A Modelling Approach for Lake Malawi/Nyasa/Niassa: Integrating Hydrological and Limnological Data

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A MODELLING APPROACH FOR LAKE MALAWI/NYASA/NIASSA: INTEGRATING HYDROLOGICAL AND LIMNOLOGICAL DATA

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Abstract This study presents a toolkit approach for linking land- and lake-based data and models to determine the impact of human activities on the water quality of rivers and lakes. The integrated modelling framework was adapted to address specific issues and scenarios. Based on the preliminary results, a hypothetical 50% re-forestation of the Linthipe Watershed in the southern part of Lake Malawi/Nyasa/Niassa may lead to a decrease in the spring peak value of total phosphorus concentration from about 15 μg/L to 10 μg/L in the top layer (0 – 40 m) of the lake's Outlet Basin. Discussions on improvement to future modelling and monitoring programs are also presented.

1. INTRODUCTION

Lake Malawi/Nyasa/Niassa (hereafter called Lake Malawi) is one of Africa's critical ecological resources and its aquatic biodiversity has drawn international attention. To protect this valuable resource and to maintain sustainable development, collaborative and cooperative efforts by the three riparian states of Malawi, Tanzania and Mozambique are required, with support from the international community. Catchment issues such as agriculture, deforestation, reforestation, transportation and regional economic development have been identified as key concerns in the area. To study the possible impact of these issues on the environment, a modelling project was conducted by the United Nations University/International Network for Water, Environment and Health, the University of Waterloo and WL|Delft Hydraulics. Supported by the World Bank, the study integrated physical and biogeochemical processes that affect water quality in Lake Malawi and its tributary rivers.

The detailed results of the modelling project can be found in the final report (University of Waterloo et al., 2000). In this paper, we focus on the discussion of one specific aspect of the preliminary model results, namely the investigation of the dependence of lake water quality on human activities in the catchment. Our main purpose is to determine how human activities such as agricultural practices and deforestation may affect the water quality of rivers and streams and subsequently lead to changes in nutrient loading to the lake. Our hypothesis is that the impact from such catchment runoff to the lake will be significant, particularly in the lake basin that receives the increased loading. To confirm this hypothesis, we first make use of all relevant meteorological, land-use, soil type, topographical and other hydrological data and knowledge for the development and calibration of a catchment model to simulate the hydrological transport of non-point and point sources of nutrients from the catchment to the river outlet. We then use meteorological and limnological data, including nutrient loading data, as well as simulated results from a lake hydrodynamic model to develop and calibrate a lake water quality model; this model simulates the transport and dispersion of nutrients within the lake, in order to predict the water quality conditions. The third step involves combining the catchment model and the lake water quality model to simulate the changes in lake water quality due to hypothetical changes in land use practices. Due to the lack of observed data to calibrate and verify the models, this study also aims to identify data and knowledge gaps to improve monitoring and modelling work. The study is therefore not designed to develop a final product for catchment management, but rather to investigate the possible outcomes and to identify the uncertainties in predicting lake water quality by varying land use practices. The emphasis is on the modelling approach and how it can be used to improve the design of future monitoring and modelling studies, with more coordinated efforts to measure and integrate meteorological, hydrological and limnological information to support better management of the lake and its environment.

2. MODELLING APPROACH

To select the appropriate modelling approach for this study, we consider the water quality condition in the lake as affected by the nutrient input. As shown in Figure 1, there are three major sources of nutrient inputs to Lake Malawi: land-based discharge, atmospheric deposition and upwelling return. Nutrients from the catchments discharge into the lake and are subject to various physical and biochemical processes. To estimate the impact of these land-based sources of nutrients, we simulate the transport of the nutrients from the catchment into the streams using a hydrological catchment model, the Agricultural Non-point Source (AGNPS) model (Young et al., 1986; Leon et al., 2000). Other inputs to the lake must also be included, such as atmospheric deposition (Bootsma et al., 1996), upwelling return from deep layers of the lake, vertical nutrient distribution and other information about water quality (Hecky et al. 1999). As the nutreints enter the lake, they are carried by lake currents and their distribution is affected by both horizontal and vertical transport and dispersion, as well as the lake's thermal regime. A hydrodynamic model, the DELFT3D model (Delft Hydraulics et al., 1999; Kernkamp et al. 1994), is used to predict these hydrodynamic and thermal regimes. Specifically, it uses advanced turbulence closure models (Delft Hydraulics et al., 1999) for the vertical mixing induced by wind, currents and stable and unstable stratification. The mass and heat fluxes from rivers are included in the model and the sources and sinks can be distributed vertically, e.g. to represent the inflow of cold river water. For the Malawi modelling study, it was modified to become a 2-dimensional (longitudinal and vertical) model, mainly for practical reasons. While the physical processes are taking place, the nutrients also undergo algal uptake, regeneration, sedimentation, nitrification, de-nitrification and other biochemical processes. These processes are simulated by a water quality model, the NWRI Water Quality Box model (Lam et al., 1987).

As shown in Figure 2, the modelling approach consists of incorporating the loading and input data and integrating the catchment and hydrodynamic model results with the lake water quality model to produce the scenario prediction. The integration step is implemented using the RAISON Decision Support System (Lam et al., 1994). The RAISON system is a generic system that offers input facilities to accept various types of data and maps, which are then stored in its own internal and fully-linked database, map subsystem and graphic components. Often, there are two phases in the construction of a decision support system (Lam, 1997): the technical user interface (TUI) and the public user interface (PUI). The technical user uses the TUI to connect databases, rule-bases and models and control decision processes, such as scenario building and testing. When completed, the TUI may form the basis of the PUI. The PUI is for managers and stakeholders and may even be used in public consultation meetings (Young et al., 2000).

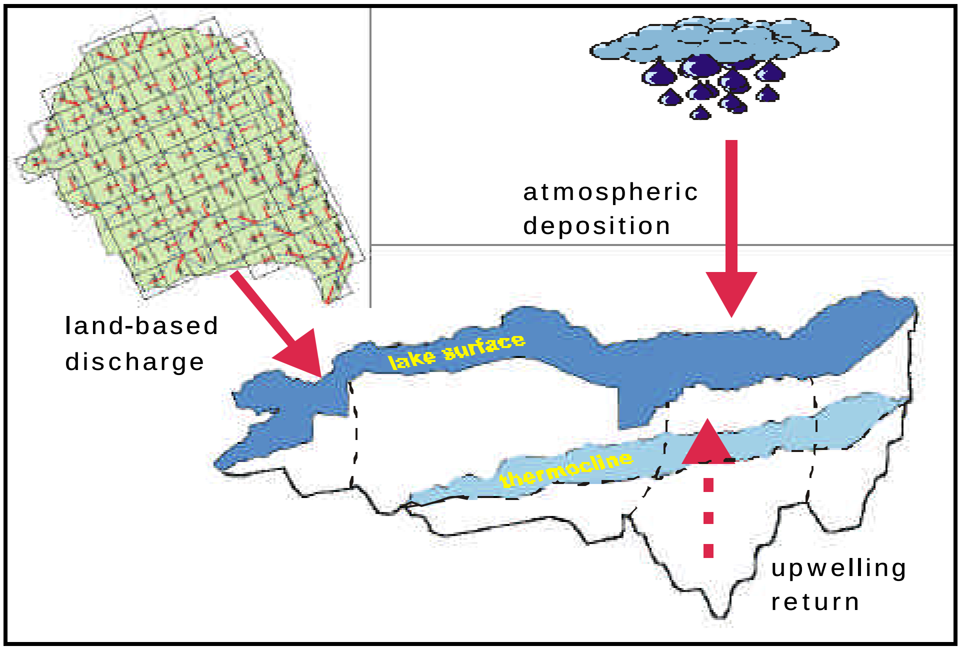

Figure 1. Schematic showing the three sources of nutrient input to the productive zone of the lake: land-based discharge, atmospheric deposition and upwelling return.

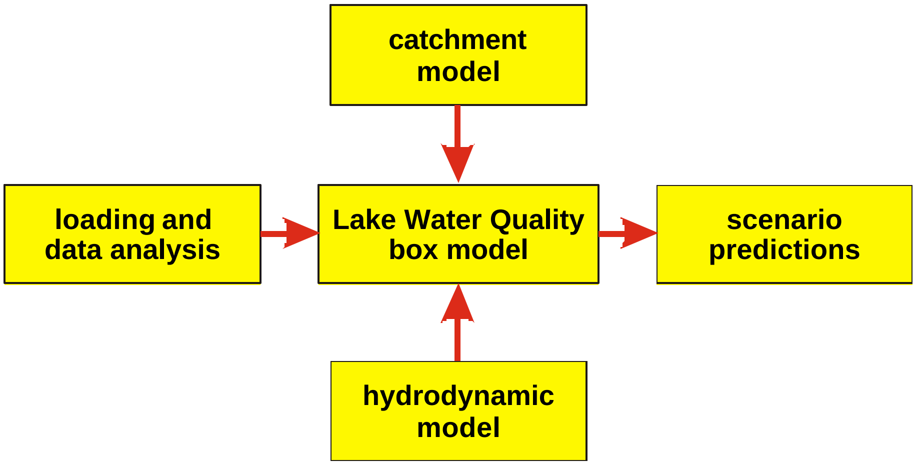

Figure 2. Linking input data and model results in RAISON.

In this paper, because we discuss only the linkage between the land-based hydrological and lake water quality models, the emphasis is on the use of TUIs. For example, data files with information on the atmosphere, river, lake and upwelling return from deep layers in the lake are input through TUIs. Also, there are three ways to incorporate models into RAISON. The first way is to run the model separately and feed the model results in as input. This is the method used to incorporate the results from the hydrodynamic (DELFT3D) model in this project. The computed results such as transport and temperature are only required by the lake water quality models. Thus, the hydrodynamic model can be left off-line from the other models, with a weak link to RAISON. The second way is to have the model linked to RAISON, with the model making use of the RAISON databases, maps and graphical facilities. An example of this method is the catchment model (AGNPS), which has its own code but its input and output files are linked through TUIs to the database, map and graphical components of RAISON. This linkage enables the catchment model to communicate directly with the water quality box model in order to generate iterative results for testing the effects of land use scenarios on lake water quality. The third way is to rewrite the code for the model in a programming language (e.g. Visual Basic) which makes it possible to link the model directly. The water quality box model (NWRI Box Model) is such a case, as the original code for this model required modification to accept input from the AGNPS and DELFT3D models, as well as to generate appropriate results for specific scenario predictions, including a new nitrogen process component. The implementation of the modelling approach is shown in Figure 2. Summer et al. (1990) used a similar approach linking the AGNPS model to a lake process model, but they did not have a technical interface as implemented here.

3. CATCHMENT MODEL

The AGNPS model (Young et al., 1986) is a distributed event-based catchment model that simulates surface runoff, sediment, and nutrient transport, primarily from agricultural catchments. The nutrients include nitrogen (N) and phosphorous (P), both essential plant nutrients and possible major contributors to surface water pollution. Runoff volume and flows are calculated using the Soil Conservation Service (SCS) curve number method (Young et al. 1986). Upland erosion and sediment transport is estimated using a modified form of the Universal Soil Loss Equation, USLE (Wishmeier and Smith, 1978). The sediment transport and depositional relationship, which is based on a steady-state continuity equation, is described by Foster *et al*. (1980). Chemical transport is calculated based on the relationships adapted from the CREAMS model (Frere *et al*., 1980 and Knisel, W.G., 1980). As a preliminary modelling effort for this project, this model was selected for application to a pilot catchment where sufficient data, in Geographical Information System (GIS) format, were available for model input and calibration. In this study, we chose the Linthipe Watershed as the pilot site, not only because there are sufficient data but also because the catchment provides land-based nutrient input, including phosphorus and nitrogen discharges, to the smallest lake basin on which we can test our hypothesis on the connection between land use and lake water quality.

3.1 INPUT TO CATCHMENT MODEL

Catchments modelled by AGNPS are divided into homogenous square working areas called cells. Subdivision of main cells into smaller sub-cells provides flexibility to account for heterogeneity in the catchment. Due to this spatial segregation, all catchment characteristics are expressed at the grid-cell level, thus requiring the input of spatially distributed data that is handled through the use of a GIS component, such as the one available in RAISON. Cell data include information on values based on topography, soil type, land use and management practices within each cell. Through the AGNPS/RAISON interface (Leon et al., 2000), we can automatically extract the required information for each of these grid cells from GIS map layers as part of the model input processes. In the model, some variables such as land slope and flow direction can be derived from a topography map, while others such as the SCS curve number are functions of soil type and land use. Thus, the automatic extraction of map data, included in the AGNPS Interface, requires a Digital Elevation Model (DEM) file as well as GIS map files for soil type and land use. Figure 3 shows the soil type map, overlain by the grid cells, and Figure 4 shows the land use map for the Linthipe Watershed. While minor adjustments were necessary to convert some local land use types to similar ones specified in the AGNPS model inputs, no further adjustments in the model coefficients defined by the map extraction process was made. The calibration results using these values were found to be adequate for the available data.

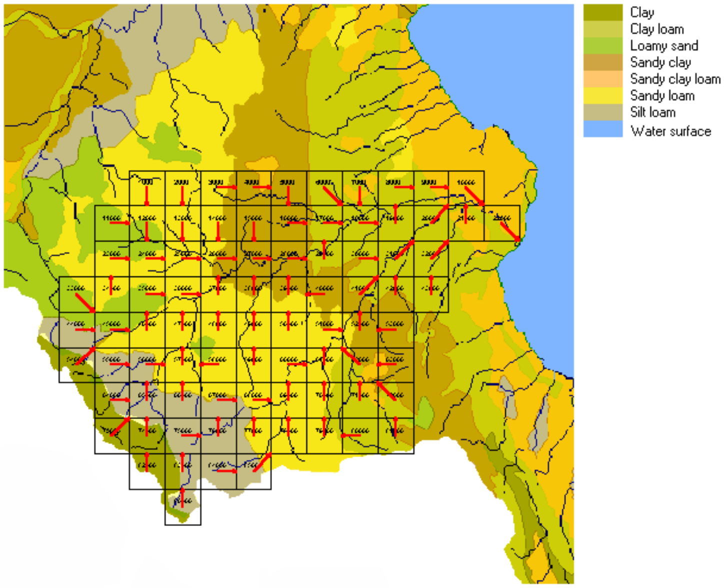

Figure 3. Soil type layer map for the Linthipe Watershed area, showing the grid cells and average flow directions used in the AGNPS model.

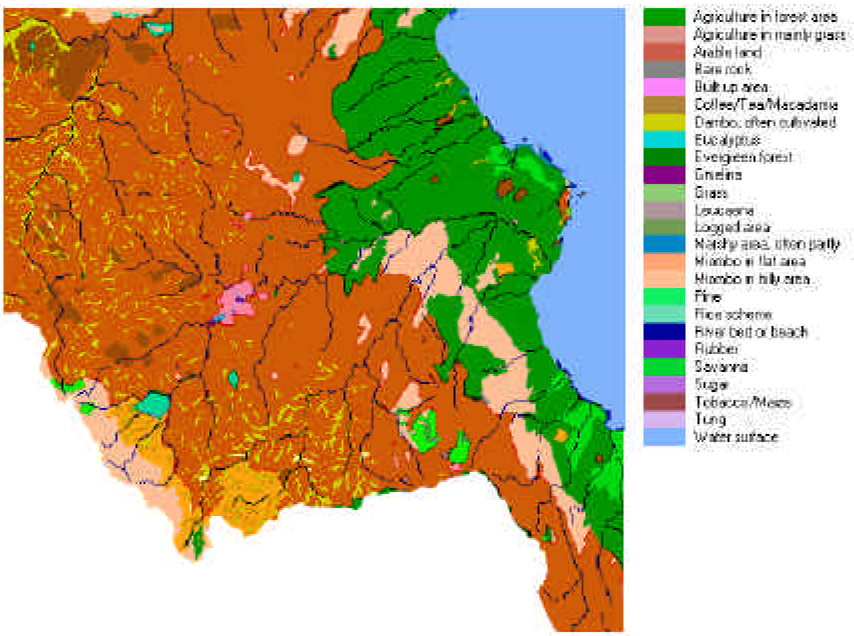

Figure 4. Landuse layer map for the Linthipe Watershed area.

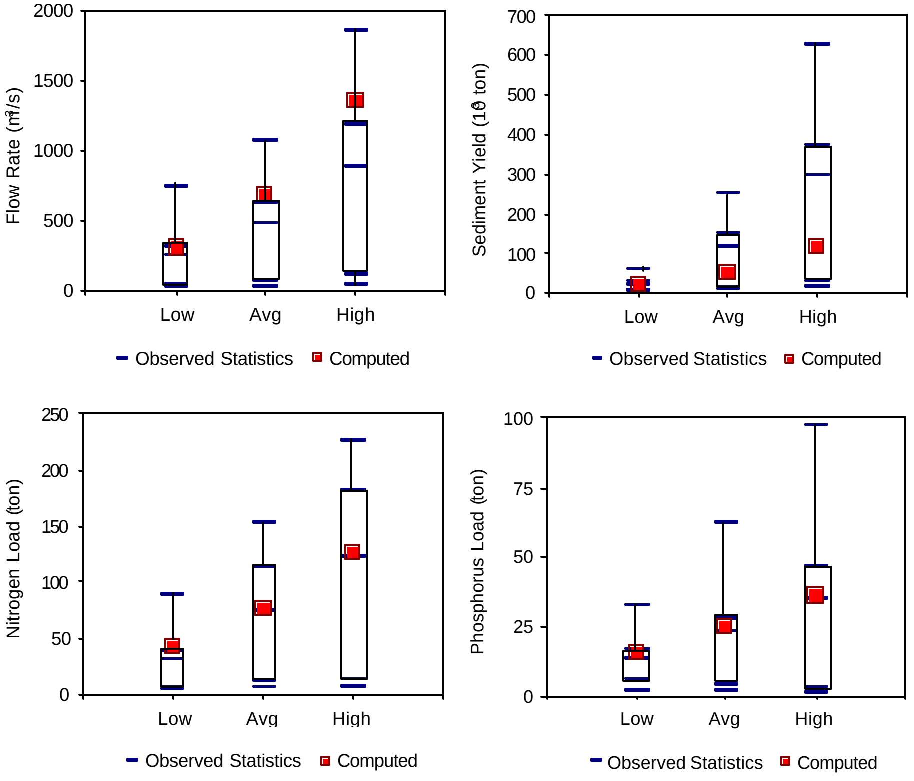

Figure 5. Comparison between observed data and AGNPS computed values at the outlet of the Linthipe River for low, average (Avg) and high rainfall events. (For the observed statistics, the bar in the middle of the box indicates the median, the top and bottom bars indicate the 75 and 25 percentiles, and the upper and lower whiskers indicate the 90 and 10 percentiles.)

3.2 CALIBRATED RESULTS OF CATCHMENT MODEL

Using the input data extracted from GIS maps and other data, such as rainfall events, we can run the AGNPS model from a TUI in the RAISON system. The model output can be displayed as tables or as thematically coloured maps in RAISON, based on the values of the computed results for the grid cells. To demonstrate how the model results compare to actual observations, however, we grouped the results by rainfall events. Figure 5 shows the computed and observed results for the stream runoff flow rate, sediment yield, nitrogen load and phosphorus load. These results are divided into three groups, the low, average and high rainfall events during the year 1997. For example, the median runoff flow is observed at about 250 m^3/s for low rainfall events, at about 475 m^3/s for average rainfall events and at about 890 m^3/s for high rainfall events. As shown in Figure 5, the computed flow rate for low rainfall events agreed well with the observed, but it was greater than the observed values for both average and high rainfall events. Similarly, for the sediment yield the computed values agreed well with the observed for low rainfall events but were lower than the observed for average and high rainfall events. However, as only a few sets of observed data were available for the construction of event statistics, the values of the observed median and range shown are subject to a high level of uncertainty. Due to the data limitations, we did not adjust the model coefficients in the USLE to achieve a better fit between computed and observed results. In general, we are satisfied that both computed and observed runoff and sediment yields increase from low to high rainfall events as they should. On the other hand, the computed and observed results for nitrogen and phosphorus loads are in agreement for all rainfall events, as shown in Figure 5. The results are encouraging in that the information from the land use and soil type maps produced reasonable values for the model coefficients.

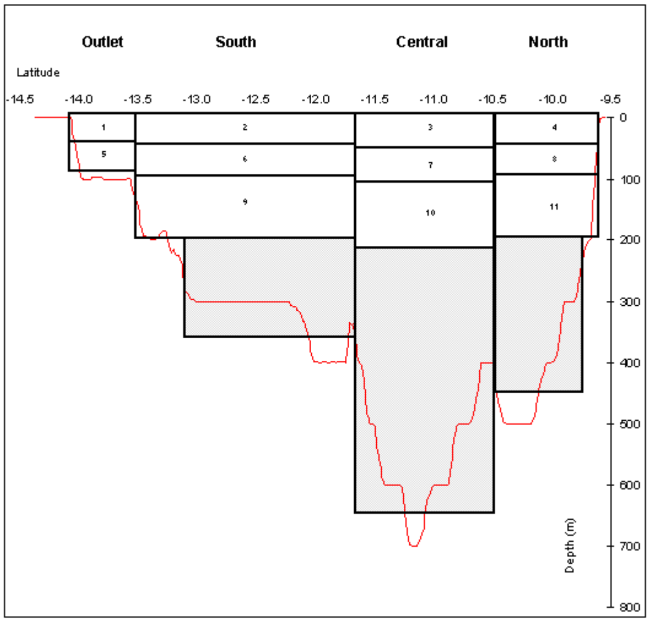

Figure 6. Schematic of the boxes used in the water quality box model; the box lengths and layer depths are averaged values; the shaded areas are deep water layers not directly incorporated in this box structure but may serve as internal sources of nutrients.

4. LAKE WATER QUALITY MODEL

While the Outlet Basin (Figure 6) in Lake Malawi has sufficient data coverage, the other basins have less data. These other basins were sampled only along the central axis of the lake and only four times each. Some of the stations in the basins were measured as vertical profiles, providing important information on the vertical exchanges. Given the data availability, we have adapted a simple box model (Lam et al., 1987) for the study in this paper to investigate the essential physical and biochemical processes in the four main lake basins (Figure 6) along the longitudinal axis, including the effects of thermal stratification and land-based discharge of nutrients.

4.1 THE NWRI WATER QUALITY BOX MODEL

The box model adapted for the study in this paper is the NWRI water quality model developed for Lake Erie (Lam et al., 1987). Its development was based on two previous versions (Lam and Halfon, 1978; Simons and Lam, 1980). Its result showed that for long term simulations (i.e. over ten years), long term data are required to calibrate model coefficients such as the settling rate of particulate phosphorus. These versions of the model evolved to become the Lake Erie model, with three horizontal boxes, three vertical layers and three water quality variables: soluble reactive phosphorus (SRP), total phosphorus (TP, as the sum of SRP and OP, where OP is the organic phosphorus) and dissolved oxygen (DO). It predicted the phosphorus dynamics due to nutrient loads and the anoxic conditions under various weather conditions affecting thermal stratification. It was calibrated, validated and post-audited with a total of 16 years of data for Lake Erie (Lam et al. 1987). Thus, this model has been applied to lakes with environmental issues and physical and biochemical processes comparable to those in Lake Malawi.

4.1.1 Model Structure

The original box model was configured as a nine box model, with three basins and three layers, for Lake Erie. To adapt it to Lake Malawi, we used an 11-box model for several reasons. As shown in Figure 6, we define four basins in Lake Malawi: Outlet, South, Central and North. There are layers of water deeper than 200m in all basins except the Outlet Basin. In the DELFT3D hydrodynamic model (Delft Hydraulics et al., 1999; Kernkamp et al. 1994), these deep layers are assumed to be isolated from the overlying waters. Thus, for practical purposes they can also be treated as such in the water quality box model, with the exception of the upwelling return of nutrients (Figure 1). Gonfianti et al. (1979) and Vollmer et al. (2001) showed that the vertical fluxes of nutrients from the deep layer to the overlying layers were possible and significant. To include this input in the water quality box model, we treated it as a source entering from the deep layer to the overlying layer, based on preliminary flux estimates (Vollmer, pers. Comm). For the overlying waters, the seasonal thermocline usually occurs at a depth of 40 to 50m. From previous measurements of pelagic photosynthesis (Degnbol and Mapila 1982; Bootsma 1993a), we considered the top layer above the thermocline to be the productive zone. We then defined the middle layer as being between the thermocline and 100m in depth, and the bottom layer as being between 100m and 200m in depth. The next consideration is the output file of lake currents computed by the hydrodynamic model. This file is structured according to the so-called “sigma coordinate”, that is, the vertical layers are such that they can expand or contract slightly according to the water movements (Delft Hydraulics et al., 1999; Kernkamp et al. 1994). To define the water transport in the water quality model, the currents computed from the hydrodynamic model are averaged for a number of layers and boxes according to the partitions given in Figure 6. Note that the boxes are all aligned vertically. Some horizontal alignments are, however, slightly off (e.g. between boxes 9 and 10). This slight offset will not cause problems for conserving water or mass, because the transports among the boxes have been directly computed from the hydrodynamic model and satisfy continuity. Adjustments are needed for the transport between the Outlet and the South Basins, because due to its shallowness there are only two layers in the Outlet Basin . While all interfaces are fixed, the lake surface itself is allowed to move up or down to simulate water elevation changes due to wind setup. The water transport is mass conservative, with the inflows balancing the outflows in all boxes in the water quality model.

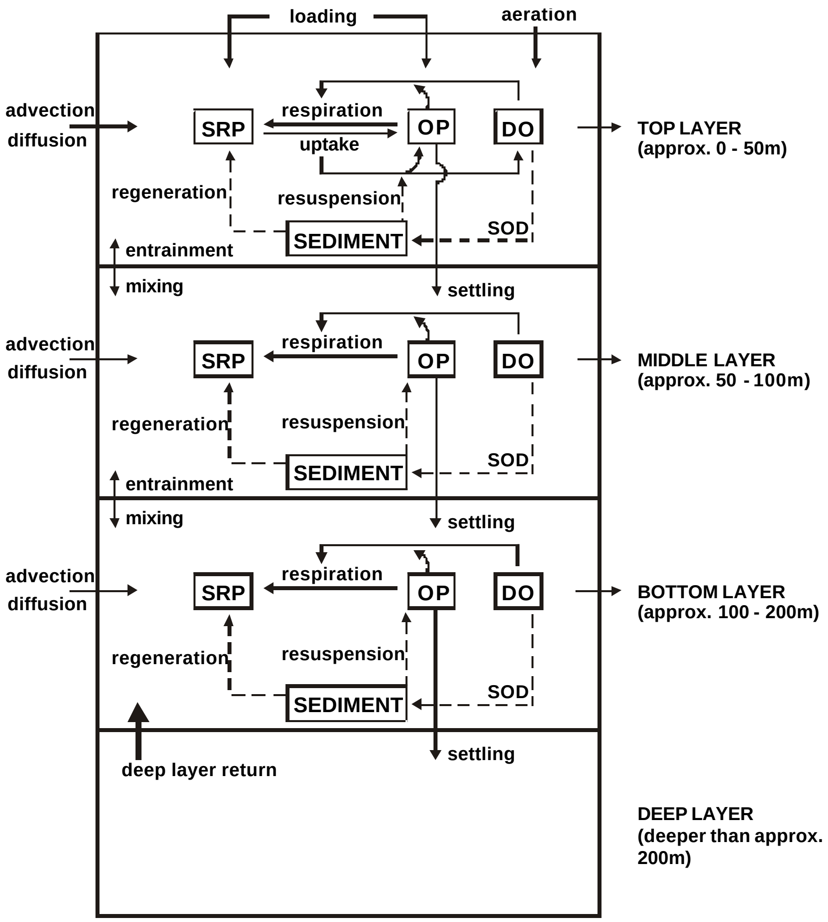

Figure 7. Schematic of the physical and biochemical processes for the phosphorus and oxygen dynamics (nitrogen processes not shown) used in the box model for Lake Malawi: SRP (soluble reactive phosphorus), OP (organic phosphorus), with TP (total phosphorus) = SRP + OP; DO (dissolved oxygen), SOD (sediment oxygen demand).

4.1.2 Model Formulation

The model formulation is based on the water quality model (Lam et al., 1987) for Lake Erie. Basically, the physical transports involve both horizontal advection as used in the hydrodynamic model and vertical transport based on the computed vertical flow. The vertical dispersion coefficient is the value computed in the hydrodynamic model, multiplied by a mixing length scale equal to the vertical distance between adjacent boxes. Thus, the physical transport equations follow those given in Lam et al. (1987), except that the internal layer depths are now fixed. Similarly the model formulation for the water quality variables are based on the Lake Erie model , using the algal uptake and regeneration between organic phosphorus (OP) and soluble reactive phosphorus (SRP), with effects on dissolved oxygen (DO) (Figure 7). This figure represents a typical basin (the North, South or Central). For the Outlet Basin, there are only two layers and the figure would be reduced accordingly. In the other basins the deep water layer forms a fourth layer beneath the hypolimnion which has a sediment layer along the sloping bottom. We have also added a component on nitrate and ammonia uptake and regeneration to the nutrient processes. The detailed model equations for the biochemical processes are provided in the project report (University of Waterloo et al. 2000).

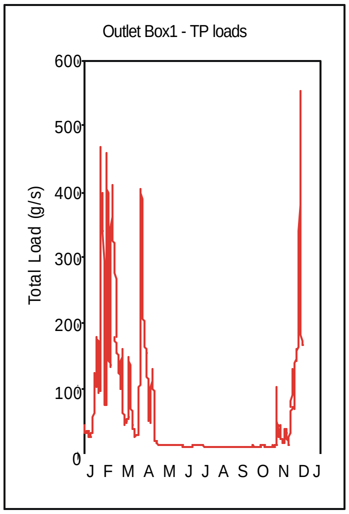

Figure 8. Estimated riverine phosphorus loads to outlet box 1 in Lake Malawi for 1997.

4.2 WATER QUALITY MODEL RESULTS

The model was calibrated using the in-lake concentration data for 1997. As the observed data are rather limited, with only two or three observed points per box , we did not calculate the statistical errors between computed and observed results. Instead, we relied on visual comparison. The emphasis here is to show how the water quality model behaves under the current nutrient loading condition and, later, how to link it to the catchment model. For example, Figure 8 shows the riverine phosphorus load to the Outlet Basin for 1997. Figure 9 shows the computed and observed TP concentrations for all basins and layers. The best agreement between observed and computed TP concentrations is in the top layer of the Outlet Basin. The spring peaks (January to April) of the riverine total phosphorus load (Figure 8) to the lake were reflected in the increase in total phosphorus concentration in the upper layer of the Outlet Basin (Figure 9).

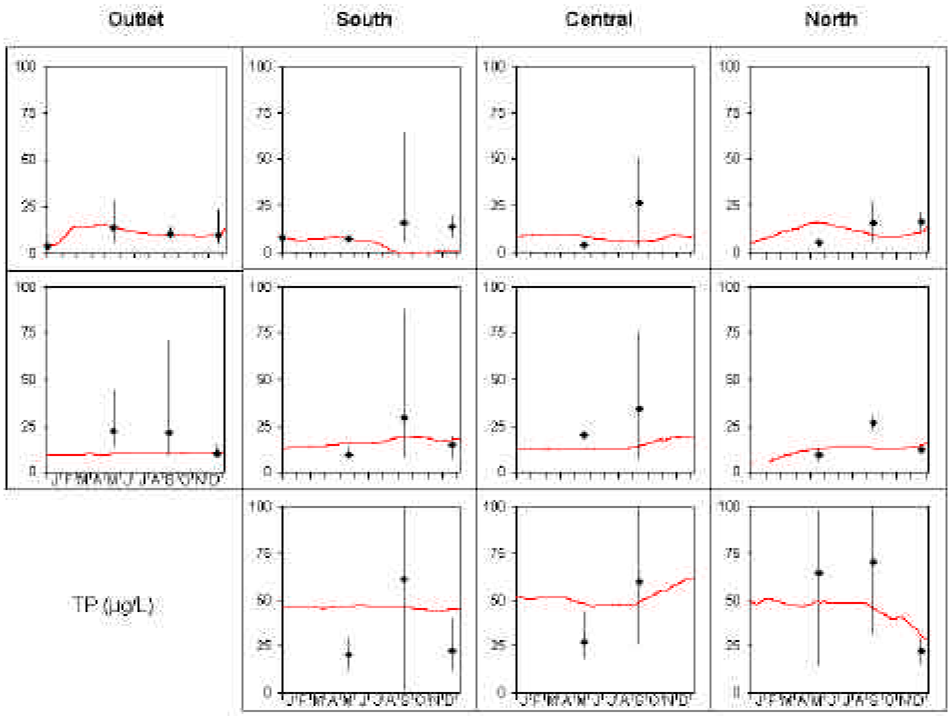

Figure 9. Computed total phosphorus concentration (dotted lines as TP in µg/L), vs. observed data (diamonds) and ranges (vertical bars) averaged for all boxes and layers, for 1997.

Previously, emphasis has been placed on the role of winds and upwelling in controlling nutrient and plankton seasonality in the southern part of the lake (Eccles 1974; Bootsma 1993b; Patterson and Kachinjika 1993). The observed and modelled results presented here suggest that river discharge is also an important factor, at least in the southern end of the lake. The low loading values for May to October lead to a relatively lower level of total phosphorus concentration in the Outlet Basin (Figure 9). Thus, the seasonal trends for river discharge and lake concentration are in good agreement. The agreement between computed and observed results for this basin is due to the availability of more data for model calibration and a more reliable set of loading estimates. This adds to our confidence in using the box model, linked with the catchment (AGNPS) model, to investigate the effect of land use management strategies for nutrients on this basin. For the other basins, the comparison of computed and observed data is reasonably good. The return of phosphorus from deeper layers (depths > 200m, Figure 1) was indicated in both the simulated and observed data in the bottom layers (depths of 100 to 200m) of the North, Central and South Basins (Figure 9). However, more data are needed to define this deep layer return accurately, and we also require a better understanding of the physical mechanisms affecting the nutrient return. The results for the other variables such as SRP and nitrogen produced similar agreement between computed and observed values (University of Waterloo et al. 2000).

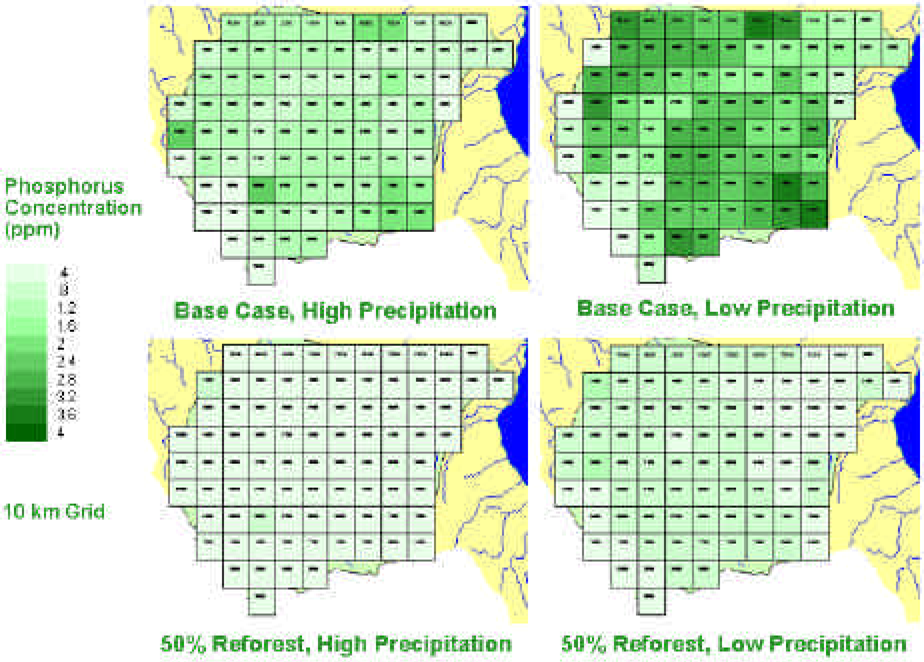

Figure 10. Computed stream total phosphorus (TP) concentration (in ppm = mg/L) averaged over each grid cell in the Linthipe Watershed for different scenarios: base case (upper diagrams) and 50% reforestation (lower diagrams) and for high (left side) and low (right side) precipitation events.

5. A LAND USE SCENARIO

Due to the data limitations, the calibrated results obtained to date for both the catchment model (Section 3) and the lake water quality model (Section 4) are preliminary. The model results were within the uncertainties of the observed data most of the time. In particular, good agreement is obtained between the computed and observed results for the total phosphorus concentration in the upper layer of the Outlet Basin, where the input loading and in-lake data were the most adequate. This provides some degree of confidence in using the model to further investigate the effects of land use on input loadings and the subsequent impact on the nutrient levels in this particular lake basin.

Input to the AGNPS catchment model can be altered to generate new results for a number of scenarios. For example, one of the scenarios considered is the hypothetical case in which 50% of the Linthipe Watershed is reforested. This hypothetical change amounts to modifying the land-use map by increasing the forested area in each grid cell by 50%. The changes to the land use pattern in turn affect the computation of the river flow, sediment yield and the nutrient concentrations. Figure 10 shows the predicted total phosphorus concentration for both high and low precipitation events before (base case) and after (50% reforestation) the hypothetical land use change, based on the AGNPS catchment model runs. The reduction in non-point sources of TP is significant for both wet and dry conditions. The reforestation has resulted in lower phosphorus concentrations at the outlet of the catchment.

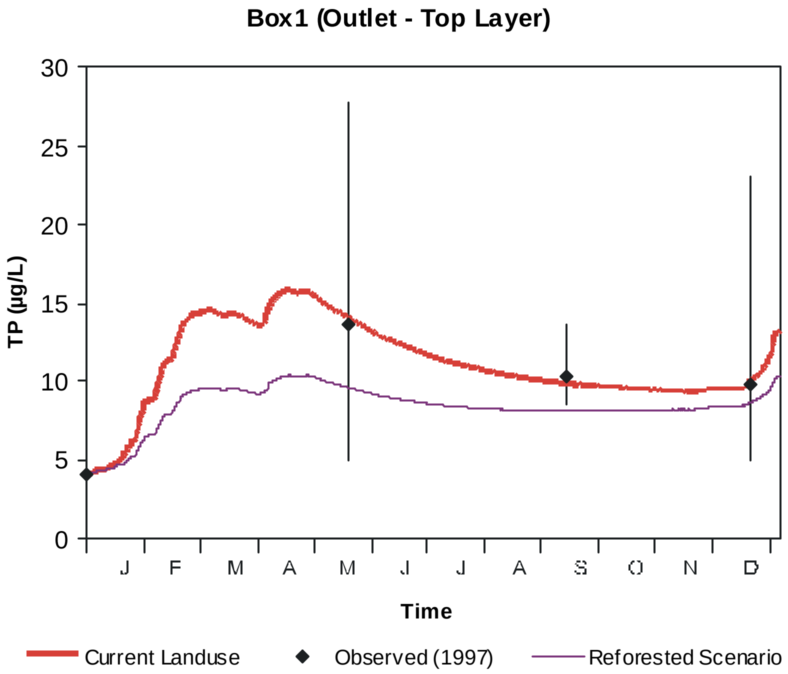

Figure 11. Computed total phosphorus (TP) concentration for the top layer in the Outlet Basin using current land use pattern (top line) in the Linthipe Watershed vs. that using a hypothetical 50% reforestation scenario (bottom line), compared to observed data (diamonds) and ranges (vertical bar) in 1997.

This reduction in non-point source input to the rivers in the Linthipe Watershed causes a decrease in the TP load to the Outlet Basin of Lake Malawi. We can link this catchment model result to the box model (Figure 2). We can modify TP load for 1997 accordingly for the 50% reforestation case and save it as a new loading file. To discover the effects of this loading reduction on the lake, we pass this new loading information to the box model via a TUI in RAISON. Figure 11 shows the computed concentration of TP for the top layer in the Outlet Basin, for both the actual TP load and the new load as modified by the output from the catchment model for the 50% reforestation scenario. The reduction in the TP concentration in the lake is significant (Figure 11), from a spring peak value of about 15 μg/L with the actual load, to a value of about 10 μg/L with the modified load. This result demonstrates that land use activities can affect the lake water quality in this area. The changes in phosphorus concentration for the other basins (not shown in Figure 11) are not as great as that in the Outlet Basin, confirming the hypothesis that non-point source input of nutrients has the greatest effect on the immediate receiving impoundment. However, some care is required in interpreting these preliminary results. For example, 1997 was a wetter year than normal and therefore the nutrient loading was probably greater than average (Kingdon et al., 1999). Further scenario simulation and comparison with long term data are required to confirm the predicted results.

6. DISCUSSION

The integration of data and models is a complex task. Designing a system that can integrate independent databases and models is only the beginning. The main difficulty is in applying them to practical problems, as required by both public and technical users. The results and examples shown here are preliminary and are mainly intended to invite feedback from water resource managers and potential users. As demonstrated in the examples provided, the technologies to link databases and models are now readily available; the challenge is to make them serve the needs of users. The process of data and knowledge integration is therefore an iterative one: only with feedback from the users can the systems be improved.

As for future needs, the integrated modelling framework (Figure 2) presented here is a viable and growing one. In time, we expect to incorporate additional data and models. For data, additional catchment information is required to complete the entire drainage basin for the lake. For models, we have one catchment model, one hydrodynamic model, and one water quality model. We welcome additional models of these types, particularly those developed and used by regional agencies in the riparian countries. There is a lack of both biological resource and socio-economic models, and water quality models must be extended to include plankton and ultimately fish. Though it is difficult to place a dollar value on environmental quality, the cost of development projects that could affect the environment can be estimated. The decision maker's job is to weigh the benefits of development with the benefits of environmental quality, which may include the preservation of valuable natural resources.

A decision support system for effective management requires all these components to function properly. There are a variety of environmental issues facing Lake Malawi and its catchment; managers and researchers may want to address these issues at different complexities and on different spatial and temporal scales, so the integrated modelling framework must take a "toolkit" approach like as the one we have outlined. While the models may be linked and used together to address complex, ecosystem-scale issues, they may also be used individually to address specific, local issues. This modular approach also simplifies the future modification of models as more data are collected and increases the likelihood that managers will see the models as practical tools relevant to local issues.

The main results achieved in this project are the use of an integrated modelling framework to model non-point source nutrient in a catchment and the linkage of the computed river discharges to a lake water quality model. This work has demonstrated the feasibility of applying advanced technologies in order to integrate models in a uniform platform with GIS capabilities. The use of the TUI interface for the AGNPS model, including the pre- and post-processing tools, allows the user to set up model grids, automatically extract input data and begin analyzing the output. This integration supports the idea that better modelling capabilities need to be combined with the application of new technologies, such GIS capabilities, to resolve problems associated with the ease of model use. One of the major benefits of this system is the automatic data extraction from digital maps, for which two basic procedures are used: one uses DEM files to extract topography-related data such as flow direction and slope, while the other uses land cover and soil type maps with polygon attributes to extract the data relevant to the model. However, there are limitations to such computer automation; the scientific basis of the land cover and soil information must be obtained from research into local land use features and practices to produce the correct values for the model coefficients. For example, local farming practices may affect nutrient discharges, and fertilizer application rates should be estimated with field surveys in the local area to provide the model with adequate applied nutrient rates.

As for the simple water quality box model, it was designed for a preliminary investigation into water quality in Lake Malawi. The existing data on loading and in-lake concentrations are useful to facilitate the modelling study. The model results obtained were reasonable and revealed several interesting interactions between physical and biochemical processes. The thermal stratification of the lake at the 40 to 50m depth plays a significant role in the vertical distribution of nutrients. Likewise, the model demonstrated the importance of significant nutrient fluxes through some form of mixing mechanism across the weak pycnocline (Wuuest et al., 1996) at 200m. Some preliminary attempts to include these fluxes were made in the box model, but they require further research. The need for adequate, reliable data is evident in the attempt to link the catchment model for the Linthipe Watershed with the lake water quality model for the Outlet Basin. They generated the best agreement between computed and observed databecause there were sufficient data to calibrate both models for this basin.

7. CONCLUSIONS

This study shows that the concept of linking different types of models can be implemented, with proper assumptions and integrated modelling tools. The connection between the catchment, hydrodynamic and water quality box models can be facilitated by technical user interfaces that help transfer key data files among the models. Additional models, particularly those used by regional agencies, should be linked to these models to provide relevant answers to water resources and fisheries management questions. Also, application of these or other models to other catchments and lake basins in Lake Malawi is possible, provided there is sufficient data and knowledge to calibrate the models. Additional model calibration for other catchments and basins is required to increase confidence in the use of such an integrated modelling approach for water resource management in Lake Malawi/Nyasa/Niassa.

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