USING MODELING, GIS AND REMOTE SENSING TO UNDER-STAND AN AFRICAN LAKE

Andreas Gyllenhammar

andgyl@gmail.com

Foreword

A Geographical Information System (GIS) is a very useful tool for research in environmental management. There are various definitions of a GIS but they all have the spatial component in focus. One commonly used definition is:

“ A system for capturing, storing, checking, integrating, manipulating,
analyzing and displaying data which are spatially referenced to the Earth ”

by Chorley (1987). This definition covers well the use of GIS in a SIDA (Swedish International Development Agency) financed project “Integrated Management of Lake Kyoga Natural Resources” where GIS, Remote Sensing and modeling were used in order to assess fish stock changes related to hydrological and environmental changes. The goal of this report is to give a brief overview of the project and showcase some uses of GIS, Remote Sensing and modeling. A full project report can be found in Gyllenhammar et al. (2006). This report is richly illustrated with maps produced by different software and techniques to show the potential of various software. In the Kyoga project, the main GIS software were ArcGIS 3.2, ArcGIS 8 and ENVI. Maps were also produced using NASAs World Wind and Google’s corresponding Google Earth.

Drying of Mukene, an important fish specie

People living on the floating sudds of Lake Kyoga (photo: Thomas Gumbricht)

Emptying the test fishing gill nets

Introduction

Lake Kyoga (figure 1) is a shallow and productive lake of about 4,000 km^2 draining large parts of Uganda (70,000 km^2). The White Nile (also called the Victoria Nile) starts its journey towards Egypt in Lake Victoria, flows into the lake, and supplies around 95 % of the water, but this water is very nutrient poor compared to the direct runoff from the degraded basin (NRSP, 2001). Half a million people live along the shores and when the project commenced people were also living on floating papyrus mats ("sudds"), but have since been evicted. The reason for them living on the sudds is the increased fish availability as a result of the microhabitats in the direct vicinity of the sudds. Due to security reasons the government has forced the sudd inhabitants to move to the lake shores and preferably one of the many landing sites. For the people living in this area, Lake Kyoga is the primary source of protein and the inhabitants rely heavily on the lake for their livelihood. An estimated 200,000 persons are directly involved in the fisheries. The annual fish catches have fluctuated between 5,000 and 160,000 mt (metric tonnes) and the income from commercial fish export is important on a national scale, second only to Lake Victoria (Allison, 2003).

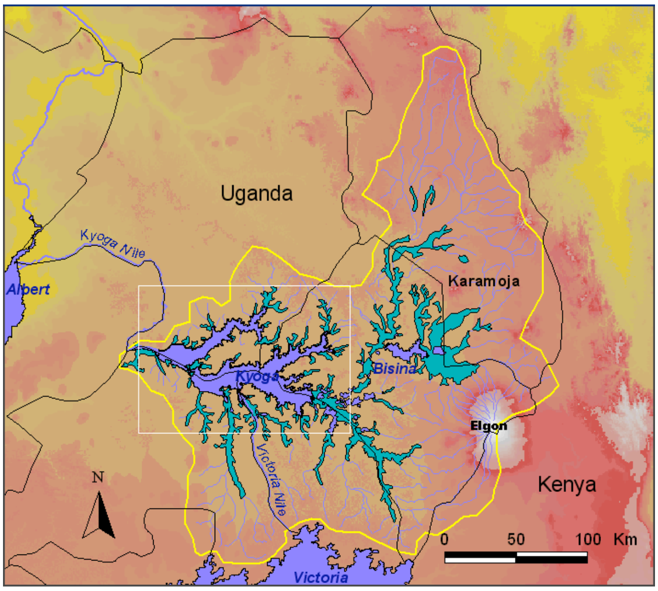

Figure 1. Lake Kyoga and its basin showing the lakes, major streams and wetlands. From Gumbricht (2005).

The 1997/98 El Niño flood displaced hundreds of families and dislocated sudds that formed a plug (figure 2) at the outlet which elevated the lake level by almost 2 meters. It was expected that this increase would be of great significance to the ecosystem, since the mean depth before the plug event was around 2 meters. The lake surface increased by approximately 10 % (Gumbricht, 2005) and the volume by 77 % (ILM, 2004). Subsequent changes in the lake ecosystem led to an initial increase in fish production, with local fishermen especially mentioning bottom dwelling species (e.g. lungfish). This increase in fish yield attracted people from the degraded basin to settle on the shores and the sudds. After the period of initial increase, the fish catch has been declining, according to the substandard (Reynolds, 1989) and scattered catch statistics (Twongo, 1994; Anon., 2004).

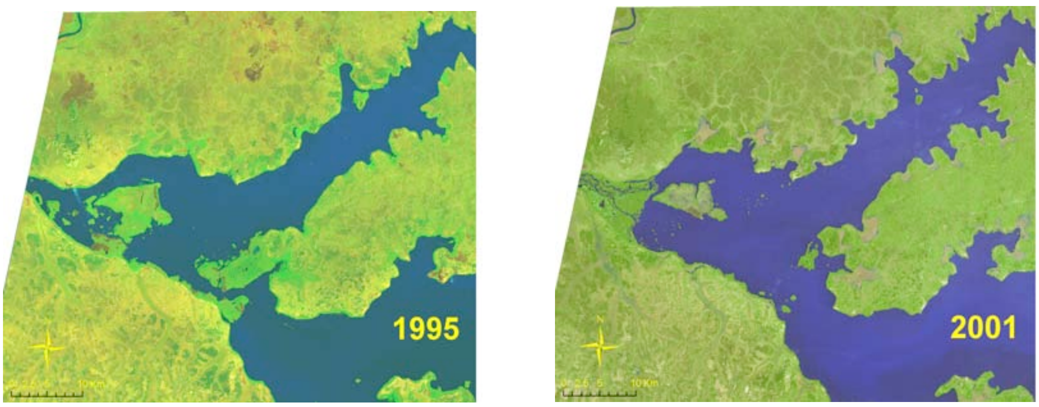

Figure 2. The outlet of Lake Kyoga before and after the papyrus blockage event shown in two Landsat (E)TM images.

The aim of the SIDA research project was to:

1. understand the dynamic response of fish populations to the sudd blockage,
2. to carry out a 1-year water quality sampling program,
3. develop a foodweb model for Lake Kyoga including a dynamic mass balance model for phosphorus,
4. make scenario simulations to forecast structural changes to the lake fish populations and
5. predict the effects of a removal of the sudd blockage.

Data for the project was collected with various methods. In addition to the use of remote sensing, a literature study was conducted and data were collected from various Ugandan institutes. However, this was not enough to understand the dynamics of the lake ecology so monthly water samples were taken and analyzed for chemistry parameters and various algal samples. A detailed study of water conductivity was also done in order to see the approximate path of inflowing water.

Remote Sensing, in its broadest sense, means acquisition of data for an object by the use of a sensing device that is not in physical contact with the studied object. However, it is most commonly used as a term for satellite acquired data. It is of great use when it comes to cost efficiency and when historic data or data from remote locations that are difficult or dangerous to reach are required. A major use of remote sensing products in the SIDA project was the use of satellite images.

Use of Remote Sensing

Remote sensing data to trace historical water levels

We used time series of satellite images, mainly Landsat Multi Spectral Scanner (MSS), Thematic Mapper (TM) and Enhanced TM (ETM) to trace recent changes in the area of Lake Kyoga, and compare this flooding data with historical water levels.

48 medium to high resolution satellite images from the period 1972 to 2003 were used for mapping the area of Lake Kyoga and its transient water level changes over this period. The lion's share of the data is freely available "quicklook" images from the Landsat program. These images are available for download as color composites, where water and cloud are easy to detect. This data was complemented with 2 radar composite scenes (JERS) from 1996. Additionally one older russian Corona ("spy") image was used to confirm the lake area in 1963. No radiometric correction was undertaken. All images were resampled to 250 m resolution and geocorrected to Universal Transverse Mercator (UTM) zone 36. The geocorrection was done manually using ground control points collected by handheld GPS as reference. To create precise geocorrections images were combined to animations, and iteratively adjusted until the animations contained no "jumps".

For all images a statistical unsupervised classification technique was used to identify clouds, water, wetland and land areas (McCarthy et al., 2003). The derived classes were manually categorized into cloud, water, wetland or land by comparing the classified images with the downloaded color composite images (figure 3). After identification the clouds were expanded by 2.5 km in all directions to accommodate for both thin clouds and cloud shadows. All images were then stacked and water occurrence in cloud free areas was estimated. If this occurrence was more than 95 % and the radar images (which are not disturbed by clouds) showed water, then that picture element (pixel) was considered to always be water. Clouds over those areas thus identified were hence changed into water in all images. Using the stacked information on water occurrence the maximum extent of the Lake and its riparian mixed land-water pixels and adjacent wetlands was estimated by using the identified core water area and a growth routine to identify all "wet" areas directly linked to the core area. For each individual image, the occurrence of water under clouds in the fringe area between the lake core and maximum extent area was resolved by using adjacent dates.

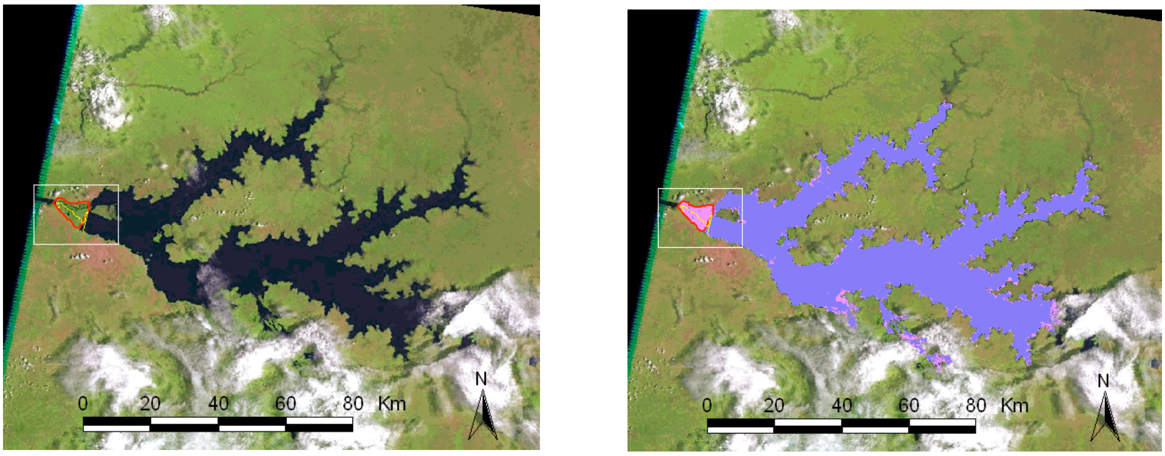

Figure 2. Image classification method exemplified by Landsat ETM from October 2002; the red area indicates the plug that formed after the 1997/98 El Niño. The yellow line is the survey line from November 2002 (see text).

Available "ground truth" data included GPS tracks and waypoints from six field visits in the period November 2002 to May 2004. A boat and flight survey conducted 18-19 November 2002 showed that the accuracy for a 5 km transect along different shorelines was 100 % when compared to water and wetlands classified from the Landsat ETM scene from October 2002 (figure 2). Also the tracks and waypoints from other visits indicate a high classification accuracy.

Two Landsat MSS, two Landsat TM and one Landsat ETM scene were acquired in full resolutions. The classification accuracy of the reduced resolution images from the same scenes was evaluated (table 1).

Table 1. Classification accuracy in 250 m resolution images as compared to full resolution images (30 to 60 m).

DATE (SENSOR)	FULL RESOLUTION WATER AREA (km^2)	LOW RESOLUTION WATER AREA (km^2)
1973-02-02/1974-01-29 (MSS)	2687	2702
1986 (TM)	2628	2574
1995 (TM)	2491	2492
2001 (ETM)	2744	2655

Data on relative water levels in Lake Kyoga was taken from the Ugandan Department of Water Development recorder in the lake. This data set has large gaps, and in cases where the mismatch between available recorded water stages and dates of satellite images was less than 1 month, the recorded data was interpolated, or in a few cases extrapolated if stable conditions prevailed in the adjacent record.

The results show that the area of Lake Kyoga has varied between 2400 and 2850 km^2, or around 10 % over the last 3 decades. From the water level recordings it is evident that the lake level has varied around 3 meters, and that the lowest recording is from 1961, before the well known rise in the lake level of Lake Victoria. The Corona satellite image over Lake Kyoga confirms the lake area, but large parts of the lake are covered in clouds in the images.

The recorded changes in lake levels and the open water area between 1994-1996 and 2000-2002 as interpreted from satellite images show a high degree of correlation (figure 4), with an R^2 of 75 %.

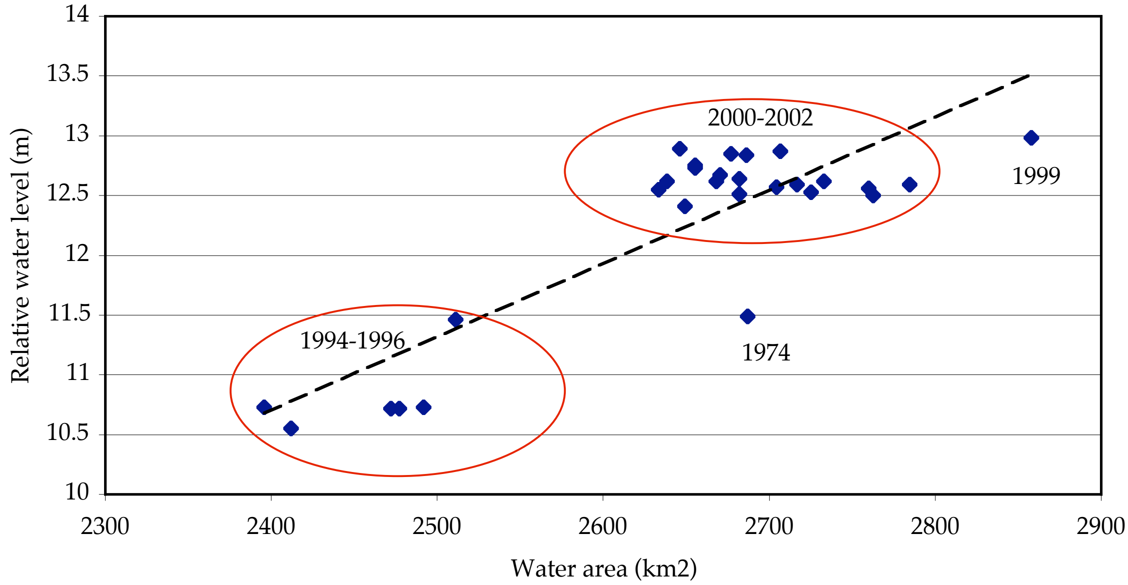

Figure 4. Lake Kyoga water area as classified from the satellite images plotted against lake water levels.

After the project ended a global study was found on the web (www.legos.obs-mip.fr/en/soa/hydrologie/hydroweb) in which many time series of water levels were assessed from satellite altimetry. Among 165 sites (lakes, reservoirs and river basins) Lake Kyoga is one of the sites where water levels are assessed from radar altimetry (LEGOS, 2008). Figure 5 shows a view of Lake Kyoga from the south to show its direct dependence of the Nile and the properties of Lake Victoria. About 95 % of Lake Kyoga's freshwater inflow is Nile water. The map is a screenshot from NASA's freeware World Wind 1.4.

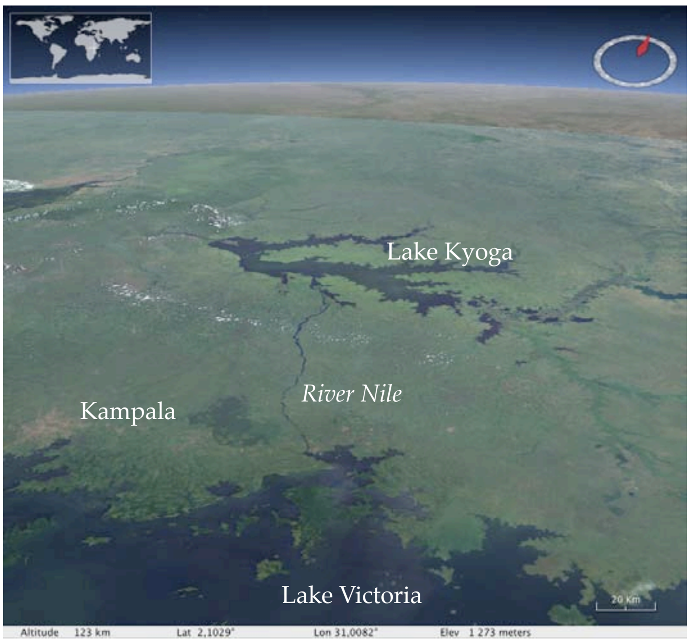

Figure 5. NASA World Wind screenshot of Lake Kyoga viewed from south.

For Lake Kyoga the study used processed remote sensing data from the satellites Jason-1 (a NASA/CNES collaboration), ENVISAT and ERS (by the European Space Agency, ESA) to obtain lake water levels. In order to compare this method to Lake Kyoga measurements figure 6 was produced (mean values have been leveled) and shows that the results are of good quality. These data can be freely downloaded for every site in their database and may be of great value to any lake ecosystem study.

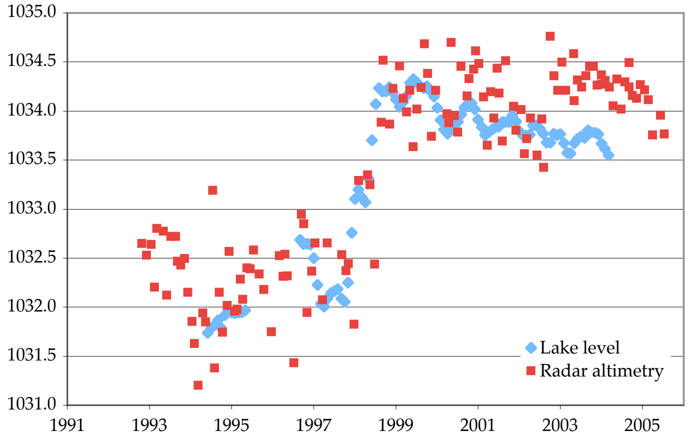

Figure 6. A comparison between lake level measurements for Lake Kyoga and lake levels obtained from radar altimetry.

Use of GIS

Analyzing water conductivity with GIS to track water flow

The goal of the intensive measurements of water conductivity was to get an overview of the spread of the inflowing water from the Nile. It was hypothesized that the ionic content would become higher in a west-east gradient if the inflow diverted directly to the west towards the outlet. Water conductivity was measured (by boat or canoe) at 30 locations near three fish landing sites with corresponding locations recorded simultaneously with a handheld GPS. These data were imported into ArcView 3.2 and with the use of a lake shore mask a conductivity map (a high resolution grid map of the lake) was interpolated. Since only a rough overview of the conductivity was needed, sophisticated interpolation technique like spline or kriging were not used, and the simpler default Inverse Distance Weighted (IDW) interpolation technique was used.

The initial hypothesis was confirmed by the resulting map (figure 7) as revealed by a sharp gradient in conductivity around the main inlet. The fact that this was a fairly stable situation was later supported by the monthly sampling results for conductivity, which showed very little seasonal variation.

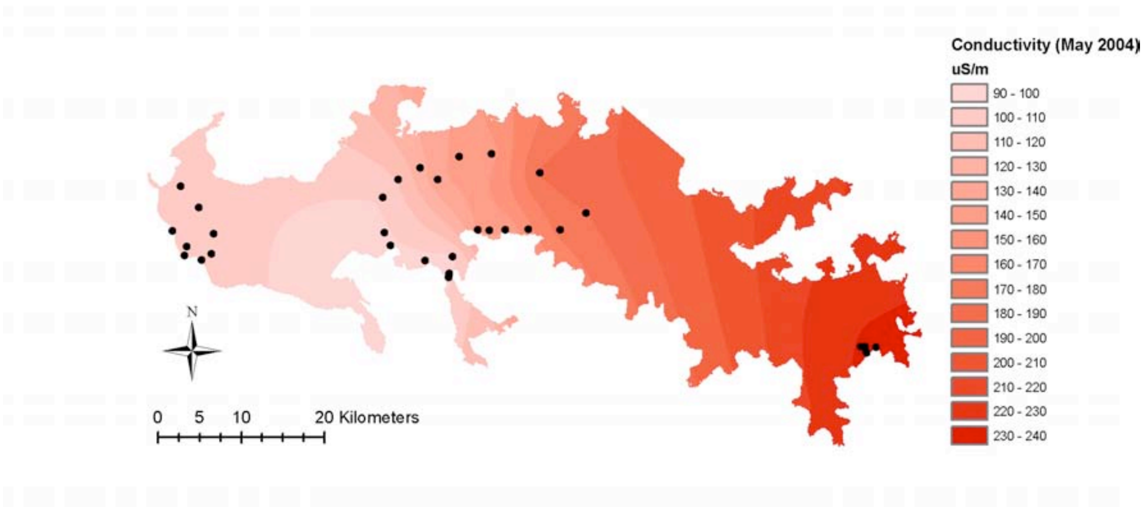

Figure 7. Lake Kyoga conductivity measurements. The map is an Inverse Distant Weighted (IDW) interpolation to stress the west-east gradient in conductivity.

Using GIS to estimate lake macrophyte cover

The model used for the lake foodweb modeling (described next in this report) needed a quantitative estimate of the macrophyte cover. It was realized that all necessary information could be taken from the satellite images combined with an image analysis. Once the spectral response of the papyrus was identified and combined that with lake shoreline masks, a good estimate could be extracted from the Landsat images (figure 8).

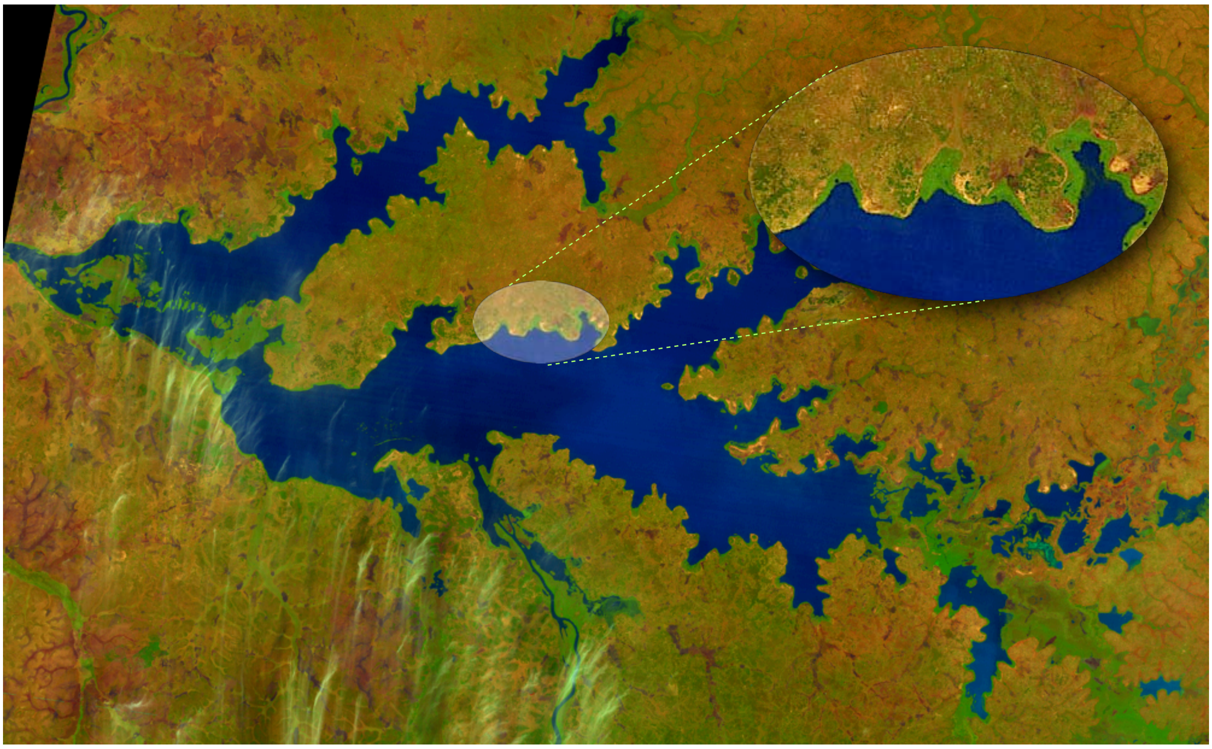

Figure 8. Lake Kyoga Landsat image from 1986. The zoomed-in shoreline clearly shows the papyrus rim.

Use of modeling

Analyzing the lake foodweb with a dynamic mass balance model

To analyze the aquatic foodweb of Lake Kyoga was the main work task and focus of the SIDA project. GIS was used as an invaluable supporting framework, providing data and structure before the modeling could be carried out, but also afterwards, to visualize and disseminate the results. However, none of the project goals could have been achieved without the development and use of an ecosystem model.

The modeling part of this project is based on the comprehensive lake foodweb model, LakeWeb (see Håkanson and Boulion, 2002). This is a general model to quantify all important lake foodweb interactions, including biotic/abiotic feedbacks (figure 9).

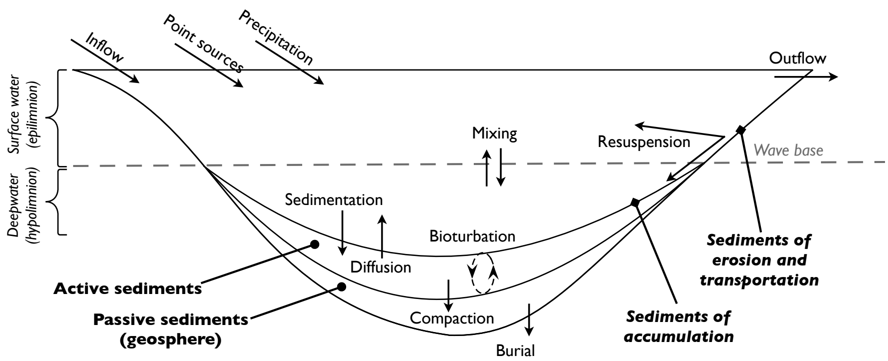

Figure 9. The abiotic/biotic interactions of the LakeWeb ecosystem model.

It has been critically tested against very comprehensive empirical data sets mainly from Eastern and Western Europe, including many new empirical models, but it has not been tested for any African lakes. LakeWeb includes the following key functional groups of organisms: phytoplankton, bacterioplankton, benthic algae, macrophytes, zoobenthos, herbivorous and predatory zooplankton, prey fish and predatory fish. LakeWeb is based on many new approaches of structuring lake foodweb interactions. It uses ordinary differential equations (the ecosystem scale) and gives weekly variations in production and biomass for its nine groups of organisms. It also includes a mass-balance model for phosphorus and approaches to quantify suspended particulate matter and the depth of the photic zone. Fundamental concepts include consumption rates, metabolic efficiency ratios, distributions coefficients, migration of fish and predation pressure. An important feature of LakeWeb is that it can be run by just a few driving variables readily accessible from standard maps and monitoring programs. LakeWeb also includes a sub-model for toxic substances in fish. Several scenarios describe how the model can be applied to address important management issues, like consequences of biomanipulations (fish kill catastrophes), changes in land-use (eutrophication and humification from an increased load of humic acids) and global temperature changes. LakeWeb is a powerful tool to simulate such measures and to get realistic expectations of positive and negative consequences of remedial measures. The LakeWeb model has been tested for lakes smaller than 300 km^2, but many of the structural components should be valid also for larger systems, for lakes from other parts of the world, for coastal areas (like the Baltic or Norwegian fjords), or the large lakes of the world (like the Great Lakes of America, the Caspian Sea or Lake Ladoga).

In order to use the LakeWeb model for Lake Kyoga, the model processes had to be reviewed to identify where the predictions were outside the model domain. This was a tedious work and due to lack of calibration data for Lake Kyoga (e.g. sedimentation rates) not all processes could be verified. However, it was possible to identify where the greatest model uncertainties were.

Different management scenarios were tested in the model and the results were compared to fish catch statistics.

Modeling results

The LakeWeb model was thoroughly reviewed and many of the biological processes regarding fish were calibrated to reflect the properties of the new tropical species (e.g. the turnover time and metabolic efficiency ratio of fish). The model was able to predict total phosphorus concentrations in the lake water very accurately. The model quickly responded to changes in lake parameters since the lake turnover time is very short and the production is very high. One potentially important process regarding biomass transfer when major changes happen in the ecosystem is fish migration. Since there was no data on fish migration up- or downstream the lake, it was not possible to validate these rates. To further improve the model, more empirical data on this would be needed.

At steady state, the model shows that Lake Kyoga produces 155,000 mt fish per year, which equals 421 kg/ha/yr (or 11.2 g/m^3/yr). Of the studies on lake fish production data for systems from many parts of the world, none can, by the author of this report, be found with any data indicating a higher production elsewhere. This indicates that Lake Kyoga might be one of the most productive lakes in the world.

A scenario run was simulated in order to analyze how the lake would likely respond to the papyrus plug formation following the El Niño events. The lake volume increase lowered the phosphorus concentration and significantly reduced prey fish biomass (see figure 10). Although predatory fish biomass increased, this could not compensate for the lower prey fish biomass and the result was a loss in fish production by about 47 % and in total fish biomass by about 43 % (see figure 11). This was actually reflected in the catch statistics (see figure 12), which recorded a lowered catch by 28 %. What the model (or the official Kyoga catch statistics) did not capture was the immediate increase in fish catch probably due to the release of nutrients from the flooded area around the lake. That was, however, recorded in the local fish statistics for Kamuli district.

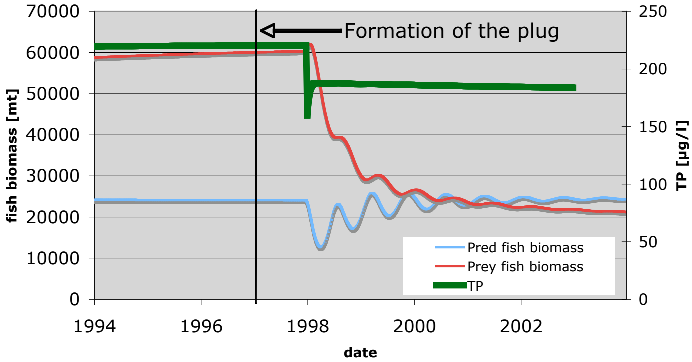

Figure 10. Modeled predatory biomass increase after plug formation.

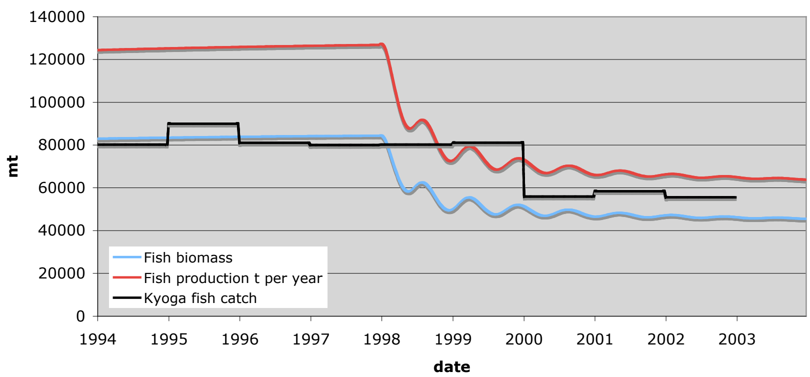

Figure 11. LakeWeb prediction of fish biomass and production response to the papyrus plug formation.

There is also evidence for the increase in predatory fish in the test fishing data from FIRRI (the Ugandan Fisheries Resources Research Institute) where the ratio of Nile perch shows a clear trend of increase (Wandera, 2006). If the Nile perch ratio that Hartsuijker et al. (1991) recorded in 1991 is added, the picture becomes even clearer (figure 13).

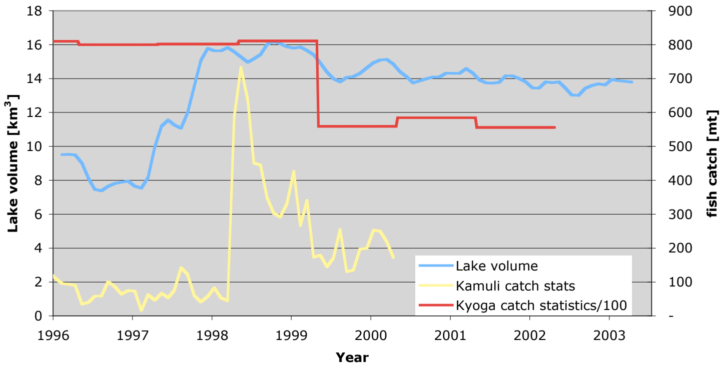

Figure 12. Lake volume and catch statistics. Data on lake volume is from EIA, 2004. Data on fish catch from Kamuli district are from Musenero (2004). Note that the Kamuli fish statistics are recorded on a monthly basis and the unit is therefore mt/month. The Kyoga catch statistics unit is given in mt/year.

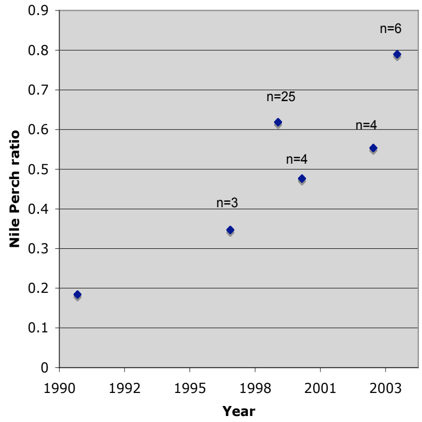

Figure 13. Mean yearly Nile perch ratio for all available test-fishing records (Wandera, 2006). The number of data (n) is shown in the figure. The value for 1990-1991 is taken from Hartsuijker et al. (1991).

The ultimate management question

was: *What would happen if the papyrus plug that was blocking the outlet was removed?* Obviously it would lower the lake water level and restore its lower volume. But would it benefit the fisheries and thereby the local people and also Uganda? The tools now existed to answer that question. The Remote Sensing analyses had given us baseline data and our GIS had given us insight, structure, baseline data and had visualized the modeling challenges. The LakeWeb model was the ultimate tool for providing us with this answer. The scenario modeling predicted that in accordance with the results of the simulation of the plug formation, a removal of the papyrus plug would result in an increase in fish production and biomass. The time response would be relatively quick and most of the increase would occur within two years (figure 14). The increase in fish production is predicted to be about 71 % in the first two years. The corresponding increase in fish biomass will be about 63 %. The fish removal from catch is set to a constant value of 50,000 mt/year. Most probably, the fish catch will increase as the fish production goes up so the increase in fish biomass will probably not be as high as in this scenario run. This was tested with an increase in fish catch (87,500 mt/year) after the plug formation. This lowered the fish production and biomass only slightly and the increase was simulated to be 62% and 54%, respectively.

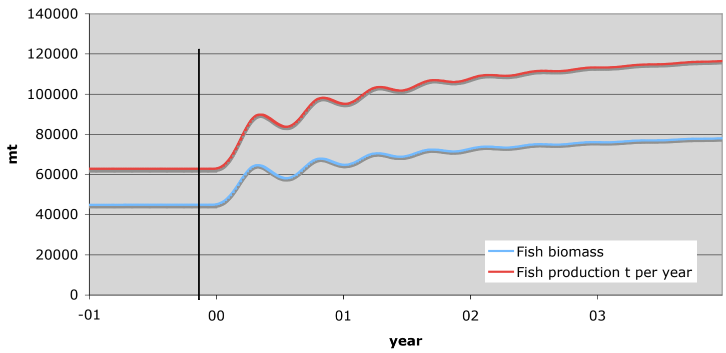

Figure 14. Model simulation of a hypothetical plug removal scenario, which would lower the lake volume to its state before the plug was formed.

Is Lake Kyoga the most productive lake in the world?

The conclusion that Lake Kyoga might be one of the most productive lake in the world is a strong statement. However, if one considers the environmental factors known to regulate fish production, it might well be so:

1. Lake Kyoga is situated on the equator, which makes the temperature constantly high, and without any colder seasons with potentially lower production.
2. It is large but yet very shallow which makes it completely mixed all year around.
3. It has a high inflow of water from the Nile River which pumps in large amounts of nutrients into the lake.
4. The lake has large areas of macrophyte cover which acts as nursing grounds and shelter for small fish.
5. No major environmental impact from factories or other pollution sources is present around the shores of the lake.
6. Much of the nutrients from the fishery are presumably transferred back to the system since many of the people and their livestock living around or on the lake deposits nutrients directly in or nearby the lake shores.
7. The Nile perch is one of the most efficient predators in the world and the stock can quickly increase in biomass when there is opportunity to do so (e.g. Barlow, 1987)

Conclusions

The SIDA project discussed here would not have been possible without the use of remote sensing, GIS or modeling. It was possible to achieve the stated goals with a constrained budget and few field trips only because of the use of these technologies. The results from this project show that the coupled use of GIS and foodweb modeling could be applied to many African lakes and thereby provide insightful support when managing lake fisheries under pressure.

The use of GIS and Remote Sensing is well suited to projects with scarce resources. A lot of data as well as competent software solutions ranging from simple mapping tools to very complex programmable research packages are freely available on the internet. Worldwide data are nowadays available not only for mapping purposes but also spatial analyses. A few sites to start with could be the Geography Network (www.geographynetwork.com), the Digital Chart of the World is still the most comprehensive freely available global GIS database although it is coming of age (www.maproom.psu.edu/dcw). USGS has a very good collection of data: the Global GIS initiative (http://webgis.wr.usgs.gov/globalgis), global landcover data (http://edcsns17.cr.usgs.gov/glcc) and elevation data (http://seamless.usgs.gov). Important factors when browsing the web for free GIS data is to collect meta data of what you download and also be aware of data formats and quality.

The limiting factor in developing countries is very often the quality and speed of internet connections. To work for improvements in this context should be a top priority. Downloading spatial data and satellite images can quickly reach up to several gigabytes. An alternative is to contact someone with a fast and reliable internet connection. Browse the web for your data needs and email your wish list with download links. Your contact could then download it for you and send you a CD or DVD with your requested material.

References

Anonymous, 2004. Estimated quantity of fish landed by Kake regions in Ugandan waters 1961-2002. Stencil from FIRRI library, unknown original publication.

Allison E, 2003. DFID LADDER project, Working Paper No. 9 - Linking national fisheries policy to livelihoods on the shores of Lake Kyoga, Uganda.

Barlow, C.G., 1987. Biology of the Nile Perch Lates Niloticus (Pisces: Centropomidae) with Reference to its Proposed Role as a Sport Fish in Australia.

Chorley, L., 1987. Department of Environment. Handling Geographic Information. Her Majesty's Stationery Office, London. The full Chorley Report.

Gumbricht, T. (2005). Lake level and area variations 1960 to 2002 in Lake Kyoga, Uganda. 11th World Lakes Conference, Nairobi, Kenya, Ministry of Water and Irrigation, ILEC.

Gyllenhammar, A., Gumbricht, T. & Håkanson, L., 2006. Integrated management of Lake Kyoga Natural Resources. Final Report. Geotryckeriet, Uppsala, Sweden.

Hartsuijker, L., Twongo, T. & Kibwika, D., 1991. Report of the Catch Assessment Survey. Fishery Survey of Kyoga Lakes. Agricultural Development Project. Jinja, Uganda.

Håkanson, L. and Boulion, V., 2002. The Lake Foodweb – modelling predation and abiotic/biotic interactions. Backhuys Publishers, Leiden.

ILM (2004). Support to the Management of Sudd Blockage on Lake Kyoga. Produced for the Integrated Lake Management Project by Environmental Impact Assessment Centre of Finland, EIA Ltd.

LEGOS, 2008. Hydrology from Space. An internet site with information on a global altimetric water level database. Available online (15/3/2008) at: http://www.legos.obs-mip.fr/en/soa/hydrologie/hydroweb/

McCarthy, J., Gumbricht, T., McCarthy, T.S., Frost, P., Wessels K. & Seidl, F., 2003. Flooding dynamics of the Okavango wetland in Botswana between 1972 and 2000. Ambio, 32: 453-457.

Musenero, R., 2004. Data on fish catch and value of fishery products for Kamuli district for the period 1994-2000. Personal communication with the District Fisheries Officer.

NRSP (Natural Resources Systems Programme), 2001. How representative is Lake Kyoga, Uganda in the context of African and other tropical wetlands. FIRRI, technical report, Jinja, Uganda.

Reynolds, J.E. (ed) (1989). FAO/UNDP project UGA/87/007. Field document No. 1. Fisheries statistics and information management in Uganda. Past approaches, current status, and future prospects.

Twongo, T., 1994. Some biological and ecological considerations for research in the management of the fisheries of Lakes Victoria and Kyoga. In: Okemwa, E.; Wakwabi, E.O.; Getabu, A . (Ed.) Proceedings of the Second EEC Regional Seminar on Recent Trends of Research on Lake Victoria Fisheries, NAIROBI : ICIPE SCIENCE, p. 167-176. Available online (15/3/2008) at: http://hdl.handle.net/1834/1282

Wandera, S., 2006. Test fishing data for Lake Kyoga, 1997-2004. Unpublished data, FIRRI, Uganda.