African Journal of Tropical Hydrobiology and Fisheries **12**: 22-30 (2009)

Lake Victoria's Water Budget and the Potential Effects of Climate Change in the 21st Century*

Sowedi M. Sewagudde

Directorate of Water Resources Management, Ministry of Water and Environment, P.O. Box 19, Entebbe Uganda
Email: sowed.sewagudde@mwe.go.ug

Abstract

This paper presents the Lake Victoria water budget for the period 1950-2004 and findings of a study on potential climate change impact on the lake's Hydrology through the 21st Century. The mass balance components are computed from measured and simulated data. A2 and B2 emission scenarios of the Special Report on Emissions Scenarios are considered in the climate change assessment. Results show that rainfall and Evaporation by far exceed catchment inflow and outflow. Rainfall over the lake exceeds evaporation by a factor of 0.1 whereas outflow exceeds inflow by a factor of 0.27. Due to climate change, increase in temperature of 4-5ºC and 2-3ºC are expected by the end of the 21st century under the A2 and B2 emission scenarios respectively. There is very significant downward trend in the lake Net Basin Supply reducing by up to 50%) by the end of the Century. Towards the end of the 21st century, the lake is likely to experience more frequent and prolonged droughts implying lower lake levels

Key words: Lake Victoria, Water budget, climate change, emission scenarios.

Introduction

Lake Victoria provides various resources and economic opportunities to about 33 million people living in its basin (in 2004). Over the past four decades or so, the lake has come under increasing pressure from a variety of interlinked human activities such as industrial pollution, eutrophication and sedimentation (Hecky 1993; Muyodi *et al.* 2005). These pressures have led to a deterioration of the lake's water quality which is threatening its capacity to provide the benefits enjoyed by the communities. Efforts have been made to reverse this situation through the Lake Victoria Environmental Management Programme (LVEMP) among others. It was realized that any strategy aimed at effective management of pollution to the lake would require a quantitative understanding of the relationship between sources, types, concentration, transportation and effects of pollutants on the lake's ecosystem. The water budget of Lake Victoria was therefore determined primarily to estimate the loading rates of major pollutants from key sources such as tributaries to Lake Victoria, atmospheric deposition, and contaminated sediments to establish baseline loading rates. It would also be used to evaluate the success of future interventions aimed at reducing pollution of the lake.

Relatively little work has been undertaken to establish the water balance of Lake Victoria. Piper *et al.* (1986) and Krishnamurthy and Ibrahim (1973)have attempted to determine this balance while other workers have only inferred it from historical records of water levels. These investigations have not benefited from a wealth of recently measured flow fluxes, a factor that could be responsible for a large margin of uncertainties. This paper presents an updated water balance for Lake Victoria for the period 1950-2004 and is a continuation of the quantification of the lake's water budget as part of a limnological study of Lake Victoria (LVEMP 2002).

Water resources are very vulnerable to the adverse effects of climate change and variability, and that relatively small climate changes could produce significant impact on water resources (Lins *et al.* 1991). This paper assesses the impact of climate change on the water balance of the lake and examines the evidence that the climate of the region might change significantly in the 21st century. The way these changes affect the lake's hydrology and the potential consequences are also discussed. The work of Georgakakos, *et al.* (2005), on which most of this review was based, is acknowledged.

Methods

Water Balance fluxes

Current knowledge of the Lake Victoria hydrologic system and ground measurements allow for a reasonable estimate of the water budget but there were shortcomings with the measurements from some stations in and around the lake. These included an insufficient length of data, missing data, and fragmented and erroneous records. The computed water balance would be expected to have a large number of uncertainties but these uncertainties have

***Paper presented to the Lake Victoria Stakeholder's Conference, Kampala, 27-30 October 2008**

been greatly reduced by using systematic checks and comparisons with the relatively long time sequences of water levels.

In view of these limitations the objective of this work was to quantify as accurately as possible the components of the water budget for Lake Victoria, particularly the flux terms involving input processes. This work sought to acquire all information relevant to the quantification of each component, develop a method for calculating it and identify the assumptions that must be made to estimate particular components. It is recognised that water budget terms vary temporarily as a result of natural precipitation patterns and variability.

The principle of conservation of mass was used in the development of the water budget and five components of the water balance were identified: (1) rainfall over the lake; (2) inflow from the catchment; (3) evaporation; (4) outflow through the Nile at Jinja and (5) storage. There is an interaction between groundwater and surface water of Lake Victoria but its influence in relation to other water balance fluxes is insignificant (Krishnamurthy and Ibrahim, 1973) and it was therefore assumed to be negligible. Catchment inflow was estimated through rainfall-runoff modelling using the Nedbor Afstromning Modele (NAM) model for the Kenyan and Ugandan catchments and the Soil Moisture Accounting Procedure (SMAP) Model was applied for the Tanzanian Catchment.

Rainfall

Continuous rainfall time series for the period 1950-2004 from selected stations in the catchment and on islands were generated using measurements, correlations with neighbouring stations and the insertion of a 'typical year'. The selected stations were representative in that they covered the geographical area of the catchments as well as areas with different rainfall characteristics. On average, 2 to 6 stations were selected in each catchment (see Figure 1 for the catchments and rainfall stations used for the computation of areal rainfall). Rainfall records were subjected to vigorous quality control checks including visual examination of raw and plotted data, computed statistical properties, comparison with records at adjacent stations, and examinations of double mass curves.

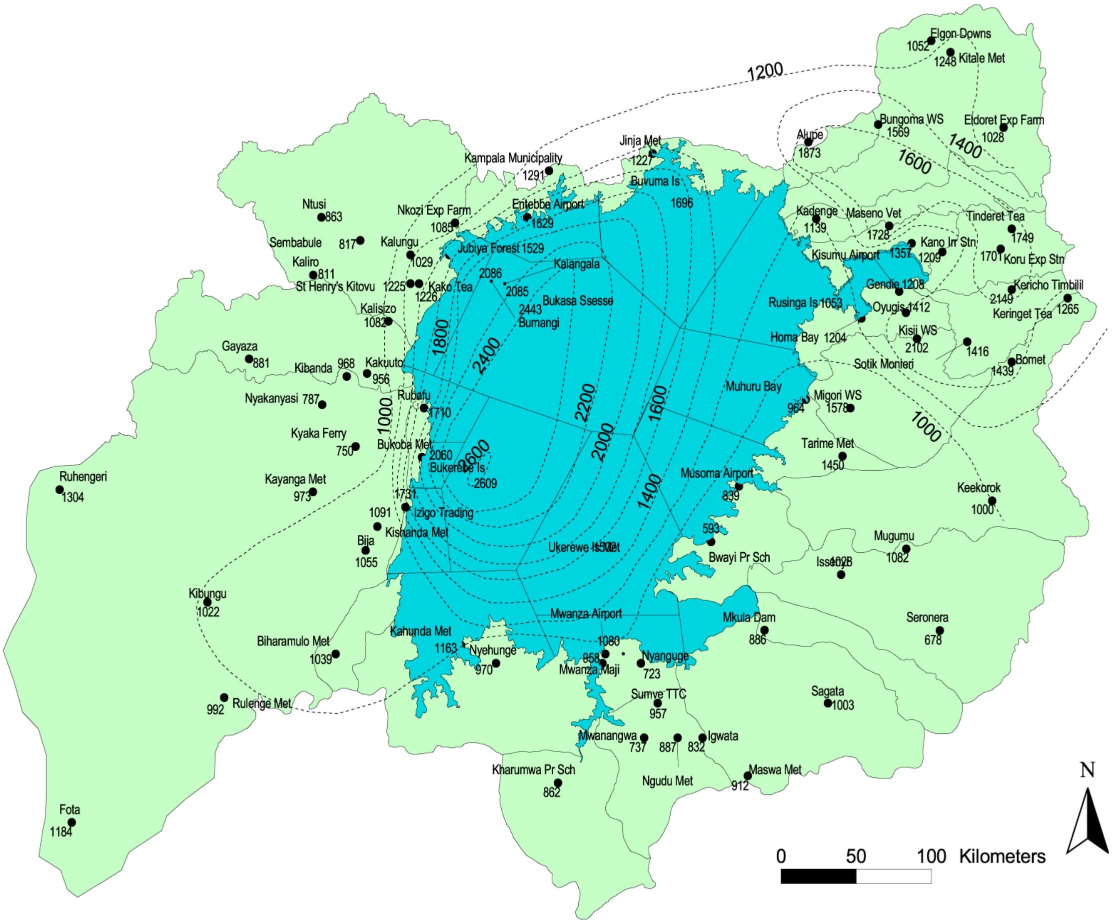

Figure 1. Catchments and rainfall stations used for computing areal rainfall over Lake Victoria.

A reference station was identified in each catchment and used to fill gaps in the records from other stations in that catchment; the reference station was usually the one with the longest continuous high quality records. A double mass curve was plotted and a trend line fitted for the subject stations and the equation for that trend line was then used to fill the gaps. For periods when records were missing from both the reference station and the other stations, a ‘typical rainfall year’ method was used, a method that was developed for this work and proved to be successful.

The idea was to fill the rainfall record gaps with data from a ‘wet’ ‘average’ or ‘dry’ hydrological year, running from 1 October to 30 September. The typical years were determined from the rise in lake level during that year with a ‘wet year’ being arbitrarily defined as one in which the lake level rose by 0.2 m or more while a ‘dry year’ was one in which the lake level fell by 0.2 m or more and in an ‘average’ year it fluctuated by ± 0.2 m. Having defined the type of year, the next step was to determine the total annual rainfall for each station during the typical year.

The rainfall over the lake was computed as a weighted sum of records from stations around the lake and on islands. The lake was divided into boxes (Figure 1), with each having a reference station and the mean annual rainfall in each box was estimated from isohyetal curves. The daily/monthly rainfall in each box was then estimated as

$$R_{box} = \frac{R_{ref} \times MAR_{box}}{MAR_{ref}}$$

where R_{box} = daily rainfall in box; R_{ref} = daily rainfall at reference station; MAR_{box} = mean annual rainfall in box and MAR_{ref} = mean annual rainfall at reference station. The average daily rainfall for the lake was then calculated as the sum of the areal weighted means of the daily rainfall in the boxes (ΣR_{box}) as

$$R_{lake} = \sum (R_{box} * W)$$

where R_{lake} = rainfall over the lake and W is a weighting factor.

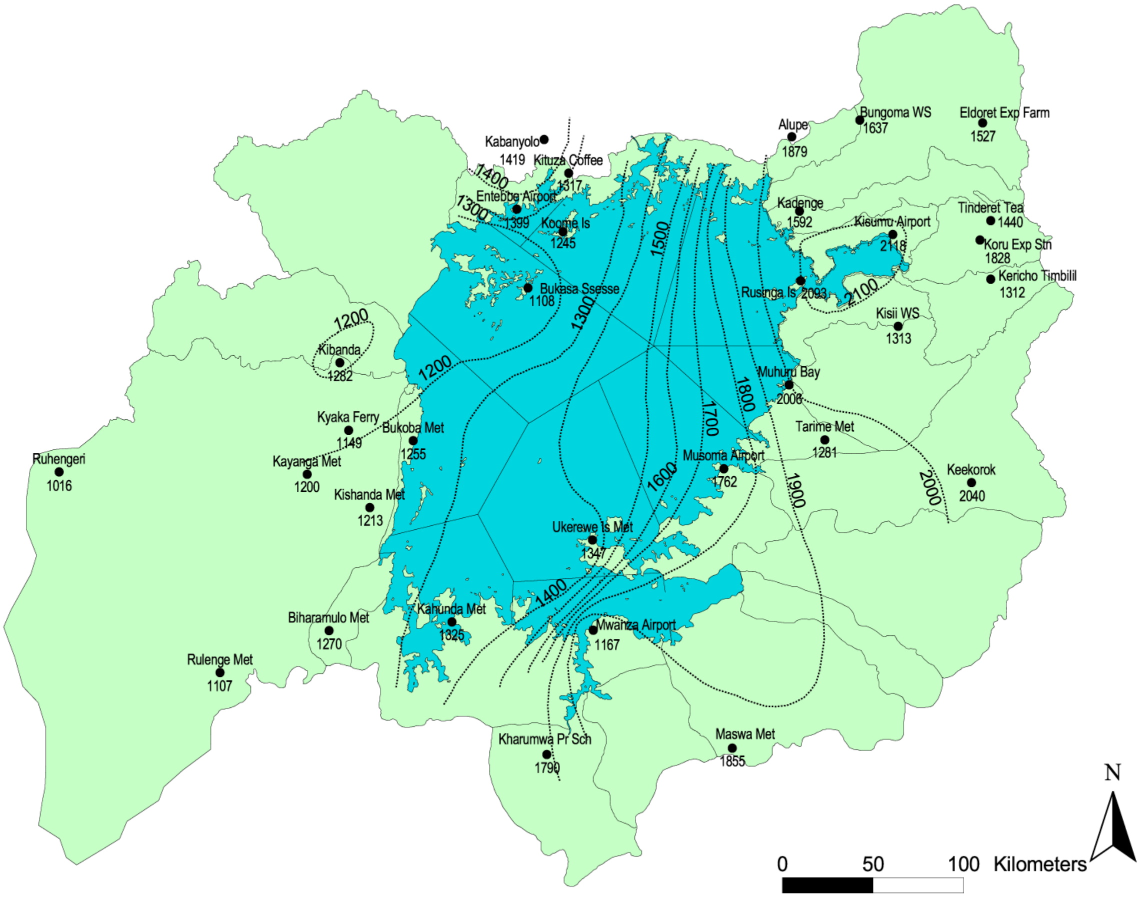

Figure 2. The location of evaporation stations used for computing evaporation over Lake Victoria.

Evaporation

Continuous evaporation time series were generated using the same methods like that for rainfall records, but with some minor changes. However, the idea of using a reference station was not applied because evaporation is determined only at full meteorological stations, which may be a considerable distance apart. The concept of a wet, average or dry year was also not used but instead the mean estimate for a particular day was used to infill records; for example, a missing station value for say 1st of October of a particular year was in-filled by using mean measurement for 1st October for other years where records were available. Figure 2 shows the evaporation stations used in the computation of evaporation on Lake Victoria. Evaporation over the lake was computed as a weighted sum of records from around the lake and islands within the lake.

Catchment Runoff

River discharges were computed on the basis of rating curves, visually inspected to remove outliers, and measured gauge heights. There are several river-gauging stations, usually located at the confluence of larger rivers, in each catchment in the Lake Victoria Basin. Since the objective was to quantify the inflow to the lake, river discharges at the closest station to the mouth of the river were used wherever possible.

Because the river gauging stations had varying length of records, rainfall runoff modelling was done to extend the flow series to cover the period 1950-2004. The NAM model a, lumped conceptual model from the Danish Technical University was employed on the Uganda and Kenyan catchments. In this model the entire catchment was considered to be a single unit with uniform properties and the flow of water through the system was conceptualized into a number of reservoirs with the parameters partly reflecting the physical characteristics of the system. The SMAP model was used for the Tanzanian catchments, because it is best suited for use with monthly data and it, too, is a conceptual model but with simpler structures. Both models were calibrated by adjusting the model parameters by trial and error until the modelled and observed accumulated discharges, peak flows, recession curves and low flows were in agreement. Given that the objective of this study was to quantify the inflow into the lake, emphasis was then placed on the correct simulation of total inflow into the lake rather than the correct simulation of flow peaks.

There are a number of ungauged catchments around the lake, most of which consisting of small rivers and swamps fringing the lake. Other catchments are gauged but their records could not be used either because the period they covered was too short, or they were erroneous or did not represent the entire catchment. Two methods were used to estimate the flows from these catchments: (1) by using one of the two models with the same parameter values from an adjacent and similar catchment, and (2) by using a modified form of the *Rational Formula*, a standard empirical formula for computing peak flow rates.

Most discharge stations were not at the river mouth and some corrections were necessary to obtain the total discharge from the basin. This was done by (1) increasing the basin discharge by a proportion of the areas i.e. basin discharge = station discharge * (basin area/gauging station area) or (2) applying rainfall runoff modelling to the entire basin. The first method was chosen to compute the final discharge for each river basin since it deals directly with the measured station discharge and the second was only used in cases where several rain gauges were required to cover the ungauged catchment.

Computation of the Water balance

The water balance was then computed as the sum of the inflows (rainfall + river discharges) minus the sum of the outflows (evaporation + discharge to Victoria Nile) and the budget was assumed to be balanced when the difference between inflows and outflows was equal to the net storage of the system. This assumption proved to be effective in reducing uncertainties in the computed flows. The storage term was translated into lake levels and then compared with the measured lake levels at the Entebbe station and correction factors were applied to the various flow components until the predicted lake levels agreed with the observed ones.

Climate Change

Two emission scenarios in the Special Report on Emissions Scenarios (IPCC, 2000) were selected for the assessment of potential impacts of future climate change on the water balance of the lake, on the basis that they represented a wide range of potential emissions in the future. The B2 scenario assumes moderate economic and population growth resulting in moderate cumulative emissions between 1990 and 2100 amounting to 1,164 Gt of carbon. The A2 scenario also assumes moderate economic growth but more rapid population growth and much higher emissions (1,862 Gt C). The final temperature and precipitation sequences for both scenarios were produced for both the lake and the watershed.

This assessment of the impact of climate change on the hydrology of Lake Victoria adopted an integrated approach using global climate models, hydrologic models for the lake and its watershed, and water resources models. The HadCM3 General Circulation Model, a coupled atmosphere-ocean model with a spatial resolution of 2.5 x 3.75 degrees, was used to simulate the response with respect to temperature and precipitation over the lake. Several bias-adjustments were employed before downscaling the model's monthly temperature and precipitation predictions for use in assessing the implications of future climate change on the lake's hydrology. The model was calibrated against observed temperature and precipitation over the lake for the period 1961 to 1980 using the Climate Research Unit TS2.0 monthly temperature and precipitation data sets at a resolution of 0.5 x 0.5 degrees. Evaporation over the lake was assumed to take place at climatic potential rate and was estimated using the Malmstrom potential evapotranspiration rate described by Dingman (2004, cited in (Georgakakos *et al.* 2005), which was

$$PET(k) = 40.90611\exp\left[\frac{17.3(T_{mean}(k) - 273.16)}{T_{mean}(k) - 273.16 + 237.3}\right]$$

where $PET(k)$ is the monthly potential evapotranspiration rate (mm) and $T_{mean}(k)$ is the mean monthly air temperature over the lake in degrees Kelvin. The watershed evapotranspiration was computed with the Pike evapotranspiration equation using the precipitation and temperature sequences from the HadCM3 regional model, where

$$ET = \frac{P}{\sqrt{1 + \left[P/PET_{(k)}\right]^2}}$$

where ET = annual evaporation (mm), P = annual precipitation (mm), and $PET_{(k)}$ is the annual potential evapotranspiration (mm).

To facilitate prediction of potential future changes in the water balance, the assessment considered two lake regulation policies: (a) the agreed curve (AC) release policy, where water is released through the Owen Falls Dam according to the natural lake outflow and (b) the energy demand-driven policy (ED) where the quantity of water released is determined by demand for energy.

Results and discussion

The water balance

The estimated inflows to and outflows from the lake are liable to errors and these were corrected by balancing all the fluxes and comparing the results with the measured lake level during the period 1950-2004. Correction factors were then applied for periods where major discrepancies were discovered. The need for correction could explain the various physical changes – land use change- within the catchment over the last fifty-five years. After these corrections were made there was a reasonably good agreement between the predicted lake level (from the computation of the water balance) and measured level (Figure 3).

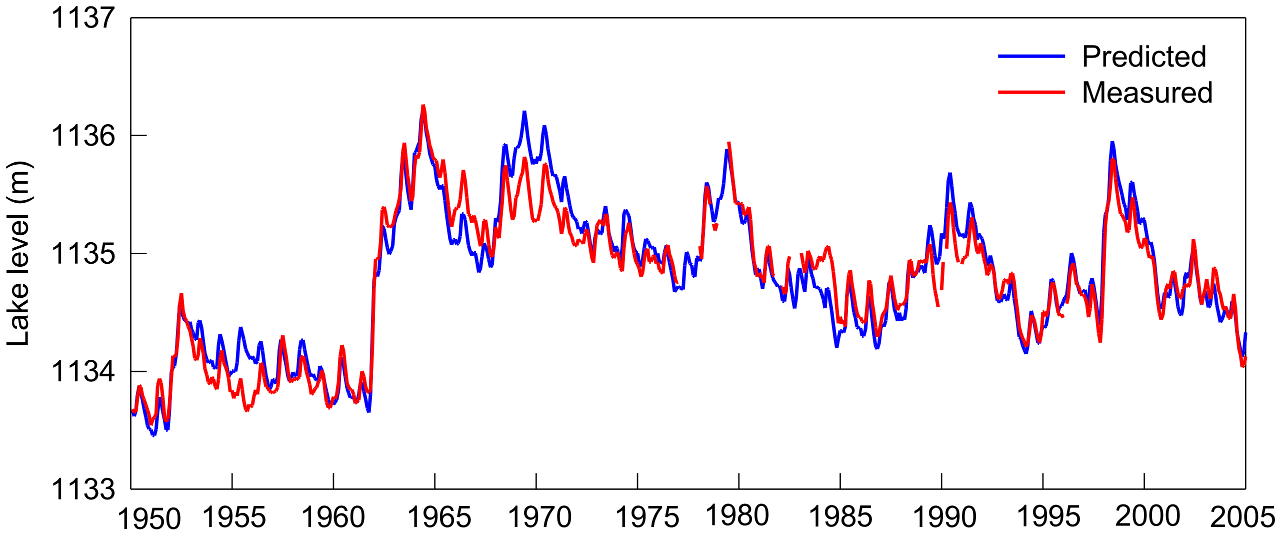

Figure 3. Predicted and measured lake levels at Entebbe, January 1950 to December 2004.

Table 1. Average annual water balance of Lake Victoria 1950-2004 (infilled data from LVEMP Database).

		Flow ($m^3\ s^{-1}$)	Volume ($km^3\ yr^{-1}$)	%
Gains	Rainfall	3,719	117	82.0
	Basin discharge	814	26	18.0
Losses	Evaporation	3,330	105	76
	River Nile	1,058	33	24
Storage		145	5	

Evaporation and direct rainfall are the most important factors in the Lake Victoria water budget (Table 1). Rainfall contributes about 117 km^3 (82%) of the total inflow and evaporation accounts for 105 km^3 (76%) of the losses from the lake. Rainfall outweighs evaporation by a factor of 0.1, but the outflow from the Nile exceeds the inflow from the other rivers by a factor of 0.27. Over time, the annual rainfall nearly equals evaporation implying that the outflow into the Nile was mainly sustained by the watershed runoff. This assertion is further explained by the comparison of the computed water balance components and those earlier estimated by Krishnamurthy and Ibrahim (1973).

Table 2. A comparison of the computed water balance from this study (km^{-3} y^{-1}) compared to that estimated by Krishnamurthy and Ibrahim (1973), abbreviated as "K and I (1973)."

		K and I (1973)	This study	Difference (%)
Inflow	Rainfall	100	117	17
	Basin discharge	18	26	44
	Total	118	143	22
Outflow	Evaporation	100	105	5
	River Nile	23	33	43
	Total	123	138	12

Table 2 shows the percentage difference between the computed water balance and earlier estimates. The basin discharges increased by 44% while Nile outflow increased by 43%, and the total gains and losses only differ by only 3.6% which is within experimental error. The significant discrepancy between the basin discharge and Nile outflow can be explained by (i) a 17% increase in rainfall; (ii) the impact of deforestation in the 30 years between the two studies, which leads to an increase in runoff because there is no vegetation to retain water, thereby affecting the quantity and timing of runoff to the lake; and (iii) changes in the lake release policy in the last decade of the assessment period

Long-term fluctuations (1950-2004) exhibit a 5-6 year cycle of water level maxima (Figure 4) which agrees with the conclusions in Temple (1969) but a review of Net Basin Supply (NBS) revealed a 10 year cycle of maxima for the period 1900-2003 (Songa and Sewagudde, 2007). The NBS (rainfall + runoff – evaporation) is a critical determinant of the lake's level and ideally it maintains a relatively stable level and volume of water. The most variable annual precipitation over the period 1950-2004 occurred in 1961-1964 and again in 1997-1998, with elevated rainfall totals attributed to the *El-Niño* Southern Oscillation. In 1961-64 the average rainfall reached 130 km^3 (1900 mm) which is 11% above average and this led to a significantly greater discharge (about 68% above average) from the rivers. As a result the lake level rose by 2.4 m over a period of four years, an enormous increase given the size of Lake Victoria (68,800 km^3). Similarly in 1997/98 the rainfall increased by only 10% but river discharges increased by about 80%.The higher river discharges in 1997/98 despite the same rainfall increase as in 1961-64 further confirms the effect of deforestation in the watershed as earlier explained.

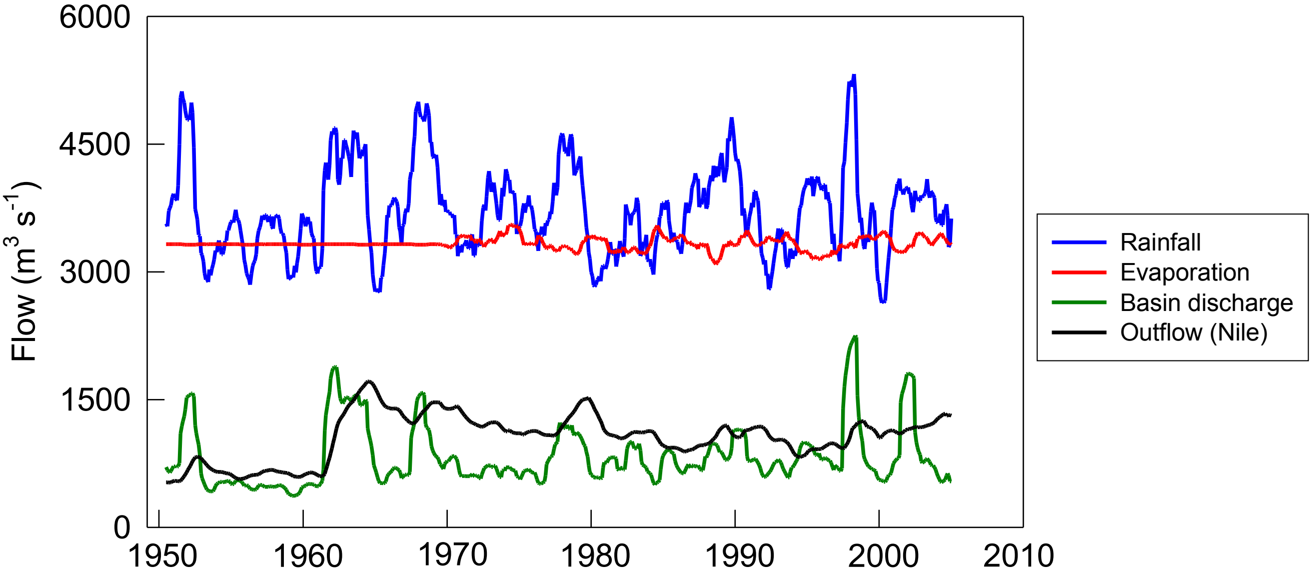

Figure 4. Historical variations in the mass balance components for Lake Victoria, 1950 -2004. Data from LVEMP

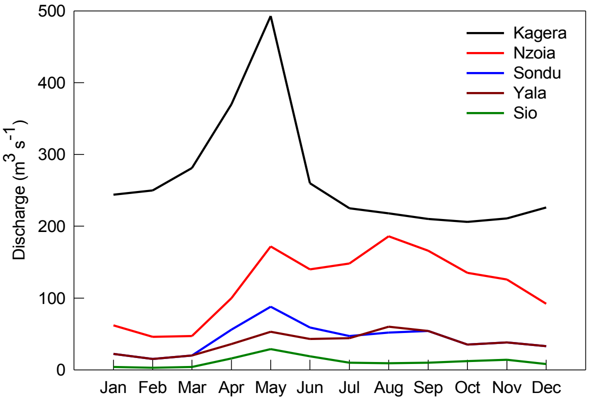

Figure 5. A comparison of the monthly discharge (m^3 s^{-1}) from the Kagera River and some major rivers flowing from Kenya.

The Kagera River is the largest river flowing into Lake Victoria and it normally contributes about 37% of the total inflow to the lake, although it was reported to have contributed about 63% in 1969 (WMO, 1974). There is some seasonal variation in the inflow from the catchment with the rivers flowing from the Kenyan highlands having their peak flows from about May to August while the Kagera, which rises on the Rwandan highlands reaches its peak flow in May, although its base flow remains above that of the other river flows (Figure 5). The Uganda catchments contribute insignificantly to the lake inflow.

The outflow from the lake through the Victoria Nile and the level of the lake are linked through a mathematical equation known as the agreed curve. It was first developed from the flow over the then Lake Victoria control (Ripon falls) before the construction of the Owen Falls dam. The outflow is presently being controlled by the Nalubale-Kiira hydropower complex. The agreed curve was followed consistently until 1998 when there was a deviation (Figure 6) caused by heavy rains in 1997/98 which were a result of the *El Niño* southern oscillation. At this time the release of water through the Owen Falls Dam was reduced in order to ease flooding downstream in the Lake Kyoga region and, as a result, there was excess storage with the lake elevation being 0.1m above the expected water level.

From June 2000 onwards the water released at Owen Falls exceeded the agreed curve to meet the demand for hydropower and for a few months this water was drawn from storage attained during the heavy rains in 1997/98. This storage was depleted by July 2001 and the water was then being drawn from the 'natural' lake storage leading to a slight decline in water levels. The situation was exacerbated by persistent droughts in the region between 2003 and 2006, which meant that the actual net input to the lake was reduced by about 50% (Songa and Sewagudde, 2007).

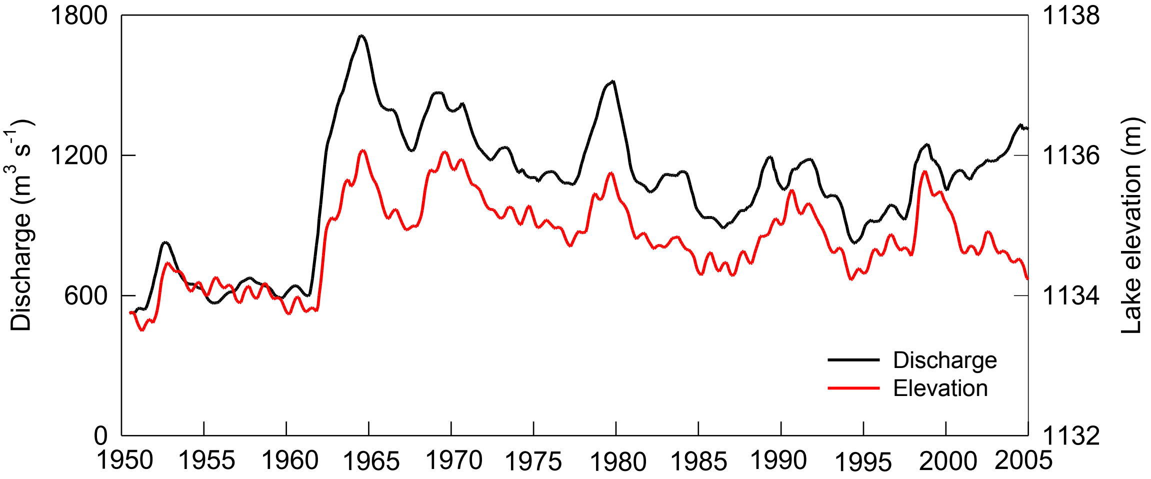

Figure 6. The relationship between the Nile discharge (m^3 s^{-1}) and the elevation of Lake Victoria (m above sea level). From the Directorate of Water Resources Management database.

Potential impact of climate change on the water balance

Temperature plays an important role in the water balance because it drives evaporation and both the A2 and B2 climate models suggest that temperatures in the region will rise in the 21st century (Figure 7). The temperature trend between A2 and B2 scenarios increases with the same slope up to 2040 when they start to diverge conspicuously. Both trends continue to increase but temperature under A2 increases at a greater rate. In the last two decades of the 21st century, the trend in B2 tends to taper off. According to the A2 climate change scenario, the average air temperature over the lake and its watersheds is expected to increase by 4 to 5 degrees Celsius by the end of the 21st century compared to present conditions. The corresponding temperature increase for the B2 climate scenario is about half.

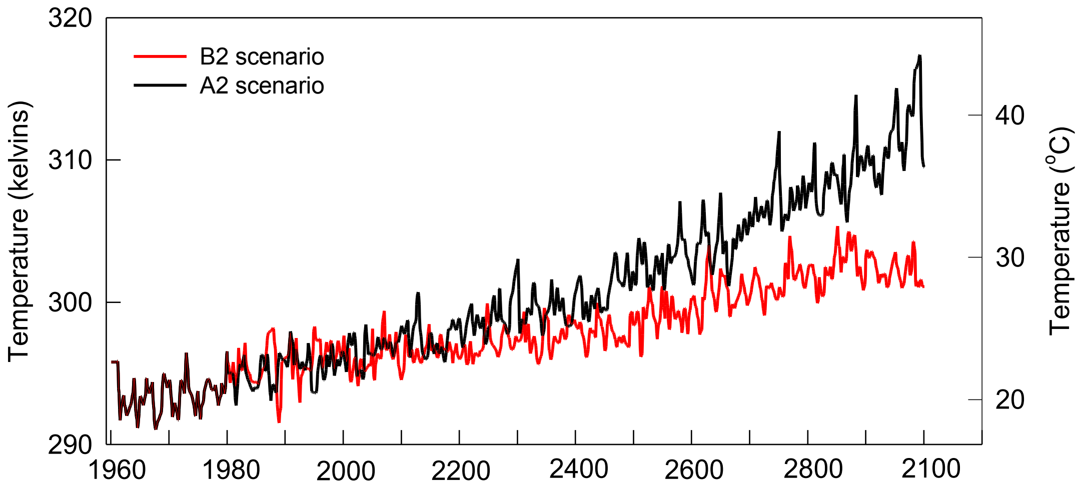

Figure 7. Predicted temperature variation over the lake in the 21st century (from Georgakakos *et al*., 2005).

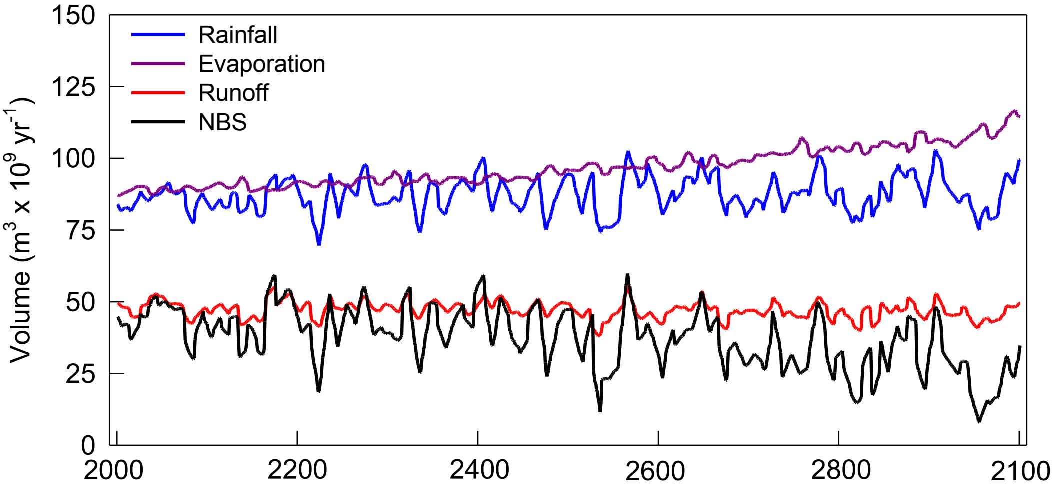

Figure 8. Changes in rainfall, evaporation, runoff and net basin supply (NBS) in Lake Victoria under the Future Climate Assessment A2 Scenario (lines are annual moving averages). NBS = net basin storage. From Georgakakos *et al.* (2005).

As a direct consequence of the increase in temperature, evaporation over the lake will increase steadily (Figure 8) but up to 2025 evaporation and rainfall balance out just as they did in the historic past. Beyond 2025 evaporation is predicted to increase steadily and by the end of the century it could exceed rainfall by 20 billion m^3 yr^{-1} (20 km^3). The mean annual lake rainfall over the lake will oscillate about the historical long-term mean throughout the century with neither a positive nor a negative trend (Figure 8). This assertion is valid for the first six months of the year where the HadCM3 exhibits commendable rainfall prediction skills but a rainfall trend could still develop as a result of rainfall variability during the last six months of the year in which the model shows weak prediction and some climate predictions have forecast increased rainfall over the region (Tate *et al.* 2004). Runoff from the catchment also exhibits a mild downward trend as a consequence of evaporative losses resulting from increased temperatures. Mean runoff reduction is not expected to exceed 5 to 10% of the present catchment discharge by the end of the century.

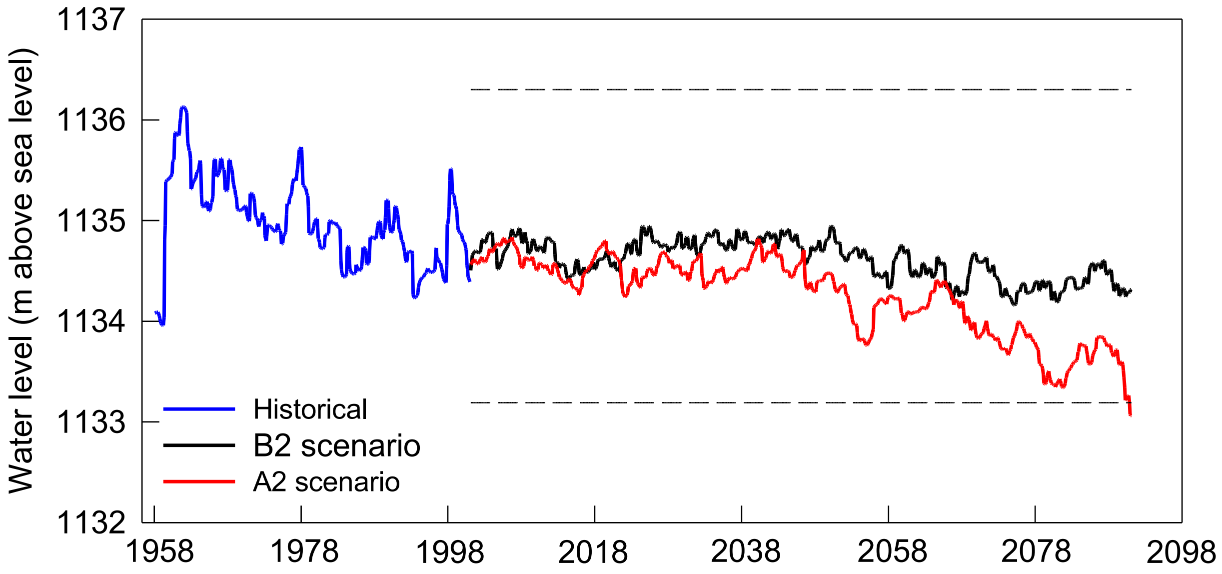

Figure 9. Current and predicted levels of Lake Victoria under the Agreed curve policy up to the end of the 21^{st} century. Adopted from Georgakakos *et al.* (2005). The broken horizontal lines indicate the historical maximum and minimum values.

Net basin supply is a critical indicator as it maintains lake levels and supports all other water uses, and predictions suggest that there will be a significant downward trend in the net basin supply over the next century. The NBS is expected to fall by about 50% (20 billion m^3 yr^{-1}) by then and this will have severe

Simulation results for lake releases made under the agreed curve policy suggest a general decline in lake levels under both climate change scenarios. The decline under the A2 scenario is quite striking and the lake level could fall to its lowest historical level (Figure 9) by the end of the century. Under the B2 scenario, the lake level gradually falls away from the historical mean but remains within the historical limits of fluctuation.

Conclusion

Rainfall and evaporation are the major players in the water balance of Lake Victoria. The large size of the lake acts as a buffer to abrupt sharp changes in water levels on an annual basis as long as the agreed curve policy is followed. However, the lake level changes significantly when rainfall over the lake is consistently above or below normal for a couple of consecutive years.

Climate change is likely to cause increase in both lake evaporation and catchment evaporation as a direct response to temperature increase. Consequently catchment runoff will reduce as a direct response to increased evaporation. However, lake rainfall is likely to fluctuate about the historical mean level. Increased evaporation and constant rainfall will imply reduced net basin supply, leading to more prolonged droughts and reduced wetland area. If the agreed curve water release policy is followed throughout the 21st century, the lake level is likely to fluctuate about the historical optimum fluctuation band under the B2 emission scenario, but reduce below the lowest optimum level under the A2 scenario. With reduced net basin supply, the ability of the lake to meet its regional water needs such as hydropower supply, irrigation needs, fisheries water requirements, etc. will be greatly hampered.

Acknowledgements

This paper stems from the working sessions for the compilation of the Lake Victoria synthesis report by the Lake Victoria Environment Management Project. I thank the members of the quantification component for their work in collecting and compiling the water budget data. I

consequences for the lake and its ability to meet the region's water needs. The NBS series indicates a significant increase in the frequency of extreme droughts and so, towards the end of the 21st century, NBS will be negligible or even negative from time to time as a result (Georgakakos *et al*., 2005).

thank Mr. Agrey Kyeye for is effort in reorganising the data into a standard format.

References

Georgakakos, A., H. Yao and A. Tidwell (2005). Climate change impact assessment. study on water management of Lake Victoria. Georgia, Atlanta, WREM International Inc.

Hecky, R. E. (1993). The eutrophication of Lake Victoria. *Verhandlungen der Internationalen Vereinigung für Theoretische und Angewandte Limnologie* **25**: 39-48.

Krishnamurthy, K. and A. Ibrahim (1973). Hydro-meteorological studies of Lakes Victoria, Kioga and Albert. In: W.C. Ackermann, G.F. White and E.B. Worthington (eds). *Man-made Lakes: Their Problems and Environmental Effects*. American Geophysical Union, Washington DC: p. 272-277.

Lins, H. F., I. A. Shiklomanov and E. Z. Stakhiv (1991). Impacts on hydrology and water resources. Climate Change: Science, Impacts and Policy, Cambridge, Cambridge University Press.

LVEMP (2002). Integrated Water Quality and Limnology Report of Lake Victoria. Lake Victoria Environmental Management Programme. Entebbe, Ministry of Water and Environment. [Unpublished report.]

Muyodi, F. J., S. Nsubuga and F. L. Orach-Meza (2005). An introductory overview to the current state of the water quality of Lake Victoria, Uganda, Ministry of Water, Lands and Environment, Entebbe. [Unpublished report]

Piper, B. S., D. T. Plinston and J. V. Sutcliffe (1986). The water balance of Lake Victoria. *Hydrological SciencesJournal* **31**: 25-37.

Songa, P. A. and S. M. Sewagudde (2007). Supply and demand: the effect of development on the hydrology of Lake Victoria. Proceedings of the 37th Annual Mississippi Water Resources Conference, Mississippi: p. 216-222.

Tate, E., J. Sutcliffe, D. Conway and F. Farquharson (2004). Water balance of Lake Victoria: update to 2000 and climate change modelling to 2100. *Hydrological Sciences Journal* **49**: 563-574.