CRANFIELD UNIVERSITY

Róisín Murray-Williams

The Water Balance of Lake Victoria: Towards an Accessible and Updateable Model

School of Applied Sciences
Water Management: Community Water and Sanitation

MSc
Academic Year: 2008 - 2009

Supervisor: Professor Richard Carter
September 2009

CRANFIELD UNIVERSITY

School of Applied Sciences
Water Management: Community Water and Sanitation

Msc

Academic Year 2008 - 2009

Róisín Murray-Williams

The Water Balance of Lake Victoria: Towards an Accessible and Updateable Model

Supervisor: Professor Richard Carter

September 2009

This thesis is submitted in partial fulfilment of the requirements for the degree of MSc Water Management

ABSTRACT

Lake Victoria is the world's second largest fresh water lake and with a basin spanning five countries the livelihoods of 30 million people depend upon its waters. Many water balance studies have been carried out yet there are often great difficulties in accurate data collection. This study aims to provide an accessible and easily updateable tool for modelling the water balance of Lake Victoria using publically available data. The study also investigates possible future lake level behaviour and the impact that water level fluctuations has on key stakeholders in the basin.

In this study lake levels are successfully modelled from 1948-present using rainfall data available publically from the WMO and the NOAA using an equation modified from one developed by Nicholson et al, 2000. This therefore provides a tool which is accessible and updateable. Modelled lake levels underestimated some of the peaks in the observed record, however the correlation between observed and modelled levels was good, $R^2 = 0.8$. As a departure around 2007/8 was observed, the performance of the NOAA data needs to be monitored over the coming years.

Modelled future lake level behaviour varied considerably. The data from one GCM resulted in a significant increase in lake levels from 2010-2099 whereas the other two showed a slight decline on present levels. A challenge is posed by a high occurrence of inter-model disparities in East Africa. Whether a rise or decline is to be expected there are many stakeholders who will be affected in particular; water supply, fishing and hydro-electric generation directly and industry indirectly through power supply.

Although there are a number of limitations of the model, this study provides a useful step in assessing the water level behaviour of a lake which is so important to the region.

Keywords:

Climate Change, Impact on Stakeholders, Publicly Available Rainfall Data

ACKNOWLEDGEMENTS

This thesis would not have been possible without the help of many people in Uganda, England and Ireland. Firstly I would like to thank the people I met in Uganda; Commissioner Callist Tindimugaya, Joel Okonga and the other staff at the Directorate of Water Resource Management, Entebbe, for their generous co-operation and sharing of data. Also Andrew Luzze (UMA), Paddy. B. Twesigye (NWSC) and John Bawira, Konstantine Odongkara and others at NaFIRRI for kindly partaking in interviews giving any help they could. For being my translators and friends in Jinja I would like to thank Lambert Igua and Ochieng Kassedde Romeo.

I am very grateful to Denis Igua and Stella Iwoku for their assistance in my preparations for and during the fieldwork in Uganda and to Justin, Pierre and Pauline for company and pineapple.

I would also like to acknowledge Eric Wolvovsky (NOAA) and Ian Truckell for technical help. Bringing everything together in the end was not an easy task and I'm thankful for friends such as Dave for proof reading. Lastly but most importantly I would like to thank Richard Carter for his assistance throughout and my parents for their unconditional emotional (and financial) support!

TABLE OF CONTENTS

TABLE OF FIGURES

TABLE OF TABLES

TABLE OF EQUATIONS

ACRONYMS

ARTES - Africa Rainfall and Temperature Evaluation System

DWRM - Directorate of Water Resource Management.

DWRM - Directorate of Water Resource Management

GCM - Global Circulation Model

IPCC – Intergovernmental Panel on Climate Change

NaFRRI - National Fisheries Resources Research Institute

NOAA - National Oceanic and Atmospheric Association

NWSC - National Water and Sewerage Corporation

UMA - Uganda Manufacturers Association

WMO – World Meteorological Organization

1. Introduction

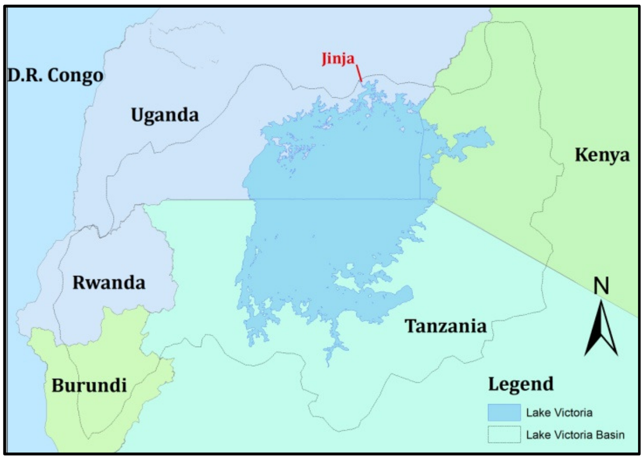

Figure 1-1. Map of Lake Victoria and its basin.

Lake Victoria is the world's second largest fresh water lake; its basin stretches across Burundi, Kenya, Rwanda, Tanzania and Uganda. The lake is consequently of international importance and the livelihoods of approximately 30 million people are dependent on its waters (Mubiru, 2006).

1.1 Hydrology of Lake Victoria

The lake has a surface area of approximately 67, 100 km^2 (Sene and Plinston, 1994). It is fed by tributaries in five countries (Figure 1), yet the only outflow is in Uganda, at Jinja, where the White Nile begins (Kite, 1981). Whether by natural or anthropogenic means, flow in the White Nile has, for the majority of its history, been regulated by the status of water levels in Lake Victoria.

Change in water levels of a lake over a period of time is a product of all the inputs, (such as rainfall and inflow) minus all the outputs (such as evaporation and outflow) during this period. This is the water balance:

$$\Delta H = \text{INPUTS} - \text{OUTPUTS.}$$

The relative importance of the different components varies from lake to lake. Over Lake Victoria, direct rainfall constitutes 80% of the refill (Institute of Hydrology, 1993) and therefore dominates the balance. It is seen that a change in stage caused by very high rainfall can be maintained by more moderate rainfall, and the period over which such changes take place is a key component in determining the magnitude of the change (Nicholson and Yin, 2001). Variations in rainfall and evaporation over the lake are related to migration of the Intertropical Convergence Zone (ITCZ) (Sene and Plinston, 1994). As a result, the basin experiences two rainy seasons, long rains in March to May and short rains in Oct to December (Swenson and Wahr, 2009).

A key issue in computing the water balance of Lake Victoria is the lack of knowledge about direct rainfall on the lake (Institute of Hydrology, 1993). Few offshore stations are present and any records are short and incomplete. Where they do exist, a significant increase compared to catchment rainfall is evident. There is a strong relationship between lake and land convective activity, therefore rainfall varies in phase (Yin and Nicholson, 1998). As a result, most studies use adjusted catchment rainfall as an alternative to direct over lake measurements.

There are similar problems with estimating over-lake evaporation. It is often estimated by an energy balance approach or by using the Penman formula, however both are sensitive to cloudiness (which is problematic to estimate) and are seasonally dependent (Yin et al, 2000).

For Lake Victoria the other components are inflow from tributaries and outflow to the White Nile which do not dominate the balance but are important nonetheless. Inflow is a relatively minor component but can be highly variable. Discharge from the lake is the most accurately known component (Yin and Nicholson, 1998), however records are not often publicly available. Secrecy surrounding dam operations can hinder collection of such data.

Lake Victoria is climatically sensitive but there is a lag between changes in external influences and changes in lake levels of 1 – 2 years. The lake is also has a ‘memory effect’ meaning levels at any given time will be influenced by previous levels (Kite, 1982).

1.2 History of Hydropower Operations

Until 1954 flow out of Lake Victoria was naturally regulated by Ripon Falls, near Jinja (Figure 1). Once construction of the Owen Falls Dam (now named Nalubaale) was completed, Ripon Falls was fully submerged and regulation of outflow was dictated by the operators of the dam. As flows from the lake are of international importance, before construction of the dam an agreement was made between Uganda and Egypt agreeing that releases would mimic those under natural conditions. An 'Agreed Curve', was created which relates lake levels at Jinja to pre construction discharge measurements on the White Nile (Kite, 1981).

The dam operated according to this curve for seven years until a sudden rise in water level of over two meters was experienced in 1961-2. This rise exceeded the limit the curve was produced to accommodate and for several years a straight line extension was used. In 1968 an extended agreed curve was produced based on studies of Ripon Falls before construction of the Dam (Sene and Plinston, 1994). The equation for the extended curve (Figure 1-2) is: $Q = 132.9(h-8.486)^{1.68}$ m^3/s **(1)**

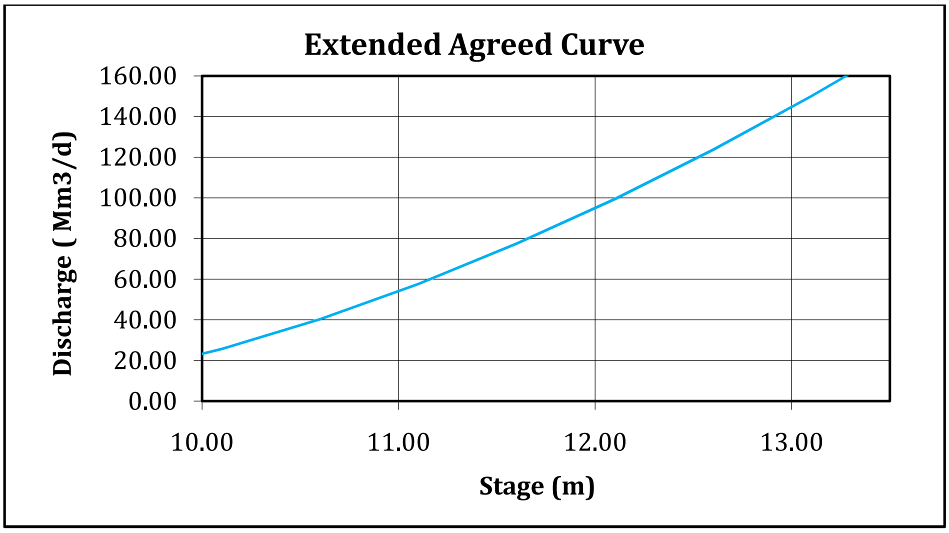

Figure 1-2. Graph showing the Agreed curve relating water levels at Jinja and lake outflow (Sutcliffe and Petersen,

This historic rise marked the beginning of a change in regime. This was at first blamed on the dam but later it was concluded that the rise resulted from natural causes: an increase in over-lake precipitation (Kite, 1981 and Piper et al, 1986).

During the era of Idi Amin, Nalubaale suffered from a lack of maintenance, until a refurbishment in 1980 increased its generation capacity. In 1993 construction began on a second dam as part of the Owen Falls Extension project. Kiira dam, 1 km downstream of Nalubaale, began to produce power in 2000. The rationale for its construction is disputed, Mubiru, 2006, states that it was a stop-gap before the implementation of the Bujagali project downstream and was to utilise the excess water which was being ‘lost’ down the spillway of Nalubaale. Mubiru claims that the complex was not meant to function as it currently does. Kull, 2006, however claims the design was based on a desire to maximise electricity generation from the beginning and therefore the complex was deliberately over-designed.

The lake water level time series suggests a steady decrease since its 1961 rise. However, around 2005, the lake experienced a significant drop in level of approximately 2 metres. If this recent drop is an indication of a return to the drier pre-1960 regime, this will have disastrous implications for hydroelectric generation in Uganda as hydrologists working on the design for Kiira assumed a 99% probability that the higher flows would continue. The complex would not be economically viable if low flows were to return (Kull, 2006). In 1991 the World Bank wrote that the only significant risk to the economic feasibility was a return to the low hydrologic regime which was existed before 1961. Demand for electricity is rapidly increasing as population and industry grow in Uganda, yet the ability of these dams to produce electricity has been severely inhibited.

Before Kiira came on line, the dam operations were adhering to the agreed curve; however since then, combined releases through Nalubaale and Kiira have exceeded the agreed flow values. One example, from 2004, shows a combined release which exceeds the agreed curve by 85% (Kull, 2006). Eskom, the South African energy company which operates the dam, blames the fall in lake level on drought in Lake Victoria's catchment, though others say it is a result of Eskom's departure from the Agreed Curve in an attempt to meet increased demand for electricity.

1.3 The Future

More recently the issue of climate change has come to the fore which has fed into the debate over anthropogenic and natural influences on the water balance of Lake Victoria. The lake is highly sensitive to changes in climate, Nicholson et al, 2000, suggest that a 4m rise experienced in the mid nineteenth century resulted from an increase in rainfall equivalent to 7% above the current average. Small changes in rainfall, cloudiness and temperature can significantly alter the surface hydrology (Nicholson and Yin, 2001).

Due to Lake Victoria's importance, there is interest in attempting to model future behaviour of the lake under altered climate conditions. Doing so in a meaningful way is difficult as it has been seen that inter-model disparities are particularly high for East Africa (Tate et al 2004). The region is expected to become wetter, on average, however the distribution will be uneven (Hepworth and Goulden, 2008).

In spite of conflicting conclusions on the 'blame' for the recent drops in lake level, all studies agree that climate has played a significant role. Both increases and decreases in water level have repercussions. This is why understanding its behaviour is essential. Many studies have been carried out into accurately modelling the water balance of Lake Victoria, varying in aim, methodology and data utilised. These will be discussed in the next chapter.

1.4 Aims and Objectives

This study broadly aims to investigate the fluctuations in water level in Lake Victoria. The specific aims are:

- To produce an up-dateable and accessible water balance model

By reviewing previous studies a model will be chosen and modified, through which the water levels can be reproduced. Instead of a one-time study and review, ideally the model used will be readily updatable using a publicly available data source, and can, therefore, be utilised in future without the need for an entirely new study. This is advantageous as collection of primary data is time consuming an often difficult when regarding a basin of this scale.

- Investigate future lake behaviour under climate change scenarios.

- Investigate the importance of lake level fluctuations on key stakeholders

2. Literature Review

Lake Victoria's importance, outlined in the previous chapter, has meant the hydrology of the lake and its basin has been a subject of great interest since the late 1800s. This chapter reviews a selection of the literature to date looking at the water balance of Lake Victoria. The review will focus on more recent studies as over time there has been replication of older ideas with improvements along the way. Studies will be considered under six headings; rainfall, evaporation, outflow and inflow, hydropower operations, climate change and miscellaneous studies.

2.1 Rainfall

In early water balance studies such as those by Kite and Piper the water balance components are calculated from whatever ground data was available to the author (Kite, 1981) (Piper et al, 1986). Rainfall has long been recognised as a dominant component of the water balance therefore many studies have focussed on its accurate estimation. Overlake rainfall is required for the water balance yet records from lake stations are rare. Most studies use adjusted lake shore station records.

The production of average rainfall maps agreed with the limited data available from stations on the lake that rainfall was significantly greater than over the land (Flohn and Fraedrich, 1966, and Flohn and Burkhardt, 1985). This is due to the presence of circulation systems over the lake. It was not until later studies however that a relationship between catchment rainfall and lake rainfall was defined. Other studies (Kite, 1981) used arbitrary increases in certain years to recreate the balance, which is not useful from a future modelling perspective. Sene and Plinston, applied a factor of 1.18 (Sene and Plinston, 1994), whereas a later study analysed satellite imagery of cold cloud frequency, producing a regression between this and rainfall and found the increase to be 25-30% (Ba and Nicholson 1998). Nicholson produced a relationship of $P_w = 1.3533P_l - 87$ for annual rainfall by using the same technique but taking into account different regression relationships during the peak rainfall season (Nicholson et al, 2000).

A progression from this has been by a recent study which uses satellite data of rainfall from NASA's Tropical Rainfall Measuring Mission (TRMM) (Swenson and Wahr, 2009)

2.2 Evaporation

Although rainfall has generally been the component under scrutiny to increase accuracy of estimation, Piper et al point out that it is difficult to differentiate between underestimation of rainfall and over estimation of rainfall (Piper et al, 1986). Originally Hurst assumed evaporation was equivalent to rainfall (Hurst, 1938), in fact this was one of the bases on which the Owen Falls Dam was constructed. However rainfall varies significantly throughout the year, much more so than evaporation (Shalash, 1980).

Unlike previous studies, Yin and Nicholson attempted to ‘close’ the balance by adjusting evaporation estimates, as they suggest there is greater difficulty estimating evaporation than rainfall (Yin and Nicholson, 1998). Cloudiness was identified as being the hardest variable affecting evaporation to estimate. This has led to studies attempting to increase the accuracy in estimating evaporation by studying cloudiness cycles (Yin and Nicholson, 2000). This study also concluded that evaporation was so variable it could contribute to explaining the major rises and falls in Lake Victoria’s history.

Estimation of both parameters has greatly improved over time yet it is difficult to pin point exactly where inaccuracies lie as there are so many potential sources.

2.3 Inflow and Outflow

Inflow and outflow tend to be overlooked as they are relatively minor compared to rainfall and evaporation.

Annual estimation of outflow has often been determined using the Agreed Curve (Sene and Plinston, 1994). This assumption is valid for the earlier part of the time series but not from 2000 onwards. Direct measurements of discharge were recently published by the Power Planning Authority (PPA, 2007), however values are only given up to 2005, and beyond this it is expected to be difficult to obtain such data. Recently, altimetry has been used to obtain lake heights in Victoria and Kyoga downstream which was used to estimate outflow from Lake Victoria. Problems arose with this technique due to the presence of floating vegetation in significant quantities blocking the inflow to the lake therefore altering the relationship between levels in Lake Kyoga and outflow from Lake Victoria (Swenson and Wahr, 2009). Remotely sensed data has obvious benefits yet it will always have to be calibrated with directly measured data to be valid.

Inflow is a minor component yet subject to considerable variability. Most studies use tributary inflow data which is available for the rivers contributing the greatest volume of water, such as the Kagera (source in Burundi) and scale this up. As complete inflow measurements are not available later studies have assumed proportionality to rainfall. This is justified by the relative size of the catchment (Swenson and Wahr, 2009). However this may not be valid under changing rainfall regimes. Inflow poses a challenge in modelling future scenarios due to the non-linear relationship with rainfall but also due to land use changes.

Up until recently all studies deemed groundwater movement as a negligible component of the lake water balance. Swenson and Wahr estimate terrestrial ground water storage using GRACE, the Gravity Recovery and Climate Experiment Satellite, relating groundwater storage to sub surface flows (Swenson and Wahr, 2009). The study claims that baseflow could contribute up to a few hundred mm annually to the lake. Their argument is that the inclusion of baseflow allowed for a better closing of the water balance. However it needs to be remembered that the water balance, particularly of such a large lake is dependent on the accuracy of the measurements of *all* the variables used (Shalash 1980).

2.4 Hydroelectric Power

Since its construction there have been concerns over the impact of Owen Falls Dam on the hydrology of the lake, it has been blamed for both rises and declines in stage. Shalash carried out a study into the effect of Owen Falls Dam on the hydrology of Lake Victoria. The conclusion was that the increase in stage since 1954 was primarily due to a change in regime instigated by the construction of the dam (Shalash, 1980). This was not done by modelling the water balance but by comparing characteristics of rainfall, runoff, lake level and evaporation before and after the dam was constructed. An increase in rainfall is acknowledged but it is not blamed for the increase. The increase in rainfall is grouped into averages for certain periods so cannot be compared on the same timescale. Graphs presented show a definite increase in stage and discharge, although it is ignored that discharge is related to stage and the increase is seen some seven or eight years after construction of the dam.

However in a 1981 study looking into increases in level experienced between 1959 and 1964, stated the opposite (Kite, 1981). It was concluded that approximately 3 cm of the rise over this period could be attributed to the dam as a result of excess storage, and therefore the major factor must be natural causes. It is acknowledged however that there are inaccuracies in the estimation of over lake rainfall. Although the water balance and lake routing models used were simple, the figure of 25-30% difference between catchment rainfall and over lake rainfall is one which has come up in later studies.

A later study confirmed what Kite had concluded. The historical water balance was accurately modelled and changes in the components on the water balance resulted in the two metre rise. In particular, an increase in rainfall, and subsequent increase in runoff to the lake, suggested that future lake behaviour could be projected by analysing the rainfall series. The rainfall series used here was in line with other studies – utilising the 8 major stations which have the longest record- and therefore produced a consistent record (Piper et al, 1986).

A report by Acres International in 1990 concluded that the recent 'unnaturally high' levels were a result of the Owen Falls Dam complex. This contradicted earlier studies not only by Kite but by the World Meteorological Organisation (WMO) and the Institute of Hydrology (IH) and so prompted a further study in 1993, a review and update, which disputed the results of the Acres report (IH, 1993).

There has been a renewed interest in the influence of the dam since the serious decline experienced in 2004-5. The relationship between lake level and releases at Jinja has been studied and found the previous relationship ceased to exist after 2001 (Mangeni, 2006). The conclusion was that the decline resulted from dam operation. Daniel Kull a Hydrologist for the UN concluded the decline could be attributed to both drought and over release but that the share was 55% due to the latter (Kull, 2006). Another study in the same year claims drought holds the majority share (Mubiru, 2006). The fact that Mubiru is an engineer involved in the HEP dam projects needs to be taken into consideration.

Even though Mubiru argues that drought is the bigger contributor, he does state that over release is responsible for 44% which is still significant. It is also argued that since February of 2006 efforts have been made to reduce outflow and yet no corresponding lake level increase had been seen (Mubiru, 2006). An opposite but similar argument is made, in that heavy rains occurred in 2006 with no impact upon lake levels (Kull 2006). Both arguments are possibly tenuous in that other authors have stated that there is a time lag and memory effect which impacts the lake level at any given time and so short term changes they mention may not be felt as quickly and within the same year (Kite, 1982).

A recent study in 2007 determined a ‘naturalised’ lake level i.e. what lake level should have been since Kiira came online if the agreed curve had been adhered to. Excess discharge was ‘added’ back to the lake and the conclusion was that the lake would be 0.61 m higher in 2006 (Sutcliffe and Petersen, 2007).

2.5 Climate Change

In terms of investigating future behaviour early studies raise concerns over the use of long term averages due to the rapid nature of the variability in lake level (Kite, 1981). Modelling needs to be able to explain the sudden rises such as 1961 (Institute of Hydrology, 1993).

Sene et al's 2001 study aimed to look at the sensitivity of White Nile Flows by modelling the water balance of Lake Victoria. The changes to the water balance components are applied to two baselines and therefore the time series, when represented graphically, follow the pattern of rainfall variability during the baseline period. The study is more an exploration of modelling aspects and possible outcomes.

Recent studies have produced rainfall based water balance models capable of investigating future lake behaviour, extending previous water balance studies (Tate et al, 2004). Climate change effects are investigated by using Global Circulation Model (GCM) outputs. Two scenarios from the HadCM3 model were used and the model was run using rainfall and evaporation variation from two time periods, 2021 -2050 and 2070-2099. Like the previous study mentioned a baseline is used to create a future time series, however the limitations of this are noted. Only one model is used, yet East Africa is known to have high inter-model disparities in climate change modelling, so perhaps it would be interesting to see the contrast between this and another model.

2.6 Other Studies

A study in 2000 proposed a novel approach, a method of reproducing lake levels using only rainfall as an input (Nicholson et al, 2000). The model is one adapted from Yin and Nicholson, 1998. The aim was to allow the recreation/estimation of rainfall from the level in Lake Victoria, in essence using the lake as a giant rain gauge. The model was created by applying regression analysis to the components of the water balance to produce equations which describe inflow and discharge in terms of lake level and rainfall. The model was then inverted which produced estimates with errors of around 1 %. Lake rainfall is produced by a regression relationship between this and catchment rainfall where as the evaporation component was left fixed at a long term average due to difficulties with accuracy. It has been seen, however, that when evaporation is considered constant this can lead to a significant underestimation of impacts (Mubiru, 2006). Equations relating inflow and discharge to rainfall and lake levels are produced using multiple regression analysis of recorded data. This does however mean that to be applied to a completely independent data source, some calibration may be needed.

Following on from this a later study by Nicholson and Yin, 2001, used the methodology to recreate rainfall conditions in the region during the nineteenth century. The model was intended to be used in this way however it would useful in its un-inverted form to estimate lake levels from rainfall values, therefore allowing the study of lake level behaviour under different rainfall conditions.

In line with the aims of this study, the past literature will of course inform the work but the most relevant studies are those where the methodology allows for the application of publicly available data. In particular Nicholson et al, 2000, will be particularly useful as minimal inputs are required for the model to function.

3. Methodology

In this chapter the data gathering process is illustrated and the method of modifying the chosen model to suit the data and using it to investigate future lake behaviour using Global Circulation Model (GCM) data is described. In addition, the approach taken to explore the impact of fluctuations on stakeholders is explained.

3.1 Lake Victoria Water Balance

The studies previous to Nicholson et al 2000 rely on data input heavy calculations and, whilst there are arguments for carrying out calculations like this in terms of accuracy, such data, spread over a number of countries and government agencies is not readily available. Water balance calculations in this study are therefore based on the Nicholson et al 2000 study.

3.1.1 Model Input Data

ARTES (Africa Rainfall and Temperature Evaluation System) is a database from which monthly rainfall and temperature values can be extracted in various forms. This study utilises sub-national resolution rainfall data from 1948 to 2001.

The rainfall values are obtained from ground station records, producing data in a gridded, binary format with a resolution of 0.5° by 0.5°. The input data is from Global Telecommunications System (GTS) stations with additional data obtained from the Global Historical Climatology Network (GHCN2) and Climate Anomaly Monitoring System (CAMS). To produce the monthly grids, stations were selected on the basis of their record containing long term means. Values are interpolated to produce a gridded dataset.

The data is extracted by selecting the sub-national regions of choice. As these are defined by political boundaries, for use in this study an approximation of the Lake Victoria basin was selected. A list of which regions were selected can be found in Appendix A. The data table is saved as a .csv file and opened in excel.

Beyond 2001 the records are publicly available from the National Oceanographic Atmospheric Administration (NOAA) in binary format or in raster format which can be utilised in ArcGIS. Rasters can be downloaded from the internet from ftp://ftp.cpc.ncep.noaa.gov/fews/GIS/AFRICA_RFE and loaded into ArcMap where data can be extracted. Each raster represents the rainfall distribution over the entirety of Africa to a resolution of 1° by 1° for a particular day.

Each daily raster for a particular month is loaded into ArcMap and the 'Raster Calculator' function, found in Spatial Analyst is used to produce a monthly raster. Care must be taken to save the monthly rasters for future processing. Once these have been processed the monthly rasters can be loaded to extract rainfall.

To enable extraction of rainfall from the same region as selected in ARTES, for continuity purposes, a shapefile is created from shapefiles of the Lake Victoria basin countries and their regions obtained from the Directorate of Water Resource Management (DWRM), Uganda (the shapefile is available on accompanying CD).

To extract the rainfall from the raster cells within this region 'Spatial Analyst' is used to 'Convert Raster to Features'. The raster is then converted to a point shapefile. Before carrying this out in Spatial Analyst the Analysis Mask must be set to the basin shapefile. The attribute table for the point shapefile produced from the monthly raster can then be exported and saved in a .csv text file format allowing it to be opened in excel.

There is potential for a publicly available source of lake levels through Altimetry. The data is publicly available from 1992 to present at: http://www.pecad.fas.usda.gov/rssiws/images/lakes/lake0314.TPJ.2.smooth.txt. However the data is presented as departures from the 10 year mean and so absolute lake levels cannot be calculated. Due to the process of altimetry it is not as simple as a value for the 10 year mean; it is a profile of values because they do not take spot heights. A mean calculated from this profile would have a very large standard deviation (Birkett, 2009).

In this study, lake levels recorded at Jinja obtained from the DWRM will be used. It is valid to use one gauge to investigate changing levels over the whole lake as the spatial variation in atmospheric pressure over the lake or strong wind which would cause level variations across the lake are not present in this region (Brooks, 1923).

3.1.2 Model

The original lake level final equation produced in the Nicholson et al study is:

$$\mathrm{H}_{\mathrm{i}} = 0.81153\mathrm{H}_{\mathrm{i}-1} + 1.0905\mathrm{P}_{\mathrm{w}\,(\mathrm{i})} + 0.2364\mathrm{P}_{\mathrm{w}\,(\mathrm{i}-1)} - 58 \quad \textbf{(2)}$$

Where H_i is the end of year lake level in mm for the year in question (year i), H_{i-1} is the end of year lake level in mm for the previous year, $P_{w(i)}$ is the total over lake rainfall in mm for year i and $P_{w(i-1)}$ in over lake rainfall in mm for the previous year.

This equation is derived from individual relationship equations produced in the study:

$\mathrm{P}_{\mathrm{w(i)}} = 1.3533\mathrm{P}_{\mathrm{l(i)}} - 87$ **(3)**

$\mathrm{I} = 0.33395\mathrm{H}_{\mathrm{i}} - 0.24311\mathrm{H}_{\mathrm{i}-1} - 0.2662\mathrm{P}_{\mathrm{l}} + 0.2356\mathrm{P}_{\mathrm{l(i}-1)} - 726$ **(4)**

$\mathrm{D} = 0.159131\mathrm{H}_{\mathrm{i}-1} + 0.07054\mathrm{H}_{\mathrm{i}} - 2223$ **(5)**

E = 1537 (Although it is unclear as to exactly what value the authors have used for evaporation.)

Where the components are the same as listed above and $P_{l(i)}$ is total over land rainfall in mm for the year in question, $P_{l(i-1)}$ is total over land rainfall in mm for the previous year, I is inflow from tributaries, D is discharge from Lake Victoria to the White Nile and E is evaporation from the lake.

These are combined with the water balance equation:

$$\Delta\mathrm{H} = \mathrm{P}_{\mathrm{w}} + \mathrm{I} - (\mathrm{E} + \mathrm{D}) \quad \textbf{(6)}$$

Where ΔH is the change in end of lake level between year i and the previous year therefore $\Delta H = H_i - H_{i-1}$.

Rainfall obtained from ARTES and NOAA raster sets described above will be first adjusted to represent over lake rainfall. The catchment rainfall supplied by ARTES varies slightly from the catchment rainfall used by Nicholson et al 2000 to produce their model. Therefore the rainfall equation will be adjusted by establishing the relationship between ARTES catchment rainfall and over lake rainfall using the original model, published in Yin and Nicholson, 2002.

Equation 2 is therefore adjusted to include this modified version of equation 3. The adjusted equation is then applied to the over-lake rainfall time series to re-produce lake levels. In the Nicholson et al 2000 study they use the original input of the actual recorded level in 1930. In this study the original input will be 1948 as this is the earliest year of the rainfall data to be used.

3.2 Future Scenarios

This study will use climate scenario data as inputs in lake level modelling to assess possible future lake level behaviour. The main three aspects to look at are changes in rainfall and evaporation and changes in inflow as a result of both rainfall and evaporation but also land use changes. Changes in demand in terms of water supply are ignored in future climate scenarios as the volumes are negligible relative to outflow and evaporation (Sene et al, 2001). In this study rainfall and evaporation changes will be the focus.

GCM outputs are used to determine changes in rainfall. Inter model disparities have been found to be high over East Africa; this is a symptom of the sensitive nature of the climate in the region (Tate et al, 2004). Therefore data from three climate models are used in this study, HadCM3 and HadGEM1 produced by the UK Meteorological Office, and GFDL-CM2.1 produced by NOAA. Two scenarios, SRA1B and SRA2 will be investigated. Details of the models and scenarios can be found in Appendix B.

SRA1B and SRA2 were chosen as these are the two scenarios which are accessible from the IPCC via the internet. Due to the high incidence of intermodel disparities it was preferable to use more than one model. Models produced by the Hadley Centre were chosen as these were the most familiar to the author, by looking at HadGEM1 and HadCM3 the comparison between an 'old' and 'new' version could be made. A third model, GFDL-CM2.1, was chosen as the creator was NOAA the same organisation from which the rainfall data was obtained.

The data is obtained from the Intergovernmental Panel on Climate Change (IPCC) at: http://www.ipcc-data.org/cgi-bin/ddc_nav/dataset=ar4_gcm. The data is available in a grid format with the resolution depending on the model. Lake Victoria is approximately latitude N 0.3 to S 2.5 and longitude E 31 to E34 therefore the closest to this lat long is selected. The format of the data used is the anomaly from the 1961-1990 mean for each grid cell selected.

Choice of baseline time period is often limited, Sene at al use 1961-1990 because pre 1961 the regime was different however they state that the choice of start, end and duration is not linked to hydrology (Sene et al, 2001). Due to the fact that anomalies are calculated from the 1961-1990 mean this is used as the baseline in this study.

3.2.1 Rainfall

Anomalies in rainfall for the periods; 2010-39, 2040-69 and 2070-99 are obtained. These anomalies are converted to a percentage of the 1961-90 mean calculated for each model and scenario. This increase is then applied to the baseline lake rainfall data. The result is a rainfall time series from 2010-2099.

This new rainfall time series is then used as an input in the model to produce lake levels. For running a time period beginning year *n* the lake level for year *n*-1 is required as an initial input. In this case year *n*-1 is 2009. This is estimated from the current record of lake levels. As this is based on assumptions a brief sensitivity analysis is carried out, varying the initial input level.

3.2.2. Evaporation

In most water balance studies the evaporation component is calculated using the Penman or energy balance method. However the requisite data to calculate a new estimation for evaporation in such future scenarios is not available from the climate modelling. Therefore an alternative method is used utilising temperature data. Temperature data is obtained in the same way as rainfall, and evaporation will be investigated using a simple temperature based method. Three methods will be compared for their estimation of 1961-90 evaporation as well as their sensitivity to temperature increases. The three methods chosen, described by Xu and Singh, are The Kharuffa, Thornthwaite and Blaney-Criddle methods (Xu and Singh, 2001). These were selected due to their input data requirements.

The Kharuffa method: where p is the total daytime hours as a percentage of the total daylight hours for the year (365 x 12).

$$ET = 0.34pT_a^{1.3} \ \textbf{(7)}$$

The Thornthwaite method: where ET' is monthly potential evapotranspiration, C is a constant (16), $a = 67.5 \times 10^{-8}I^3 - 77.1 \times 10^{-6}I^2 + 0.0179I + 0.492$ and I is the annual heat index which is a sum of the monthly heat index: i.

$$ET' = C\left(\frac{10T_a}{I}\right)^a \ \textbf{(8)}$$

$$i = \left(\frac{T_a}{5}\right)^{1.51} 1 \ \textbf{(9)}$$

The Blaney-Criddle Method: where p is the mean daily percentage of annual daytime hours

$$ET = p(0.46T_a + 8) \ \textbf{(10)}$$

Of the three methods Xu and Singh found that Blaney-Criddle produced the least error; however this was specific to the study region in North America (Xu and Singh, 2001). A study comparing evaporation equations in investigating evaporation from a lake found that Thornthwaite performed better than Blaney-

Criddle (Rosenberry et al, 2007). Each method will be applied to temperature data and the most appropriate chosen.

The evaporation values obtained will be used to determine an expected percentage increase in evaporation compared to the 1961-1990 average. This percentage is applied to the value of 1537 mm used in the Nicholson et al, 2000 study. This means modification of the final equation for each time period. To see the difference this makes to levels predicted by only changing rainfall the altered rainfall time series will be inputted to the model where the equation changes as evaporation changes. Sensitivity of the model to changes in evaporation will be determined by changing evaporation by arbitrary amounts of 1, 2, 5, 10 and 20%.

3.3 Impact of Fluctuations on Stakeholders

It is important to assess what water level decline and recharge means to various stakeholders in the Lake Victoria basin. The impacts will be established through correspondence with the stakeholders themselves. In this situation informal conversations will be used instead of a formal survey or semi-structured interview approach. This was chosen as this is not the main focus of the research and the resulting information will not need to undergo statistical analysis.

Stakeholders to be approached will be those in water supply, hydroelectric power generation, industry and fishing. National Water and Sewerage Corporation (NWSC) supplies the main cities of Kampala, Jinja and Entebbe with water, therefore information will be gathered from them with regards to abstraction of water during times of lake level decline. Eskom run the HEP complex at Lake Victoria's outlet and so they will be important people to talk to about lake level. The Ugandan Manufacturers Association (UMA) will be contacted to discuss how the lake levels indirectly impacted upon production in Uganda due to the impact on electricity generation. Fishing is a major industry for the Lake Victoria region in Uganda; the National Fisheries Resources Research Institute (NaFIRRI) will be contacted along with fishermen at landing sites.

Although no formal structure is defined, each correspondent will be asked about the impact and importance, particularly with regard to the most recent declines. It will need to be taken into consideration that bias in views over the causes of lake level decline may colour opinions of stakeholders.

4 Results and Analysis

This chapter presents and analyses the results of the study in terms of rainfall, modelled lake levels for the period 1948-2008 and modelled lake levels for the period 2010-2099 using GCM scenario data. Sensitivity tests run on the model using varied evaporation and initial lake level inputs are also examined. In the final sections the findings from stakeholder interviews are explained, covering the main themes which emerged.

4.1 Water Balance Modelling

4.1.1 Rainfall

As described in the methodology over lake rainfall values for 1931-1994 (Yin and Nicholson 2002) were compared with the ARTES catchment values for the same period. A new relationship between catchment rainfall and over lake rainfall was produced by regression analysis:

$$P_{w(i)} = 1.5189\,P_{l(i)} - 171.23 \quad \mathbf{(11)}$$

The record of annual over lake rainfall produced from ARTES (1948-2001) and NOAA rasters (2001-2008) using equation 11 is shown below in figure 4-1. Original Monthly rainfall is available in Appendix C. the long term average over the period 1948-2008 in this study of 1700 mm yr^{-1} is comparable

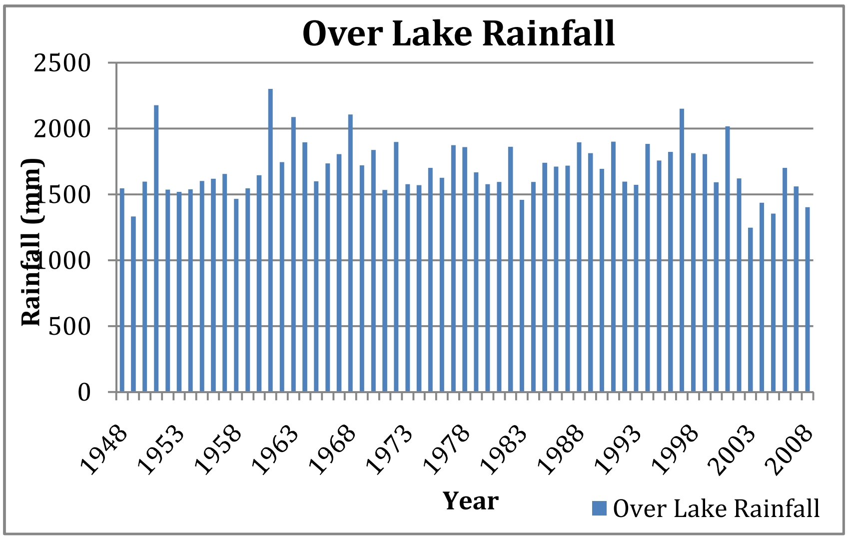

Figure 4-1 Graph showing over lake rainfall calculated from catchment rainfall. Source 1948-2001: ARTES, 2002-2008: NOAA.

with the value of 1791 mm produced by Yin and Nicholson 1998.

It appears from the graph that there is a relative decrease in rainfall from around 2001 however this may be an artefact of the change in data source. To discern whether there are significant discrepancies between the two sets of rainfall data the period which is common to both sets is examined. There is only an overlap of 12 months between the two datasets therefore it is difficult to assess the continuity. However even looking at these 12 months there are significant differences between the two sets (Table 4.1). The differences range from - 0.5% and + 44%. This may mean the equation relating catchment rainfall to over lake rainfall would need to be re-calibrated for more recent years.

Month	ARTES	NOAA	Difference	% Difference
Jan	224.6473	125.3163	99.33101	44.21643
Feb	74.32697	73.9136	0.413365	0.556144
Mar	146.1341	158.2845	-12.1504	-8.31455
Apr	165.5018	129.0187	36.48312	22.04394
May	118.1482	95.77334	22.37483	18.93794
Jun	57.20247	51.88566	5.316805	9.294713
Jul	72.84495	58.15758	14.68737	20.16251
Aug	63.94494	47.89578	16.049155	25.0984
Sep	149.0412	104.8524	44.18883	29.64873
Oct	124.019	124.6846	-0.665565	-0.53666
Nov	155.4354	120.0078	35.42755	22.79247
Dec	89.00599	71.3559	17.65009	19.83023

Table 4-1. Comparison of rainfall from ARTES and NOAA for 2001

4.1.2 Modelled Lake Levels

Modifying the rainfall equation changes the lake level equation. The new derivation, details of which can be found in Appendix D, is:

$$H_i = 0.81152H_{i-1} + 1.119675P_w + 0.210582P_{w(i-1)} - 58.9875 \quad \mathbf{(12)}$$

The lake level time series is reproduced using Equation 12 (figure 4-2, below) (values found in Appendix E) with a Nash-Sutcliffe model efficiency coefficient of 0.77 meaning the modelled values match well with observed values and so the model performs well. The root mean square deviation value for the lake level time series is 281 mm, which is 2.4% of the average model output. There is general agreement between observed and calculated levels, however there are some discrepancies worth noting: In particular there is an underestimation of lake levels for the first half of the 1960's. The 1961 rise is not accurately reproduced, similar to previous studies (Kite, 1981). When the rainfall record from ARTES for this time period is examined the increase in rainfall in the catchment is 675 mm which is significant when compared to general year to year variation. However this is not maintained, as observed in previous studies and rainfall decreases by 557mm in the next year in this record.

In the re-produced lake level time series there is an overestimation before 1961, a general underestimation between 1961 and 1990, followed by an overestimation until 2000. This follows the same pattern which was found in earlier studies (Tate et al, 2004).

The model has a significant departure from the observed lake levels in 2007 and 2008. It may be expected that such a departure would coincide with a departure of releases from the Agreed Curve however this occurred in 2000/2001. It does on the other hand coincide with restrictions put in place by the DWRM.

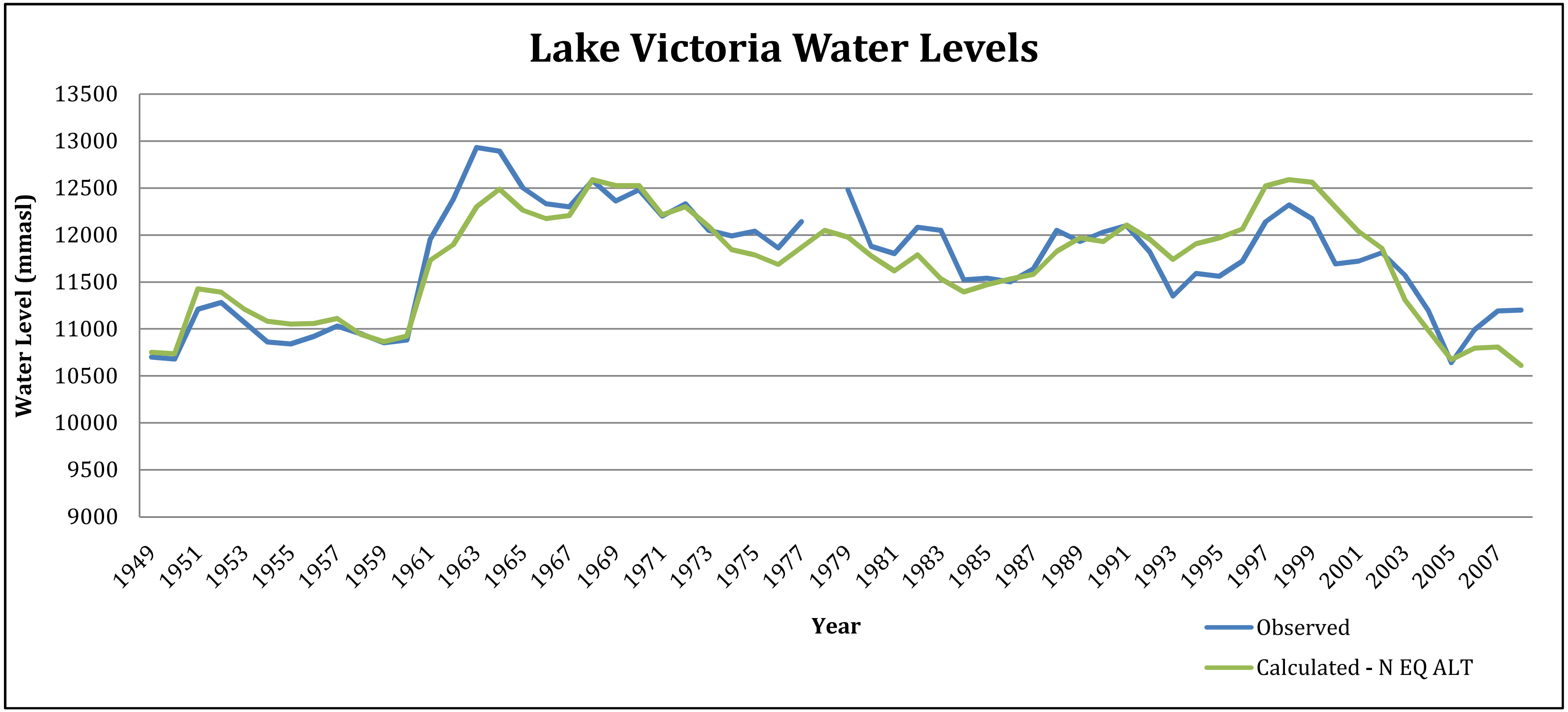

Figure 4-2 Graph showing modelled lake levels and observed lake levels (Source DWRM). The gap in observed lake levels is common in data available from the DWRM as this is a result of difficulties during the Idi Amin regime.

4.2 Climate Scenario Modelling

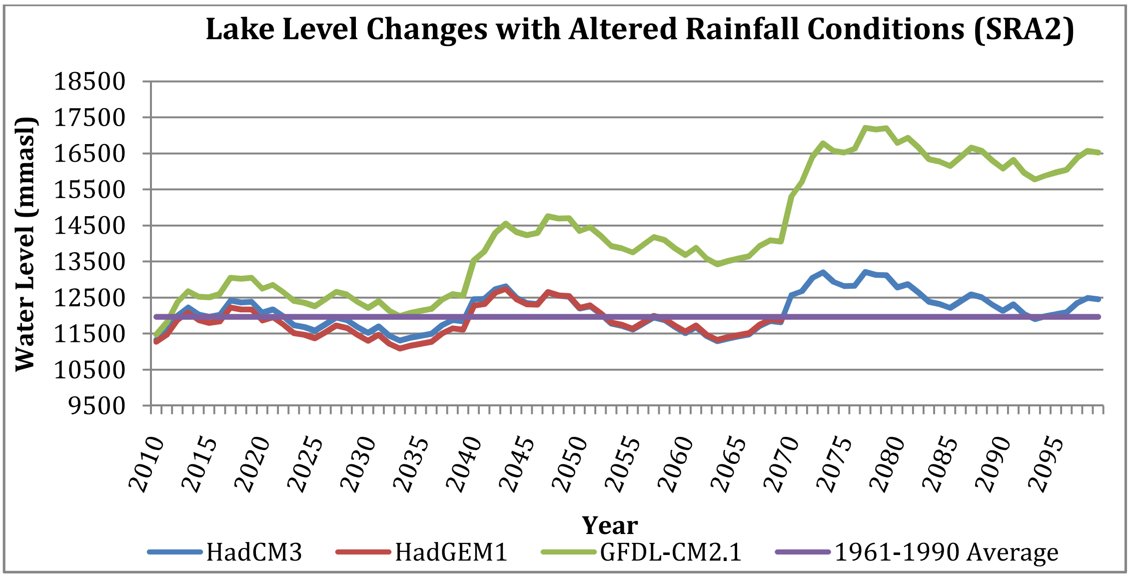

Figure 4-3 Graph showing the time series of lake level changes under altered rainfall using scenario SRA2.

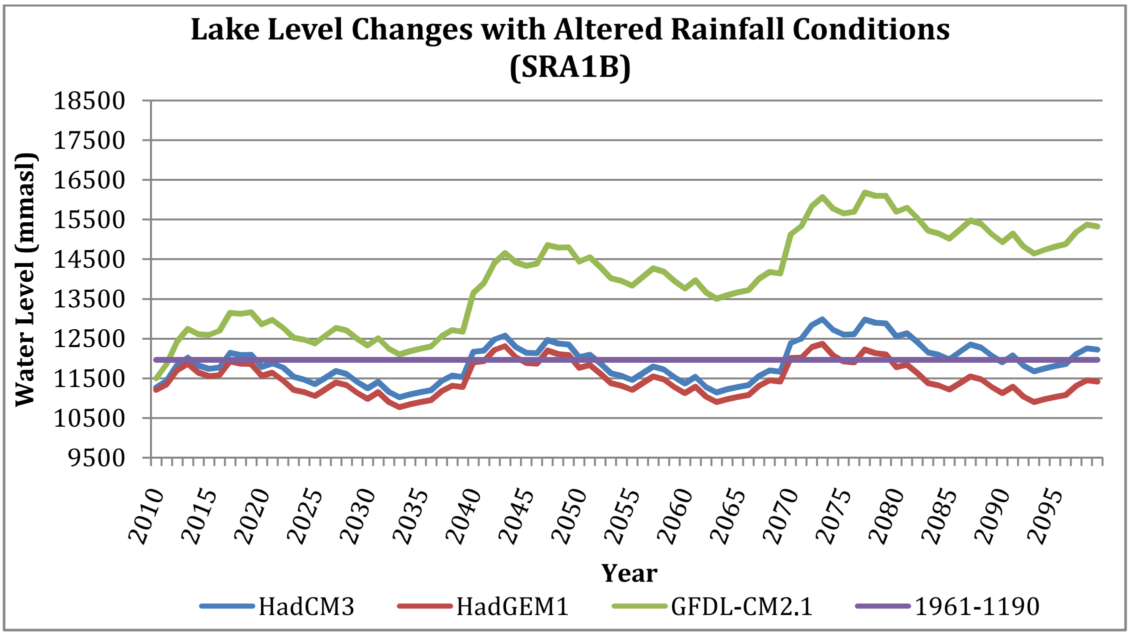

Figure 4-4 Graph showing the time series of lake level changes under altered rainfall using scenario SRA1B.

When comparing the lake level time series' shown in figures 4-3 and 4-4, the inter-model disparities are evident (full data set available in Appendix F). Averages for the different periods are shown in Table4-2. When rainfall is the only component altered, in all scenarios there is a general agreement of an increase in lake level

Model	**HadCM3**		**HadGEM1**		**GFDL-CM2.1**	
Scenario	**SRA1B**	**SRA2**	**SRA1B**	**SRA2**	**SRA1B**	**SRA2**
2010-2039	11564	11814	11328	11617	12543	12435
2040-2069	11817	11990	1156	11994	14132	14037
2070-2099	12317	12545	11580	-	15376	16401

Table 4-2 Average lake levels for each model, scenario and time period.

over the 100 year period. However GFDL-CM2.1 shows the greatest increase by far and the gap between models increases over time. HadGEM1 levels stay relatively constant, slightly below the 1961-1990 average of 11964 mm. The pattern of the time series itself is not necessarily reflective of shorter term variation during the period 2010-2099. The baseline chosen here was1961-1990 and so values are relative to this and follow a similar pattern.

4.2.1 Sensitivity to Lake Level Initial Input

To run the model producing future water levels from predicted rainfall, an initial input of water level is needed. This is a disadvantage in that a data set cannot be used where there is a gap between this set and previous modelled levels or recorded lake level.

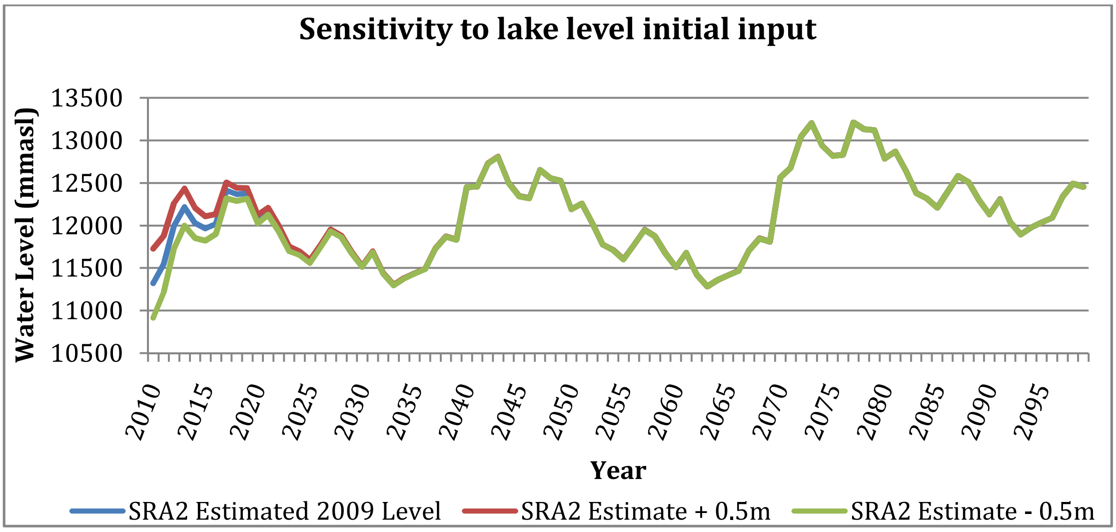

Figure 4-5 Graph showing the time series of lake levels under the HadCM3 SRA2 Scenario when initial lake level input is altered.

The initial input of lake level in this study was an estimated end of 2009 value of 10492.24 mm. The sensitivity of running the model to this input was tested by running the model with an initial input which varied +/- 500 mm. A difference can be discerned in the first 20 years of the model run (figure 4-5). After this time period no difference is made to predicted lake levels. This needs to be taken into consideration when considering the results of future modelling.

4.2.2. Evaporation

The original Nicholson et al model assumes a constant evaporation value, however it has been suggested that this can lead to a significant underestimation of impact on lake levels (Mubiru, 2006).

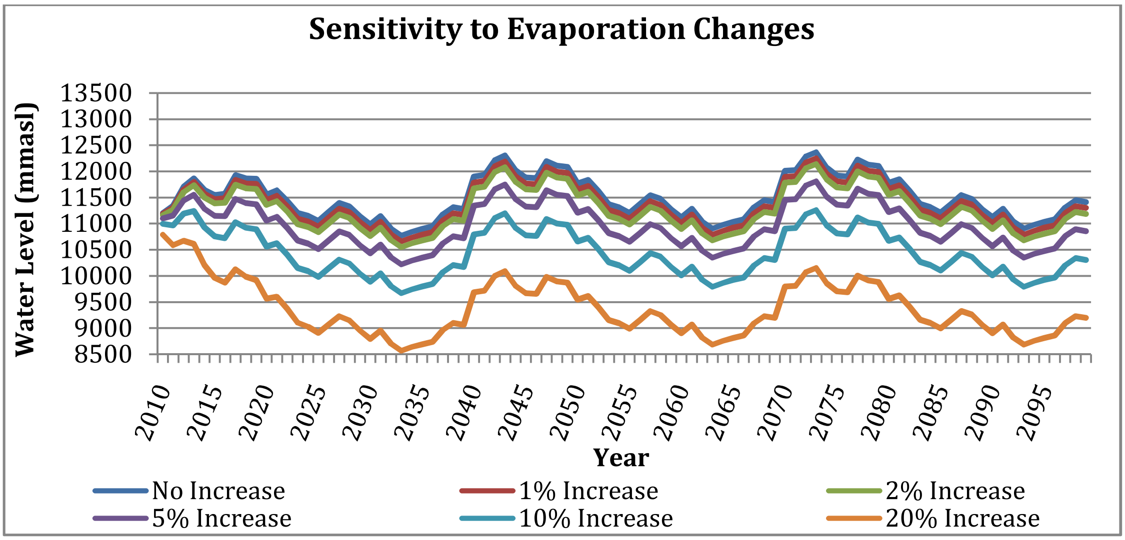

Figure 4-6 Graph showing the time series of lake levels using the HadCM3 SRA2 scenario with changing evaporation values.

Evaporation Decrease (%)	Average Lake Level 2010-2099 (mm)	Lake Level Decrease (%)
1	11383.96	-0.93
2	11278.54	-1.87
5	10962.29	-4.81
10	10435.20	-10.10
20	9381.02	-22.47

Table 4-3 Sensitivity of the model to changing evaporation

Average lake level over the period 2010-2099 produced from the HadGEM1 Scenario SRA1B data are compared to running the same data with the model but adjusting the equation to change the evaporation component. Evaporation was increased by arbitrary amounts of 1%, 2%, 5%, 10% and 20% from the long term average that is assumed in the Nicholson et al 2000 equation of 1537 mm. It is evident that this climate model is highly sensitive to changes in evaporation. Increases in evaporation are realised as decreases in lake level of approximately the same magnitude. This can be seen in Table 4.3 above.

As outlined in the methodology, a simple temperature based evaporation equation, is used to calculate the change in evaporation from the relative changes in temperature for each model, scenario and time period. The Blaney-Criddle equation was chosen from the three mentioned in the previous chapter as the estimation of 1961-1990 average evaporation (1760 mm) was the closest to the long term average used in the Nicholson equation of 1537 mm. Previous literature also quotes values between 1200 and 1700 mm. This compares to 1766 mm when using the Kharuffa method and 1164 mm when using the Thornthwaite method. The Kharuffa method was similar, however it is much more sensitive to temperature increases than Blaney-Criddle and as studies tend to use the temperature insensitive Penman or energy balance methods, Blaney-Criddle was chosen.

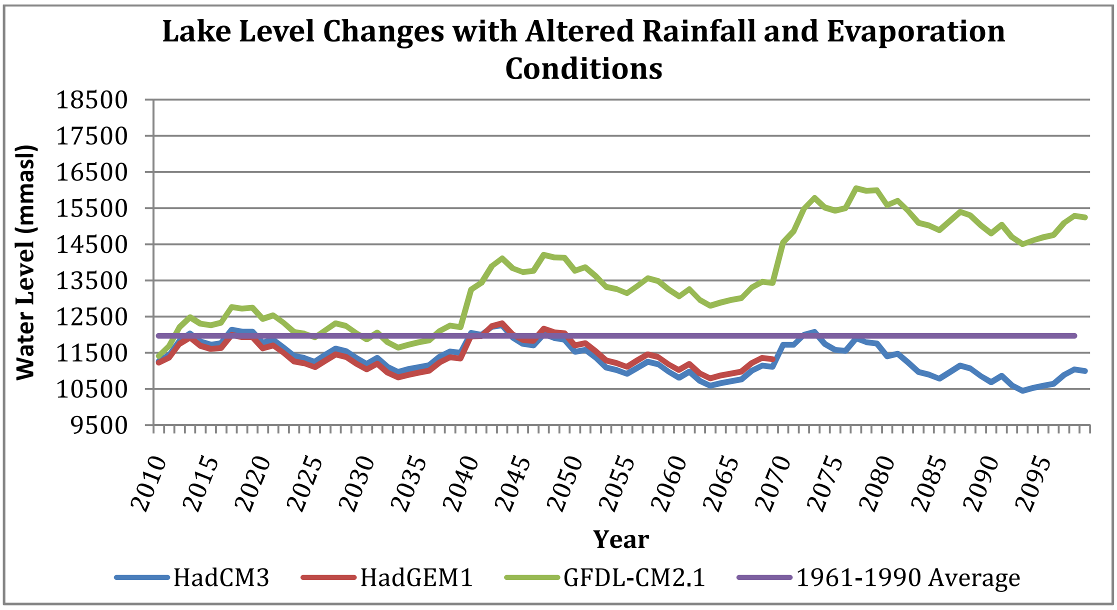

Figure 4-7 Graph showing the time series of lake levels under the SRA2 scenario with altered rainfall and evaporation.

The Blaney-Criddle method is applied to the temperatures produced by the GCM scenarios (see Appendix G) to assess the difference in evaporation which may be expected. Throughout the three models and two scenarios the evaporation increase in 2010-2039 varied between 2.42% and 3.25%, for 2040-2069 between 4.81% and 6.37% and for 2070-2099 between 7.80% and 10.13%.

These values are used to alter the model equation for each model, scenario and time period. When evaporation changes are used to alter the model equation and it is applied to the altered rainfall it can be seen that there is a definite decrease in the lake levels predicted (figure 4.7, values available in Appendix H), compared to the graphs in figures 4.3 and 4.4. GFDL still shows a significant lake level increase however HadCM3 and HadGEM1 show a decrease in lake level over the period. Due to inter model disparities it is difficult to come to conclusions about possible lake level behaviour.

4.3 Impact on Stakeholders

The following section is the result of interviews with Paddy Twesigye of the NWSC, Andrew Luzze of the UMA, Peter Tentena of Eskom, John Balirwa and colleagues at NaFIRRI and fishermen at Masesse landing site, Jinja.

4.3.1 Water Supply

The NWSC is the body in charge of water supply to Uganda's main urban centres, Kampala, Jinja and Entebbe. Each is served by one intake point which abstracts water from Lake Victoria. When constructed it was considered that Lake Levels were relatively stable and so fixed abstraction points were installed 1.5-2m below the water level at the time. In 2004-5 the water level dropped by 2m, so exposing the abstraction points to the air, causing major problems in water supply (Twesigye, 2009).

In addition to the intakes becoming exposed, a decline in lake level also impacts upon the quality of the water abstracted. As the population has increased around Lake Victoria the waters have become more polluted, with Nitrates and Phosphates posing a particular threat. Light can penetrate 1-2 m into the water and so it is in this region where algal blooms form, as water levels fall, more algae is taken in with the abstracted water. Floating material also becomes a problem. The intakes create a vortex in the water surrounding them, this is not a problem when water levels are at a reasonable height, however when levels fall, the vortex is created at the surface and so traps floating material such as water hyacinth. Therefore the cost of treatment and amount of chemicals needed is significantly increased (Twesigye, 2009).

Due to the risk of exposed intakes and problems with water treatment, abstraction points are being moved to deeper water. The decline in water levels seen 2004-5 coincided with a planned expansion of abstraction by the NWSC. During this time construction was underway in Entebbe so this was the first extension to go ahead, extension at Jinja is proceeding now and the contract has just been signed for

Kampala. The cost of these extension projects will be €1.4m, €3m and €6.5 m respectively (Twesigye, 2009).

4.3.2 Hydropower

Eskom have come under scrutiny as their management is one suspected cause of the recent decline in lake level. In 2006 the regulator, the DWRM, imposed restrictions as a result of external pressure. Permitted release was reduced significantly in February 2006 (Tentena, 2009).

The complex is running significantly below its built capacity as they cannot release enough water. It is expected that Kiira would not be economically viable if water levels returned to pre 1960's values (Kull, 2006).

Due to a decrease in hydroelectric generation, the Ugandan government have had to invest in thermal power in recent years. Currently only 50% of electricity in Uganda is produced via Hydropower, the remaining 50% is accounted for by thermal power (Luzze, 2009).

A further HEP dam downstream at Bujagali Falls is under construction. This will improve electricity generation as this dam is in series and not parallel to the current complex. However it will possibly suffer from the same restrictions as Nalubaale/Kiira if lake levels continue to decline.

4.3.3 Industry

Uganda is highly dependent on the electricity produced by HEP. The water level decline therefore also indirectly has an impact on industry.

As water levels fall, hydroelectric generation is curbed. Since 2004/5 the supply has been significantly reduced and inconsistent. Industry was affected in terms of quality, availability and cost of power. Particularly affected were those industries which rely on uninterrupted power supply for their processes for example leather, textiles and plastics. When power stops, batches often need to be recycled or are lost entirely, both at a cost to the company (Luzze, 2009).

The inconsistent supply is not predictable, companies do not know when they have power and so have to pay staff for time which they may not be working so that they are available when there is power. This resulted in a substantial amount of redundant labour again at a cost to the company.

The financial year, 2005/6, following the onset of the most recent decline saw a considerable decrease in the contribution of industry to the GDP of Uganda. Before 2005 industry had grown to 5%, yet in one year this figure declined to 0.1%. Industry recovered somewhat in the following years; however this was due to a government subsidy on diesel for industry (Luzze, 2009).

The Ugandan government has been driven to investing in thermal power and co-generation schemes to make up the gap in power generation. Uganda does not produce oil and this is reflected in the cost of electricity to industrial users which has risen 67% since 2005/6.

Most industries in Uganda cannot reach 65% capacity; return on investment is therefore low. With increased costs and reduced capacity, the competitiveness of Ugandan industries in the region is impacted upon. All this affects the Ugandan economy as a whole (Luzze, 2009).

4.3.4 Fishing

The dynamics of fish populations are closely linked to fluctuations in lake levels. Fishing in Lake Victoria has been affected by many factors other than lake levels in recent times, most importantly pollution and illegal fishing practices (New Vision, 2009), however water level is still important.

The bathymetry of Lake Victoria is characterised by a shallow gradient around its shores. The shoreline areas are common breeding sites and so as the lake retreats, a relatively small drop can be realised as a significant lateral retreat. This leaves structures abandoned, particular piers at landing sites (Odongkara, 2009).

Decline forces the fish into smaller areas which can make fish easier to catch but will negatively affect fish breeding and therefore the fish stock for future years (Balirwa, 2009).

Fishermen at Masesse landing site near Jinja experience lake level fluctuations differently. The decline in fish stock has impacted their livelihood greatly but this is due to the factors mentioned above. The general opinion is that on seasonal scales when lake levels are lower the fish are easier to catch as they are forced into deeper water.

5. Discussion

This chapter discusses the findings of the study in terms of the success in achieving its aims and reflects on the limitations of the model and the methodology chosen to carry out the study.

5.1 Rainfall Data

An important point to discuss is the data source. As described in previous chapters rainfall for 1948-2001 was taken from the ARTES database produced by NOAA and the WMO. This database is organised spatially in that regions must be selected to obtain rainfall statistics. As these are political and not hydrological boundaries the total area selected was an approximation of the Lake Victoria Basin. In an attempt to achieve suitable continuity between the two data sets the same area was used to extract data from the NOAA rasters. There are some issues with possible underestimation in the most recent data which may be due to the area from which rainfall was extracted.

5.2 Model

This study aimed to investigate fluctuations in the water level in Lake Victoria; to review previous water balance studies; to select and, if necessary, modify a model in order to recreate water levels to date from a source of data which was publicly available. These aims would allow for the study to be updated in the future without having to attempt to collect new primary data. The study also sought to consider future lake level behaviour by running the model with data from GCMs.

In terms of reproducing the time series of lake levels from a publicly available source of data this study was reasonably successful, with a Nash-Sutcliffe efficiency of 0.77. Each component of the water balance in this model has been related to rainfall and water levels by determining relationships from recorded data gathered in the Nicholson et al 2000 study. The rainfall data set used in the original study, and included in the regression analysis to create the component equations, may significantly differ from the rainfall dataset used in this study. Only one relationship was altered, that being the catchment rainfall to over lake rainfall relationship. The inflow and outflow regression equations remained unaltered. This raises issues for its applicability to a completely independent dataset. However lake levels were reproduced to a relatively high degree of accuracy, despite some of the peaks being underestimated.

In this study the discharge equation was not adjusted. In the original Nicholson et al, 2000, study when determining the relationship between discharge and lake level, agreed curve discharge was assumed however this is not the case any more. After Kiira came online the discharges began to exceed the agreed curve values (figure 5-1) and since 2006 restrictions have been put in place on dam releases due to historically low lake levels.

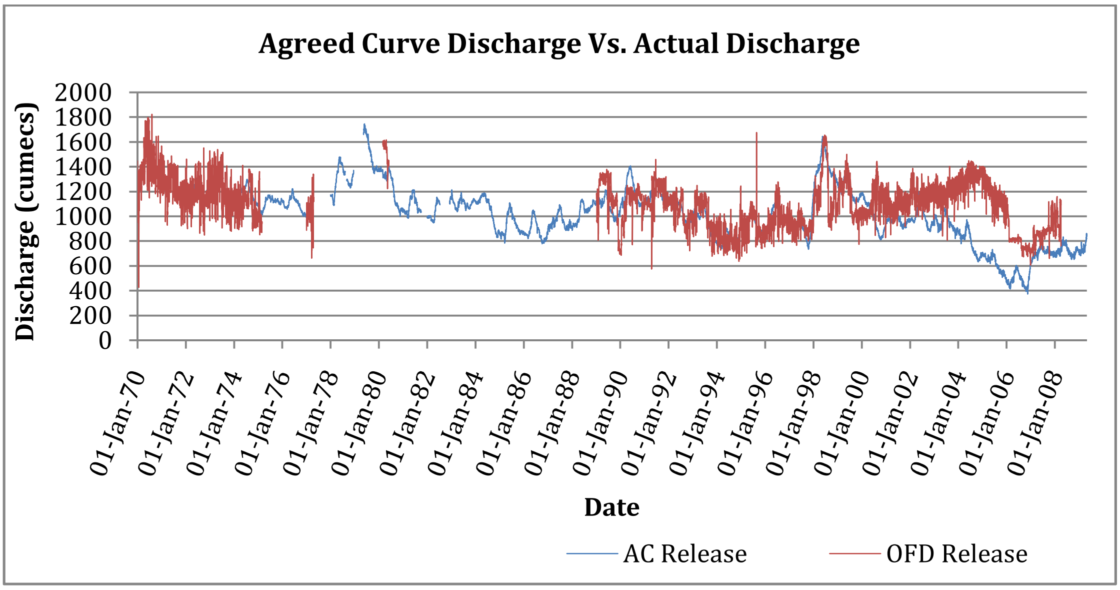

Figure 5-1 Graph showing the time series of Actual outflow from Lake Victoria compared to outflow according to the Agreed Curve.

The equation used in this study relies on an initial input of the water level from the year previous to the start year of the time period being investigated. This means that annual rainfall estimates are needed for every year back to the point where the last water level which was recorded or estimated using the same method. For example the period 2070-2099 could not be investigated without including annual rainfall data from 2069 right back to present day, unless the study were to use an estimated 2069 lake level as an input.

In this study, end of year lake water level for 2009 was estimated to allow the model to be run for the period 2010-2099. Sensitivity tests were run to determine the impact of changing this initial input as it was estimated. It was seen that after approximately 20 years no difference was felt but this needs to be taken into consideration when looking at predicted lake levels for the first 20 years.

The model runs on an annual basis. This is useful when analysing levels over a long period of time however annual averages tend to dampen out seasonal variation which is of great importance. The region has two rainy seasons; long rains in March to May and short rains in October to December (Swenson and Wahr, 2009) therefore how rainfall change is distributed over the year is very important to the response of the lake. In particular the long dry period is critical to lake level (Balirwa, 2009).

A key point that was noted regarding the reproduced time series was that there was over estimation in the early part of the series up to 1961 where there is a period of underestimation which lasts until approximately 1990 after which there is another period of over estimation. This has been noted in previous studies (Tate et al, 2004). The lake has what is called a memory effect and so previous levels determine present levels, however this model determines components by current and previous year lake levels. Effect of certain rainfall events may carry on longer as the period over which an event takes place is as important as the magnitude of the event.

5.3 Future Scenarios

Investigating possible lake behaviour under different climate change scenarios poses a number of difficulties. Firstly, the region is climatically sensitive and not fully understood. Lake Victoria also behaves in a non-stationary fashion and so using relationships derived under present conditions may not be a valid in the future.

It is difficult to predict future lake level trends as when the past century is analysed it can be seen that periods of homogeneous climate are broken up by unpredictable jumps (Sene and Plinston, 1994). The rise witnessed in 1961 has been attributed to a sudden increase in rainfall. These kind of sudden increases are not something which can be easily predicted. The time scale of the record of lake levels in not long enough, and does not include enough jumps of this magnitude, to determine any sort of pattern. GCM outputs of rainfall will produce averages for a certain period in the future, not whether a jump occurs. These jumps are incredibly important in understanding the lake level behaviour. Studies before have pointed out the difficulty of predicting future behaviour due to the occurrence of such random jumps (most recently Sutcliffe and Petersen, 2007), without the inclusion of a stochastic element. Simple calculations can show that the sheer volume of water that was added to the lake in the early 1960's due to the sustained increase in rainfall would mean a significant period of time before the lake would recover as such.

Artificial jumps are created in the lake level time series partially because in the period used the first year of the baseline, 1961, is a jump in itself. Further, because an average increase was applied to each year of this baseline, which increased to some degree depending on the model between 30 year periods, therefore creating a 'jump' between periods.

In this study the baseline used was 1961-1990 as this is the reference period used in the models. The baseline chosen is not related to the hydrology, however it is most useful in terms of prediction if the period is reflective of 'typical' conditions (Sene et al, 2001). If the time series of recorded lake levels from 1948 to present is examined, even just visually it appears that this period is not necessarily reflective of average behaviour. It is not ideal that the first year of the baseline period happens to be the year in which a random jump in lake levels occurred.

The inflow equation is not adjusted in modelling future scenarios, however there will be an impact of increased rainfall and evaporation. The equation relating inflow to lake levels and rainfall is an empirical relationship, its derivation is not process based. The relationship is a part of the soil water balance in the basin and therefore is not linear. Increasing rainfall and evaporation values as done in this study will not necessarily result in an accurate realisation of changes in tributary inflow.

Evaporation in this study was estimated using a temperature based method which was chosen for it's simple nature and minimal input data required. Most previous studies have used the Penman or energy balance methods which are more data intensive and therefore not utilised here. However Penman is insensitive to temperature increases, whereas the very nature of a temperature based equation is that it is sensitive to changes.

The scenarios used may not be the most reflective of future conditions. The climate change scenario results are an indication of the magnitude of change in lake level that might be expected in the future under certain rainfall conditions.

5.4 Impact on Stakeholders

Looking at the lake levels produced through the climate change scenarios. Under GFDL-CM2.1 a significant increase in lake level would be expected over the period 2010-2099. This would superficially be beneficial to hydroelectric generation and therefore indirectly to industry. However as the lake is so climatically sensitive, relying, long term, on an adequate supply for generation would not be practical especially after experiencing the impact of the 2005 drop. The increase shown in the GFDL model was of 3-4 m over the period 2010-2099. An increase in water level of this magnitude would be very disruptive to infrastructure, affecting many sectors including water supply, hydropower and industry. Many low lying areas in Kenya are already vulnerable to flooding (Odongkara, 2009); therefore an increase of this size would be disastrous.

HadCM3 and HadGEM1 on the other hand show a slight decrease from present levels. This would have further negative impacts for hydropower in particular. Kiira will not be economically viable and production will be below capacity. Release restrictions will need to continue to be enforced if the fall is not to be exacerbated. This strain on electricity demand will mean alternatives will have to be sought by the Ugandan government, possibly leading to further increase in the cost and unreliability of electricity.

Any conclusions drawn from the climate change modelling are tenuous however as it is difficult to determine which, if any, climate change scenario is most likely.

6. Conclusions and Recommendations

This chapter looks at recommendations which can be made for future work on this topic, with regards to the data used, the model and the methodology, particularly l the investigation of future lake level behaviour.

6.1 Water Balance Model

As mentioned in the discussion, the fact that the model works on an annual basis does not allow seasonal variations to be investigated. To produce a model which works on monthly relationships would be more useful in future speculation and planning. By carrying out the same regression analysis on monthly data, monthly component equations could be determined therefore providing a monthly water balance equation.

The original equation was developed under the assumption that outflow from Lake Victoria via the Nalubaale/Kiira hydropower complex would follow the agreed curve relationship between lake level and outflow. However as can be seen in figure 5.1, since around the year 2000 the agreed curve does not appear to govern flows. It is also know that since 2006, outflows are restricted by limitations put in place by the DWRM. To adjust this equation to this new arrangement may be more useful in recreating the water balance. However if this regulatory restriction continues this would add complexity as a new relationship cannot be determined to use for the foreseeable future as these restrictions can change regularly and rapidly depending on the decisions of the DWRM.

6.1.1 Rainfall

As time goes on and a longer period of data will be available in these NOAA raster data sets, then relationships may be redefined to improve the output.

A useful direction to go in with the NOAA data would be to possibly produce a more accurate rainfall record by changing the shapefile which is used in ArcMap to extract the relevant data. For continuity reasons the shapefile created in this study was the boundary containing the regions which had been selected in the ARTES database. However as mentioned previously this is a rough approximation of basin. It would be interesting to see what difference is made if Arc Hydro were used along with elevation data to produce a shapefile which was more reflective of the basin. This may not have a significant affect because of the way the data is gridded to produce the rasters but it would be of interest for future studies using NOAA data.

Extraction of the relevant rainfall data from the NOAA raster datasets is relatively straight forward. The process however is time consuming. Therefore coding in ArcMap could be used to expedite this process. Another direction would be to investigate extracting the relevant rainfall from the data available in binary format, however this requires experience of using FORTRAN coding language.

6.2 Future scenarios

This study used data from climate change scenarios which produced 30 year estimates, which can only give a limited indication to possible future lake level behaviour. Added to this is the high occurrence of inter model disparities in East Africa. Three models were used in this study to give some indication of disparities. From each three the same two scenarios were selected; SRA1B and SRA2. SRA1B, however, may not be the most realistic scenario as it assumes low population growth, very high GDP growth and low land use changes. This is contrasted with SRA2 which assumes high population growth, medium GDP growth and medium/high land use changes. For a full investigation of possible future lake behaviour other more diverse scenarios should be investigated.

As mentioned in the discussion, only one of the component equations was altered in this study. It would be very useful to investigate modifying the inflow and discharge components of the Nicholson et al 2000 model. Land use changes are not taken into consideration in future predictions, yet such changes can have a massive impact on rainfall-runoff relationships.

Lake Victoria as a resource is vital to the livelihoods of millions of people across its basin countries. For this reason the improvement of our understanding of the lakes processes and ability to explore its behaviour is of great importance.

This thesis aimed to provide an accessible and easily updateable tool to investigate water levels, to explore future water level behaviour and the key impacts which fluctuating lake levels have on stakeholders. Having evaluated previous studies, the model developed by Nicholson et al 2000 was deemed the most appropriate starting point as input required was reduced to one dataset, limiting data collection. A publicly available source of rainfall data was established meaning studies following on from this could simply download and extract rainfall data remotely.

Modifications were made to the model, adapting it to this source of rainfall and the utility and sensitivity of the model was investigated, the results were encouraging. The model was also utilised to investigate lake behaviour over the next century under changing climate conditions, conclusions are not easily drawn from the results however, due to inter-model disparities. There are a number of pros and cons to the model and methodology used, however this study provides a useful step in producing a tool to investigate lake level behaviour, informing future models.

The interviews conducted with a variety of stakeholders serve to illustrate the human ramifications of changes to this body of water and thus the need for accurate data on which those who are responsible for resource management can rely.

6.3 Conclusions

Lake levels were successfully recreated from publicly available rainfall. The model produced results with a Nash-Sutcliffe efficiency of 0.77 despite periods of under and over estimation. It is however important to consider the departure of modelled values around 2007-2008 which would need to be considered in future studies.

In terms of investigation of future water levels there are issues with the models suitability under future conditions but the most important issue is the high occurrence of intermodel disparities in East Africa which adds more uncertainty to any results. This is evident even in the limited number of models used in this study. The difference in predicted lake levels varied by up to 4 m in some situations.

Understanding lake behaviour and patterns of fluctuation is difficult but of great importance. Changing levels of water in Lake Victoria has many impacts upon various stakeholders both in terms of increases and decreases. Increasing lake level as suggested by the GDFL-CM2.1 climate scenarios would mean flooding of low lying areas, submergence of infrastructure and possibly a change in fish population dynamics. In the case of a decline this produces difficulties for water abstraction, hydroelectric generation, industry, fishing and navigation.

Although there are limitations to the model and methodology, which are discussed previously, this study provides a step towards independent assessment and investigation of lake levels which can be built upon.

REFERENCES

Anon (2009) 'Uganda fish exporters worry as stocks dwindle'. *New Vision Online* [internet] 3 July. Available at: http://www.newvision.co.ug/D/8/220/686691/fishing [Accessed 6 July 2009].

Ba, M. B. & Nicholson, S. E. (1998) Analysis of convective activity and its relationship to the rainfall over the Rift Valley lakes of East Africa during 1983-1990 using the METEOSAT infrared channel. *Journal of Climate and Applied Meteorology.* 10, p. 1250-1264.

Balirwa, J. (2009) *Discussion on the impacts of lake level fluctuations on fishing*. [Interview] (Personal Communication, 8 July 2009).

Birkett, C., cmb@essic.umd.edu, (2009) *altimetric lake levels* [e-mail]Message to R. Murray-Williams (r.murray-williams@cranfield.ac.uk) Sent 3 June 2009 14:59 [Accessed 3 June 2009]

Brooks, C. E. P. (1923) Variations in the levels of central African Lakes Victoria and Albert. *Geophysical Memoirs*, 20, p. 337–344.

Flohn, H. and Burkhardt, T. (1985) Nile runoff at Aswan and Lake Victoria: a case of a discontinuous climate time series. *Z. Gletscherk. Glazialgeol*. 21, p. 125-130.

Flohn, H. and Fraedrich, K. (1966) Tagesperiodische Zirkulation und Niederschlagsverteilung am Victoria-See (Ostafrika) (The daily periodic circulation and distribution of rainfall over Lake Victoria). *Meteorologische Rundschau*, 19, p. 157-165

Hepworth, N. and Goulden, M. (2008) Climate Change in Uganda: Understanding the implications and appraising the response, LTS International, Edinburgh.

Institute of Hydrology (1993) *Review and update of the water balance of Lake Victoria in East Africa*. Institute of Hydrology, Wallingford, UK.

Kite, G. W. (1981) Recent changes in level of Lake Victoria. *Hydrological Sciences Bulletin*, 26 (3), p. 233 – 243.

Kite, G. W. (1982) Analysis of Lake Victoria Levels. *Hydrological Sciences Journal.* 27 (2) p. 99-110

Kull, D. (2006) Connections between recent water level drops in Lake Victoria, dam operations and drought. [internet] Available at: http://www.irn.org/programs/nile/pdf/060208vic.pdf. [Accessed 20 May 2009]

Luzze, A. (2009) *Discussion on the impacts of lake level fluctuations on industry*. [Interview] (Personal Communication, 29 June 2009)

Mangeni, B. T. (2006) The dwindling Lake Victoria water level. *Environmentally Sound Technology in Water Resources Management Proceedings 2006*. Gaborone, Botswana Sept 11-13, 2006. [internet] Available at: http://www.actapress.com/PaperInfo.aspx?PaperID=28258 [Accessed 25 May, 2009]

Mubiru, P. (2006) Causes of the decline of Lake Victoria levels during 2004 to 2005. December 2006 [internet]. Available at: http://www.energyandminerals.go.ug/ [Accessed 20 May, 2009]

Nicholson, S. E., Yin, X. and Ba, M. B. (2000) On the feasibility of using a lake water balance model to infer rainfall: an example from Lake Victoria. *Hydrological Sciences Journal*, 45 (1), p. 75 – 95.

Nicholson, S. E. and Yin, X. (2001) Rainfall conditions in Equatorial East Africa during the Nineteenth Century as inferred from the record of Lake Victoria. *Climatic change,* 48, p. 387-398.

Odongkara, K. (2009) *Discussion on the impacts of lake level fluctuations*. [Interview] (Personal Communication, 6 July 2009)

Piper, B. S., Plinston, D. T. and Sutcliffe, J. V. (1986) The water balance of lake Victoria. *Hydrological Sciences Journal*, 31 (1), p. 25 - 37

Power Planning Associates (PPA) (2007) Bujagali II – Economic and Financial Evaluation Study, Final Report. International Finance Corporation. [internet] Available at: http://siteresources.worldbank.rg/EXTBUJHYDPOWPRO/Resources/BujagaliEconFnclEvalStudyMainText.pdf. [Accessed 25 May, 2009]

Rosenberry, D. O., Winter, T. C., Buso, D. C. And Likens, G. E. (2007) Comparison of 15 evaporation methods applied to a small mountain lake in north-eastern USA. *Journal of Hydrology*, 340, p. 149-166.

Sene, K. J. and Plinston, D. T. (1994) A review and update of the hydrology of Lake Victoria in East Africa. *Hydrological Sciences Journal*, 39, (1), p. 47-63.

Sene, K. J., Tate, E.L., Farquharson, F.A.K., (2001) Sensitivity studies of the impacts of climate change on White Nile flows. *Climate Change* 50, p. 177–208.

Shalash, S. (1980) *Effect of Owen Falls Dam on the hydrological regime of Lake Victoria*. The Influence of man on the hydrological regime with special reference to representative and experimental basins. Proceedings of the Helsinki Symposium, June 1980. IAHS Publication no. 130.

Sutcliffe, J. V. and Petersen, G. (2007) Lake Victoria: derivation of a corrected natural water level series. *Hydrological Sciences Journal*, 52 (6), p. 1316 – 1321.

Swenson, S. and Wahr, J. (2009) Monitoring the water balance of Lake Victoria, East Africa, from space. *Journal of Hydrology*, 370, p. 163-176.

Tate, E. L., Sutcliffe, J. V., Conway, D. and Farquharson, F. (2004) Water balance of Lake Victoria: update to 2000 and climate change modelling to 2100. *Hydrological Sciences Journal*, 49 (4), p. 563 – 574.

Tentena, P. (2009) *Discussion on the impacts of lake level fluctuations on hydroelectric generation*. [Interview] (Personal Communication, 07 July 2009)

Twesigye, P. E. (2009) *Discussion on the impacts of lake level fluctuations on water supply*. [Interview] (Personal Communication, 22 June 2009)

Xu, C. Y. and Singh, V. P. (2001) Evaluation and generalization of temperature-based methods for calculating evaporation. *Hydrological Processes*, 15, p. 305-319.

Yin, X. and Nicholson (1998) The water balance of Lake Victoria. *Hydrological Sciences Journal*, 43, p. 789-811

Yin, X., Nicholson, S. E. and Ba, M. B. (2000) On the diurnal cycle of cloudiness over Lake Victoria and its influence on evaporation from the lake. *Hydrological Sciences Journal*, 45 (3), p. 407 – 424.

Yin, X. and Nicolson, S. E. (2002) Interpreting annual rainfall from the levels of Lake Victoria. *Journal of Hydrometeorology,* 3. P. 406 – 416.

APPENDIX A
Sub-national Regions selected in ARTES

Country	Region
Burundi	Cankuzo
	Gitega
	Kirundo
	Karuzi
	Kayanza
	Muramwa
	Muyinga
	Ngozi
	Rutana
	Ruyigi
Kenya	Nyanza
	Western
Rwanda	Butare
	Byumba
	Gikongoro
	Gisenyi
	Gitarama
	Kibungo
	Kibuye
	Kigali
	Ruthongen
Tanzania	Mara
	Mwanza
	Ziwa Magharibi
Uganda	Busoga
	Central
	North Buganda
	South Buganda

APPENDIX B
Model Information

HadCM3 (2000)

- Produced by The Hadley Centre for Climate Prediction and Research for the Third Assessment Report.
- Spatial resolution - 2.5° latitude by 3.75° longitude.
- Details available at: http://www-pcmdi.llnl.gov/ipcc/model_documentation/HadCM3.htm

HadGEM1 (2006)

- Produced by The Hadley Centre for Climate Prediction and Research.
- Spatial resolution - 1.25° latitude by 1.875° longitude.
- Details available at: http://www-pcmdi.llnl.gov/ipcc/model_documentation/HadGEM1.htm

GFDL-CM2.1 (2005)

- Produced by the Geophysical Fluid Dynamics Laboratory, NOAA.
- Updated version of GFDL-CM2.0.
- Spatial resolution - 2.0°latitude by 2.5° longitude.
- Details available at: http://www-pcmdi.llnl.gov/ipcc/model_documentation/GFDL-cm2.htm

Scenarios Used

	SRA1B	**SRA2**
Population growth	low	high
GDP growth	very high	medium
Energy use	very high	high
Land- use changes	low	medium/high
Resource availability	medium	low
Pace and direction of technology	rapid	slow
change favouring	balanced	regional

APPENDIX C

Monthly Catchment Rainfall

Catchment Rainfall 1948-2001. Source: ARTES

	1948	**1949**	**1950**	**1951**	**1952**
January	92.48558	45.088863	77.253	85.51529	44.54373
February	61.177536	65.60251	55.74609	118.24907	90.365685
March	119.814476	51.716454	190.39731	168.78107	153.06871
April	182.80501	213.19328	197.45766	235.65195	211.09702
May	141.3469	87.706154	150.09831	152.19667	180.83258
June	56.148087	45.584232	42.736565	63.192146	35.164135
July	48.320816	55.06357	48.535755	36.486973	33.79281
August	59.32895	71.55388	70.78866	55.055378	66.30115
September	93.17789	74.898094	73.059166	62.45525	91.769615
October	96.376976	75.20514	89.28757	119.874	75.987686
November	89.92422	69.98267	76.296104	200.54263	109.92568
December	89.23424	135.00589	92.75685	247.41129	30.761934
TOTAL	**1130.14**	**990.60**	**1164.41**	**1545.41**	**1123.61**

	1953	**1954**	**1955**	**1956**	**1957**
January	79.47287	52.79181	91.837296	118.032265	98.40003
February	44.907448	76.83281	108.02397	75.21388	76.4584
March	125.16387	79.34821	121.924706	127.35638	138.5002
April	196.42519	226.3796	164.63293	205.35278	226.9325
May	106.60969	183.8856	130.30833	128.75832	168.6369
June	67.02525	51.83342	33.10512	40.89014	57.908096
July	23.924612	58.509716	56.707695	32.15732	34.203045
August	48.067554	50.214325	60.049416	62.36405	45.61695
September	96.849266	79.22482	108.42196	79.83598	38.309116
October	103.2179	64.197525	73.72577	85.53233	74.39234
November	140.2206	78.806366	79.7771	108.63277	112.94099
December	81.33197	123.49208	138.8747	114.25765	130.77136
TOTAL	**1113.22**	**1125.52**	**1167.39**	**1178.38**	**1203.07**

	1958	1959	1960	1961	1962
January	61.114605	83.52462	123.58278	47.940956	97.334984
February	87.01701	83.768524	119.31484	120.9477	46.76959
March	134.77638	131.18846	189.02368	149.31877	138.63509
April	172.01794	163.6108	232.49094	166.95049	186.20587
May	127.04924	104.35924	97.26776	131.11963	178.1089
June	73.67021	43.114822	32.61799	42.724804	62.997543
July	38.431698	32.939575	24.99161	53.871056	30.05152
August	52.148743	58.156113	42.31278	67.35613	68.73056
September	55.85023	79.794716	89.01701	121.8931	93.975555
October	68.69149	105.29201	85.12869	187.51027	149.11234
November	80.07362	164.37213	104.655685	369.58496	112.16851
December	126.37389	80.21606	55.225334	168.88788	97.22242
TOTAL	**1077.22**	**1130.34**	**1195.63**	**1628.11**	**1261.31**

	1963	1964	1965	1966	1967
January	156.43651	69.49558	40.529446	86.96503	55.751385
February	112.80013	146.09024	74.420876	126.918945	45.419292
March	152.26503	161.61514	143.73503	186.08727	129.82239
April	234.07605	291.70627	184.56544	219.80124	186.17618
May	201.03851	112.935	104.6175	68.23048	191.54797
June	42.60588	56.03066	26.641499	55.070816	58.772064
July	31.169739	47.040775	34.31906	23.99913	43.21967
August	38.346077	60.5886	44.55686	68.07468	43.32408
September	51.558266	79.91668	81.68935	105.15262	104.7173
October	60.244465	100.609505	128.91084	100.08801	125.16307
November	228.54602	104.60139	174.92401	136.68669	230.60541
December	177.20618	130.83157	126.548584	78.263306	87.00372
TOTAL	**1486.29**	**1361.47**	**1165.46**	**1255.34**	**1301.52**

	1968	1969	1970	1971	1972
January	39.599567	125.94004	128.53163	89.29958	99.57399
February	163.94234	146.39062	88.72008	60.132645	125.98986
March	193.66023	136.32368	210.41223	83.16519	94.63912
April	279.73334	136.15198	230.13855	227.24765	160.7707
May	148.80672	165.70267	144.01443	148.10683	159.67572
June	79.81468	44.43191	34.794395	33.33694	90.96178
July	24.125154	36.362255	41.29553	69.354416	24.770145
August	34.7808	38.039284	70.73337	64.55672	56.978172
September	61.459156	79.491234	64.77445	77.762955	77.45604
October	124.28558	100.4987	86.244995	79.44959	137.96947
November	196.74243	158.47484	104.468185	112.04454	221.19121
December	153.5366	77.44102	118.73059	78.932106	112.329
TOTAL	**1500.49**	**1245.25**	**1322.86**	**1123.39**	**1362.31**

	1973	1974	1975	1976	1977
January	83.1875	68.78189	48.19646	58.93759	140.20055
February	100.645	69.134705	93.35125	129.29308	65.68997
March	76.470695	160.18968	171.21225	105.75856	143.66591
April	208.93272	227.86794	176.83806	184.01459	234.59035
May	137.29388	102.75024	142.87073	150.15717	138.72537
June	55.354538	76.96745	53.578022	51.691677	57.18721
July	14.331689	84.55709	76.259285	47.337097	30.321102
August	57.08413	36.922558	52.98947	75.22936	64.170525
September	112.3207	72.16764	136.80505	82.70273	68.38027
October	89.435425	64.95446	106.29883	64.63195	108.20037
November	145.09392	97.389336	68.738625	132.04166	190.50748
December	71.69197	84.7387	106.38944	101.39645	105.23085
TOTAL	**1151.84**	**1146.42**	**1233.53**	**1183.19**	**1346.87**

	1978	1979	1980	1981	1982
January	64.81807	119.11921	67.05154	59.059887	91.61138
February	135.70885	136.48561	62.98554	67.68965	51.22772
March	198.40424	134.07785	138.65208	199.08478	115.56862
April	205.4276	193.54773	169.57034	179.09354	187.70956
May	125.9132	144.85585	184.81544	144.64223	188.21303
June	45.361317	60.356987	33.14898	25.081284	51.389812
July	27.522812	23.45662	24.448301	51.754745	32.01525
August	54.605354	45.30396	51.065052	67.53498	50.03802
September	63.42323	50.418842	80.916725	83.789406	77.94009
October	120.22847	55.476692	83.33132	99.01445	173.1868
November	140.63187	121.11277	158.59921	90.21327	215.85011
December	155.47464	126.65473	96.89303	95.81036	104.12129
TOTAL	**1337.52**	**1210.87**	**1151.48**	**1162.77**	**1338.87**

	1983	1984	1985	1986	1987
January	53.808342	68.68296	111.99008	63.6608	108.31007
February	48.73323	74.132324	69.07144	98.81135	104.6966
March	87.48667	93.13248	152.1683	137.03725	143.68097
April	160.75511	212.16656	214.14233	215.9286	185.63528
May	148.00359	96.22608	176.79889	139.57643	171.75922
June	54.045876	44.57639	55.112125	42.190987	64.11457
July	45.30368	57.63309	42.269955	21.76917	21.26214
August	71.02917	57.041256	36.507915	29.316715	39.146908
September	86.470085	60.16145	70.44748	68.044464	97.279396
October	121.84525	93.0482	72.99985	135.89088	84.72566
November	94.71537	197.4295	127.96062	130.1805	169.02371
December	100.28795	108.948586	128.66357	156.19087	53.894367
TOTAL	**1072.48**	**1163.18**	**1258.13**	**1238.60**	**1243.53**

	1988	**1989**	**1990**	**1991**	**1992**
January	123.53727	70.46323	73.32989	98.27682	84.212204
February	93.86068	77.99907	140.50246	88.72438	55.646507
March	147.44247	140.17366	192.53629	161.62689	88.79568
April	228.07748	168.36813	195.06699	213.98494	152.87292
May	115.44252	162.03572	114.173355	241.41667	114.707016
June	41.851105	57.82756	18.399168	64.57325	67.279465
July	47.827415	37.40468	16.949863	42.7699	51.97042
August	100.29208	61.554962	46.30745	56.908737	44.586155
September	128.83835	95.96371	70.13707	54.695805	91.91153
October	96.01064	111.01789	126.4637	183.18893	136.41959
November	122.00954	138.57077	112.45768	91.76808	128.55087
December	115.61508	185.79263	121.403694	65.2975	146.69565
TOTAL	**1360.80**	**1307.17**	**1227.73**	**1363.23**	**1163.65**

	1993	**1994**	**1995**	**1996**	**1997**
January	107.73351	51.795197	58.52687	97.60197	105.583786
February	137.72462	68.964935	90.15822	119.32785	71.24259
March	120.80297	180.34436	126.526665	224.39915	139.8916
April	161.54446	177.61128	212.4809	175.36766	218.453
May	163.44397	184.96942	139.19269	118.23959	167.4707
June	70.93325	49.840603	74.10299	59.15645	67.25284
July	19.386904	44.57421	37.184998	47.212543	30.700336
August	47.758038	70.885345	28.477608	53.252083	46.766705
September	62.552025	44.656822	101.915375	126.00182	19.494114
October	77.03869	91.69263	195.41168	89.145584	148.16882
November	109.280426	321.9401	111.61715	138.67361	228.45717
December	69.87804	65.57074	94.21532	64.23132	285.18445
TOTAL	**1148.08**	**1352.85**	**1269.81**	**1312.61**	**1528.67**

	1998	1999	2000	2001
January	239.29941	88.21027	76.50157	224.64731
February	111.01673	24.725874	55.136185	74.326965
March	88.67493	204.1573	114.06836	146.1341
April	196.49127	196.15285	164.12445	165.50182
May	134.60628	130.68167	133.23506	118.14817
June	85.06824	58.78932	52.043503	57.202465
July	25.671532	43.696842	36.96746	72.84495
August	50.57613	74.88483	66.396324	63.944935
September	68.3699	89.63029	78.42186	149.04123
October	113.97907	111.765816	100.583466	124.019035
November	113.41648	165.33838	142.41177	155.43535
December	78.726944	114.01522	140.46008	89.00599
TOTAL	**1305.90**	**1302.05**	**1160.35**	**1440.25**

Catchment Rainfall 2001-2009. Source: NOAA

	2001	2002	2003	2004	2005	2006
January	125.32	129.48	51.90	130.98	110.06	60.57
February	73.91	69.24	52.40	77.84	64.61	77.07
March	158.28	166.51	113.77	128.77	167.48	147.47
April	129.02	199.16	113.77	173.75	133.58	180.67
May	95.77	107.34	119.93	60.39	133.11	135.03
June	51.89	22.35	57.15	21.00	62.51	20.10
July	58.16	18.82	38.43	17.69	39.48	26.64
August	47.90	32.37	66.17	48.88	46.55	42.15
September	104.85	41.46	62.25	78.39	73.00	52.38
October	124.68	110.72	64.05	74.56	65.30	78.37
November	120.01	135.75	99.07	116.47	62.51	233.25
December	71.36	146.80	95.51	129.82	46.31	179.21
TOTAL	**1161.15**	**1179.99**	**934.40**	**1058.56**	**1004.51**	**1232.93**

	2007	2008	2009
January	104.67	111.33	95.53
February	111.87	100.05	104.40
March	103.73	173.27	130.49
April	170.22	84.33	154.70
May	140.59	76.92	93.91
June	45.29	34.25	29.23
July	47.91	35.06	
August	50.92	40.59	
September	101.51	83.91	
October	75.99	136.55	
November	99.93	106.91	
December	87.50	53.92	
TOTAL	**1140.15**	**1037.10**	

APPENDIX D

Derivation of Equation 12

$$\mathrm{H}_{\mathrm{i}} = 0.81152\mathrm{H}_{\mathrm{i}-1} + 1.119675\mathrm{P}_{\mathrm{w}} + 0.210582\mathrm{P}_{\mathrm{w(i}-1)} - 58.9875$$

The component equations below:

$\mathrm{P_w} = 1.5189\ \mathrm{P}_l - 171.23$

$\mathrm{I} = 0.33395\mathrm{H}_i - 0.24311\mathrm{H}_{i-1} - 0.2662\mathrm{P}_l + 0.2356\mathrm{P}_{l(i-1)} - 726$

$\mathrm{D} = 0.159131\mathrm{H}_{i-1} + 0.07054\mathrm{H}_i - 2223$

E = 1537

Are combined in the format of the general water balance equation:

$\Delta\mathrm{H} = \mathrm{P_w} + \mathrm{I} - (\mathrm{E} + \mathrm{D})$

Where:

$\Delta\mathrm{H} = \mathrm{H}_i - \mathrm{H}_{i-1}$

Therefore:

$$\begin{aligned}\mathrm{H}_i - \mathrm{H}_{i-1} &= 1.5189\mathrm{P}_l - 171.23 + 0.33395\mathrm{H}_i - 0.24311\mathrm{H}_{i-1} - 0.2662\mathrm{P}_l \\ &\quad + 0.2356\mathrm{P}_{l(i-1)} - 726 - 1537 - 0.159131\mathrm{H}_{i-1} - 0.07054\mathrm{H}_i \\ &\quad + 2223 \\ &= -0.73659\mathrm{H}_i + 0.597759\mathrm{H}_{i-1} + 1.2527\mathrm{P}_l + 0.2356\mathrm{P}_{l(i-1)} - 211.23\end{aligned}$$

$$0.73659\mathrm{H}_i = 0.597759\mathrm{H}_{i-1} + 1.2527\mathrm{P}_l + 0.2356\mathrm{P}_{l(i-1)} - 211.23$$

Convert $\mathbf{P}_l$ to $\mathbf{P}_w$ using: $\mathrm{P}_l = 0.658371\mathrm{P}_w - 112.7329$

$$0.73659\mathrm{H}_i = 0.597759\mathrm{H}_{i-1} + 0.824742\mathrm{P}_w + 141.2205 + 0.155112\mathrm{P}_{w(i-1)} + 26.55987 - 211.23$$

$$0.73659\mathrm{H}_i = 0.597759\mathrm{H}_{i-1} + 0.824742\mathrm{P}_w + 0.155112\mathrm{P}_{w(i-1)} - 43.4496$$

$$\mathbf{H}_{\boldsymbol{i}} = \mathbf{0.811522H}_{\boldsymbol{i-1}} + \mathbf{1.119675P}_{\boldsymbol{w}} + \mathbf{0.210582P}_{\boldsymbol{w(i-1)}} - \mathbf{58.9875}$$

APPENDIX E
Observed and Modelled Lake Levels 1948-2008

YEAR	Observed Level (mm)	Modelled Level (mm)
1948	11080	
1949	10700	10751.15
1950	10680	10735.14
1951	11210	11425.70
1952	11280	11390.62
1953	11070	11209.55
1954	10860	11080.21
1955	10840	11050.39
1956	10920	11058.29
1957	11030	11110.19
1958	10950	10946.18
1959	10850	10863.16
1960	10880	10923.82
1961	11950	11729.43
1962	12380	11897.74
1963	12930	12299.62
1964	12890	12485.42
1965	12500	12262.93
1966	12330	12172.54
1967	12300	12206.49
1968	12580	12587.18
1969	12360	12525.67
1970	12480	12526.12
1971	12200	12212.06
1972	12330	12299.72
1973	12050	12089.35
1974	11990	11842.09
1975	12040	11787.84
1976	11860	11686.07
1977		11865.75
1978		12048.01
1979	12480	11977.54
1980	11880	11778.83
1981		11617.78
1982	12080	11790.20

1983	12050	11533.40
1984	11520	11394.04
1985	11540	11471.45
1986	11500	11531.41
1987	11640	11582.21
1988	12050	11824.46
1989	11930	11967.35
1990	12030	11931.04
1991	12100	12106.62
1992	11820	11953.02
1993	11350	11738.05
1994	11590	11906.86
1995	11560	11968.13
1996	11720	12064.08
1997	12140	12523.08
1998	12320	12585.82
1999	12170	12558.93
2000	11690	12294.90
2001	11720	12036.66
2002	11810	11859.40
2003	11570	11303.91
2004	11200	10985.71
2005	10640	10675.27
2006	10990	10794.54
2007	11190	10806.59
2008	11200	10611.44

APPENDIX F

Rainfall and according lake level changes (SRA1B)

YEAR	HadCM3		HadGEM1		GFDL-CM2.1	
	P_w	H_i-H_{i-1}	P_w	H_i-H_{i-1}	P_w	H_i-H_{i-1}
2010	2225.22	764.3	2178.33	711.8	2442.03	1007.1
2011	1686.61	176.5	1651.07	136.8	1850.95	360.4
2012	2016.98	399.8	1974.48	362.1	2213.50	574.0
2013	1833.67	188.7	1795.04	161.0	2012.34	316.9
2014	1545.86	-207.7	1513.28	-222.6	1696.48	-138.8
2015	1677.84	-81.4	1642.48	-95.3	1841.32	-17.0
2016	1745.66	37.7	1708.87	24.2	1915.74	100.0
2017	2037.82	372.0	1994.88	353.8	2236.38	455.9
2018	1663.02	-56.2	1627.98	-63.4	1825.06	-23.1
2019	1776.99	3.0	1739.54	-3.8	1950.13	34.7
2020	1484.08	-301.5	1452.81	-300.7	1628.68	-305.4
2021	1834.91	86.5	1796.25	80.2	2013.70	115.5
2022	1614.91	-102.3	1493.71	-201.4	1674.53	-204.9
2023	1517.90	-238.0	1485.92	-235.9	1665.80	-247.5
2024	1645.81	-70.3	1611.13	-52.8	1806.17	-45.5
2025	1571.90	-112.9	1538.77	-97.5	1725.05	-98.2
2026	1812.25	161.9	1774.06	169.1	1988.82	198.6
2027	1798.52	166.7	1760.62	171.7	1973.75	199.8
2028	1612.53	-75.9	1578.56	-67.3	1769.65	-69.5
2029	1525.33	-198.4	1493.19	-188.6	1673.94	-206.6
2030	1541.91	-160.8	1509.42	-152.9	1692.14	-167.4
2031	1800.50	162.5	1762.56	162.8	1975.93	185.7
2032	1409.33	-251.6	1379.63	-243.3	1546.65	-270.2
2033	1542.51	-137.5	1510.01	-132.1	1692.80	-146.0
2034	1681.94	72.6	1646.50	73.1	1845.82	83.6
2035	1653.26	56.2	1618.42	56.6	1814.34	64.8
2036	1660.50	47.6	1625.51	48.0	1822.29	54.9
2037	1832.71	233.0	1794.09	229.2	2011.28	257.8
2038	1753.95	137.2	1716.99	135.2	1924.85	152.3
2039	1637.29	-35.9	1602.79	-34.4	1796.82	-38.0
2040	2250.93	633.4	2203.38	620.5	2716.31	971.7
2041	1706.10	33.2	1670.06	32.9	2058.83	246.1
2042	2040.28	286.4	1997.18	280.6	2462.11	512.8
2043	1854.86	95.2	1815.68	93.4	2238.35	250.5
2044	1563.72	-287.8	1530.68	-281.5	1887.01	-237.2
2045	1697.22	-145.4	1661.37	-142.2	2048.12	-86.1
2046	1765.83	-13.0	1728.52	-12.7	2130.91	56.8

YEAR	**HadCM3**		**HadGEM1**		**GFDL-CM2.1**	
	P_w	**H_i-H_{i-1}**	**P_w**	**H_i-H_{i-1}**	**P_w**	**H_i-H_{i-1}**
2047	2061.37	334.8	2017.82	327.8	2487.55	462.8
2048	1682.24	-90.6	1646.70	-88.6	2030.03	-61.6
2049	1797.52	-24.3	1759.55	-23.7	2169.15	9.4
2050	1501.23	-327.2	1469.51	-320.2	1811.60	-363.4
2051	1856.11	69.5	1816.90	68.0	2239.86	109.3
2052	1543.49	-218.9	1510.88	-214.3	1862.60	-243.5
2053	1535.44	-252.5	1503.00	-247.2	1852.89	-287.9
2054	1664.83	-61.8	1629.66	-60.4	2009.02	-60.9
2055	1590.06	-106.6	1556.47	-104.3	1918.80	-117.6
2056	1833.18	170.0	1794.46	166.4	2212.19	214.1
2057	1819.30	173.6	1780.86	169.9	2195.43	216.8
2058	1631.17	-72.7	1596.71	-71.1	1968.41	-81.8
2059	1542.95	-197.4	1510.35	-193.2	1861.95	-233.4
2060	1559.72	-160.0	1526.77	-156.6	1882.19	-189.2
2061	1821.30	166.6	1782.83	163.1	2197.85	204.2
2062	1425.61	-252.8	1395.50	-247.4	1720.35	-302.5
2063	1560.33	-137.6	1527.37	-134.7	1882.92	-164.0
2064	1701.37	74.6	1665.43	73.0	2053.13	91.7
2065	1672.36	57.8	1637.03	56.5	2018.11	71.1
2066	1679.68	49.0	1644.20	47.9	2026.95	60.2
2067	1853.88	236.3	1814.72	231.3	2237.17	286.1
2068	1774.22	139.3	1736.74	136.3	2141.03	168.8
2069	1656.21	-35.9	1621.22	-35.1	1998.63	-42.7
2070	2355.08	728.5	2203.28	598.9	2939.33	988.6
2071	1785.04	100.1	1669.98	11.5	2227.87	203.8
2072	2134.68	352.7	1997.09	263.3	2664.26	504.2
2073	1940.68	142.7	1815.59	79.3	2422.13	229.9
2074	1636.07	-266.2	1530.61	-293.0	2041.95	-290.1
2075	1775.75	-123.7	1661.29	-151.4	2216.28	-120.3
2076	1847.53	9.4	1728.44	-20.2	2305.86	39.4
2077	2156.74	368.9	2017.73	321.7	2691.79	483.0
2078	1760.07	-79.6	1646.62	-93.6	2196.71	-81.1
2079	1880.69	-13.1	1759.46	-27.7	2347.25	-1.5
2080	1570.69	-332.3	1469.44	-323.5	1960.34	-402.7
2081	1941.99	80.8	1816.82	65.4	2423.76	110.6
2082	1614.91	-222.5	1510.81	-216.4	2015.53	-269.8
2083	1606.48	-258.9	1502.93	-248.9	2005.02	-316.7
2084	1741.86	-60.3	1629.58	-61.9	2173.98	-70.0
2085	1663.63	-108.0	1556.39	-105.5	2076.34	-130.6
2086	1918.00	180.7	1794.37	165.5	2393.82	229.0
2087	1903.47	183.9	1780.78	169.2	2375.69	232.4

YEAR	**HadCM3**		**HadGEM1**		**GFDL-CM2.1**	
	P_w	**H_i-H_{i-1}**	**P_w**	**H_i-H_{i-1}**	**P_w**	**H_i-H_{i-1}**
2088	1706.64	-74.2	1596.63	-71.8	2130.02	-90.3
2089	1614.34	-205.0	1510.28	-193.7	2014.83	-254.0
2090	1631.89	-166.2	1526.70	-157.0	2036.73	-205.9
2091	1905.57	175.3	1782.75	162.7	2378.31	220.0
2092	1491.57	-263.7	1395.43	-247.7	1861.61	-328.1
2093	1632.52	-143.3	1527.30	-134.9	2037.52	-178.1
2094	1780.09	78.6	1665.35	72.9	2221.70	98.7
2095	1749.74	60.9	1636.95	56.4	2183.81	76.5
2096	1757.40	51.6	1644.12	47.8	2193.38	64.8
2097	1939.66	247.6	1814.63	231.2	2420.85	309.3
2098	1856.31	145.9	1736.66	136.3	2316.82	182.4
2099	1732.84	-37.4	1621.15	-35.2	2162.73	-46.4

Rainfall and according lake level changes (SRA2)

YEAR	**HadCM3**		**HadGEM1**		**GFDL-CM2.1**	
	P_w	**H_i-H_{i-1}**	**P_w**	**H_i-H_{i-1}**	**P_w**	**H_i-H_{i-1}**
2010	2283.74	829.8	2240.99	781.9	2418.69	980.9
2011	1730.97	226.2	1698.56	189.9	1833.25	340.7
2012	2070.02	446.8	2031.27	412.4	2192.34	555.2
2013	1881.90	223.3	1846.66	198.1	1993.10	303.1
2014	1586.51	-189.1	1556.81	-202.7	1680.26	-146.3
2015	1721.96	-64.0	1689.72	-76.7	1823.72	-23.9
2016	1791.57	54.5	1758.02	42.2	1897.43	93.3
2017	2091.42	394.6	2052.26	378.1	2215.00	446.8
2018	1706.76	-47.3	1674.80	-53.8	1807.61	-26.7
2019	1823.72	11.6	1789.58	5.3	1931.48	31.3
2020	1523.11	-302.6	1494.59	-301.8	1613.11	-305.0
2021	1883.17	94.3	1847.91	88.6	1994.45	112.4
2022	1565.99	-202.8	1536.67	-202.2	1658.53	-204.6
2023	1557.82	-240.5	1528.65	-238.6	1649.87	-246.5
2024	1689.09	-49.9	1657.47	-51.1	1788.90	-46.2
2025	1613.24	-97.8	1583.03	-97.7	1708.56	-98.1
2026	1859.91	180.9	1825.08	176.1	1969.81	195.9
2027	1845.82	182.9	1811.26	178.4	1954.89	197.3
2028	1654.94	-68.2	1623.96	-67.9	1752.73	-69.4
2029	1565.44	-195.8	1536.13	-192.9	1657.94	-205.0
2030	1582.46	-158.7	1552.83	-156.3	1675.97	-166.1
2031	1847.85	172.0	1813.26	168.3	1957.04	183.7
2032	1446.39	-254.1	1419.31	-249.7	1531.86	-267.8
2033	1583.08	-137.7	1553.44	-135.4	1676.62	-144.8
2034	1726.18	77.3	1693.86	75.6	1828.18	82.7
2035	1696.74	59.9	1664.97	58.5	1797.00	64.1
2036	1704.17	50.7	1672.26	49.6	1804.87	54.3
2037	1880.91	240.6	1845.69	236.0	1992.05	255.3
2038	1800.08	142.0	1766.38	139.2	1906.45	150.7
2039	1680.35	-35.8	1648.89	-35.3	1779.65	-37.7
2040	2278.60	615.5	2286.86	660.9	2699.63	972.8
2041	1727.07	8.0	1733.33	51.0	2046.19	251.6
2042	2065.36	269.1	2072.85	304.9	2446.99	515.3
2043	1877.66	79.5	1884.46	108.0	2224.61	253.6
2044	1582.94	-305.0	1588.68	-283.2	1875.43	-232.0
2045	1718.09	-158.3	1724.31	-140.2	2035.55	-82.5
2046	1787.53	-22.2	1794.01	-7.2	2117.82	58.9
2047	2086.71	331.6	2094.27	345.0	2472.28	462.0
2048	1702.92	-97.7	1709.09	-88.0	2017.57	-59.6

YEAR	HadCM3		HadGEM1		GFDL-CM2.1	
	P_w	H_i-H_{i-1}	P_w	H_i-H_{i-1}	P_w	H_i-H_{i-1}
2049	1819.61	-29.4	1826.21	-21.4	2155.83	10.7
2050	1519.68	-335.1	1525.19	-329.8	1800.48	-360.1
2051	1878.93	67.1	1885.74	72.7	2226.11	109.5
2052	1562.46	-224.2	1568.13	-220.7	1851.17	-241.3
2053	1554.31	-257.7	1559.95	-255.2	1841.51	-285.6
2054	1685.29	-64.2	1691.40	-61.6	1996.69	-60.1
2055	1609.60	-109.3	1615.44	-107.4	1907.02	-116.4
2056	1855.72	171.0	1862.44	173.5	2198.61	213.1
2057	1841.66	174.8	1848.33	177.0	2181.95	215.7
2058	1651.22	-74.3	1657.20	-73.4	1956.32	-81.1
2059	1561.92	-200.4	1567.58	-200.1	1850.52	-231.8
2060	1578.89	-162.4	1584.62	-162.2	1870.64	-187.9
2061	1843.69	168.2	1850.37	169.5	2184.36	203.0
2062	1443.14	-256.2	1448.37	-256.6	1709.79	-300.5
2063	1579.51	-139.6	1585.23	-139.6	1871.37	-162.9
2064	1722.29	75.3	1728.53	76.0	2040.53	91.2
2065	1692.92	58.3	1699.05	58.8	2005.73	70.7
2066	1700.33	49.4	1706.49	49.8	2014.51	59.9
2067	1876.67	239.1	1883.47	240.2	2223.44	284.4
2068	1796.03	140.9	1802.54	141.5	2127.89	167.8
2069	1676.57	-36.4	1682.65	-36.4	1986.36	-42.4
2070	2399.73	755.0			3164.53	1254.9
2071	1818.88	114.6			2398.56	408.9
2072	2175.15	369.6			2868.39	696.6
2073	1977.47	153.7			2607.70	372.3
2074	1667.08	-264.5			2198.39	-211.0
2075	1809.42	-120.6			2386.09	-47.3
2076	1882.55	14.0			2482.53	109.1
2077	2197.63	379.5			2898.03	574.1
2078	1793.44	-78.2			2365.02	-43.4
2079	1916.34	-11.0			2527.09	34.0
2080	1600.46	-336.7			2110.54	-404.7
2081	1978.81	83.9			2609.46	142.5
2082	1645.52	-225.5			2169.96	-271.4
2083	1636.94	-262.8			2158.64	-325.5
2084	1774.88	-60.6			2340.54	-62.8
2085	1695.17	-109.4			2235.42	-130.4
2086	1954.37	184.7			2577.23	254.8
2087	1939.56	187.9			2557.70	256.9
2088	1738.99	-75.2			2293.22	-91.8
2089	1644.94	-208.6			2169.20	-269.1

YEAR	HadCM3		HadGEM1		GFDL-CM2.1	
	P_w	H_i-H_{i-1}	P_w	H_i-H_{i-1}	P_w	H_i-H_{i-1}
2090	1662.82	-169.1			2192.77	-218.1
2091	1941.70	178.8			2560.53	239.8
2092	1519.85	-268.5			2004.24	-350.9
2093	1663.47	-145.9			2193.63	-189.8
2094	1813.84	80.2			2391.92	107.9
2095	1782.91	62.1			2351.13	83.6
2096	1790.72	52.6			2361.43	70.8
2097	1976.43	252.3			2606.33	333.8
2098	1891.50	148.8			2494.33	197.1
2099	1765.69	-38.0			2328.43	-49.4

APPENDIX G

GCM Predicted Temperature increase (% of 1961-1190 Mean)

Model	**HadCM3**		**HadGEM1**		**GFDL-CM2.1**	
Scenario	**SRA1B**	**SRA2**	**SRA1B**	**SRA2**	**SRA1B**	**SRA2**
2010-2039	0.44	0.41	0.36	0.33	0.44	0.42
2040-2069	0.86	0.88	0.70	0.66	0.81	0.78
2070-2099	1.28	1.47	1.21		1.08	1.21

APPENDIX H

Modelled Lake Levels under altered rainfall and evaporation (SRA1B)

YEAR	Change in Lake Level (mm)		
	HadCM3	HadGEM1	GFDL-CM2.1
2010	764.3	711.8	1007.1
2011	176.5	136.8	360.4
2012	399.8	362.1	574.0
2013	188.7	161.0	316.9
2014	-207.7	-222.6	-138.8
2015	-81.4	-95.3	-17.0
2016	37.7	24.2	100.0
2017	372.0	353.8	455.9
2018	-56.2	-63.4	-23.1
2019	3.0	-3.8	34.7
2020	-301.5	-300.7	-305.4
2021	86.5	80.2	115.5
2022	-102.3	-201.4	-204.9
2023	-238.0	-235.9	-247.5
2024	-70.3	-52.8	-45.5
2025	-112.9	-97.5	-98.2
2026	161.9	169.1	198.6
2027	166.7	171.7	199.8
2028	-75.9	-67.3	-69.5
2029	-198.4	-188.6	-206.6
2030	-160.8	-152.9	-167.4
2031	162.5	162.8	185.7
2032	-251.6	-243.3	-270.2
2033	-137.5	-132.1	-146.0
2034	72.6	73.1	83.6
2035	56.2	56.6	64.8
2036	47.6	48.0	54.9
2037	233.0	229.2	257.8
2038	137.2	135.2	152.3
2039	-35.9	-34.4	-38.0
2040	633.4	620.5	971.7
2041	33.2	32.9	246.1
2042	286.4	280.6	512.8
2043	95.2	93.4	250.5
2044	-287.8	-281.5	-237.2
2045	-145.4	-142.2	-86.1

YEAR	**Change in Lake Level (mm)**		
	HadCM3	**HadGEM1**	**GFDL-CM2.1**
2046	-13.0	-12.7	56.8
2047	334.8	327.8	462.8
2048	-90.6	-88.6	-61.6
2049	-24.3	-23.7	9.4
2050	-327.2	-320.2	-363.4
2051	69.5	68.0	109.3
2052	-218.9	-214.3	-243.5
2053	-252.5	-247.2	-287.9
2054	-61.8	-60.4	-60.9
2055	-106.6	-104.3	-117.6
2056	170.0	166.4	214.1
2057	173.6	169.9	216.8
2058	-72.7	-71.1	-81.8
2059	-197.4	-193.2	-233.4
2060	-160.0	-156.6	-189.2
2061	166.6	163.1	204.2
2062	-252.8	-247.4	-302.5
2063	-137.6	-134.7	-164.0
2064	74.6	73.0	91.7
2065	57.8	56.5	71.1
2066	49.0	47.9	60.2
2067	236.3	231.3	286.1
2068	139.3	136.3	168.8
2069	-35.9	-35.1	-42.7
2070	728.5	598.9	988.6
2071	100.1	11.5	203.8
2072	352.7	263.3	504.2
2073	142.7	79.3	229.9
2074	-266.2	-293.0	-290.1
2075	-123.7	-151.4	-120.3
2076	9.4	-20.2	39.4
2077	368.9	321.7	483.0
2078	-79.6	-93.6	-81.1
2079	-13.1	-27.7	-1.5
2080	-332.3	-323.5	-402.7
2081	80.8	65.4	110.6
2082	-222.5	-216.4	-269.8
2083	-258.9	-248.9	-316.7
2084	-60.3	-61.9	-70.0
2085	-108.0	-105.5	-130.6

YEAR	**Change in Lake Level (mm)**		
	HadCM3	**HadGEM1**	**GFDL-CM2.1**
2086	180.7	165.5	229.0
2087	183.9	169.2	232.4
2088	-74.2	-71.8	-90.3
2089	-205.0	-193.7	-254.0
2090	-166.2	-157.0	-205.9
2091	175.3	162.7	220.0
2092	-263.7	-247.7	-328.1
2093	-143.3	-134.9	-178.1
2094	78.6	72.9	98.7
2095	60.9	56.4	76.5
2096	51.6	47.8	64.8
2097	247.6	231.2	309.3
2098	145.9	136.3	182.4
2099	-37.4	-35.2	-46.4

Modelled Lake Levels under altered rainfall and evaporation (SRA2)

YEAR	Change in Lake Level (mm)		
	HadCM3	HadGEM1	GFDL-CM2.1
2010	766.5	731.4	915.8
2011	174.8	148.9	287.8
2012	405.1	379.2	512.4
2013	189.5	171.1	268.3
2014	-216.6	-224.6	-174.5
2015	-86.3	-94.5	-46.8
2016	36.4	27.8	74.7
2017	380.0	366.4	431.7
2018	-59.2	-63.3	-38.9
2019	1.9	-2.4	21.3
2020	-310.4	-308.0	-313.1
2021	87.9	83.5	105.9
2022	-207.9	-206.3	-209.9
2023	-244.7	-242.0	-250.8
2024	-53.3	-53.8	-49.7
2025	-100.6	-99.9	-101.0
2026	178.6	174.3	193.6
2027	181.1	176.9	195.5
2028	-69.7	-69.0	-70.9
2029	-197.0	-193.8	-206.2
2030	-159.7	-157.1	-167.1
2031	171.2	167.6	182.9
2032	-254.7	-250.2	-268.5
2033	-138.2	-135.8	-145.3
2034	76.9	75.2	82.2
2035	59.5	58.3	63.8
2036	50.4	49.4	54.0
2037	240.4	235.8	255.0
2038	141.8	139.1	150.6
2039	-36.0	-35.4	-37.8
2040	545.9	611.0	1037.8
2041	-48.6	10.4	186.6
2042	223.2	272.0	462.6
2043	42.2	81.3	210.8
2044	-335.3	-304.9	-266.7
2045	-182.8	-157.8	-110.7
2046	-42.1	-21.5	36.0
YEAR	**Change in Lake Level (mm)**		

	HadCM3	HadGEM1	GFDL-CM2.1
2047	315.4	333.4	443.4
2048	-110.8	-97.5	-74.6
2049	-40.1	-29.1	-1.5
2050	-343.7	-336.0	-370.0
2051	60.1	67.7	101.5
2052	-229.9	-224.8	-247.8
2053	-262.3	-258.5	-290.9
2054	-68.0	-64.3	-64.4
2055	-112.3	-109.5	-119.9
2056	168.5	171.7	210.3
2057	172.8	175.5	213.4
2058	-76.0	-74.5	-83.0
2059	-201.7	-201.1	-233.3
2060	-163.5	-163.0	-189.1
2061	167.4	168.9	202.1
2062	-256.9	-257.1	-301.3
2063	-140.1	-140.1	-163.6
2064	74.9	75.6	90.7
2065	57.9	58.5	70.3
2066	49.1	49.6	59.5
2067	238.9	240.0	284.1
2068	140.7	141.4	167.6
2069	-36.6	-36.5	-42.6
2070	613.1	-	1131.1
2071	-0.5	-	308.4
2072	276.2	-	615.0
2073	77.8	-	306.2
2074	-326.0	-	-264.7
2075	-170.6	-	-90.9
2076	-26.6	-	73.8
2077	346.6	-	545.4
2078	-104.9	-	-66.7
2079	-32.6	-	15.1
2080	-354.3	-	-420.0
2081	69.6	-	130.1
2082	-237.0	-	-281.5
2083	-272.2	-	-333.7
2084	-68.2	-	-69.5
2085	-115.6	-	-135.8
2086	179.7	-	250.4
YEAR	**Change in Lake Level (mm)**		

	HadCM3	HadGEM1	GFDL-CM2.1
2087	183.8	-	253.3
2088	-78.5	-	-94.7
2089	-211.3	-	-271.4
2090	-171.2	-	-220.0
2091	177.0	-	238.2
2092	-269.9	-	-352.1
2093	-147.1	-	-190.8
2094	79.3	-	107.0
2095	61.3	-	83.0
2096	52.0	-	70.3
2097	251.8	-	333.4
2098	148.4	-	196.7
2099	-38.4	-	-49.7