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Management of Eutrophication in Lake Chivero; Success and failures: A Case Study.

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ABSTRACT

The Lake Chivero case study illustrates a number of lake management issues. The lake is downstream to the City of Harare and its satellite urban settlements. Consequently the urban wastewater effluent is upstream of the lake. About fifteen years after its filling, the lake became hypereutrophic. The restoration measures taken to restore it were based on scientific data. Good management and investment in infrastructure and nutrient removal wastewater treatment technology resulted in reducing the trophic state to mesotrophic state by the end of the 1970s. From 1980 onwards there was a surge in urban population, with a doubling period of about 12.5 years. Inflow into the lake diminished, resulting in reduction of the flushing rate by precipitation runoff from the watershed. As the population grew, the proportion of wastewater returns into the lake to precipitation runoff inflows increased to extent that wastewater return is the main inflow into the lake during the dry season. These developments, in the context of inadequate investment in wastewater treatment facilities, poor infrastructure maintenance, low operating capital and poor governance, have resulted in the lake reverting to hypereutrophic state, and now poses health risk.

INTRODUCTION

Lake Chivero is a Southern African tropical impoundment created in 1952 primarily to supply water to the City of Harare, then Salisbury a well as satisfying downstream irrigation water rights. It is located in Zimbabwe at longitude 17° 54'S and Latitude 30°47'S. It is on the Manyame River watershed with an upstream catchment of 2136 km^2. Its surface area is 26 km^2 with a mean depth of 9m. at an elevation of some 1300m above sea level.

Several studies have examined the limnology and management issues of Lake Chivero (Magadza, 1992, 1994, 1997, 2002, 2003a, 2003b, Hillman 1996 Marshall 1991, Marshall, and Falconer 1973. Mathutu *et al*. 1997, Nduku, 1976 Robarts1979, Roberts and Mitchell 1976, Thornton, 1980. Thornton. (Ed.) 1982, Ndebele and Magadza 2006. Nhapi 2004), Ward 1982). These studies have focussed on the deteriorating condition of the Lake, and span a period of over thirty years.

The city, now called Harare, began as a settler settlement, in 1890, established by the Pioneer Column, a band of opportunistic explorers lead by Cecil Rhodes. It was then called Fort Salisbury, and later simply became Salisbury. It became a municipality in 1897 and a city in 1935. It was established by a small stream now called the Mukuvisi River. A small impoundment, Cleveland Dam, was constructed upstream of the city, and supplied the city until the city outgrew the dams capacity to satisfy the city's needs. A bigger dam, Prince Edwards, (now called Seke Dam) was constructed on the Manyame River, with a capacity of 3.38 ML. Later this was supplemented by Harahwa (Henry Harlem) Dam with a 9.03 ML capacity.

Historical context

Fig. 2 A&B show the growth of Harare City. By 1950 the city of Harare manufacturing sector was beginning to grow. From Fig. 2B the combined growth of the Harare plus satellite settlements the post 1975 period gives a doubling period of about 12.5 years. By the 1950s the water supply of the Harare city from the existing Manyame River dams was approaching the limits of their supply capacity. A bigger supply reservoir was needed. Up to this stage waste water was discharged into the Mukuvisi River and flowed away from the city and its supply reservoirs (Fig. 1).

For the new supply reservoir to have sufficient storage for the growing city, including having sufficient storage to tide the city over a drought period, the dam site had to be further downstream on the Manyame river than the existing ones. This dam was the now Lake Chivero, or Lake McIlwaine, as it was called then. Lake Chivero elevation is about 200m lower then the average elevation of Harare. Consequently its location meant that waste water from the City of Harare and its satellite settlements on the Manyame watershed drained into the new lake.

Early impact of waste water on Lake Chivero.

At the time when Lake Chivero was planned and constructed, concepts of lake eutrophication were only beginning to be developed (e.g. National academy of Sciences 1969, *Eutrophication, Causes and Consequences*.). At the time, to most engineers, dilution was the common method of dealing with waste waters discharge into public waterways. If the volume of the receiving water was large then the effects of the effluent discharge would be diluted to beyond measurable impacts. The relationship between water quality and nutrient concentration, modulated by lake properties of residence time, thermal stratification etc, were little understood, especially by hydrologists.

Thus was the reasoning of the planners of Lake Chivero. The new Lake, with a capacity of 250 ML, would be able to cope with the incoming wastewater inflow by dilution, as well as the seasonal flushing of the lake during the rainy period. By the mid 1960s the lake was invaded by water hyacinth, *Eichhornia crassipes.* This exotic invasive plant had been reported in Zimbabwe watersheds as early as the 1940s, but had not posed a management problem. Its sudden explosive growth in Lake Chivero was the first visible sign of eutrophication in the lake. It was then controlled by application of 2, 4-D, which became linked to an increase on still born and defective births in Harare.

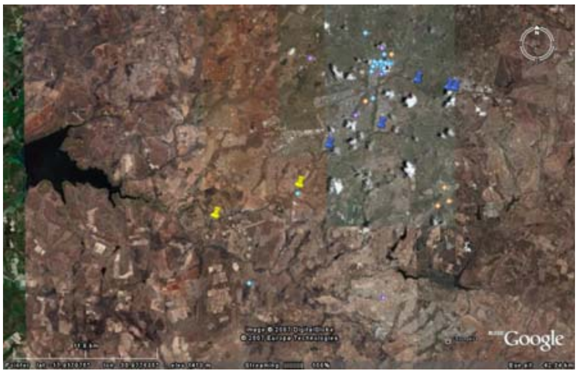

Figure 1 is an overlay of the Google earth image over part of Harare, showing same of the relevant features discussed below.

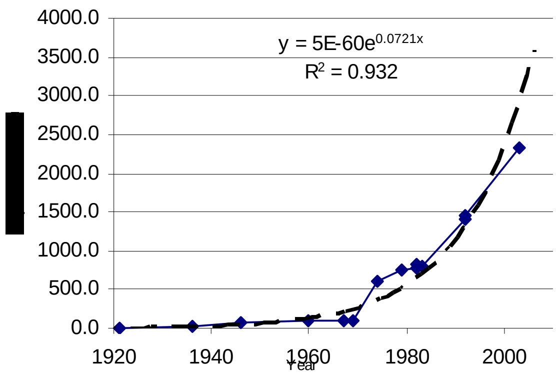

Figure 2A. Population growth of Harare and satellite settlements.

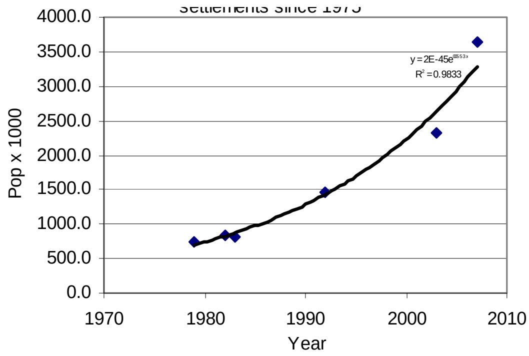

Figure 2B. Population growth of Harare nd satellite settlements since 1975.

The eradication of water hyacinth was then followed by massive blooms of *Anabaenopsis sp.* which gave the lake a feotid smell. In the city enteritis complaints increased (Marshall 1991).

Research by the University, supported by the then Salisbury City Council and the University lead to the linking of the lakes eutrophic condition to the nutrient loading, primarily phosphorus and nitrogen, in sewage effluent treated only for BOD and suspended matter removal by a primary treatment trickle filter plant. The effluent from the sewage treatment plant was discharged into the Mukuvisi River, a tributary of the lake's drainage system.

Restoration.

The realisation of the role played by the waster water discharges lead to three significant measures:

- The promulgation of the 1975 Rhodesia Water Act, which set a dissolved concentration of $1mg/l^{-1}$ as the maximum permissible phosphorus discharge, and
- The design and construction, by the Salisbury Municipality, of a Biological Nutrient Removal (BNR) sewage treatment plant of the Bardenfo type.
- The establishment of irrigated pastures for the disposal of treated sewage that did not meet the statutory limitation for discharge to public streams.

Table 1 shows changes in phosphorus loading to the lake following the remedial measures for the pre and post remediation period of 1968 and 1978. Fig. 3 shows changes in secchi disc transparency before and after the restoration measures.

Considering that the BNR system was commissioned only early 1975, the lake's response to the measures was remarkably rapid. These measures, and a constant surveillance to manually remove water hyacinth plants that appeared after the spray programme, allowed the lake to recover from a hypereutrophic state to a mesotrophic state Thornton (1982).

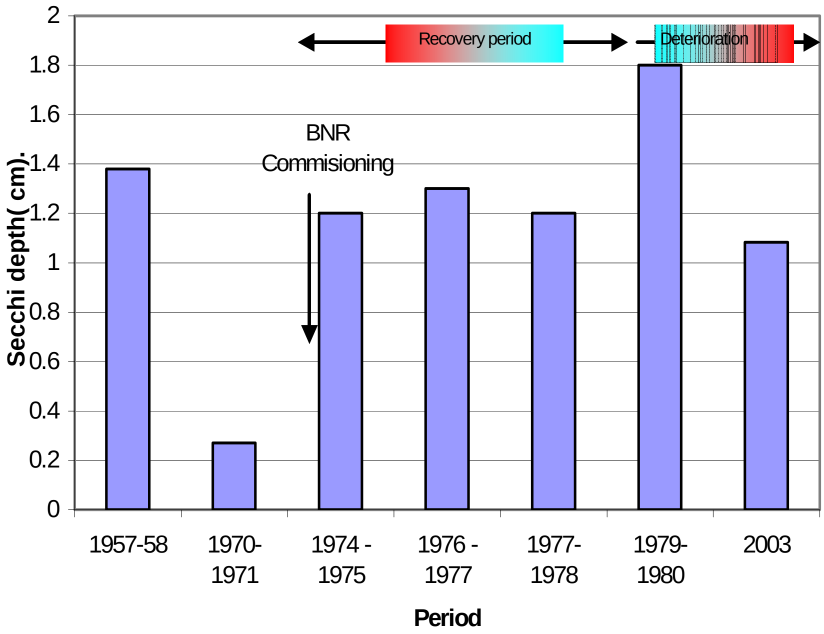

Figure 3. Sacchi disc changes following restoration measures (data from Thornton 1982, Ndebele and Magadza 2006)

Table 1. Historical changes in phosphorus regime in L. Chivero (after Thornton, 1982*, Magadza 1997).

Parameter	1967	1978	1996	2006 (Ndebele and Magadza 2006)
P-load (tonnes pa)	685 (27.4 g m^{-2})	39.6 (1.5 g m^{-2})	350 (14 g m^{-2})	
Mean P- conc. mgl^{-1}	2.8	0.13	1.8 (Manyame)	2.67 (2.42 – 3.18)
Conductivity μScm^{-1}	160	120	800	2124.5 μScm^{-1} (Wet season values)

.

The total phosphorus loading was reduced from nearly 300 tonnes per annum to less than 40 tonnes per annum. Secchi disc transparency increased to above one metre. Water sport (sailing, water skiing) tourist industry generally revived. However, as part of the recovery evaluation process Magadza (1992), using experience from New Zealand, where he showed that plankton species were much more sensitive indicators of trophic status than limnochemical measurements and used zooplankton assemblages to evaluate the trophic status of the lake in the post remediation period. He concluded that the lake was in a metastable condition and that unless stringent measures to control nutrient inflows were adhered to it could rapidly revert to a eutrophic state. The inlet of the Marimba River, which still collected effluent from a primary treatment sewage plant then, and the area adjacent to the pasture irrigation with primary treatment effluent, were easily detected by this method.

Nevertheless, this case study shows that a hypereutrophic tropical impoundment, which ranks among the class of large lakes of the world, could be restored by controlling nutrient loading into the lake. The tragedy of Lake Chivero is what has happened from the post 1980 period up to now. Table 2 shows the status of some of the wastewater treatment plants in the Harare Municipality. As shown above in Figure 2B shows that the urban population of the Lake Chivero watershed is doubling every 12.5 years since 1975. The data include the population of the Chitungwiza city, established in the early 1960s to curb urban migration by providing employment to rural population outside the then Salisbury City. The sudden rise in the overall population in the mid 1970s shows the population surge in Chitungwiza. However this city lacks an industrial employment base, and thus has no revenue base, apart from household utility charges. Consequently the city is unable to invest in public services works to manage, among other things, its wastewaters.

The post 1980 era

Table. 2. Waste water treatment capacity at some of the Manyame watershed sewage works.

Plant	Trickle filter	Year	Activated sludge (BNR)	Year	Ponds	Year	Total capacity	Present flow
Firle	36	1960	18	1982			144	**250**
			18	1974				
			72	1998				
Crowborough	36	1957	18	1982			54	**120**
Donnybrook					2.3	1953-1972	2.3	**10**
Marlborough					2	Post 1980	2	**7**
Total							202.3	**387**

To summarise the major developments that have lead to the sorry state of the present Lake Chivero:

- The establishment of a high density low income urban settlements in the lake's watershed that have very weak fiscal base to provide basic services.
- The rapid population growth, with a doubling period of only 12.5 years, of settlements in the lake's watershed, with a mismatch between population growth rate and investment in civic works
- The progressive breakdown in infrastructure maintenance, leading to chronic sewer breaches that go unattended for long periods
- The breakdown in city sanitation services which results in heaps of uncollected refuse.
- Central government interference with urban councils that results in incompetent politically appointed "commissions" to run city affairs.
- Development of a non consultative style of governance in which ratepayers face ever escalating charges for substandard services.

From a hydrological point of view there have been significant changes in the lakes watershed.

Run off and flushing rates

Fig. 4 shows the annual flushing rate, calculated as total run off divided by lake volume. The data show high variability but on the whole the pre 1980 period had higher flushing rates, such that the flushing rates of the post 1980 era is on the average half of the pre 1980. Thus in the post 1980 period the lake has received less runoff from the watershed and the water has stayed longer in the lake

Constituent flows

The Manyame River has traditionally been regarded as the main inflow into Lake Chivero, with 92% of the lake's watershed drained by this river. Urban drainage is principally through the Marimba, Mukuvisi and Nyatsime rivers. These latter tributaries have increasingly become waste water conveyances to the lake. For example the conductivity of the Mukuvisi river changes from an average of 50 μScm^{-1} at Cleveland Dam, to over 2000 μScm^{-1}, as it passes through the city and received partially treated (and often . untreated) sewage from the sewage works. Figure 5 shows an increasing ratio of wastewater bearing inflows to the inflows of the major watershed runoff. This is particularly conspicuous during drought periods when wastewater effluent can be as much as five times the run off inflows from precipitation in the watershed. Indeed during the dry season Lake Chivero's inflow consists almost entirely of waste water returns. Thus increasingly the lakes water is being constituted mainly of urban waste waters.

Non point source inflows

The result of progressive breakdown in civic services by the Harare municipal authorities has been the accumulation of uncollected garbage and increase incidences of sewer breaches that go unattended for considerable periods. Magadza (2003a) has estimated the non point source export of phosphorus and nitrogen from Harare suburbs. Thornton (1982) estimated phosphorus loads from "other sources" as 18 tonnes per annum. From the results given in Table 3 for the sub-watersheds that drain into Lake Chivero it is clear that the current non point source loadings have increased by at least fifteen times. Then 1978 value. It thus clear that managing piped waste water out put from the city through the wastewater treatment plants will still leave a considerable loading of nitrogen and phosphorus to the lake which is of the same magnitude as the pre-restoration period. This means that investing in high technology waste water treatment plants will no longer solve the pollution problems of the lake, as it did in the mid to late 1970s, because sufficient nutrient loading from non point source will maintain the hyper-eutrophic state of the lake.

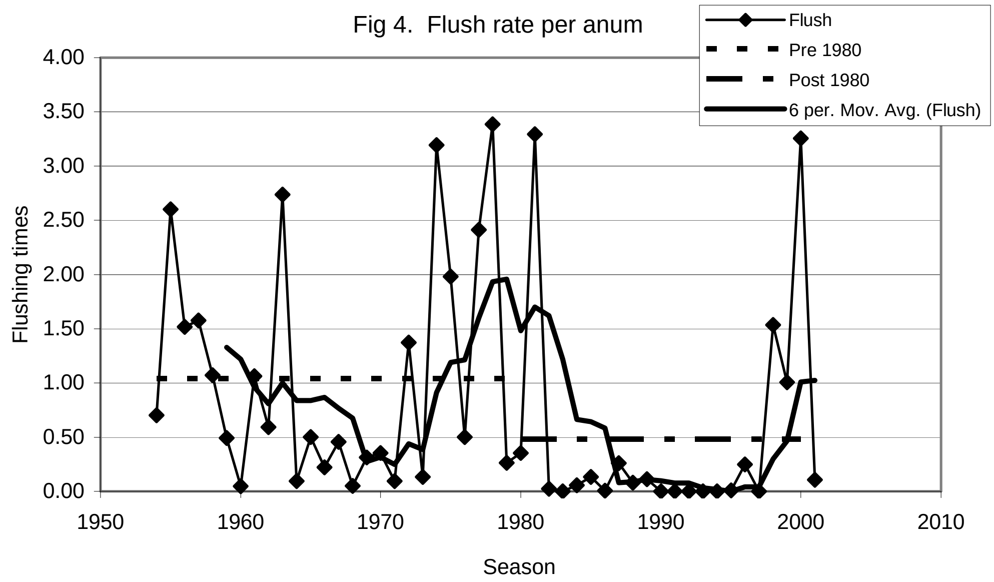

Figure 4. Flush rate per anum.

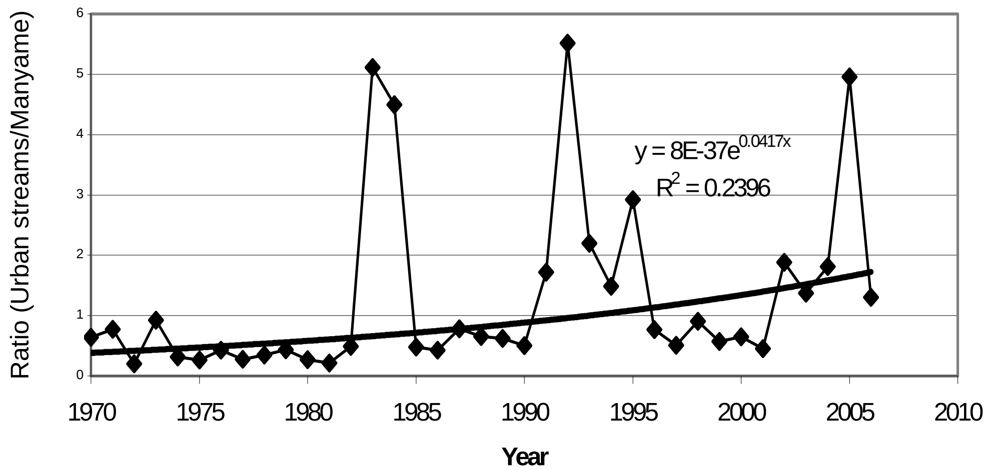

Figure 5. Ratio of waster carrying streamflows to Manyame River flow.

Table 3. Nutrient exports during wet season from Harare suburbs to L. Chivero (excluding Chitungwiza)

Catchment/ Suburb	Type		Phosphorus		Nitrogen		Total export	P/N ratio
		Tonne km^{-2}	Kg $Capita^{-1}$	Tonne km^{-2}	Kg $Capita^{-1}$	P tonne	N - Tonne	
Kuwadzana	High	0.08	0.17	0.47	0.96	2.88	16.75	5.81
Budiriro	High	2.30	0.23	13.77	1.35	22.08	132.17	5.99
Mukuvisi	High/Industrial	10.28	1.00	39.98	3.89	98.99	385.04	3.89
Epworth	High	3.38	1.11	12.20	4.00	103.12	371.88	3.61
Glenview	High	0.30	0.39	1.09	1.44	30.23	111.39	3.68
Marimba	Mixed/industrial	0.13	0.77	0.86	4.98	9.28	60.31	6.50
Mean or total		2.75	0.61	11.40	2.77	**266.59**	**1077.53**	4.91

Current status and impacts of eutrophication of L. Chivero.

Lake Chivero is a hypereutrophic lake. The result of sewage effluent discharge can be illustrated by the conductivity data (Fig 6). Mean total phosphorus concentrations, as determined by Ndebele and Magadza (2006) for the period March to April 2003 ranged between 1.98 mgl^{-1} and 2.99 mg l^{-1} at three sampling sites on the lake, with a mean of 2.24 mg l^{-1}. This is about three orders of magnitude higher than the 1967 value (0.04 mg l^{-1}), during which the lake was already hypereutrophic, and over 20,000 times the mean value during the recovery period (c.f. Table 1). Chloride levels ranged between 71.03 mgl^{-1} and 174.78 mgl^{-1}. Magadza (2003b) showed the existence of thermohaline stratification and declining oxygen levels, to the extent that the lake suffers from frequent anoxia leading to fish kills (Moyo 1997.).

From a health point of view Ndebele and Magadza (2006) showed the presence of microcystin levels well above the WHO limit. In the period 1991 to 2001 the incidences of gastroenteritis and liver cancer have increased, with liver cancer incidences doubling between 1998 and year 2000. Box 1 is a media portrayal of the health risks that the waters of L. Chivero now pose. Magadza (2002) noted the rise in bloody diarrhoea incidences among five year olds in Harare during the rainy season (Fig 7). This is explained by the mingling of rain water runoff with breached sewer outflows, rendering children who play in the puddles susceptible to gastroenteritis infections.

Nuisance invasive aquatic weeds (*Eichhornia crassipes* and *Hydrocotyl*) have become pervasive, with *Hydrocotyl* increasingly replacing *Eichhornia*. The cost of treating the L. Chivero water to potable standards has escalated, and that in the context of an ailing economy, the water authority is no longer able to supply the urban population with adequate water with several suburbs going without piped water supply for weeks and months, though the lake storage is high. Cholera cases have been reported in the media (Box 1).

Box 1

As a result, the incidence of waterborne diseases such as dysentery, diarrhoea and cholera has increased to such an extent that the Harare City Council (HCC) is obliged to offer free treatment. The city's health department last month warned of an imminent disaster in the capital if the water situation was not addressed.

The Cape Argus (SA), 8 October, cited in ZWNEWS 09/10/07
http://www.zwnews.com/

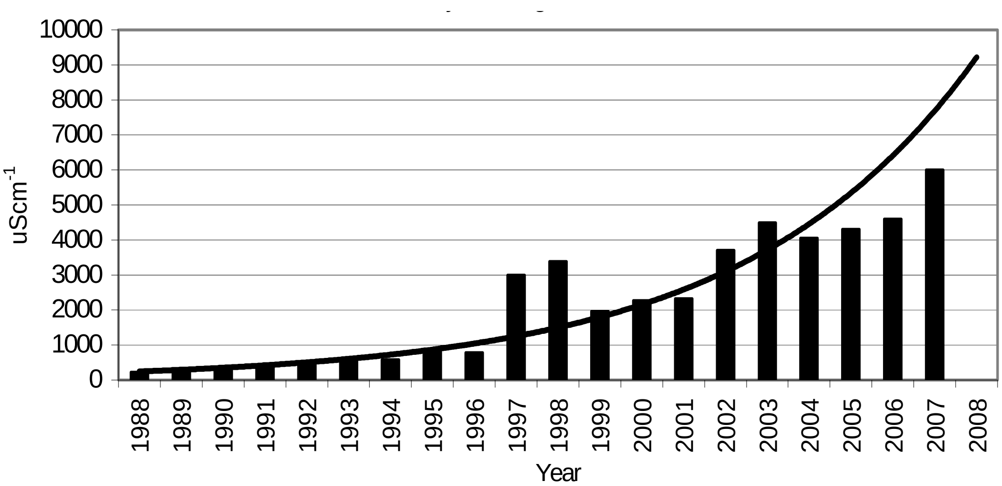

Figure 6. Conductivity in L. Chivero. Data compiled from Harare Municipality, Zimbabwe Water Authority and Magadza 2006.

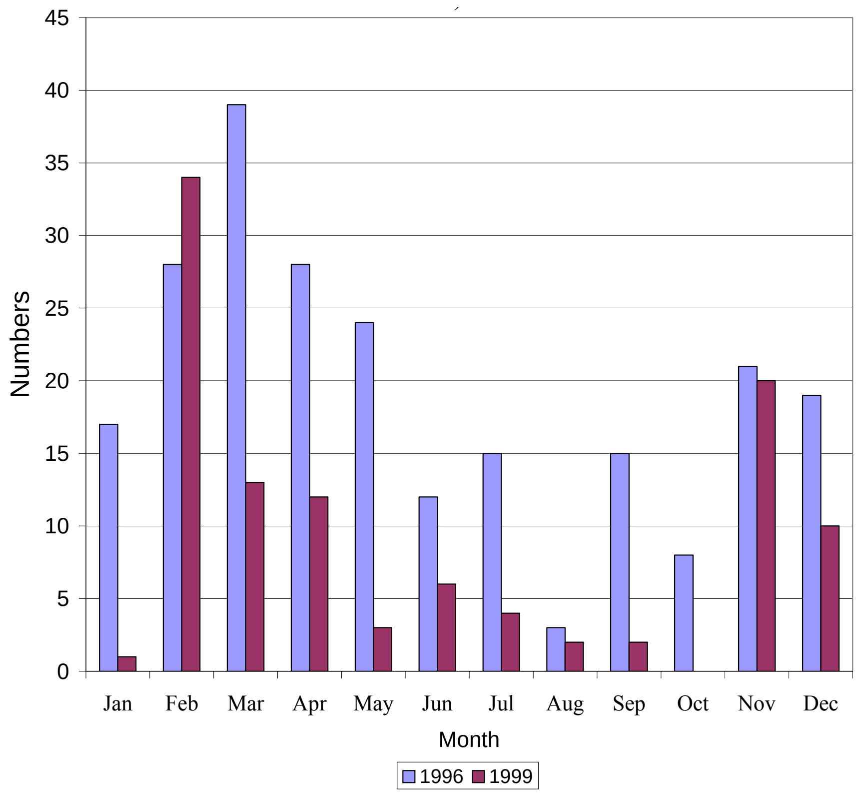

Figure 7. Bloody diarrhoeia, over 5 year olds, Mbare (Magadza 2001

What can be done?

The current management strategy is to seek more funds to construct more wastewater treatment works. A total of 255 ML capacity expansion at a cost of approximately US$353 million is planned. This is indeed a priority, but such funding is unlikely to be available from local resources in the present economic circumstances.

Figure 8. Hydrocotyly in Manyame River

Nevertheless we have shown earlier that the non point source of phosphorus and nitrogen can maintain the lake in a hypereutrophic state given that the sum total of this source of nutrients exceeds the 1967 levels when the lake was hypereutrophic (Tables 3 above). Thus the high technology wastewater treatment strategy now needs to be complemented by other strategies.

One strategy is the implementation of the Seven Principles recommended by World Lake Vision Committee (2003). This requires a major mind shift on the part of the management authorities on the rights and obligations of stakeholders. In Laguna de Bay it has been amply shown that involvement of citizens, at the lowest level, can yield very satisfactory results, which could not have been achieved by a top down management style. On the part of the citizens it requires a sustained educational and awareness programme to educate them in how they impact on their water resources.

The other strategy is use of ecological methods for runoff water quality control. Studies on the Mukuvisi River, one of the major nutrient contributors to the lake, have shown that the wetlands associated with this river have considerable water quality restoration (self purification) capacity (Machena 1997). Prior to 1980 urban wetlands were left undeveloped as “ecological lungs” to the city, but now these wetlands are being increasingly converted for property development. It is recommended here that the State develops a clear policy and implementation strategy for wetlands conservation. Within the urban areas of Harare and surrounding urban settlements we recommend that the authorities develop and implement an extensive programme of wetlands management, such as constructed wetlands. In this respect it should be pointed out that The United Nations Environmental Programme-International Environmental Technology Centre (UNEP-IETC) has case studies of ecological technologies for sound environmental management of water resources, e.g. Planning and Management of Lakes and Reservoirs: an integrated approach to eutrophication.

Evaluation of the Lake Chivero management against the World Lake Vision Committee (WLV) Seven Principles of Lake Management

Table 4. Evaluation of the management of Lake Chivero against World Lake Vision Committee (2003) Seven Principles (International Lake Environment Committee (IEC)/ United Nations Environment Programme-International Environmental Technology Centre (UNEP-IETC).

Principle	Compliance status	Comment
1. A harmonious relationship between humans and nature is essential for the sustainable use of lakes	Conflicts between nature and human	Poor compliance of policy and legal provisions by society, industry and state institutions
2. A lake drainage basin is the logical starting point for planning and management actions for sustainable lake use	Principle not applied	No linkages between various jurisdictions and management authorities in the drainage basin, in spite of institutional structures (watershed councils) set up to facilitate this.
3. A long-term, preventative approach directed to preventing the causes of lake degradation is essential	No evident long-term plan	Management strategies now consist of responding to crises, through aid assistance requests.
4. Policy development and decision making for lake management should be based on sound science and the best available information	Poor application of scientific approach.	In initial planning of the lake scientific knowledge on function of aquatic systems was limited, but subsequent research by independent researchers has built up a good knowledge base which can be used for management of the lake.
5. The management of lakes for their sustainable use requires the resolution of conflicts among competing use of lake resources, taking into account the needs of present and future generations and of nature	No attempt to resolve conflicts	The major conflict is the use of the lake for potable water supply, recreation and fisheries and as a wastewater receptacle at the same time.
6. Citizens and other stakeholders should be encouraged to participate meaningfully in identifying and resolving critical lake problems.	Principle not adhered to	The state system has very little room for inclusive participation by non state entities. There is no intension by managers to consult with rate payers, or consult other technical expert groups, such as universities and the Zimbabwe Academy of Sciences
7. Good governance, based on fairness, transparency and empowerment of all stakeholders, is essential for sustainable lake use.	Poor, but punitive governance.	Although the national water authority was set up in the spirit of this principle it has turned out to be principally a revenue collector for little services in return. Breached sewers go unattended for weeks or months. On the part of the municipality, refuse collection is infrequent.

Table 4 is an evaluation of the management of Lake Chivero against the Seven Principles developed by the World Lake Vision Committee (2003).

Planning personnel in the water resource management have indicated to the author that a major development project cycle, from the initial decision to commissioning is often more than ten years. With a doubling period of 12 years, it means such a planning near term cycle scenario can never be up to date with the growth of services demand. This means that the planned utility life span for the service being developed must be at least two to four times the demand doubling period. This implies some ingenious financing strategy in which the unborn pay for their anticipated services well in advance.

CONCLUSION

The lake Chivero case is a typical example of how poor governance, hydrological changes and urban population growth and lack of anticipatory management can lead to an environmental crisis. Prior to 1980, professional and technical experts made the technical management decisions. But since the 1980s political considerations have frustrated sound management. This, added to burgeoning population pressures, and thus more wastewater output, has now developed into a major crisis with regard to the management of lake Chivero and the goods and services it is supposed to provide. However it has been demonstrated before that application of sound scientific principles and good management and governance can result in restoration of a hypereutrophic lake. With foresight this possibility still remains.

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