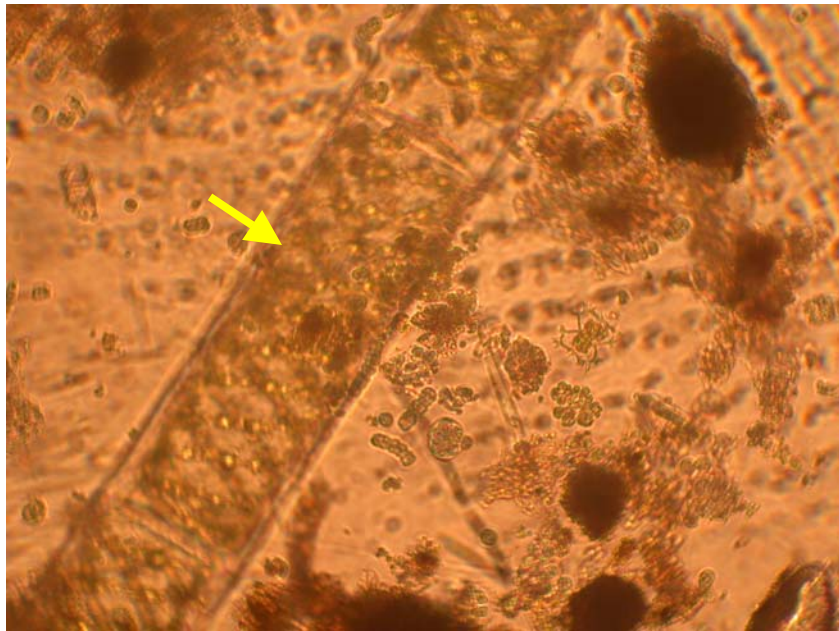


Plate 3: Some of the phytoplankton from the impoundments, *Spirogyra*

Using algal composition in the respective dams, the five impoundments were classified by cluster analysis into three groups (Figure 9). Harava Dam, Seke Dam and Lake Manyame were showed to be similar to each other while Lake Chivero and Bhiri were different from the other dams. Using physico-chemical variables, the impoundments were clustered into three groups with Bhiri Dam and Lake Manyame in one group, Harava Dam and Seke Dam in the other while Lake Chivero constituted the last group.

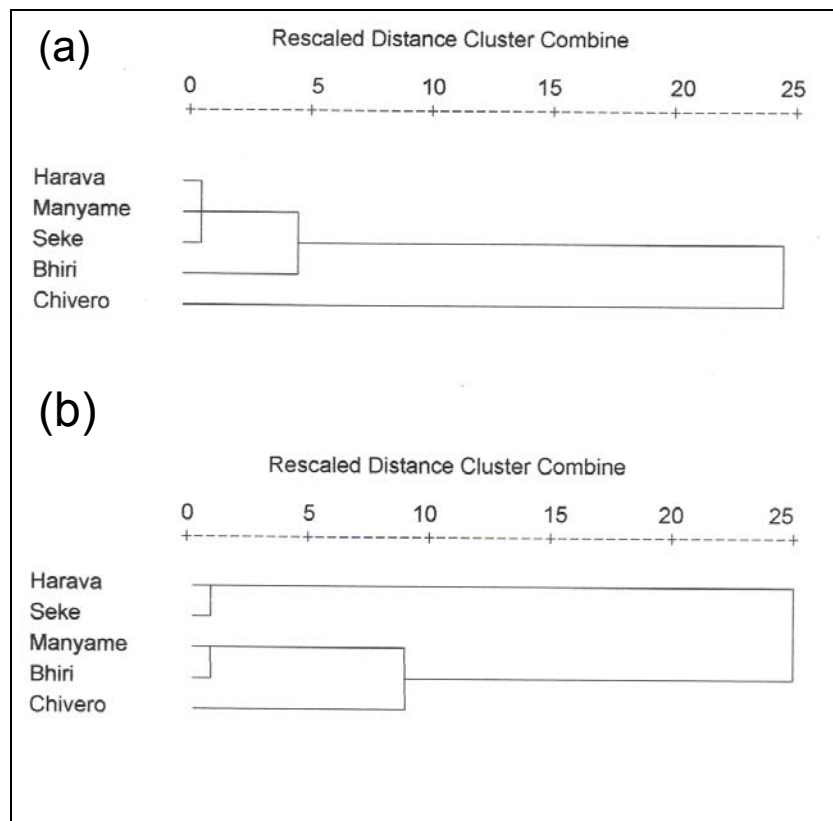


Figure 9: The relationships among the five impoundments based on a cluster analysis of (a) algal composition and (b) physico-chemical variables.

Discussion

The most distinctive feature of these five impoundments was the highly eutrophic state of Lake Chivero. The lake has been in this state since the 1960s (Munro, 1966) and is likely to remain so because the local authorities responsible for sewage treatment have not been able to keep up with the population growth in Harare and Chitungwiza (Marshall, 2005). Lake Chivero's eutrophic condition is reflected in all physicochemical variables and by a much higher density and biomass of phytoplankton than in the other impoundments, and by the fact that algal growth in the bioassay is not limited by any nutrients (Table 7). The transparency in the lake is low and it is likely that productivity may now be limited by light, as it was in the 1970s (Robarts, 1979; Robarts et al., 1982).

Table 7: The mean maximum growth response (expressed as mg l^{-1} of chlorophyll *a*) of *Selenestrum capricornutum* after nine days of incubation in membrane filtered lake water with different nutrient enrichments in 1974-75 (Robarts and Southall, 1977) and 2004-05 (the present study).

	Harava (Ruwa)		Harava (Manyame)		Seke Dam		Lake Chivero	
	1974-75	2004-05	1974-75	2004-05	1974-75	2004-05	1974-75	2004-05
All Nutrients	162	186	170	186	148	159	175	201
No nutrients	4	20	5	25	4	28	6	25
No	170	186	100	120	75	119	145	189
Micronutrients								
No NaHCO_3	125	146	150	165	145	163	170	188
No CaCl_2	150	166	160	189	150	179	165	161
No MgSO_4	75	88	60	79	75	91	175	202
No MgCl_2	160	182	90	116	155	188	160	180
No K_2HPO_4	8	123	6	133	7	130	16	161
No NaNO_3	12	21	11	36	15	31	5	146

The key questions being addressed in this investigation was whether or not the Harava and Seke Dams had become more eutrophic in the thirty years since Robarts and Southall (1977) worked in them. The likelihood that they may have become enriched has been increased because of the rapid urbanisation of the Ruwa River catchment,

which now includes at least two sewage works. Since the Manyame River drains a largely rural catchment the two arms of the Harava Dam might be expected to be different but this has not been the case with no significant differences recorded in their physicochemical status. The only notable biological difference between them was the much lower phytoplankton density and lower proportion of blue-green algae in the Manyame arm. This arm was unusual in having a high proportion of *Ceratium* in its phytoplankton, common in waters relatively rich in plant nutrients such as nitrates and phosphates (Lund and Lund, 1995) but whether this reflects differences in water quality is unclear.

The eutrophic status of these impoundment was also determined by examining the differences between the *Selenastrum capricornutum* bioassays done thirty years ago and those in the present study. The most significant differences in growth response occurred when no nutrients were added and when no phosphorus was added (Table 7). The 15-17-fold increase in the growth response without the addition of phosphorus suggests that this nutrient no longer limits algal growth in either the Harava or Seke Dams. This was confirmed by the bioassays, which indicated that nitrogen is now the main limiting nutrient, a situation quite different from that prevailing in the 1970s when phosphorus was limiting (Robarts & Southall, 1977). The switch from N-limitation to P-limitation is generally an indication of enrichment in southern Africa where the soils tend to be deficient in phosphorus while nitrogen deficiencies can be made up though nitrogen fixation by blue-green algae (Thornton, 1980)

A second important question was whether or not the impoundments below Lake Chivero were being enriched by the discharge of nutrient-rich water from the lake. These impoundments downstream have not yet become eutrophic and Lake Chivero is therefore acting as a nutrient trap. Conductivity seems to be an exception to this general trend because it was high in both Lake Manyame and Bhiri Dam. This suggests that

water from Lake Chivero was affecting these impoundments, although this is contradicted by the decrease in calcium and chloride in the two lower impoundments. One possible explanation for the high conductivity in Lake Manyame and Bhiri Dam is they both receive water from the Great Dyke (Figure 1), a unique geological feature consisting of mafic and ultramafic rocks such as norite, pyroxenite and serpentine (Worst, 1960). The streams originating on the dyke have an unusually high concentration of magnesium (Harrison *et al.*, 1966) and this might explain the high conductivity of the two lower impoundments.

The bioassays with *Selenastrum capricornutum* showed that productivity in Lake Chivero, as in the study by Robarts and Southall (1977), is limited by light rather than by any nutrient. This suggestion is supported by the low transparency of the lake. Phosphorus is commonly the limiting nutrient in southern African inland waters (Thornton and Walmsley, 1982; Allanson *et al.*, 1990) and it was the limiting nutrient in the Harava and Seke Dams in the 1970s (Robarts and Southall, (1977). The fact that it is no longer the limiting nutrient in these dams, and Lake Manyame suggests that they have been enriched to some extent but are not yet eutrophic. The discharge of sewage effluent into the Ruwa River by the growing urban areas of Ruwa and Epworth probably accounts for the enrichment of Harava and Seke dams and the situation may have been worse were it not for the fact that they are relatively small and have a low water retention time, which means that nutrients would be flushed out every rainy season when the dams overflow.

Lake Manyame, a lake reported to be mesotrophic by Watts (1982), is at risk the growth of Norton and the western suburbs of Harare. Bhiri Dam is the only one that seemed to be oligotrophic with phosphorus as the limiting nutrient. Paradoxically, it is the only one with an anoxic hypolimnion, a feature normally associated with eutrophic conditions. However, larger reservoirs in Zimbabwe have anoxic hypolimnion, regardless of their trophic status and deoxygenation of deeper waters is particularly associated with

new impoundments (Coche, 1974; Mitchell and Marshall, 1974; Masundire, 1992; Donnelly and Marshall, in prep.).

The contradictory results between the bioassays with the lake's phytoplankton and those with *Selenastrum capricornutum* for Seke Dam could have been caused by the species composition of the inoculum where the presence of one species can deplete one nutrient and that nutrient becomes first even if it is not limiting the growth of the whole phytoplankton community. Similar observations were made by Boyd *et al.*, 1998.

The dominance of *Microcystis* and other blue-green algae in all the impoundments was unexpected because this suggests that they might all be enriched since most oligotrophic Zimbabwean reservoirs are dominated by green algae (Osborne, 1972). There has been a change in the dominant algae of the Ruwa and Manyame arms of Harava Dam, Seke Dam and Lake Chivero over the last thirty years. Unlike in the 1974-75 study, *Microcystis* was the dominant genera in all six sites in the present study although at least one genus has maintained its dominance in each: *Melosira* in the Ruwa arm, *Ceratium* in the Manyame arm and Seke Dam, *Microcystis* and *Anabaena* in Lake Chivero (Table 8).

Table 8: The dominant genera in 1974-75 (from Robarts and Southall, 1977) and 2004-05 (present study).

Site	1974-1975	2004-2005
Harava Dam (Ruwa arm)	<i>Volvox</i> <i>Melosira</i> <i>Zygnema</i>	<i>Microcystis</i> <i>Oscillatoria</i> <i>Pandorina</i> <i>Melosira</i>
Harava Dam (Manyame arm)	<i>Volvox</i> <i>Ceratium</i> <i>Zygnema</i>	<i>Microcystis</i> <i>Ceratium</i> <i>Tabellaria</i> <i>Staurastrum</i>
Seke Dam	<i>Ankistrodesmus</i> <i>Ceratium</i> <i>Flagellates</i>	<i>Microcystis</i> <i>Anabaena</i> <i>Ceratium</i> <i>Staurastrum</i> <i>Pinnularia</i> <i>Sirurella</i> <i>Gonyostomum</i>
Lake Chivero	<i>Microcystis</i> <i>Anabaena</i>	<i>Microcystis</i> <i>Anabaena</i> <i>Staurastrum</i> <i>Sirurella</i> <i>Oscillatoria</i>
Lake Manyame	-	<i>Microcystis</i> <i>Oscillatoria</i> <i>Chroococcus</i>
Bhiri Dam	-	<i>Microcystis</i> <i>Pediastrum</i> <i>Chlamydomonas</i>

The cluster analysis (Figure 9) indicated that the algal composition in Lake Manyame, Seke Dam and Harava Dam was generally similar while Lake Chivero and Bhiri Dam were in groups on their own. The physico-chemical variables (Figure 10) grouped Seke and Harava Dams into one group, Lake Manyame and Bhiri Dam into the other, with Lake Chivero in a group of its own. From these findings, the lakes can be classified into three distinct groups, oligotrophic (Bhiri Dam), mesotrophic (Harava Dam, Seke Dam and Lake Manyame) and eutrophic (Lake Chivero). The small sizes and shorter retention times of Harava and Seke Dam probably play a part in the nutrient status of the two dams and prevented them from becoming as eutrophic as Lake

Chivero. As indicated Lake Chivero seemed to be an effective nutrient trap but it can only continue doing so if its self purification capacity is not exceeded. If it fails to retain nutrients Lake Manyame, which is already showing signs of eutrophication, could be at risk of getting hypereutrophic.

This study has shown the importance of controlling nutrient inputs to Harare's reservoirs. Management options for the Manyame system should include reducing nutrient loading through more effective treatment of sewage, diversion of sewage effluent and other measures. At present local authorities are dealing with the symptoms of eutrophication, through water treatment, rather than dealing with its cause through better sewage treatment, which is likely to be more cost-effective in the long run. Unfortunately, Zimbabwe's economic decline is now so severe that the responsible authorities are very unlikely to find the resources to do this and the problem of eutrophication can be expected to become more severe.

References

- Allanson, B.R., Hart,,R.C. O'Keeffe, J.H. and Robarts, R.D. 1990. *Inland Waters of Southern Africa: An Ecological Perspective*. Kluwer Academic Publishers, Dordrecht. 458 pp.
- Bartram J and Balance R. 1995. *Water Quality Monitoring*. E & FN Spon for UNEP & WHO: pp. 146-147.
- Beardall, J, Young, E and Roberts, S. 2001. Approaches for determining phytoplankton nutrient limitation. *Aquat. Sci.* **63**: 44-69.

- Boyd, P., Berges, J. A and Harrison, P. J. 1998. *In vitro* enrichment experiments at iron-rich and poor sites in the NE Subarctic Pacific. *J. Exp. Mar. Biol. Ecol.* **227**: 133-151.
- Cloern, J. E. 2001. Our evolving conceptual model of the coastal eutrophication problem. *Mar. Ecol. Progr. Ser.* **210**: 223-253.
- Coche, A.G. 1974. Limnological study of a tropical reservoir. *In Lake Kariba: A man made tropical ecosystem in Central Africa* (E. K. Balon and A. G. Coche, eds), pp 1-227.
- Cotterill, N.G. and J.A. Thornton (1985) Hydroclimate development following impoundment in a tropical African man-made lake (Lake Robertson, Zimbabwe). *J. Limnol. Soc. Sthn. Afr.* **11**; 54-61.
- Cullen, J. J, Yang, X. and MacIntyre, H. L. 1992. Nutrient limitation of marine photosynthesis. In: *Primary productivity and biogeochemical cycles in the sea* (ed. P. G. Falkowski and A. D Woodhead). Plenum Press. New York: pp. 69-88.
- Donnelly, B.G and Marshall, B.E. in prep. Aspects of the limnology of the Mtshelili Dam, an oligotrophic Zimbabwean reservoir.
- Elenbaas, P.F.M. 1994. *Field and laboratory work on ecology in Zimbabwe*. Centre for Development Cooperation Services, Vrije University, Amsterdam, Netherlands.
- Elrifi, I. R and Turpin, D. H. 1987. Short term physiological indicators of N deficiency in phytoplankton: a unifying model. *Mar. Biol.* **96**: 425-432.
- Falkowski, P. G. 2000. Rationalising elemental ratios in unicellular algae. *J. Phycol.* **36**: 3-6.
- Flynn, K. J. 1998. Estimation of kinetic parameters for the transport of nitrate and ammonium into marine phytoplankton. *Mar. Ecol. Progr. Ser.* **169**: 13-28.

- Goldman, J. C and Gilbert, P. M. 1983. Kinetics of inorganic nitrogen uptake by phytoplankton. In: *Nitrogen in the Marine Environment*. (Carpenter, E. J and Capone, D. G. Eds), Academic Press, London: pp. 233-374.
- Gotham, I. J and Rhee, G. 1981. Comparative kinetics studies of phosphate-limited growth and phosphate uptake in phytoplankton in continuous culture. *J. Phycol.* **17**: 257-265.
- Guildford, S. J, Hecky, R. E, Taylor, W. D, Mugidde, R and Bootsma, H. A. 2003. Nutrient enrichment experiments in tropical Great Lakes Malawi/Nyasa and Victoria. *J. Great Lakes Res.* **29** (supplement 2): 89-106.
- Haarhoff, J., Langenegger, O. and van der Merwe, P.J. Van Der.1992. Practical aspects of water treatment plant design for a hypertrophic impoundment. *Water S. Afr.* **18**: 27-36.
- Harrison, A.D., Nduku, W. and Hooper, A.S.C. (1966). The effects of a high magnesium-to-calcium ratio on the egg-laying rate of an aquatic planorbid snail, *Biomphalaria pfeifferi*. *Ann. Trop. Med. Parasitol.* **60**: 212-214
- Hayes, P. K, Whitaker, T. M and Fogg, G. E. 1984. The distribution and nutrient status of phytoplankton in the Southern Ocean between 20° and 70° W. *Polar Biol.* **3**: 153.
- Healey, P. F. 1979. Short term responses of nutrient deficient algae to nutrient addition. *J. Phycol.* **15**: 289-299.
- Kuang, Q, Bi, Y. Xia, Y and Hu, Z. 2004. Phytoplankton community and algal growth potential in Taipinhu reservoir, Anhui Province, China, *Lake Reserv: Manage.*, **9**: 119-124.
- Lean, D. R. S and Pick, F. R. 1981. Photosynthetic response of lake plankton to nutrient enrichment: A test for nutrient limitation. *Limnol. Oceanogr.* **29**: 1001-1019.
- Lund H. C. and Lund J.W. 1998. *Freshwater algae-their microscopic world explored*. Biopress Ltd, Bristol.

- Magadza C.H.D. 1997. Water pollution and catchment management in Lake Chivero. In: Moyo N.A.G. (ed.). *Lake Chivero A Polluted Lake*. University of Zimbabwe Publications, Harare, Zimbabwe: pp. 13-26.
- Marshall, B.E. 1994. Ecology and management of the Manyame lakes. In *Wetlands Ecology and Priorities for Conservation in Zimbabwe* (T. Matiza and S.A. Crafter, eds). Gland, Switzerland; *I.U.C.N.* p. 55-68.
- Marshall, B.E. 2005. The impact of eutrophication on Lake Chivero, Zimbabwe: a tropical African reservoir. In: Reddy M.V. (ed.) *Restoration and Management of Tropical Eutrophic Lakes*. Science Publishers, Enfield, New Hampshire, USA: pp. 165-186.
- Masundire, H.M.1992. The filling phase of Mazvikadei Reservoir, Zimbabwe. *Hydrobiologia* **232**: 11-17.
- Miller, W. E, Greene, E. J. C and Shiroyama, T. 1978. The *Selenastrum capricornutum* Printz algal assay: bottle test. Experimental design, application and data interpretation protocol. EPA (USA)-600019-78-018. pp.124.
- Mitchell, D.S. and Marshall, B.E. 1974. Hydrobiological observations on three Rhodesian reservoirs. *Freshwat. Biol*, **4**, 61-72.
- Moss, B. 1969. Limitation of algal growth of some Central African waters. *Limnol. Oceanogr.* **14**: 591-601.
- Munro, J.L. 1966. A limnological survey of Lake Mcllwaine, Rhodesia. *Hydrobiologia* **28**: 281-308.
- Panosso, R., and Granéli, E.2000. Effects of dissolved organic matter on the growth of *Nodularia spumigena* (cyanophyceae) cultivated under n and p deficiency. *Mar. Biol.* **136**:331-336.

- Parslow, J. D, Harrison, P. J. and Thompson, P. A. 1984a Development of rapid ammonium uptake during starvation of batch and chemostat cultures of the marine diatom *Thalassiora pseudonana*. *Mar. Biol.* **83**: 43-50.
- Parslow, J. D, Harrison, P. J. and Thompson, P. A. 1984b Saturated uptake kinetics: Transient response of the marine diatom *Thalassiora pseudonana* to ammonium nitrate, silicate or phosphate starvation. *Mar. Biol.* **83**: 51-59.
- Rabalais, N. N., and Turner, R. E (Eds). 2001. Coastal hypoxia: Consequences for Living Resources and Ecosystems, *Coas.Estua.Stud.* **58** American Geophysical Union. Washington DC.
- Redfield, A. C. 1958. The biological control of chemical factors in the environment. *Am. Sci.* **46**: 205-221.
- Reynolds, C. S. 1999. Metabolic sensitivities of lacustrine ecosystems to anthropogenic forcing. *Aquat. Sci.* **61**: 183- 205
- Robarts R. D and Southall G. C. 1977. Nutrient limitation of phytoplankton growth in seven tropical man-made lakes, with special reference to Lake Mcllwaine, Rhodesia. *Arch. Hydrobiol.* **79**: 1-35.
- Robarts, R.D. 1979. Underwater light penetration, chlorophyll *a* and primary production in a tropical African lake (Lake Mcllwaine, Rhodesia). *Archiv für Hydrobiologie* **86**: 423-444.
- Robarts, R.D. 1979. Underwater light penetration, chlorophyll *a* and primary production in a tropical African lake (Lake Mcllwaine, Rhodesia). *Archiv für Hydrobiologie* **86**: 423-444.
- Robarts, R.D. 1981. The phytoplankton. *Zimb. Sci. News* **15**; 95-96.
- Robarts, R.D. and G.C. Southall. 1975 Algal bioassays of two tropical Rhodesian reservoirs. *Acta Hydrochim Hydrobiol.* **3**: 369-377.

- Robarts, R.D., J.A. Thornton and C.J. Watts (1982) Phytoplankton, primary production and nutrient limitation. In *Lake Mcllwaine: The Eutrophication and Recovery of a Tropical African Lake* (J.A. Thornton, ed.), pp. 106-133. Dr W Junk Publishers, The Hague. pp 23-35
- Schindler, D. W, Armstrong, F. A, Holmgren, S. K and Brunskill, G. J. 1971. Eutrophication of Lake 227, Experimental Lakes area, Northwestern Ontario, by addition of phosphorus and nitrate. *J. Fish. Res. Bd. Can.* **28**: 1763-1782.
- Schindler, D. W. 1977. The evolution of phosphorus limitation in lakes. *Science*. **195**: 260-262.
- Smayda, T. J. 1997. Harmful algal blooms: their ecophysiology and general relevance to phytoplankton blooms in the sea. *Limnol. Oceanogr* **42**, 1137-1153.
- Thomas, W., Hastings, J., and Fujita, M. 1980. Ammonium input to the sea via large sewage outfalls - part 2: Effects of ammonium on growth and photosynthesis of southern California phytoplankton cultures. *Mar Envir Resear.* **3**: 291-296.
- Thornton, J A. 1980. A review of limnology in Zimbabwe: 1959-1979. National Water Quality Survey Report. Series No 1. Ministry of Water Development and National Parks and Wildlife Management, Harare. **86**: 36-42.
- Thornton, J.A. and Walmsley, R.D. 1982. Applicability of phosphorus budget models to southern African man-made lakes. *Hydrobiologia* **89**: 237-245.
- UNEP. 2000. Planning and Management of lakes and Reservoirs: An integrated approach to eutrophication/
- UNEP. 2003. World Lake Vision: A call to action. World Lake Vision committee.
- Vollenweider, R. A. 1992. Coastal marine eutrophication: principles and control. In R. A Vollenweider, R. Marchetti and R. Viviani (eds), *Marine Coastal Eutrophication, Science of the Total Environment Suppl.*, Elsevier, Amsterdam: pp. 361-365.

- Watts, C. J. 1982. An examination of phytoplankton nutrient limitation in Lake Mcllwaine and the Hunyani River system. In: J. A Thornton (ed.). Lake Mcllwaine: the eutrophication and recovery of a tropical lake. Dr. W. Junk. The Hague. pp 117-133.
- White, E and Payne, G. 1980. Distribution and biological availability of reactive molecular weight phosphorus in natural waters in New Zealand. *Can. J. Fish. Aquat. Sci.* **37**: 664-669.
- Wood, M. D and Oliver, R. L. 1995. Fluorescence transients in response to nutrient enrichment of nitrogen and phosphorus limited *Microcystis aeruginosa* cultures and natural phytoplankton populations: a measure of nutrient limitation. *Aust. J. Plant Physiol.* **22**: 332-340.
- Worst, B.G. 1960. The Great Dyke of Southern Rhodesia. *S. Rhod. Geol. Surv. Bull.* No. 47: 234 pp.

Appendix 1

Physico-chemical variables of the impoundments in relation to depth.

Site	Depth (m)	PH	Cond uS/cm	DO (mg/L)	Ca ug/L	Cl g/L	Temp °C	Ammonia mg/L	N (mg/L)	P (mg/L)
Harava (Ruwa)	0.0	6.2	241	5.1	29	5.1	24.5	0.14	1.5	0.74
	0.5	6.2	249	5.0	28	4.9	24	0.21	1.4	0.75
	1.0	6.1	253	4.6	21	4	23.2	0.15	1.35	0.76
	2.0	7.7	254	4.0	19	6.7	22.7	0.12	1.5	0.93
Harava (Manyame)	0.0	6.2	204	6.3	28	3.3	24.6	0.13	1.1	0.95
	0.5	6.2	215	6.1	26	3	23.2	0.14	0.82	0.71
	1.0	6.3	216	5.7	22	4.4	23.1	0.1	0.7	0.6
	2.0	6.1	215	4.7	26	2.7	22.7	0.9	0.91	0.95
	3.0	6.0	217	4.9	15	8.1	22.8	0.27	1.2	2.44
Seke	0.0	7.3	238	6.9	44	0.99	24.9	0.04	1.4	0.8
	0.5	6.8	236	5.8	28	2.4	23.1	0.03	0.3	0.68
	1.0	7.0	235	4.9	24	1.7	22.7	0.02	0.4	0.83
	2.0	7.0	246	5.0	20	1.1	22.6	0.02	0.5	0.44
Chivero	0.0	8.4	252	9.1	156	4.8	24.1	1.1	2.3	3.57
	0.5	8.2	254	9.2	146	5.5	24.1	1	2.43	3.54
	1.0	8.2	258	9.1	140	7.7	24	1	2.8	3.5
	2.0	8.2	328	7.0	139	5.0	24	1.4	1.9	3.5
	3.0	8.3	389	6.5	138	5.2	23.9	1.3	2.1	3.49
	4.0	8.3	390	5.4	130	3.2	23.9	0.8	2.5	3.49
	6.0	8.9	420	5.2	127	2.5	23.8	1.3	2.7	3.26
	8.0	8.9	435	5.2	125	2.1	23.5	0.6	3	3.31
	10.0	8.9	458	4.8	120	1.9	23.1	1.6	3.1	3.16
	12.0	8.9	498	4.7	116	1.6	23.1	5.9	3.2	3.81
Manyame	14.0	8.9	510	4.7	102	1.4	23	1.1	3.5	3.77
	0.0	5.8	321	6.8	57	13	25	0.12	1.4	0.89
	0.5	5.6	421	6.9	52	19	24.8	0.14	1.38	0.85
	1.0	5.5	379	7.0	51	18	24.7	0.21	1.2	0.76
	2.0	5.6	371	7.0	51	18	24.5	0.18	1.1	0.71
	4.0	5.6	374	6.9	55	11	24.3	0.16	1	0.7
	6.0	5.5	383	6.5	68	5.3	24.2	0.22	1.3	0.72
	8.0	5.7	355	6.5	83	4	24.2	0.25	1.5	0.69
Bhiri	0.0	5.1	220	7.7	23	11	28.8	0.11	1.2	0.86
	0.5	5.2	320	7.8	21	12	28	0.15	1	0.88
	1.0	5.1	412	7.8	21	11	27.9	0.16	0.8	0.82
	2.0	5.1	330	7.9	21	9	27.2	0.19	0.9	0.81
	4.0	5.1	323	7.6	22	10	26.6	0.21	1.1	0.79
	6.0	5.1	371	5.8	26	4.1	26	0.19	1.3	0.75
	8.0	4.8	399	0.8	37	2.7	23.5	0.16	0.9	0.7
	10.0	5.4	406	0.3	57	3.5	21	0.12	0.7	0.8

Appendix 2

ANOVA on the physico-chemical variables in the five impoundments.

Level 1: Harava Dam (Ruwa arm)
 2: Harava Dam (Manyame River)
 3: Seke Dam
 4: Lake Chivero
 5: Lake Manyame
 6: Bhiri Dam

Analysis of Variance on pH

Source	DF	SS	MS	F	p
Site	5	67.720	13.544	131.25	0.000
Error	32	3.302	0.103		
Total	37	71.022			

				Individual 95% CIs for Mean Based on Pooled StDev	
Level	N	Mean	StDev	-----+-----+-----+-----	
1	4	6.5500	0.7681	(--*-)	
2	4	6.2000	0.0816	(--*-)	
3	4	7.0250	0.2062	(--*-)	
4	11	8.5545	0.3357		(*-)
5	7	5.6143	0.1069	(-*-)	
6	8	5.1125	0.1642	(-*-)	
Pooled StDev = 0.3212				-----+-----+-----+-----	
				6.0	7.2 8.4

Analysis of Variance on conductivity

Source	DF	SS	MS	F	p
Site	5	168987	33797	8.85	0.000
Error	33	126013	3819		
Total	38	295001			

				Individual 95% CIs for Mean Based on Pooled StDev	
Level	N	Mean	StDev	-+-----+-----+-----+-----	
1	4	249.25	5.91	(-----*-----)	
2	5	213.40	5.32	(-----*-----)	
3	4	238.75	4.99	(-----*-----)	
4	11	381.00	95.68		(----*---)
5	7	372.00	30.18		(-----*-----)
6	8	347.63	64.04		(-----*-----)
Pooled StDev = 61.79				-+-----+-----+-----+-----	
				160	240 320 400

Analysis of Variance on Calcium

Source	DF	SS	MS	F	p
Site	5	78620	15724	108.53	0.000
Error	33	4781	145		
Total	38	83402			

Individual 95% CIs for Mean Based on Pooled StDev					
Level	N	Mean	StDev	-----+-----+-----+-----	
1	4	24.25	4.99	(---*--)	
2	5	23.40	5.18	(--*--)	
3	4	29.00	10.52	(--*--)	
4	11	130.82	15.11		(-*--)
5	7	59.57	11.91	(--*--)	
6	8	28.50	12.72	(--*--)	
				-----+-----+-----+-----	
Pooled StDev = 12.04				35	70 105

Analysis of Variance on Chloride

Source	DF	SS	MS	F	p
Site	5	488.0	97.6	8.09	0.000
Error	33	398.1	12.1		
Total	38	886.1			

Individual 95% CIs for Mean Based on Pooled StDev					
Level	N	Mean	StDev	----+-----+-----+-----+--	
1	4	5.175	1.124	(-----*-----)	
2	5	4.300	2.219	(-----*-----)	
3	4	1.548	0.648	(-----*-----)	
4	11	3.718	2.039	(---*---)	
5	7	12.614	6.181		(----*-----)
6	8	7.912	3.826	(----*-----)	
				----+-----+-----+-----+--	
Pooled StDev = 3.473				0.0	5.0 10.0 15.0

Analysis of Variance on Ammonia

Source	DF	SS	MS	F	p
Site	5	15.256	3.051	4.57	0.003
Error	33	22.029	0.668		
Total	38	37.284			

Individual 95% CIs for Mean Based on Pooled StDev					
Level	N	Mean	StDev	-+-----+-----+-----+-----	
1	4	0.1550	0.0387	(-----*-----)	
2	5	0.3080	0.3373	(-----*-----)	
3	4	0.0275	0.0096	(-----*-----)	
4	11	1.5545	1.4679	(-----*-----)	
5	7	0.1829	0.0464	(-----*-----)	
6	8	0.1612	0.0348	(-----*-----)	
Pooled StDev = 0.8170				-+-----+-----+-----+-----	
				-0.80	0.00 0.80 1.60

Analysis of Variance on Nitrogen

Source	DF	SS	MS	F	p
Site	5	22.331	4.466	38.27	0.000
Error	33	3.851	0.117		
Total	38	26.182			

Individual 95% CIs For Mean Based on Pooled StDev					
Level	N	Mean	StDev	-----+-----+-----+-----	
1	4	1.4375	0.0750	(---*---)	
2	5	0.9460	0.2037	(---*---)	
3	4	0.6500	0.5066	(---*---)	
4	11	2.6845	0.4920	(---*---)	(---*---)
5	7	1.2686	0.1777	(---*---)	
6	8	0.9875	0.2031	(---*---)	
Pooled StDev = 0.3416				-----+-----+-----+-----	
				0.80	1.60 2.40

Analysis of Variance of Phosphorus

Source	DF	SS	MS	F	p
Site	5	56.3891	11.2778	132.83	0.000
Error	33	2.8018	0.0849		
Total	38	59.1909			

Individual 95% CIs for Mean Based on Pooled StDev				
Level	N	Mean	StDev	-----+-----+-----+-----
1	4	0.7950	0.0904	(--*--)
2	5	1.1300	0.7480	(-*--)
3	4	0.6875	0.1773	(--*--)
4	11	3.4909	0.1960	(-*)
5	7	0.7600	0.0792	(--*-)
6	8	0.8012	0.0574	(-*--)
Pooled StDev = 0.2914				-----+-----+-----+-----
				1.0 2.0 3.0

Appendix 3

One-Way ANOVA on physico-chemical variables of both arms of Harava Dam

Source	DF	SS	MS	F	p
Sites	1	435	435	0.07	0.795
Error	61	387897	6359		
Total	62	388332			

Individual 95% CIs for Mean Based on Pooled StDev				
Level	N	Mean	StDev	-----+-----+-----+-----+
1	28	41.61	86.70	(-----*-----)
2	35	36.32	73.76	(-----*-----)
Pooled StDev = 79.74				-----+-----+-----+-----+
				20 40 60 80

Appendix 4

Analysis of Variance on biomass

Source	DF	SS	MS	F	
Site	5	2813.82	562.76	440.33	0.000
Error	24	30.67	1.28		
Total	29	2844.50			

Individual 95% CIs for Mean Based on Pooled StDev				
Level	N	Mean	StDev	-----+-----+-----+-----
1	5	12.020	0.672	(*)
2	5	12.140	0.647	(*)
3	5	14.060	1.220	(*)
4	5	39.640	2.037	(*)
5	5	17.792	0.764	(*)
6	5	14.860	0.760	(*)
Pooled StDev = 1.131				-----+-----+-----+-----
				20 30 40