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Full Length Research Paper

Modeling the fluxes of nitrogen, phosphate and sediments in Linthipe catchment, Southern Lake Malawi Basin: Implications for catchment management

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This study was carried out to investigate the fluxes of nutrients and sediments in Linthipe River catchment of Lake Malawi basin and the manner in which it is affected by anthropogenic activities and natural processes. Data on climate, nutrients, land use, soil and hydrology were collected to model fluxes of nutrients and sediments using the generalized watershed loading function (GWLF) model. The correlation coefficient (r^2) derived from comparing the observed and simulated river discharge was 0.92. For sediments, total nitrogen and total phosphorus, comparison of predicted values with observed data were not statistically significant. The data was also used to model hypothetical management scenarios. A hypothetical 10% deforestation of the catchment may lead to an increase in annual sediment, nitrogen and phosphorus loads by 27.1, 15.7 and 2.9%, respectively. The GWLF approach overall appears to provide reasonably good estimates of mean annual sediment and nutrient loads. Results from this study suggest that anthropogenic activities (agriculture and deforestation) may be by far the largest source of sediment and nutrient loading especially during the rainy season.

Key words: Fluxes, nutrients, sediments, anthropogenic activities, catchment management.

INTRODUCTION

There have been several ecological changes in Linthipe River and its receiving water body, Lake Malawi related to elevated sediments and nutrient levels in recent decade. For example, the decline in rock-algae production has been observed where sediments cover the rock sub-stratum in Lake Malawi (Munthali, 1997) and this causes a disruption of the littoral food web (Worthington and Lowe-McConnell, 1994). Furthermore, sediments clog breeding sites for the rock-dwelling cichlids such as the ‘Mbuna’, which comprise almost 50% of all fish species in the lake (Reinthal 1993; Munthali, 1997). The collapse of Ntchila (*Labeo mesops)* stocks is speculated to be due to habitat degradation, water quality changes and overfishing. These species migrate in groups into rivers to spawn. The *Labeo* species were abundant in the rivers and the lake and formed the basis of an important fishery in the 1950 and l960s. Currently, the gill net catch of these species has declined to less than 1% of their former levels (Bootsma and Hecky, 1999). Other changes such as decline of commercial important species, plankton succession and encroachment of invasive aquatic weeds such as water hyacinth have also been documented (UNEP-IETC, 2003; World Bank, 2003). The fact that changes in sediment and nutrients’ fluxes related to anthropogenic pressure are inevitable, raises the question: what will be the ecosystem’s response to these changes? Since different data sets are available in the catchment, it is possible to integrate these data sets into models in order to comprehend nutrient and sediment fluxes response to anthropogenic impacts such as land use change.

In recent years, there have been several successful applications of the General Watershed Loading Function (GWLF) model to watershed studies (Howarth et al., 1991;

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Abbreviations: GWLF, Generalized watershed loading function; **SWAT,** soil and water assessment tool; **SWMM,** storm water management model; **HSPF,** hydrologic simulation program- Fortran; **SCS-CN,** soil conservation service curve number; **USLE,** universal soil loss equation.

Table 1. Major database that were used for Linthipe watershed model simulation.

Database	Information sources
Climate (daily precipitation and temperature 1996)	Literature data
Land use/land cover 1996	Literature (SADC GEF Project data base)
Elevation and slope	Literature
Soils parameters	Local soil maps
Hydrography	Local hydrograph map
Nutrient concentration in runoff and soils	Literature and GWLF manual
Water discharge and water quality data	Literature and UNESCO database
Population	National statistical office (NSO) database
Sewer system or septic tanks	Literature estimates
Point sources	State and local statistics

Dodd and Tippett, 1994; Swaney et al., 1996). This particular model is therefore a good tool to exploit, in order to study sediment and nutrient loads over others primarily because of ease of use and reliance on data input that is less exotic and easier to compile than other watershed oriented water quality models such as soil and water assessment tool (SWAT), storm water management model (SWMM) and hydrologic simulation program-fortran (HSPF) (Deliman et al., 1999). The model has been endorsed as a good mid-level model that exhibit algorithms for simulating key mechanisms controlling nutrient and sediment fluxes in watersheds (US EPA, 1999). Although a number of studies have been attempted on erosion rates, modeling, poverty and river system management in the catchment (Mkanda, 2002; Lam et al., 2002; Kaunda and Chapotoka, 2004), there is still minimal understanding on the transport of dissolved nutrients and sediments, their fluxes, potential sources and processes. This paper presents results of modeling the nutrients and sediment fluxes in the Linthipe River catchment, a mid-sized tropical river that is under ecological pressure due to intensive human activities in the catchment.

MATERIALS AND METHODS

The GWLF model built on BasinSim (desktop simulation system software) was used to investigate the river's response to changing scenarios. The general structure and the mathematical description of the GWLF model are given in (Haith et al., 1987, 1992; Dai et al., 2000). The primary emphasis of this research was to statistically evaluate calculated and predicted mean annual river discharge, sediment and nutrient fluxes in the interest of determining utility of GWLF modeling approach in the basin and propounding management implications. It was hypothesized that the GWLF modeling framework can be applied to simulate the changing fluxes of nutrients and sediments in response to land use change and management choices.

Collection of catchment wide data

The first step involved collection of data. In this case catchment wide data was collected on climate, land use, soil, nutrients, water quality and population maintained by different agencies (Table 1) in order to model the fluxes of nutrients and sediments in Linthipe catchment.

Using the catchment wide data and the GWLF model for nutrient and sediment simulation

The second step involved using the collected catchment wide data to model nutrient and sediment fluxes using the GWLF model. For nutrients (N and P) and sediment simulation, three input files were constructed namely the transport file, nutrient file and weather file. In addition, seven optional files were supplied to use the advanced features of BasinSim (e.g. displaying maps and databases, customizing septic system parameters, etc.). Input data for the GWLF model was obtained through databases maintained by various agencies such as the Meteorology Department, SADC/GEF project, District assemblies, etc. Other input parameters were estimated based on literature research and the GWLF 2.0 manual (Haith et al., 1992). The input files and information sources are summarized in Table 1. This data was used to parameterize a GWLF catchment model to simulate the hydrological transport of non-point and point sources of sediments and nutrients from the catchment to the river outlet. Detailed description on how to customize the input files is given in Dai et al. (2000). The model calibration was based on comparing observed discharge (literature) with predicted discharge.

Using the GWLF model to simulate hypothetical scenarios

The third step involved simulation of river discharge, N, P and sediment load based on hypothetical scenarios (*vis a vis* 10% deforestation scenario, reduction of sediment delivery through construction of bunds scenario and baseline). In this step three hypothetical scenarios described below were simulated and results were compared with the baseline scenario. The scenarios were selected on the basis of what is possible in the framework of the current agri-environmental policies and deforestation rate.

Scenario I

This was the baseline scenario where a given land use and soil characteristics were used to simulate river discharge, N and P fluxes.

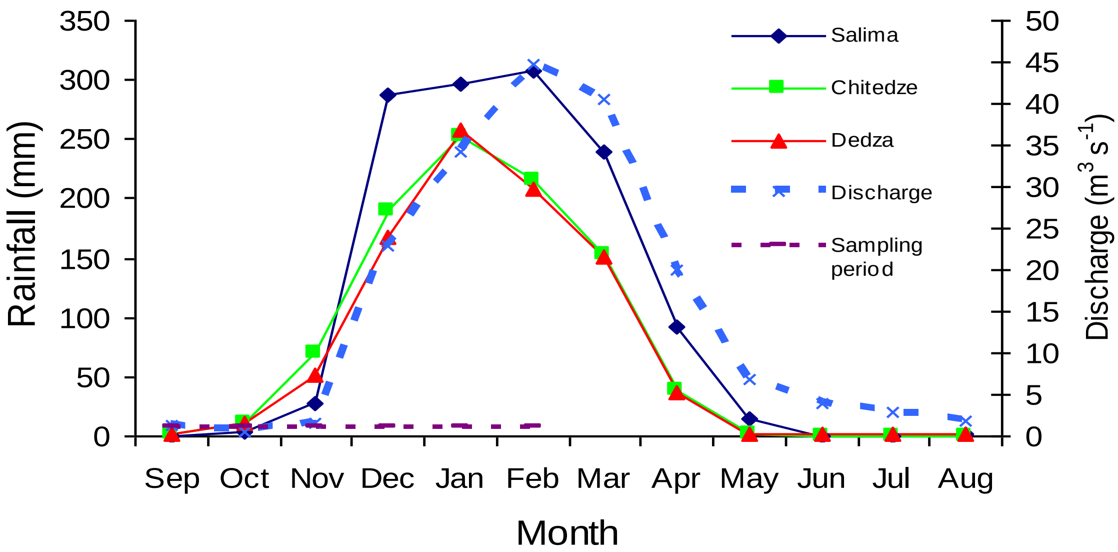

Figure 1. Rainfall and discharge data from Linthipe catchment. (Salima, Chitedze and Dedza are the three stations located in Lakeshore Plain, Lilongwe Plain and Dedza Hills, respectively. Rainfall data from 1996 to 2006. Mean discharge is based on 10 year data recorded at Malapa station).

Scenario II

This is one of the most classical solutions to reduce the sediment delivery by construction of large retention bunds. Here, three sediment retention bunds which can lead to reduction of sediment delivery ratio by 30% were simulated.

Scenario III

In this scenario, a hypothetical 10% deforestation of the Linthipe catchment is simulated concurrent with 10% agriculture land increase. With the current rate of deforestation of 1.6% per annum (SOER, 2002), 10% deforestation can be attainted in 6¼ years.

For most parameters, relevant statistical tests such as t tests were performed to compare observed parameters with simulated parameters using Graphpad Instat Software (Wass, 1998). For all tests, a fiducial significance level of $p < 0.05$ was chosen.

RESULTS

Average rainfall and river discharge data (Figure 1) from three stations in the catchment show that the rainy season begins from early or mid November and ends in mid May. In this case all data from September to mid November were categorized as dry season period and all data from end November to mid February were categorized as rainy (wet) season.

The correlation coefficient (r^2) derived from comparing the observed and simulated value was 0.92 for river discharge (Figure 2). In general, the GWLF model over predicted the river discharge, especially during the rainy season. Predicted river discharge, sediment, nitrogen and phosphorus are given in Figure 3. Using the Welch corrected t test, the predicted mean annual TSS, total nitrogen and total phosphorus values were not statistically different ($p = 0.531$, $p = 0.216$, $p = 0.300$) from the calculated/observed values at the 95% confidence interval (Table 2). With dissolved phosphorus, however, results based on Welch corrected t test showed some differences ($p = 0.047$). Based on these findings, the framework was then applied to simulate the three scenarios described earlier in this paper, to investigate the nutrient and sediment response to different management scenarios.

Using the GWLF model to simulate hypothetical scenarios

Applying the GWLF model to simulate scenario II and III with reference to scenario I as baseline, yielded interesting results from management point of view. Based on scenario I as baseline, preliminary results indicate that scenario II would lead to a reduction in sediment, total nitrogen and phosphorus fluxes by 33.1, 12.9 and 17.8%, respectively. A hypothetical 10% deforestation of the Linthipe catchment (scenario III) may lead to an increase in annual sediment, total nitrogen and total phosphorus loads by 27.1, 15.7 and 2.9%, respectively (Table 2).

DISCUSSION

Modeling sediment and nutrient fluxes

Although the observed river discharge closely agreed with predicted river discharge ($r^2 = 0.92$), the GWLF over predicted river discharge especially during the periods of high flow (Figure 2). This may be due to groundwater

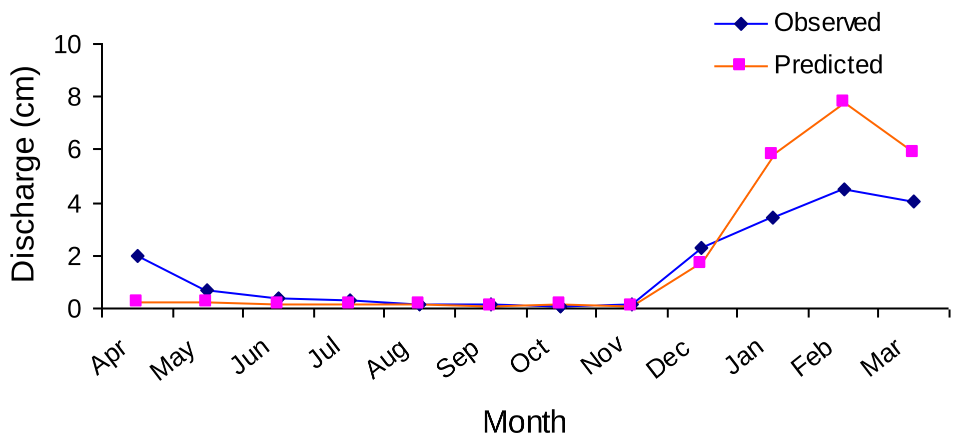

Figure 2. Simulated and observed discharge in Linthipe River. (r^2 = 0.92 and Pred/Obs =1.467. Note: the GWLF model calculates daily discharge in units of centimeters of water depth over the surface area of the watershed).

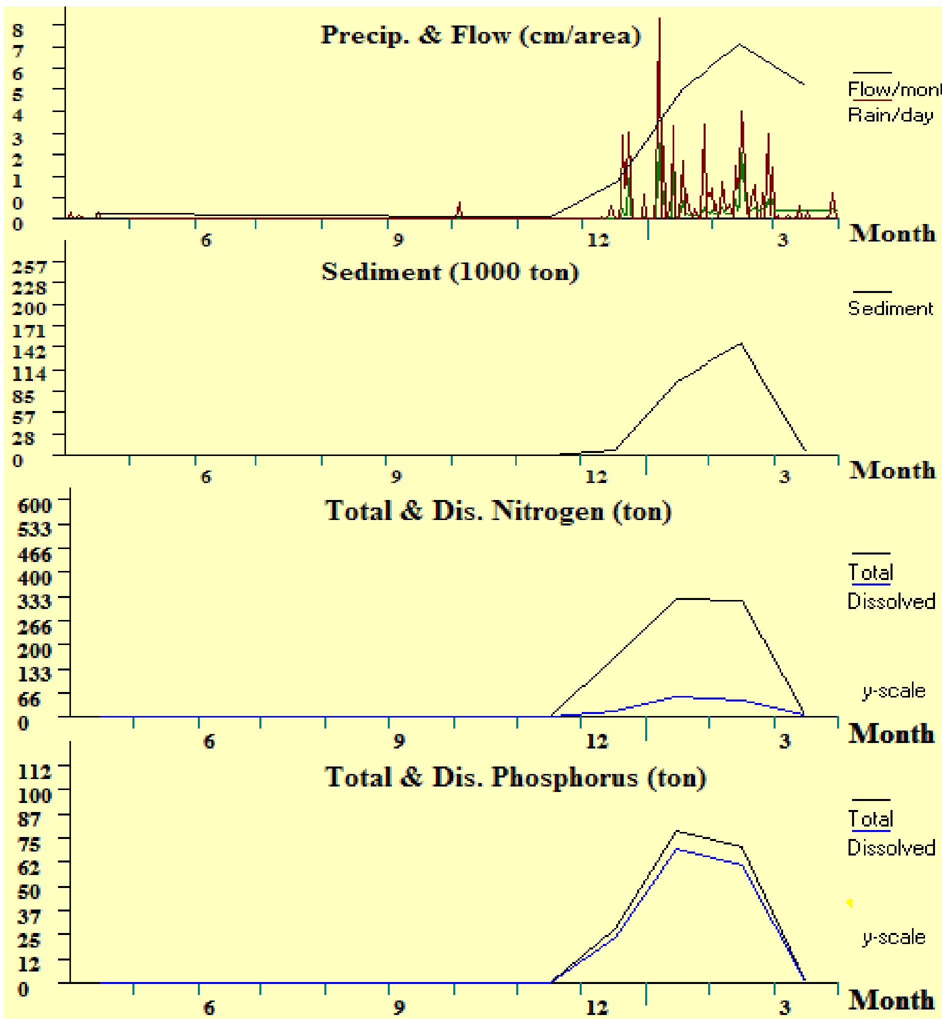

Figure 3. Precipitation, simulated discharge, sediment, nitrogen and phosphorus in Linthipe River (Month are represented according to hydrological year starting with April ending in March see Haith et al., 1992. 4=Apr, 5=May, 6=Jun, 7=Jul, 8=Aug, 9=sep, 10=Oct, 11=Nov, 12=Dec, 1= Jan, 2=Feb, 3=Mar).

Table 2. Simulated discharge (stream flow), nitrogen and phosphorus for three scenarios in Linthipe catchment.

Flux	Calculated/observed flux (Baseline) (1996 data)	Scenario I Predicted flux	Scenario II		Scenario III	
			Flux	Change	Flux	Change
TSS ($\times 10^5$ ton yr^{-1})	2.56	2.69	1.78	-33.1%	3.24	+27.1%
Dis N ($\times 10^2$ ton yr^{-1})	1.69	1.78	1.24	-27.1%	297	+73.5%
Tot N ($\times 10^2$ ton yr^{-1})	8.20	8.46	7.16	-12.9%	9.52	+15.7%
Dis P ($\times 10^1$ ton yr^{-1})	1.47*	2.51*	1.34	-3.2%	1.45	+4.8%
Tot P ($\times 10^2$ ton yr^{-1})	1.77	2.16	1.41	-17.8%	1.77	+2.9%
Stream flow ($\times 10^1$cm)	1.83*	2.27*	2.29	0%	2.43	+8.9%

Statistically significance tested at 0.05 fiducial level.

drainage in the watershed. The GWLF model assumes that all groundwater flow in a surface subwatershed stays in that watershed. However, several studies have reported that a large portion of the groundwater flow may discharge into streams (Winter, 1999; Klijn et al., 1999).

In general the predicted mean annual total nitrogen, total phosphorus and sediment load were extremely good. Although it appears that some modeling accuracy is lost with respect to dissolved phosphorus, the differences were weakly statistically significant ($p = 0.047$, Table 2 and Figure 3). Evans et al. (2002) suggest that for P modeling accuracy improves as one move from shorter time periods to longer time periods. In line with the findings of this study, other studies have observed that fluxes of sediment, nitrogen and phosphorus in Linthipe River were higher during the rainy season than during the wet season (Gomani, 2007). This may be caused by changes in soil erosion rates (K) factor during the rainy season discussed later in this paper. Since the predicted total nitrogen, total phosphorus and sediments were not statistically significant from observed values, the GWLF approach is a viable approach. Based on these results, the GWLF approach overall appears to provide reasonably good estimates in sediment and nutrient simulation.

Applying the GWLF model to simulate hypothetical scenarios

In order to understand the mechanism governing the behavior displayed by the three scenarios, there is a need to understand the model facility. GWLF models surface runoff using the Soil Conservation Service Curve Number (SCS-CN) approach with daily weather (temperature and precipitation) inputs. Erosion and sediment yield are estimated using monthly erosion calculations based on the Universal Soil Loss Equation (USLE) algorithm (with monthly rainfall-runoff coefficients) and a monthly composite of KLSCP values for each source area (e.g., land cover/soil type combination). The KLSCP factors are variables used in the calculations to depict changes in soil loss/erosion (K), the length/slope factor (LS), the vegetation cover factor (C), and the conservation practices factor (P). The two hypothetical scenarios influenced the transport capacity by manipulating KLSCP factors (Lee et al., 2000).

Scenario II changes the slope length while scenario III changes vegetation cover thereby affecting sediment and nutrient fluxes differently. The decrease in sediments and nutrients simulated by scenario II is a common phenomenon of managed catchments because of reduction of physical transport. The increase in nutrient and sediment load simulated by scenarios III (Table 2) is a common phenomenon of disturbed catchments because of increased physical transport. Both scenarios are potentially important ecological function which can be achieved by different management choices. The fluxes of sediments, nitrogen and phosphorus simulated from III of the model, are consistent with general ideas of disturbed ecosystems (Boynton, 1995). Increase in sediment loads and associated nutrients in surface runoff should therefore be fairly a universal effect of degraded catchments, because of the physical nature of the processes involved (see Humborg et al., 1997; Milliman, 1997). However, the influence of episodic events such as floods may be difficult to predict and need to be better understood (Swanston, 1991).

Application of the modeling approach, achievements and gaps

Application of the GWLF modeling framework in Linthipe catchment gave promising results. It appears that catch-fment activities such as land use change (deforestation) may be by far the largest source of sediment and nutrient load to receiving waters especially during the rainy season (Table 2, Scenario III). Interestingly, matching the hydrological cycle and agriculture cycle suggests similar results. The question that arises is what happens to the recipient water body, Lake Malawi? Data from this study are insufficient to determine conclusively these questions. This topic is potentially ripe and can constitute an important area for future research. Therefore, the behavior of sediment and nitrogen and phosphorus fluxes depicted under scenarios I to III, are potentially possible important ecological trajectory and signal of ecosystem's response from a disturbance. It is encouraging however to note that results similar to those presented here, have been obtained by closely analogous studies (Lee et al., 2000; Howarth, 1991).

However, there are a number of limitations to this modeling framework. Due to lack of detailed observed data for the model, this study used available literature data in the study area to produce the best estimate values for the model coefficients (Table 1). Most recent reliable data on land cover and soil information is needed to improve this modeling framework. For example, local farming practices may affect nutrient discharges, therefore fertilizer application rates should be estimated with field surveys in the local area to provide the model with adequate applied nutrient rates. The need for adequate, reliable data is evident in application of many modeling frameworks to generate the best agreement between computed and observed data. However this does not undermine the findings of this study. Since historical water quality measurements are not routinely available for Linthipe catchment and many catchments in Lake Malawi basin, the potential use of the GWLF approach in such situations cannot be underestimated. In essence, it has helped the study to identify data and knowledge gaps to improve future monitoring and modeling work in the catchment. Results of the study are therefore not a final product for catchment management, but rather an investigation of the possible states which the catchment may attain depending on management choices.

Results from this study therefore illustrate that the GWLF approach overall appears to provide reasonably good estimates of mean annual sediment and nutrient loads in Linthipe catchment. Application of the modeling framework to simulate hypothetical scenarios suggest that anthropogenic activities (agriculture and deforestation) may be by far the largest source of sediment and nutrient loading especially during the rainy season.

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