THE IMPACT OF SEWAGE EFFLUENT AND NATURAL SELF-PURIFICATION IN THE UPPER CHINYIKA RIVER BELOW HATCLIFFE SEWAGE WORKS, HARARE

by

Taurai Bere

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University of Zimbabwe

Faculty of Science

Department of Biological Sciences

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Abstract

The impact of sewage effluent and natural self-purification in the upper Chinyika River was investigated during the period October 2004 to February 2005. The physico-chemical and river flow variables, and water samples, were colleted on monthly basis. The samples were analysed for total nitrogen, total phosphorus, chemical oxygen demand and total dissolved solids using the appropriate methods. Sediment samples were also collected once during the dry months and also once during the wet months and were analysed for total nitrogen, total phosphorus and heavy metals. The nutrient concentrations in the water column and loading levels in the sediments were high just below sewage outflow in to the river, generally decreasing with increasing distance from the point of sewage outflow because of self-purification. The nutrient concentration was high during the dry months with the highest mean values (N = 6.35; P = 4.01 mg l^{-1}) being recorded in November and was low during the wet months with the lowest values (N = 1.33; P = 0.57 mg l^{-1}) being recorded in January and December respectively, suggesting dilution effect. The nutrient load, on the other hand, was high during the wet months with the highest mean values (N = 8704.80 ; P = 2434.00 kg $month^{-1}$) being recoded in January suggesting that organic matter was washed away from the catchment (diffuse inputs) in to the river channel resulting in high nutrient loading levels. The nutrient level in the sediments was high during the dry months (mean N = 1.01; mean P = 0.39 mg g^{-1} dry sediment) and low during the wet months (mean N = 0.37; mean P = 0.06 mg g^{-1} dry sediment) probably due to sediment re-suspension and the subsequent transportation because of storm action. There were no detectable temporal and spatial trends observed in heavy metal levels in the sediments. The other physico-chemical variables showed a general tendency of deteriorating just below sewage outflow and then improving with increasing distance downstream because of self-purification, except conductivity. High self-purification capacity was observed in the upper Chinyika River during the dry and wet months though it was generally lower in the latter coinciding with the observed riparian vegetation senescence, thus, emphasizing the importance of riparian vegetation in water quality monitoring in river channels. Conservation of riparian wetlands is, thus, central to sound watershed management. The capacity of rivers to purify themselves should be managed so that they can absorb pollution before discharging into lakes and reservoirs.

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INTRODUCTION

The success of human civilization is largely due to our skills as ecosystem engineers. Although these engineering activities are primarily directed towards achieving some specific purposes (e.g. industrial production), most have major indirect and unintended effects on ecosystems (e.g. eutrophication and water pollution) (Tanner, 2001). The disposal of human waste, for instance, is one of the greatest challenges of urbanization in both developed and developing countries (Zimmels *et al*., 2004). The problem is more severe in developing countries like Zimbabwe where urbanization is proceeding alongside rapid population growth (UNEP-IETC, 1999).

Waterways have been treated as convenient, cheap and effective way of disposing off human waste products, which has led to problems such as the eutrophication in water bodies receiving these wastes (Mason, 1981; Harper, 1992). This has captured public interest because of the consequent deterioration of water quality, health problems, pest plants and animals, and other problems (Salvia *et al.,* 1999).

What is the fate of nutrients in sewage effluent discharged into a river channels? To what extent is the riparian system capable of coping with extra nutrient loading from sewage works? Are there any seasonal variations in nutrient loading and the river's capacity for self-purification?

The present study was carried out in an attempt to answer these questions in the Chinyika River which receives sewage effluent from the Hatcliffe Sewage Works on the northern edge of the city of Harare, Zimbabwe. This was done by determining the levels of nitrogen and phosphorus in the water column and sediments and other physico-chemical variables from the point of sewage outflow downstream. The nutrient budgets for the different sections of the river channel, the seasonal changes in nutrient loading and retention capacity and the improvement in water quality during its passage through the different sections of the river channel were also considered.

LITERATURE REVIEW

All over the world rivers and streams have been considered as open systems with their functions being determined by the external load of matter (Puchalski, 2000). They form the fundamental components of regional and global biogeochemical cycles, acting as both transport pathways and sites of elemental transformations and storage. Under natural conditions, riverine cycles of nutrients are intricately woven into the overall balance of the riparian ecosystem (McClain *et al*., 1998).

While nutrients are naturally present and are an integral part in all healthy aquatic systems, an excessive supply of nutrients, almost always human induced, disrupts the natural functioning of the these systems (Bartram and Ballance, 1996; Hanrahan *et al*., 2001; Bourne *et al*., 2002). Rivers worldwide have doubled their content of nitrogen and phosphorus since the beginning of the industrial era further disrupting the natural functioning of the aquatic systems (Harper, 1992).

Nutrient loading in river systems

Nitrogen and phosphorus enter rivers through several hydrological, geological and biological pathways depending on the natural and anthropogenic processes taking place in the catchment (McClain *et al*., 1998; Wassman and Olli, 2004). These processes are generally known from numerous studies of small catchments as well as from recent global and continental scale assessments of nutrient sources (Howarth *et al*., 1996; Jordan and Weller, 1996; Carpenter *et al*., 1998).

The natural source of phosphorus is the weathering of phosphorus-containing rocks such as apatite (Harper, 1992). Nitrogen is also present in igneous rocks at low concentrations but the main source of nitrogen for all biological activity is the atmospheric reservoir of gaseous nitrogen that is made available to ecosystems by fixation into a variety of oxides or reduced to ammonia as a result of fixation by microorganisms (Harper, 1992).

The growth of human population and an increase in its capacity to alter the environment has increased the supply of nutrients to rivers and human activities in the watersheds are now important contributors of nutrients to rivers (Wassman and Olli, 2004). The major point sources of nutrients to rivers are sewage and industrial effluent discharges (Harper, 1996; Moyo and Worster, 1997). These play a major role in most severe cases of river pollution (Wassman and Olli, 2004) depending on the population, or size of and type of activity discharging the waste, the capacity of the water body to dilute the discharge, and the ecological sensitivity of the receiving water body (Bartram and Ballance, 1996).

The principle of sewage treatment is that the capacity of sewage to pollute a river is reduced by the bacterial oxidation of organic matter derived from excreta and other organic matter in the treatment plant rather than in the water course. Typically around 80% of the organic matter is oxidized in this way (Mason, 1981) but in doing so all the major elements from the wastes, such as carbon, nitrogen and phosphorus are oxidized and those which are soluble may be present in high concentrations in the effluent from such plants (Harper, 1992). As soon as they are operational, sewage treatment plants thus become point sources of nitrogen and phosphorus at concentrations as high as 15 and 3 mg l^{-1} respectively (Bourne *et al*., 2002).

Besides these point sources, there are also diffuse sources of pollution in the catchment that contribute to nutrient loading in rivers. Unlike point sources of pollution which are easily identified, diffuse sources of pollution are difficult to identify and extremely complex and costly to remedy (Hranova, 2003). Agriculture is considered to be an important diffuse source of nutrients exported from catchments (Dillon and Kirchner, 1975). Large losses of nutrients from agricultural land may be caused by intensive use of fertilizers (Stålnacke *et al*., 2003) and several investigations have shown that concentrations of nutrients in river water were strongly correlated to the percentage of agricultural land in the study basins (Sharpley and Withers, 1994; Grimvall and Stålnacke, 1996; Stålnacke *et al*., 2003). Other diffuse sources include atmospheric deposition, urban runoff, animal manure and fertilizers applied to cultivated fields, and runoff from livestock feedlots.

Nutrient retention and loss in river channels

The total quantity of nutrients discharged into surface waters in a river basin is normally larger than the nutrient load at the river mouth (Wassman and Olli, 2004). This discrepancy can be explained by the process of nutrient retention, which is a collective expression for a large number of biogeochemical and hydrological processes that temporarily decrease, decay, degrade, transform, or permanently retard and remove the substance from the river channel. Once in the river nutrients follow a complex downstream process, which includes cycling between organic and inorganic forms, chemical species transformation in response to changing redox conditions, sorptive partitioning onto particulate surfaces, movement into and out of streamside soils, and periods of immobilization and storage.

The cycling and transport of nutrients along rivers involves (1) physical processes such as dilution, volatilisation, sedimentation, and adsorption; (2) chemical processes such as oxidation, reduction, dissolution, nitrification and denitrification; and (3) biological processes such as uptake by plants or micro-organisms, or microbial oxidation and reduction (Fauvet *et al*., 2001; Wetzel, 2001). Phosphorus retention occurs through sedimentation, plant and microbial uptake, the accumulation of organic matter, immobilization and soil sorption (Hunt and Poach, 2001). Nitrogen is removed from the wastewater through filtration, sedimentation, uptake by plants and microorganisms, adsorption, nitrification and denitrification, and volatilisation (Hunt and Poach, 2001). The losses of nitrogen gas through nitrification and denitrification can be very large; they are generally the most important mechanisms for the removal of nitrogen from riparian ecosystems (Hunt and Poach, 2001; Wassman and Olli, 2004).

All along the mainstream of the river and in its stagnant sections, such as ponds or reservoirs, these natural ecological mechanisms for the retention or elimination of nutrients greatly modify the quantities of nutrients that are transported downstream (Wassman and Olli, 2004). The complexity of the process is important for upgrading and maintaining the quality of water in the rivers and for providing habitats for aquatic species as they allow the rivers to purify themselves (Wuhrmann, 1972; Koppe, 1973).

This self-purification process is very effective and the system will suffer no permanent damage as long as its capacity has not been exceeded (Spellman, 1996). If this capacity is exceeded the system will become ecologically stressed with the symptoms of pollution becoming increasingly obvious and extensive. An understanding of the self-purification process is therefore important to prevent overloading the system (Nhapi *et al*., 2001).

Nutrient removal rates vary widely in response to climate, topography, soils, vegetation, physical and hydraulic properties of rivers (Johnson, 1992; Howarth *et al*., 1996; Alexander *et al*., 2000), the trophic status and depth of the water body, water residence time, nutrient loading, and denitrification activity (Wassman and Olli, 2004). Temperature, hydrological regimes and biological communities appear to be very important among the complex factors governing nutrient retention in rivers (D'Angelo *et al*., 1991; McClain *et al*., 1998).

Temperature is a fundamental variable in many of the processes involved in nutrient cycling since changes in temperature affect the biotic and abiotic processes that govern nutrient fluxes through riverine ecosystems. As temperature increases, so does microbial activity, which leads to high rates of organic matter processing and redox reactions, as well as nutrient mineralization and uptake. Plant metabolism is also accelerated by increasing temperature, thereby increasing nutrient uptake (McClain *et al*., 1998).

Nutrient fluxes tend to increase with increasing flow because high flow create high-energy environments in rivers which re-suspend and transport previously deposited sediments and organic particulate material (Kronvang *et al*., 1999). These materials along with their associated nutrients are carried downstream until energy levels decrease and they are again deposited (McClain *et al*., 1998). The efficiency of nutrient removal may also decrease because at high velocity there is less contact between the sediments and water (D'Angelo *et al*., 1991) in contrast to low velocities where there is more contact between sediments and water and consequently more nutrient uptake (Bencala, 1983).

Riparian vegetation forms an integral and important part of any river ecosystem and it makes a number of important geomophological, ecological and social contributions to the condition and functioning of the river itself (Arthington *et al.*, 1993) and regional biodiversity (Naiman *et al*., 1993). Riparian wetlands can be used in wastewater management because of their ability to absorb large amounts of organic and inorganic nutrients as well as a variety of toxic substances (Kotze, 2000; Zimmels *et al*., 2004).

Wetlands have been used for this purpose in various parts of the world (Wuhrmann, 1972; Kadlec and Kadlec, 1979; Hammer, 1992). The narrow strips of vegetated riparian land can retain and reduce nutrient loading to channels by 65-100%, thus functioning as barriers to eutrophication of rivers and the subsequent lakes and reservoirs into which these rivers feed (Hammer and Kadlec, 1983).

Several physical, chemical and biological processes are involved in the transformation of nutrients within wetlands (Kattelmann and Embury, 1996; Zimmels *et al*., 2004). The major physical process in wetland is sedimentation which depends on the retention time. Chemical processes, which include absorption, chelation, precipitation and ionic exchange, are responsible for major removal of phosphorus compounds (Kattelmann and Embury, 1996). The most important biological processes are those mediated by microorganisms such as the oxidation and reduction of nitrogen (Kattelmann and Embury, 1996). The waters in most wetlands provide suitable conditions for denitrification by anaerobic bacteria, which is the primary mechanism for nitrogen removal (Sather and Smith, 1984).

Wetlands have several attributes that enhance their capacity for nutrient retention including a high capacity for reducing the velocity of the flow of water, thus, enhancing sedimentation (Kadlec and Kadlec, 1979). They allow for a considerable contact between sediments and water because of the shallow water and the fact that they are generally characterized by sheet flow, spread out across the wetland rather than being concentrated in a channel means that they offer an increased surface area over which the biological, chemical and physical processes can operate (Kadlec and Kadlec, 1979).

Wetlands alone, however, cannot solve all eutrophication problems since every wetland has a finite capacity to assimilate nutrients and overloading it will reduce its ability to perform this and other functions (Kotze, 2000). Moreover, the uptake of nutrients by plants does not permanently remove nutrients, but stores them temporarily as a stage in the cycling and recycling of chemicals between the biotic and abiotic components of wetland systems (Helfield and Diamon, 1997). This temporary retention capacity is also finite in itself (Wetzel, 2001).

Nevertheless, wetlands have a key role to play in integrated water quality management problems as their shortcomings are outweighed by their benefits (Kotze, 2000). Riparian areas are likely to remain a critical environmental issue for the foreseeable future because of their broad ecological values, and they should be given a high priority in any type of watershed analysis, project planning, land management, construction activity or restoration work. Conservation of riparian areas is central to sound watershed management (Kattelmann and Embury, 1996).

Nutrient retention and elimination in impoundments is the result of the number of ecological processes taking place in them, which are governed mainly by the retention time of the water (Fiala and Praha, 1982). Phytoplankton activity is important in nutrient retention through the creation of particulate matter. Sedimentation of the phytoplankton and other particulate matter then occurs and is enhanced by the presence of natural precipitants and flocculants and an appropriate phytoplankton structure (Benndorf and Putz, 1987). Benthic denitrification can easily eliminate 80% of the incoming loads of nitrate which emphasises the importance of impoundments as efficient denitrification sites along the river channel (Fiala and Praha, 1982).

The functioning of riverine ecosystems is strongly conditioned by the levels and proportions of nitrogen and phosphorus in the water (McClain *et al*., 1998; Wassman and Olli, 2004). Phosphorus is required in photosynthesis in plants and in energy transfer in both plants and animals (Bourne *et al*., 2002) and the productivity of many rivers is limited by low concentrations of phosphorus. Nitrogen is present in amino acids, nucleotides, and chlorophyll and is therefore a necessary nutrient for all living organisms. It is not as important a limiting nutrient as phosphorus because atmospheric nitrogen can be fixed by microbes, including many species of cyanobacteria found in water.

The levels of nitrogen and phosphorus are critical for aquatic ecosystem functioning (Carpenter *et al*., 1998) but an excess of these nutrients in aquatic ecosystems (particularly as a result of sewage effluent discharge) will change the system with undesirable environmental and economic consequences (McClain *et al*., 1998). Eutrophication leads to an increase in the growth of aquatic plants, often to the point where they become serious problems, and is followed by an increase in animal productivity although changes in the taxonomic composition of these communities may lead to a reduction in their complexity and biodiversity (Behrendt and Optiz, 2000). Some of the problems that result from this high productivity include oxygen depletion and fish kills, unpleasant tastes and odours, increased water treatment costs, the production of toxins from blue-green algae and diminished recreational and aesthetic values (Bourne *et al*., 2002).

An environment that is being polluted can only be managed effectively if information about the quantities, sources and distribution of pollutants and their effects on the environment is available. Data on trends in concentration and the cause and effect of changes, and how far these inputs, concentrations, effects and trends can be modified and by what means and at what coast are also required (Holdgate, 1979). Since the 1960s, the role of nutrients in controlling the trophic state of aquatic systems has been extensively studied but the research has often focused mainly on lakes (Wassman and Olli, 2005) with little attention being paid to rivers and streams which are the major means of nutrient transfer to lakes and reservoirs (UNEP-IETC, 1999).

The capacity of rivers to purify themselves should be managed so that they can absorb pollution before discharging into lakes and reservoirs (Spellman, 1996; Machena, 1997). By understanding the mechanisms governing nutrient retention and their relative importance over a range of conditions, the consequences of certain land use practices can be predicted before their implementation (D'angelo *et al*., 1991). Reliable monitoring data are indispensable for such assessments (Bartram and Ballance, 1996).

MATERIALS AND METHODS

Study area

The study area is located about 17 km north of the Harare city centre (Figure 1) and covered an area of about 1371 ha (Table 1) in the upper part of the Chinyika River, a tributary of the Mazowe River. The river starts in the commercial areas close to Hatcliffe Township. The river flows through Hatcliffe Township, which consists of both a formal settlement and an extensive informal shantytown area and had a population of 23 834 according to the Zimbabwe 2002 census. This is likely to be an underestimate because of the rapid growth of the informal settlements that has taken place since then.

Domestic waste from the township and from the Scientific and Industrial, Research Development Centre, a government research centre, is channelled to the Hatcliffe sewage works where it is treated by a combination of a modified activated sludge system and an extended aeration system. The sewage works is designed to deal with a dry weather flow of 2500 m^3 per day although the wet weather flow can be as much as 3500-6000 m^3 per day. Clear effluent from the clarifiers is discharged into the Chinyika River while solid waste (sludge) is pumped into drying beds from where it spills in to the river and is used as manure by the council workers and nearby community contributing to diffuse pollution.

Below the sewage discharge point, the river passes a squatter settlement where people live in shacks and makeshift houses on the northern side, while on the southern side there are some housing stands where the owners also live in shacks because they occupied these stands despite the fact that basic services like water and sewage are not yet in place. Both the squatters and the stand holders rely on wells and boreholes for drinking water but water is also taken from the river for domestic purposes. There is no sewage system in these areas so residents have to use pit latrines and the bush, thus further threatening water quality in the area.

The major part of the river has a dense growth of *Typha capensis* and *Phragmites australis.* There are two small impoundments in the study area that are primarily used as sources of water for irrigation. Further downstream there are at least eight registered water users who abstract water from the Chinyika River (Mazowe Catchment Office, personal communication) and the possibility that effluents from Hatcliffe now pollute the river is a matter of concern.

Apart from settlement, the study area is predominantly agricultural and the Chinyika River is an important asset to the farmers. The study area is more or less divided by a road running from north to south (Figure 1). To the east of this road, where most settlements are located, all vacant land is heavily cultivated by individuals who have established gardens close to the river and cleared most of the riparian vegetation. A small wetland, which is too wet for cultivation, occurs behind the road and supports a dense population of *Typha capensis*.

Two small commercial farms are located to the west of the road and each has one of the small reservoirs. The first farm is primarily a crop producer and lacks cattle; because of this the upper impoundment supports dense marginal vegetation consisting of *Typha capensis*, while its open water is densely and almost completely covered by *Hydrocotyle spp* and *Lemna spp.* The second farm produces chickens and has large numbers of cattle which have destroyed the marginal vegetation around the lower impoundment. The dam in this farm is surrounded by dense growth of *Typha capensis* while its open water is densely and almost completely covered by *Ceratophyllum* sp.

Table 1: Area of the different sub-catchments in the study area. The sub-catchments represent the area before each sampling station.

Sub-catchment	1	2	3	4	5	6	7	8 (Total)
Area (ha)	1065	1110	1146	1187	1246	1268	1357	1371

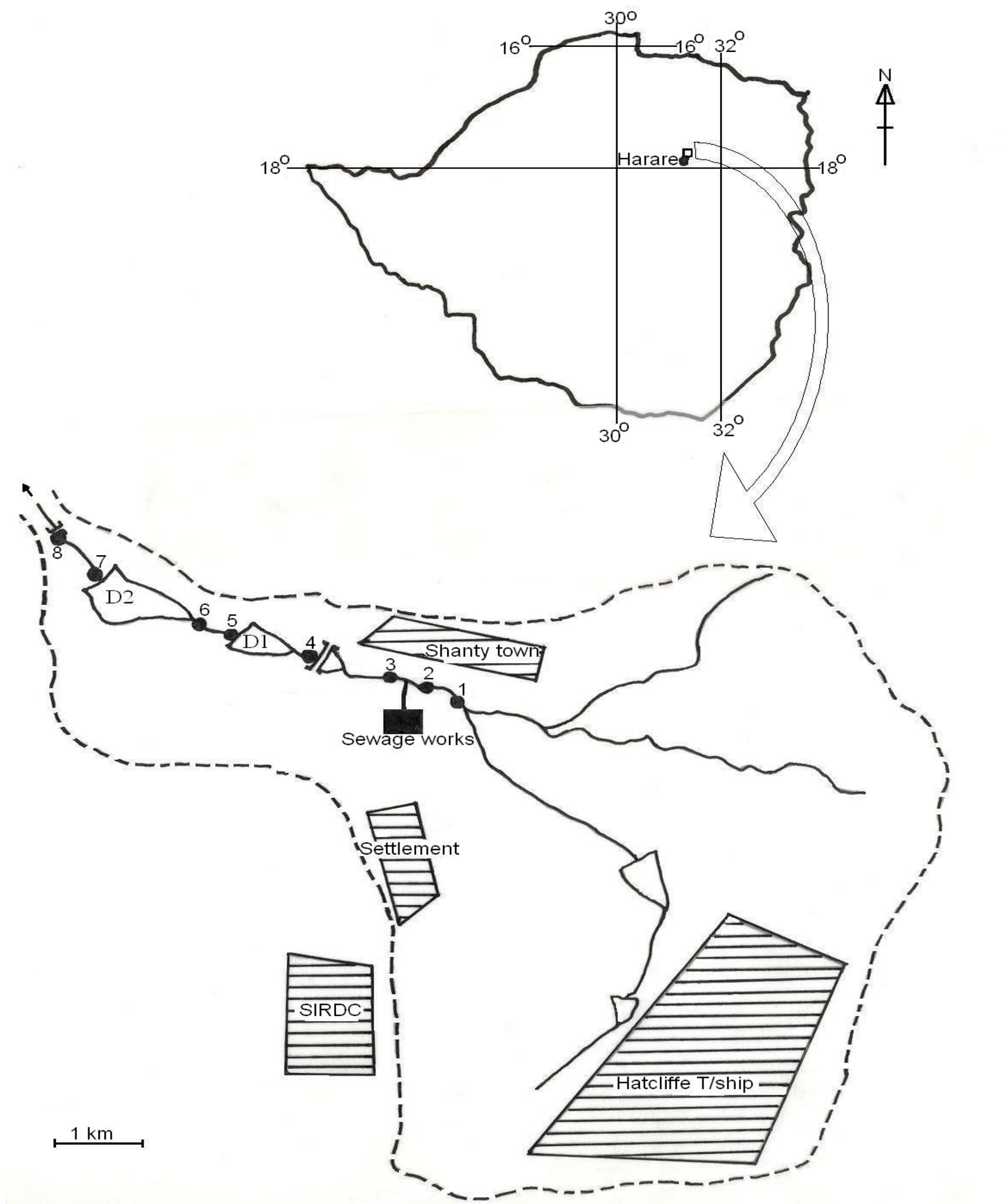

Figure 1: The location of the upper Chinyika River Basin showing the location of sampling stations and human settlements (D1 = dam 1; D2 = dam 2 and wt = wetland).

Data collection

A total of eight sampling stations were established along the river (Figure 1). Stations 1 and 2 were located above the outflow from the sewage works and were intended to be reference points showing the condition of the river before sewage discharge. Both sites were open to contamination from other sources such as accidental discharges from blocked manholes and diffuse pollution from agricultural activities taking place in the catchment. Station 3 was located below the sewage outflow to detect the effect of effluent from clarifiers as well as sludge from drying beds which occasionally spill into the river. Station 4 was at the outflow from the artificial wetland created as a result of road construction while station 5 was located on the outflow of the upper impoundment (D 1). Station 6 was on the inlet of the lower impoundment (D 2) and station 7 was on the outflow from this impoundment. The last station (station 8) was about 700 m downstream from the second impoundment.

Samples were collected each month from October 2004 to February 2005. At each site, dissolved oxygen, electrical conductivity, temperature and pH were measured with the appropriate meters. The concentration of total dissolved solids was measured with a Horiba U23 meter.

The current velocity was measured with a FP 201 global flow probe. The width of the stream was measured with a tape measure stretched across the stream. Depth was measured with a staff gauge across a transect at intervals that were determined by the cross section of the river, being closely spaced where it was irregular or where there was a rapid change in velocity and more widely spaced in the centre of the stream where the flow was uniform.

Water samples for chemical analysis were collected each month from October 2004 to February 2005. Before sampling the sample bottles were cleaned by soaking in a detergent for 24 hours, followed by rinsing with tap water until they were free of detergent. They were then soaked in 5% nitric acid overnight and then rinsed with distilled water. In the field the bottles were rinsed three times with water at the sampling station before the sample was collected, care being taken to throw the rinsed water downstream of the point where the sample was to be collected.

At each sampling point, three grab samples were collected within a distance of five metres of each other and tightly sealed, labelled with date, time and station number and taken to the laboratory for analysis. No preservations were added to the samples before analysis but they were refrigerated within 12 hours of collection.

Laboratory analysis and statistical treatment

The cross-sectional view of each site was plotted on graph paper using the width and depth measurements obtained in the field to obtain cross-sectional area of flow. The discharge was then estimated by the velocity area method using the relation:

$$Q = VA$$

where Q = discharge ($m^3 s^{-1}$), V = mean velocity ($m s^{-1}$) and A = area of cross-section (m^2) (Schumm, 1977).

The concentrations of total phosphorus and total nitrogen, as well as the Chemical Oxygen Demand were determined with a Hach DR/2010 spectrophotometer using the appropriate methods (Hach Company, 1996-2000). These values were then used to estimate the nutrient load in the water at a given time since the nutrient load is the product of concentration and discharge, as follows:

$$L = QC$$

where L = nutrient load (g s^{-1}), Q = discharge (m^3 s^{-1}) and C = concentration (g m^{-1}) (Bourne *et al*., 2002).

The degree of self purification that took place between stations was calculated as follows:

$$S_m = (L_1 - L_2)$$

where S_m = self purification (g s^{-1}), L_1 and L_2 = nutrient load (g s^{-1}) at the upstream and downstream stations, respectively (Bourne *et al*., 2002).

Trace metal levels in sediments were analyzed by Atomic Absorption Spectrophotometry at the Institute of Mining Research Department, UZ.

The significance of the differences in nutrient concentrations from site to site and from one month to another were tested by means of a two-way analysis of variance, as were the differences in nutrient load, self-purification and physicochemical variables from site to site and between seasons. Regression analysis was used to assess the relationship between distance from point of sewage outflow and nutrient levels in water and sediments at stations downstream of sewage outflow.

RESULTS

Physico-chemical conditions in the river

This investigation began in the late dry season (October 2004) and continued into the peak of the rains in January up to February (2005), which meant that there was considerable variation in the flow of the upper Chinyika River. The flow was very low in October (mean = 0.05 $m^3\ s^{-1}$) and November (mean = 0.05 $m^3\ s^{-1}$) but rose in December with the first rains reaching a peak (mean = 1.41 $m^3\ s^{-1}$) in January (Figure 2,). February was unusually dry and the discharge fell to a mean of 0.21 $m^3\ s^{-1}$. The highest discharge generally occurred at station 3 just below sewage outflow, except for the month of January where it occurred at station 6, with the lowest at station 8 suggesting that the two small dams were retaining water and reducing downstream flow (Table 2).

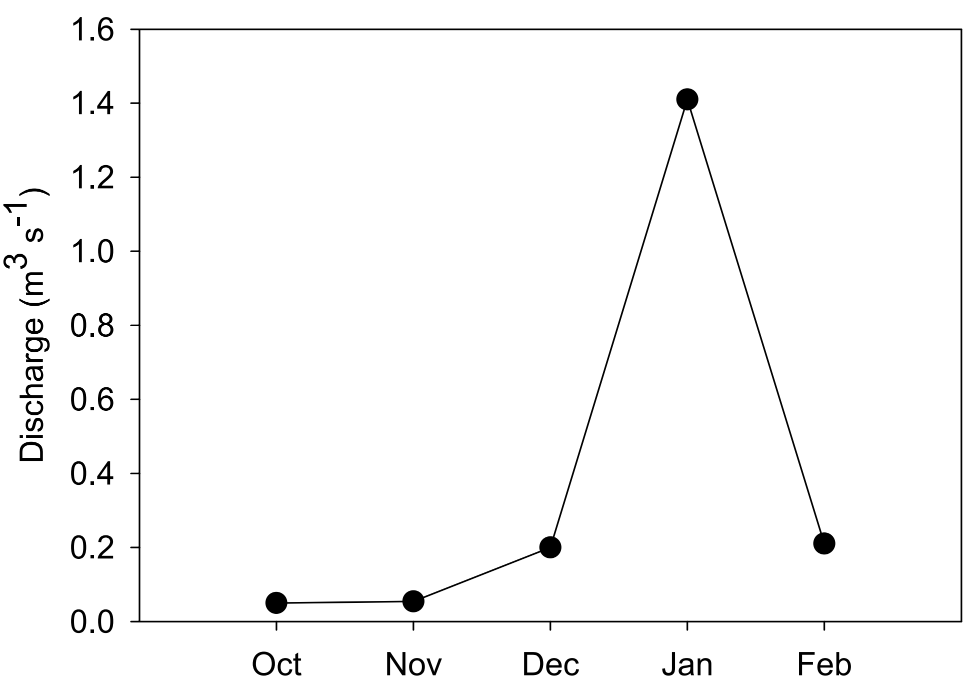

Figure 2: The mean discharge of the Chinyika River at station 8, October 2004 to February 2005.

Table 2: The discharge (m^3 s^{-1}) recorded at eight stations along the Chinyika River, October 2004 to February 2005. The broken vertical line in this and subsequent tables and figures denote the position of the sewage outflow.

	Sampling stations							
	1	2	3	4	5	6	7	8
October	0.06	0.07	0.1	0.05	0.04	0.03	0.03	0.02
November	0.07	0.06	0.09	0.06	0.06	0.05	0.03	0.01
December	0.21	0.23	0.29	0.16	0.15	0.19	0.18	0.21
January	1.25	1.71	1.77	1.71	1.68	1.82	0.73	0.63
February	0.18	0.27	0.31	0.18	0.21	0.17	0.17	0.16

The temperature of the water varied from 19.8°C to 24.4°C (Table 3) but there was no significant variation in temperature among months (Analysis of Variance: $p > 0.05$; F = 1.39) or stations ($p > 0.05$; F = 1.27).

Table 3: The temperature (°C) recorded at eight stations along the Chinyika River, October 2004 to February 2005.

	Sampling Stations							
	1	2	3	4	5	6	7	8
October	20.0	20.0	19.8	20.5	22.4	23.8	23.9	24.4
November	20.3	21.0	21.5	21.1	21.7	22.5	23.1	23.8
December	20.5	20.4	21.1	21.5	21.9	22.2	22.6	22.4
January	21.7	21.8	22.1	22.6	23.2	22.8	22.6	23.1
February	21.3	21.2	21.8	21.6	21.9	21.8	21.7	23.0

The conductivity of the river ranged from about 250-550 μS cm^{-1} during the study period (Figure 3). Generally the conductivity increased from the point of sewage outflow downstream suggesting that (1) the system could not reduce the conductivity of the water and (2) sources of ions other than sewage outflow, such as ground water seepage, also come into play. There was relatively little variation between stations in October but as the rainy season progressed it began to increase at the downstream stations, an effect that was especially pronounced in February. One possible explanation for this is that the river was now feeding the groundwater and at the same time, as the river moves downstream, evaporation concentrated the surface water leading to increased conductivity. There was a significant difference in conductivity between stations upstream and those downstream of the point of sewage outflow (Analysis of variance: $p < 0.05$; F = 4.94) and between the dry and wet months (Analysis of variance: $p < 0.05$; F = 12.29), being higher in the wet season (especially in February).

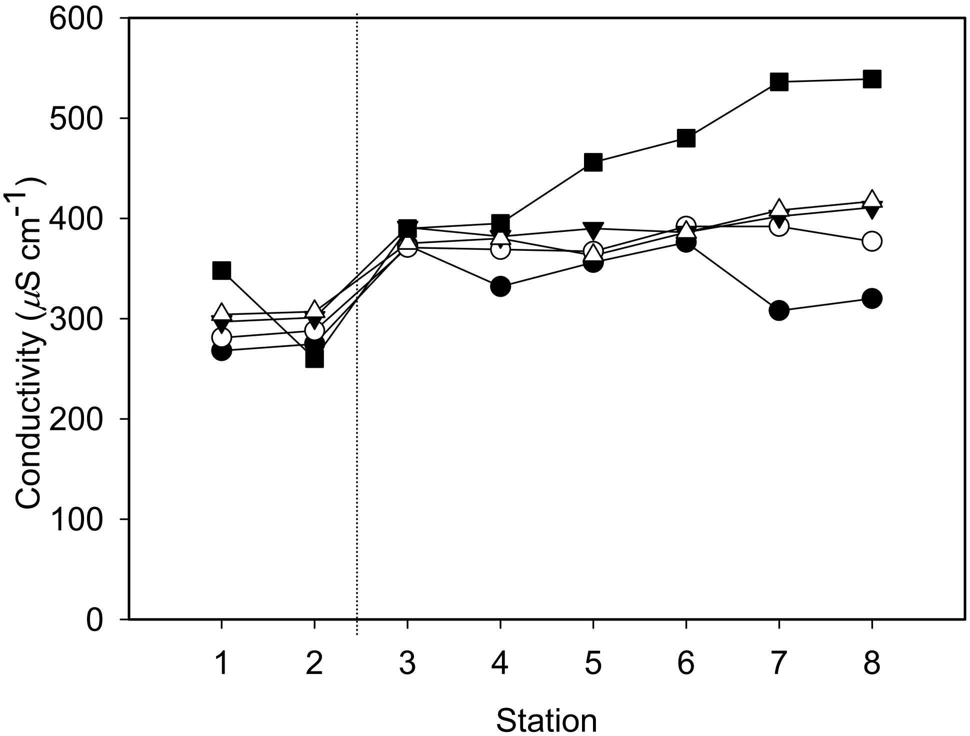

Figure 3: The conductivity of the water at each station in October (●), November (○), December (▼), January (△) and February (■), 2004-05. The broken vertical line in this and subsequent figures denotes the position of the sewage outflow.

The concentration of dissolved oxygen was generally lowest at Station 3 just below the sewage outflow although very low values were recorded at Station 4 in January and February suggesting that organic matter had been washed downstream into the upper wetland by the rains (Figure 4). The lowest values of dissolved oxygen recorded at station 4 also coincided with the observed general senescence of the vegetation in the wetland before this station. There was a general trend of increasing oxygen concentration at the downstream stations. There was significant variation among stations (Analysis of variance: $p < 0.01$; F = 5.41) as well as among months ($p < 0.001$; F = 27.46) being lower during the wet, possibly because of extra loading and movement of organic matter.

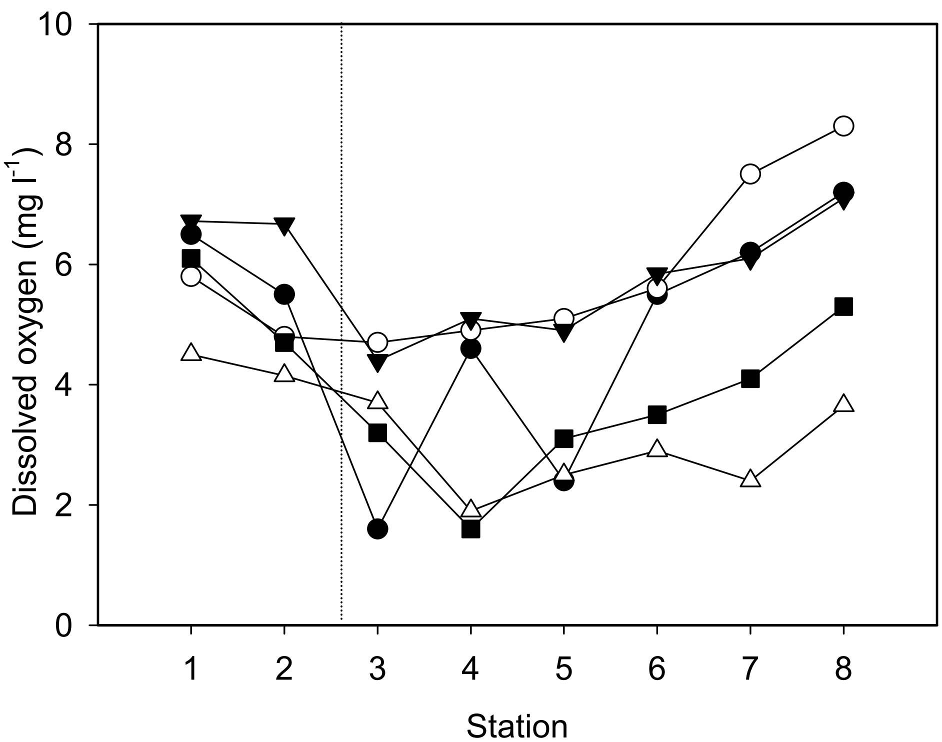

Figure 4: The dissolved oxygen content of the water at each station in October (●), November (○), December (▼), January (△) and February (■), 2004-05.

The water in the river was very slightly alkaline with a mean pH around 7.5 and there was little variation either between stations or between months (Figure 5). The pH values recorded in January and February (mean = 7.5) were slightly higher than those from October to December (mean = 7.3, excluding station 4 in October). The peak in pH at station 4 in October could not be explained and may be an error.

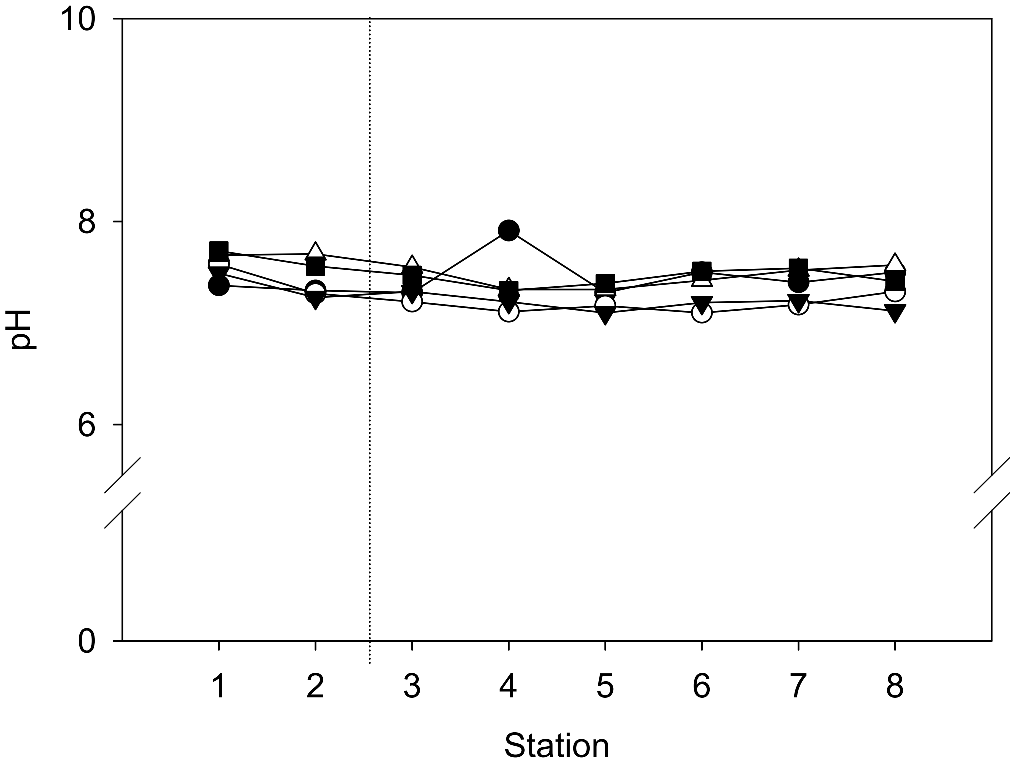

Figure 5: The pH of the water at each station in October (●), November (○), December (▼), January (△) and February (■), 2004-05.

The concentration of total dissolved solids was generally very low, especially in the dry months when it was generally less than 0.1% (Figure 6). The concentrations rose in January and February to mean values of 0.24% and 0.55%, respectively. [The October mean does not include the two peaks recorded at Stations 2 and 8, which cannot be explained.] There was a significant difference among months (Analysis of variance: $p < 0.05$; F = 14.81) and no significant variation was observed among stations $p > 0.05$; F = 0.71)

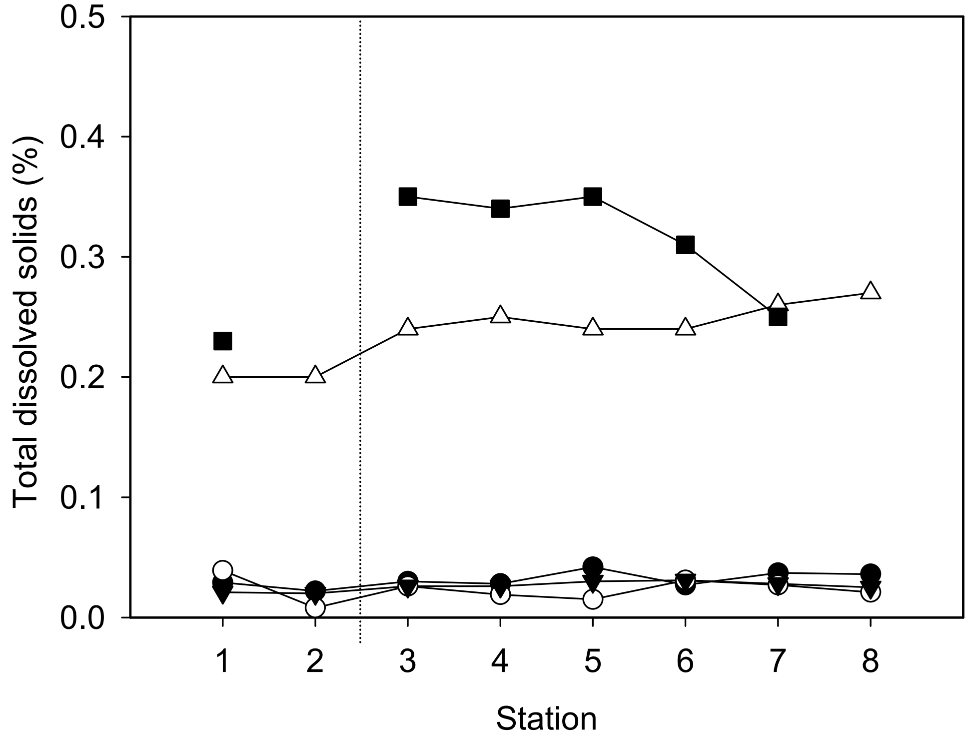

Figure 6: The concentration of total dissolved solids in the water at each station in October (●), November (○), December (▼), January (△) and February (■), 2004-05. The values recorded at station 2 and 7 in February because they could be due to experimental error.

The turbidity of the water was highly variable, ranging from a mean of 5.79 FAU in December to 51.75 FAU in February (Figure 7). There was no clear pattern to the variation in turbidity apart from a tendency to increase immediately below the sewage outflow and then to decrease quite rapidly downstream presumably because of the effects of the wetland and the two dams. There was a significant variation among months (Analysis of Variance: $p < 0.01$; F = 12.68) with the lowest values generally being recorded in dry months, and there was also significant variation among stations ($p < 0.01$; F = 5.29).

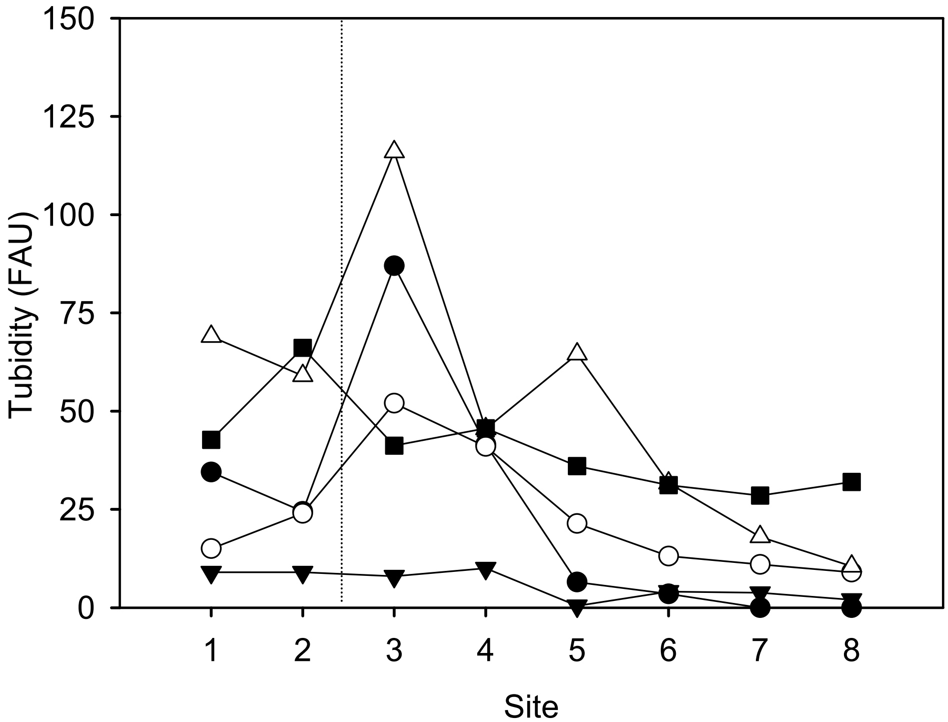

Figure 7: The turbidity of the water at each station in October (●), November (○), December (▼), January (△) and February (■), 2004-05.

Nutrient concentration in water.

The concentrations of total nitrogen tended to be high during the dry months with the highest mean value (6.35 mg l^{-1}) being recorded in November (Table 4). The concentrations fell markedly in December and January but rose again in February, probably because (1) the ratio of sewage outflow to river flow was increasing and (2) organic matter was no longer being flushed from the system. The concentration of total nitrogen varied significantly among stations (Analysis of variance: p < 0.05) and was generally high at station 3 just below sewage outflow with the lowest values being recorded at station 8 suggesting nutrient retention in the system. The concentration of total nitrogen also varied significantly among the dry and wet months (Analysis of variance: $p < 0.05$). The low total nitrogen concentration recorded during the wet season coincides with peak discharge suggesting dilution effect.

There was a general decrease in the concentration of total nitrogen with distance from the sewage outflow (Table 4). This trend varied with season, however, and while there was a strong correlation between the total nitrogen concentration and distance from the sewage outflow in the dry months this was not the case in the wet ones (Figure 8). This is probably because of dilution and the increased flow which carried nitrogen further downstream.

Table 4: Mean concentrations of total nitrogen (mg l^{-1}) recorded at each Station for October, November, December, January and February.

	Sampling stations							
	1	2	3	4	5	6	7	8
October	0.77	1.33	8.50	6.50	5.00	5.50	3.53	0.57
November	0.10	0.27	13.63	12.47	10.17	8.90	5.10	0.17
December	0.10	0.70	1.57	4.00	1.20	1.60	0.83	0.63
January	1.93	3.23	4.70	2.67	1.13	0.87	0.77	1.00
February	5.20	5.16	5.63	6.70	6.10	5.80	6.20	5.90
Mean	1.62	2.14	6.81	6.47	4.72	4.53	3.29	1.65

In February the concentration of total nitrogen rose considerably downstream of the sewage outflow suggesting that the system could no longer reduce the nitrogen level in the water. This coincided with the disintegration of the wetland through the senescence of aquatic plants, especially the bulrushes (*Typha capensis*), which occurred at this time and may have reduced biological uptake of nutrients and hence the system's self-purification capacity.

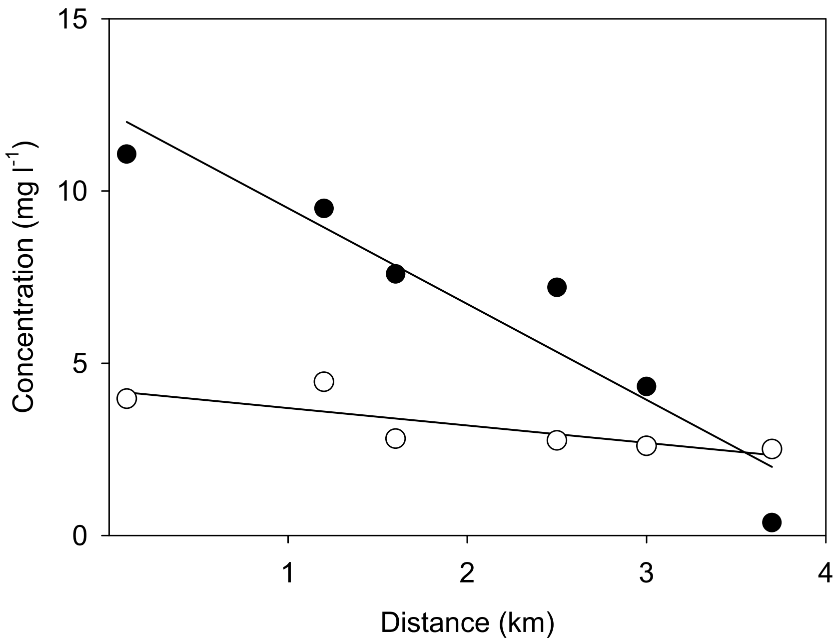

Figure 8: The relationship between the mean concentration of total nitrogen and the distance from the sewage outflow in the dry months, October–December (●) and the wet months, January-February (○). Regression lines were fitted as follows: $y = 12.09-2.71x$, $r^2 = 0.89$, $p < 0.05$ (dry months); $y = 4.16 - 0.49x$, $r^2 = 0.64$, $p > 0.05$ (wet months).

The pattern for total phosphorus was very similar to that for total nitrogen with high concentrations in October and November that decreased in December and January when the rains fell, reflecting the effects of dilution (Table 5). The concentrations rose again in February as flow decreased. Phosphorus concentration was generally highest at station 3 just below the sewage outflow and was lowest at the last station (station 8), except in February when the highest phosphorus values were recorded at station 4 situated below the wetland. This suggested that the wetland was no longer retaining nutrients probably because of the senescence and breakdown of the wetland plants that occurred at that time. As with total nitrogen, this pattern was not consistent and there was a strong negative correlation between phosphorus concentration and distance below the outflow in the dry months (suggesting phosphorus retention in the system), but not in the wet ones probably due to dilution effect (Figure 9).

Table 5: Mean concentrations of total phosphorus (mg l^{-1}) recorded at each station for October, November, December, January and February.

	1	2	3	4	5	6	7	8
October	0.43	0.80	9.30	7.30	4.77	0.43	0.23	0.10
November	0.20	0.27	11.13	7.37	6.57	5.30	0.93	0.27
December	0.40	0.27	0.40	0.50	1.25	0.90	0.70	0.40
January	0.63	0.67	0.90	0.57	0.73	0.57	0.40	0.10
February	0.13	0.33	0.50	4.50	0.53	0.37	0.43	0.30
Mean	0.36	0.47	4.45	4.05	2.77	1.51	0.54	0.23

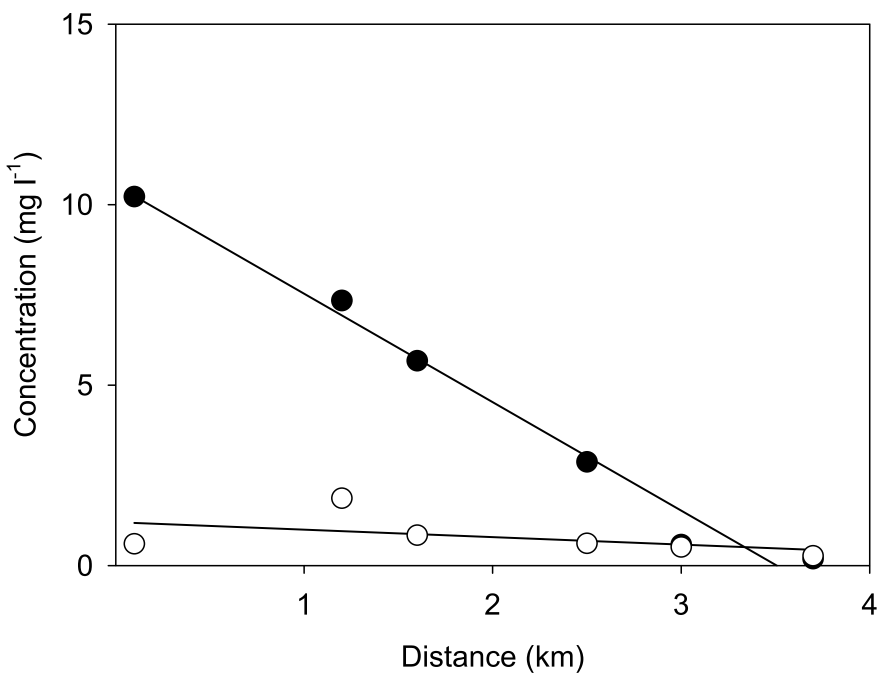

Figure 9: The relationship between the mean concentration of total phosphorus and the distance from the sewage outflow in the dry months, October–December (●) and the wet months, January-February (○). Regression lines were fitted as follows: $y = 10.35\text{-}2.94x$, $r^2 = 0.98$, $p < 0.05$ (dry months); $y = 1.17 – 0.96x$, $r^2 = 0.22$, $p > 0.05$ (wet months).

Nutrient loading and retention

The loading of nitrogen was high during the wet months with a mean (8705 kg $month^{-1}$) being recorded in January (Table 6). This was in contrast to the concentration of total nitrogen, which tended to be highest during the dry months. The loading was lowest in October (mean = 548 kg $month^{-1}$); it increased in November (mean = 982 kg $month^{-1}$) and dropped in December (mean = 690 kg $month^{-1}$). The nutrient loading rose considerably in January (mean = 8705 kg $month^{-1}$) and then dropped sharply in February (mean = 2915 kg $month^{-1}$). This pattern is similar to that of discharge (Figure 2) suggesting that organic and inorganic matter was washed from the catchment to the river channel resulting in the high nutrient loads. High loading was generally recorded at station 3, just after the sewage outflow and the lowest loading was recorded at the last station (8) suggesting that self-purification had taken place between these two stations.

During the dry months, an average of 223 kg $month^{-1}$ of total nitrogen came from the catchment above the sewage outflow and about 1796 kg $month^{-1}$ was added by the sewage works. The section of the river between the sewage outflow and station 4, just after the first wetland, retained 531 kg $month^{-1}$. The subsequent section which includes the first dam retained 665 kg $month^{-1}$ while the wetland between dams 1 and 2 retained 40 kg $month^{-1}$. Dam 2 retained 428 kg $month^{-1}$ and the wetland between dam 2 and the last station retained 219 kg $month^{-1}$.

During the wet months, an average of 6380 kg $month^{-1}$ of total nitrogen came from the catchment above the sewage outflow and 2684.68 kg $month^{-1}$ was added by the sewage works. The subsequent sections retained 3383, 2502, 517, 1150 and 84 kg $month^{-1}$ respectively.

Table 6: The total nitrogen loads (kg month^{-1}) recorded at each Station for October, November, December, January and February. December was included in the calculation of mean monthly loadings for dry and wet months in this and other subsequent tables and figures since it marked the end of the dry season as well as the beginning of the wet season.

	Sampling Stations							
	1	2	3	4	5	6	7	8
October	161	241	1768	830	535	482	295	27
November	26	26	3110	1866	1451	1037	337	3
December	54	402	1179	1768	482	830	428	375
January	6348	15374	21829	12374	5838	4714	1473	1687
February	2322	3363	4185	2903	3217	2443	2637	2226
Mean for dry months	80	223	2019	1488	823	783	353	135
Mean for wet months	2908	6380	9064	5682	3179	2662	1513	1429

The quantity of nutrients retained through self-purification (Table 7) varied insignificantly between the different subsections of the river downstream of the sewage outflow (Analysis of variance: $p > 0.05$) as well as between the dry and wet months (Analysis of variance: $p > 0.05$).

Table 7: The quantity of total nitrogen (kg month^{-1}) (self-purification capacity) retained in different sections of the Chinyika River downstream of the sewage outflow.

	Stretches between stations					
	3 & 4	4 & 5	5 & 6	6 & 7	7 & 8	Mean
October	937	295	54	187	268	348
November	1244	415	415	700	334	622
December	-589	1286	-348	402	54	161
January	9455	6535	1125	3241	-214	4028
February	1282	-315	774	-194	411	392
Mean for dry months	531	665	40	430	219	
Mean for wet months	3383	2502	517	1150	84	

During the wet months some sections of the river acted as sources of nutrients instead of sinks resulting in negative self-purification (or nutrient retention) values (Table 7). This suggests that previously retained nitrogen may have been re-suspended during storms or extra nutrients were coming from other sources in the sub-catchments. This also coincided with the disintegration of the wetland through the senescence of its vegetation suggesting that a reduced uptake of nutrients by plants contributed to reduced self-purification.

Table 8: The total phosphorus loads (kg month^{-1}) recorded at each station for October, November, December, January and February.

	Sampling Stations								
	1	2	3	4	5	6	7	8	Mean
October	107	134	1929	937	509	27	27	11	460
November	26	52	2644	1089	959	622	52	8	681
December	348	402	911	777	509	482	348	214	499
January	2250	3107	4044	2518	3268	2812	964	509	2434
February	73	218	363	1959	242	121	145	121	405
Mean for dry months	160	196	1828	934	659	377	142	78	
Mean for wet months	890	1242	1773	1751	1340	1138	486	281	

Table 9: The quantity of total phosphorus (kg month^{-1}) (self-purification capacity) retained in different sections of the Chinyika River downstream of the sewage outflow.

	Stretches between stations					
	3 & 4	4 & 5	5 & 6	6 & 7	7 & 8	Mean
October	991	428	482	0	16	384
November	1555	130	337	570	44	527
December	134	268	27	134	134	139
January	1526	-750	455	1848	455	707
February	-1597	1718	121	-24	24	48
Mean for dry months	893	275	282	235	65	
Mean for wet months	21	412	201	653	204	

The pattern for total phosphorus was very similar to that of total nitrogen. The loading was directly proportional to discharge (Figure 2) being high during the wet months possibly because of a lot of organic matter and soil that was being washed away from the catchment by runoff into the river (Table 8). The loading was also lowest in

October (mean = 460 kg month^{-1}) when discharge was low and was highest in January (mean = 2434 kg month^{-1}) when discharge was also high. The highest loading was generally recorded at station 3 just after sewage outflow as expected and lowest levels was recorded at the last station suggesting phosphorus retention between the two both during the dry and wet months. The total phosphorus retention /self-purification capacity varied insignificantly among the different subsections of the river downstream of the sewage outflow (Analysis of variance: $p = > 0.05$) as well as between the dry and wet months (Analysis of variance: $p = > 0.05$).

During the wet months, an average of 1242 kg month^{-1} of total phosphorus came from the catchment above the sewage outflow, and 531 kg month^{-1} was added by the sewage works. The section between the sewage outflow and station 4 just after the first wetland retained 21 kg month^{-1}, a value that is lower than the one obtained during the dry season (893 kg month^{-1}) possibly because of reduced residence time of the water and reduced sedimentation, which is the main process of phosphorus retention in wetlands. This also suggests that previously retained phosphorus was flushed away during storms and this section acted as source rather than a sink as in February where negative self-purification was recorded (Table 9). The low nutrient retention capacity could also be attributed to wetland disintegration through vegetation senescence during this period, suggesting reduced nutrient uptake by plants. This was probably true for all the other sections where negative self-purification amounts were recorded.

The section of the river between stations 4 and 5 that includes the first dam retained 412 kg month $^{-1}$ while the wetland between dams 1 and 2 retained 205 kg month

$^{-1}$. Dam 2 retained 653 kg month $^{-1}$ and the wetland between dam 2 and the last station retained 204 kg month $^{-1}$.

During the dry months, an average of 196 kg month^{-1} of total phosphorus came from the catchment above the sewage works and 1632 kg month^{-1} were added by the sewage works. The subsequent sections retained 893, 275, 282, 235 and 63 kg month^{-1} respectively. The annual estimates of loading and retention of nutrients in the different sections of the Chinyika River followed monthly values (Table 10) for the same reasons.

Table 10: Estimates of the annual nutrient loading (tonnes yr^{-1}) at the eight sampling stations along the Chinyika River.

	Sampling stations							
	1	2	3	4	5	6	7	8
Total nitrogen	21	47	77	47	28	23	12	10
Total phosphorus	7	9	24	17	13	10	4	2

Relationship between catchment area and nutrient loading.

There was a general tendency towards an increase in nutrient loading with increasing catchment area from station 1 up to station 3, just after the sewage outflow suggesting a cumulative effect which could not be corrected possibly because of the degradation of riparian vegetation as a result of stream-bank and streambed cultivation in this area (Figure 10). From station 3 downwards, there was an inverse relationship between catchment area and nutrient loading. This suggests retention of nutrient by the riparian vegetation in the first wetland which is too wet to be cultivated and in the area after the road where the riparian belt is protected by commercial farmers.

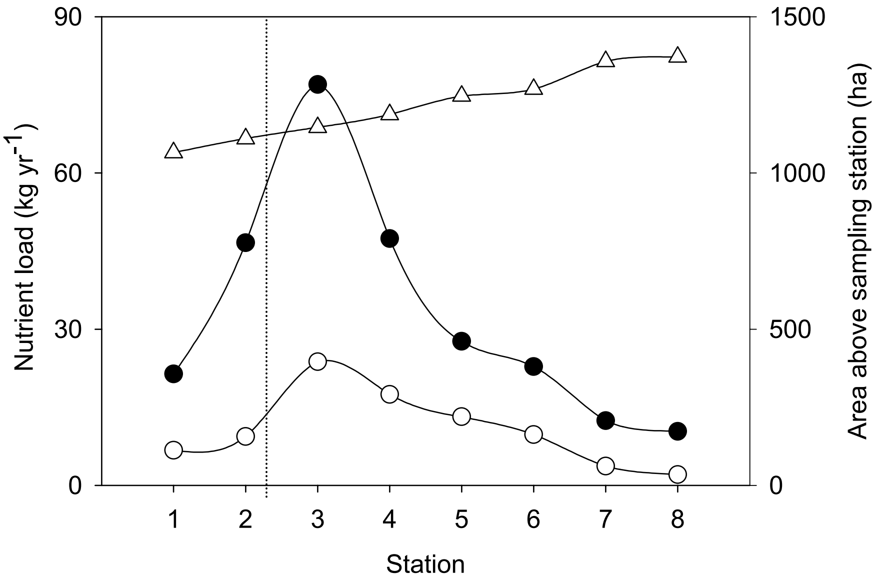

Figure 10: The estimates of total nitrogen (●) and total phosphorus (○) loading in relation catchment areas (△) above each sampling station in the upper Chinyika River.

Nutrient concentration in sediments

The levels of nutrients in the sediments followed a broadly similar pattern to those in the water being highest immediately below the sewage outflow and then decreasing with distance downstream (Table 11). The concentrations of both nitrogen and phosphorus were significantly different in the dry and wet months (Paired T-Test: nitrogen, $p < 0.05$. T = 3.81; phosphorus, $p < 0.05$, T = 3.61), being high in the dry months. This is probably because the nitrogen and phosphorus retained in the streambed sediments during low flow was re-suspended and flushed away during storms. High flow creates high energy environments in the river which suspend and transport previously deposited sediments. The sediments, along with their associated nutrients, are carried downstream until energy levels decrease and they are again deposited. In contrast to the situation with nutrients in the water, there was a significant negative correlation, in both the dry and wet months, between the distance below the sewage outflow and the levels of total nitrogen (Figure 11) and phosphorus (Figure 12) in the sediments. This suggests that, unlike the flowing water body, sediments were not prone to dilution effect.

Table 11: The levels of total nitrogen and total phosphorus (mg g^{-1} dry sediment) in the sediments during the wet and the dry months. The horizontal broken line denotes the position of the sewage outflow.

	Total nitrogen		Total phosphorus	
Station	Dry months	Wet months	Dry months	Wet months
1	0.41	0.11	0.02	0.01
2	0.53	0.12	0.19	0.01
3	2.97	1.51	1.31	0.27
4	1.67	0.55	0.98	0.12
5	1.19	0.31	0.46	0.04
6	0.73	0.16	0.11	0.02
7	0.38	0.13	0.01	0.01
8	0.19	0.08	0.01	0.01
Mean	1.01	0.37	0.39	0.06

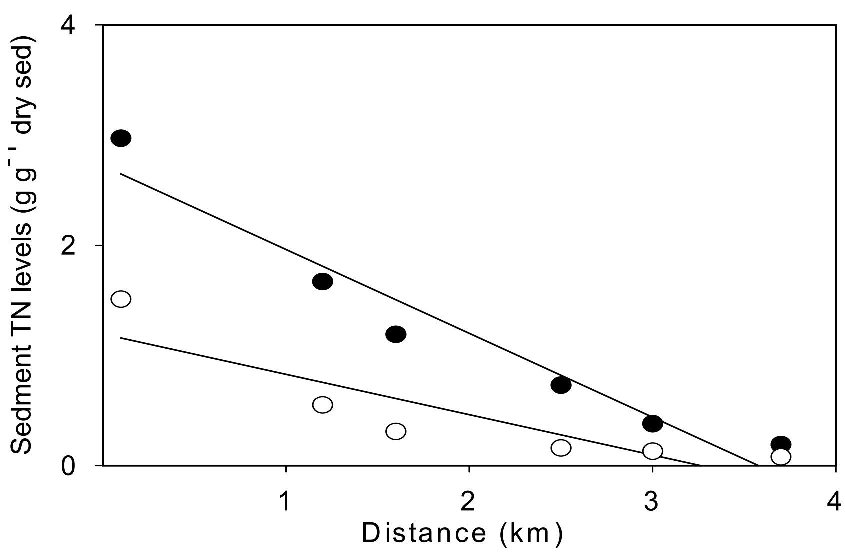

Figure 11: The relationship between the levels of total nitrogen in sediments and the distance from the sewage outflow in the dry months, October–December (●) and the wet months, January-February (○). Regression lines were fitted as follows: $y = 2.68 - 0.75x$, $r^2 = 0.95$, $p < 0.05$ (dry months); $y = 1.18 - 0.36x$, $r^2 = 0.78$, $p < 0.05$ (wet months).

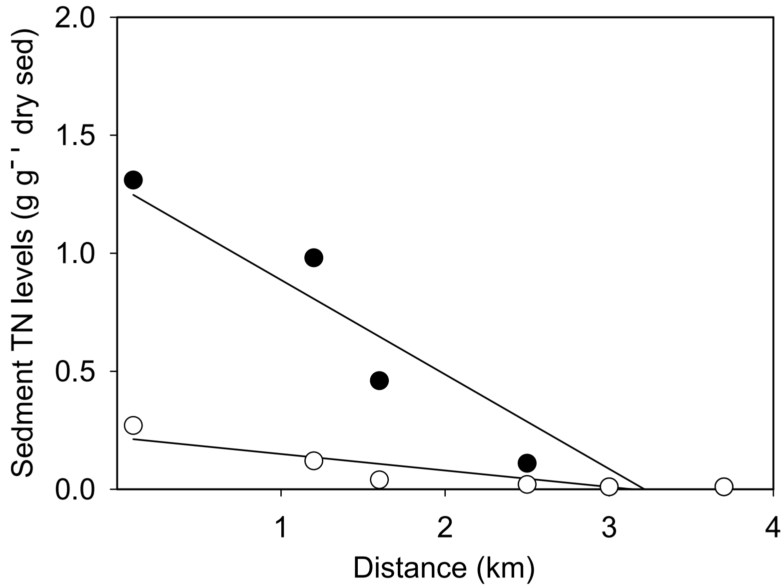

Figure 12: The relationship between the levels of total phosphorus in sediments and the distance from the sewage outflow in the dry months, October–December (●) and the wet months, January-February (○). Regression lines were fitted as follows: $y = 1.26 - 0.39x$, $r^2 = 0.91$, $p < 0.05$ (dry months); $y = 0.22 – 0.07x$, $r^2 = 0.8$, $p < 0.05$ (wet months).

Heavy metals level in sediments

In any situation where sewage is discharged there is always the possibility of heavy metal contamination. The levels of heavy metals showed no detectable pattern on all the stations both during the dry and wet months (Table 12). An exception to this was the level of cadmium which could not be detected during the dry months and this could not be explained.

The heavy metal levels were expected to be highest just below the point of sewage outflow (station 3) and then decrease downstream due to retention processes operating in the river channel, but this was not the case in this study. This suggests low heavy metal levels in sewage effluent, a situation which can be explained by the observation that no much industries discharging heavy metal-reach effluent are connected to the sewage system. The heavy metal levels varied insignificantly between the wet and the dry months (Paired T-Test: Cu, $p > 0.05$, T = 0.00; Fe, $p > 0.05$, T = -2.40; Ni, $p > 0.05$, T = -0.84; Zn, $p > 0.05$, T = 1.20)

Table 12: The trace metal levels in sediment from the upper Chinyika River in the wet and dry months. Nd = not detected, broken horizontal line denotes position of sewage outflow. All values in parts per million (ppm) except for iron which is a percentage.

	Cadmium		Copper		Iron		Nickel		Zinc	
Station	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet
1	Nd	5.4	96.8	130.6	8.7	8.5	50.5	97.0	142.2	158.8
2	Nd	5.6	106.4	144.2	5.0	4.9	66.8	102.2	144.0	202.0
3	Nd	5.2	162.2	137.8	6.2	8.2	96.9	76.2	483.0	390.0
4	Nd	5.0	166.6	150.8	5.8	8.3	98.5	86.0	318.2	384.0
5	Nd	5.0	147.6	157.6	5.6	4.7	90.1	116.2	292.2	118.6
6	Nd	4.2	131.9	116.0	5.6	8.1	86.8	80.8	190.1	102.6
7	Nd	4.6	122.5	136.6	5.1	8.1	79.1	88.8	165.8	117.0
8	Nd	2.8	113.3	73.8	5.3	8.3	70.8	53.6	81.2	63.6

DISCUSSION

The nutrients from the sewage effluent discharged into the upper Chinyika River are retained in a distance of about 4 kilometres from the point of sewage outflow. Since high levels of nutrients are undesirable in aquatic systems and the reclamation of the system is in most cases a very difficult tusk, this natural system that effectively removes nutrients from water in the river channel should be closely monitored. Working towards protecting and improving the upper Chinyika River system's nutrient retention capacity should be considered as a complement to other programmes and efforts to protect water quality.

The self-purification process in upper Chinyika River can result in water quality similar to that of the stream above the sewage works in a distance of about 4 kilometres from the point of sewage outflow. This is very important as it guards against water quality deterioration in downstream impoundments such as the Mazowe Dam. Since the effluent of some towns becomes the water supplies of the other towns downstream (Mason, 1981), this study is very important for downstream water users who may use the river as source of their domestic water. This is often the case in Zimbabwe since large part of the rural population relies on river water.

High self-purification capacity occurs in the section of the river whose riparian wetlands have been greatly modified by stream-bank and streambed cultivation and cattle grazing. What if riparian wetlands could be restored and monitored? This will dramatically improve the self-purification capacity of the system. The proper construction, design, monitoring and maintenance of the effectiveness of the riparian wetlands along the Chinyika River and other rivers in Zimbabwe, therefore, holds great potential as cheap and environmentally friendly technology for enhancing riverine self-purification.

A small wetland (about 1.5 ha) between stations 3 and 4, that could not be cultivated because it is very wet, appeared to retain a lot of nutrients annually. Like other wetlands, however, its retention capacity is finite and as Hatcliffe Township continues to grow, a point will be reached where the wetland can no longer cope with nutrients in sewage effluent and this is likely to have an impact on downstream water users. All attempts to improve the wetland’s processes and functions will fail if the wetland continues to be regarded as infinitely robust and more effluent continues to be discharged in to the river system because of population growth. The situation is likely to be further complicated in future by the forecasted high frequency with unpredictable occurrence and distribution of extreme whether events such as severe rain storms, droughts, and severe winter spells that are likely to affect the water quality of rivers (IUCN, 2003).

As a way of ensuring the continued functioning and better service provision by this wetland, its area should be increased so as to increase the time and area over which biological, physical and chemical processes operate. This can be achieved by banning urban agriculture, which has been the policy of the government for years but its implementation remains to be seen. The other option for increasing wetland area is to rise the walls of the bridge at station 4 by say 0.5 m and this is likely to more than double the area covered by the wetland because of the flatness of the terrain.

The use of wetlands for wastewater reclamation has been applied in several similar incidences and has proved to work quite efficiently. In 1970, Harare City Council used effluent from sewage treatment plant for irrigating pastures so as to reduce nutrient loading in Lake Chivero and it proved to be quit effective at list for some time (Marshall, 1997). On the Yellow Jacket stream, riparian wetlands were shown to be effective pollution controllers (Magadza and Masendu, 1986) and some data on the Mukuvisi River show similar possibilities (Machena, 1997). In Uganda the National Sewage and Water Cooperation supported conservation of papyrus swamps and other wetlands near Kampala because of the role they pay in purifying water supplies (Barbier *et al*., 1997).

The other option of maintaining or improving self-purification in the Chinyika River amidst future threats on water quality is construction of more impoundments. The two small impoundments currently in this system greatly enhance the self-purification capacity of the Chinyika River. The construction of more impoundments downstream is likely to improve the self-purification capacity of the river and should be an option worth considering by local authorities to safe guard downstream water quality.

The self-purification capacity was low in February because of riparian vegetation senescence. The nutrients previously locked up in plant matter were released back in to the system as the vegetation decayed. The permanent removal of nutrients locked up in vegetation from the system can be achieved through vegetation harvesting (Zimmels *et al*., 2004)

The nutrient loading increased with increasing discharge, probably because of organic and inorganic matter being washed from diffuse sources in the catchment, supplying sufficient nutrients to maintain a eutrophic state in the system. The ZINWA effluent standards which form the basis of the present pollution control activities in Zimbabwe provide no framework for control of non-point sources of pollution such as storm water runoff in this case. These guidelines can, therefore, not guarantee that quality objectives in receiving waters will continue to be met (Gumbo, 1997). A closer examination of these guidelines is, thus called for so that they factor in diffuse pollution, but this is admittedly difficult and costly.

Several management options may be considered to reduce the impact of storm water runoff on receiving water bodies such as routing of storm water through wastewater treatment works, creation and maintenance of riparian wetlands, or the combination of the above (Thornton and Nduku, 1981). The first option is expensive as it involves the construction of additional sewer mains and expansion of wastewater treatment facilities that will be used, under Zimbabwean conditions, only for a fraction of a year. The second option has been the policy of the government for years and this study has shown the important role played by riparian wetlands in storm water reclamation. The protection of the riparian wetlands in the upper Chinyika River, therefore, constitutes a promising water quality maintenance tool worth considering by the local government.

The self-purification capacity of the upper Chinyika River has been successfully quantified. This enables ascribing of economic value to the system to be made (Constanza *et al*., 1997) which gives ecosystem services more weight in policy decision. This gives ecosystems a legitimate place in consideration of options for water quality management. The restoration of riparian wetlands and design of shallow impoundments on tributaries of reservoirs such as Lake Chivero for management of water quality in the system is, thus recommended. The harnessing of the natural self-purification process in constructed wetlands where optimum conditions can be maintained for treatment of municipal wastewater is also an option worth considering by local authorities.

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