DEVELOPMENT AND APPLICATION OF DECISION SUPPORT SYSTEMS FOR IMPROVED PLANNING AND OPERATION OF LARGE DAMS ALONG THE WHITE NILE

By

Benon Tamukedde Zaake

School of Engineering
Submitted in fulfilment of the requirements
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College of Agriculture, Engineering and Science
University of KwaZulu - Natal
Pietermaritzburg
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PREFACE

As the candidate's Supervisor I agree/do not agree to the submission of this thesis.

Signed:
Professor J.C. Smithers (supervisor)

The analytical work documented in this thesis for the PhD was carried out in the former School of Bioresources Engineering and Environmental Hydrology and current School of Engineering, University of KwaZulu-Natal, Pietermaritzburg, from March 2006 to December 2015, under the supervision of Professor Jeff Smithers and Dr Matthew McCartney.

These studies represent original work by the author and have not otherwise been submitted in any form for any degree or diploma to any University. Where use has been made of the work of others, it is duly acknowledged in the text.

Zake

Signed:
Zaake Tamukedde (candidate)

Signed:
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DECLARATION 1 - PLAGIARISM

I, Zaake Tamukedde Benon, declare that,

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ABSTRACT

In this study the regulation of Lakes Victoria, Kyoga and Albert in East Africa are investigated with the objective of maximising hydropower production subject to system constraints for existing and future planned dams along the Upper White Nile in Uganda. A Decision Support System (DSS) has been assembled and applied to search for efficient lake-reservoir operating rules for this basin. Elements of the DSS include power plant functions, a simulation model of the Upper Nile Equatorial Lake Basin, the Stochastic Analysis Modelling and Simulation (SAMS) computer software package for analysing hydrologic time series and the Colorado State University Dynamic Programming (CSUDP) model for solution of the optimisation problem.

A concurrent record of observed lake levels and outflows for the three lakes during the reference period 1899 – 2008 has been constructed from various long term monitoring stations and utilised to derive net basin supply or net inflow time series at a monthly and annual time scale. Statistical tests confirmed the non-stationarity of the annual lake net basin supply time series. A justification to model the stochastic process of the monthly inflows as a Markov process was also reached. A Univariate Shifting Mean model was fitted to the annual historical data in tandem with a model for temporal disaggregation of annual to monthly net basin supplies for the purposes of generating synthetic flow series. The model performed well in terms of preserving the statistical characteristics of the historical reference set for each lake. The synthetic time series are considered to be a useful reference data set for future research in generating reservoir operating rules.

Two Dynamic Programming (DP) models that may be used to generate reservoir operating rules were investigated. The desired scope of optimization was however curtailed by the well-known dimensionality problem of DP. Application of the deterministic method of Incremental Dynamic Programming (IDP) to the optimisation problem could only be carried out on a monthly time step and for single years separately. Annual time step optimization could only be carried out for the historic net inflows. The 1000 stochastically generated time series of net basin supplies could not be utilized within the implicit framework of deriving operating rules due to impractical computational requirements. The IDP however, yielded a realistic set of optimal operating policies at an annual time scale for the historical reference period (1898 – 2008). The beginning of year lake levels and annual release magnitudes obtained were compared against similar data for natural unregulated lake conditions. It is concluded that, in general, lake regulation would yield desirable benefits in terms of hydropower generation but would lead to marked deviation from natural lake levels and more variable outflows. The Stochastic Dynamic Programing (SDP) model was only applied to Lake Victoria in single reservoir optimization scheme due to limitations imposed by the large dimensionality of the problem and difficulty of simultaneously incorporating multiple lake reservoir transition probability matrices in the model. Application of the model for Lake Victoria showed that, it was feasible to define final storage levels for discretized initial storage and previous period inflow class combinations. The results from the study indicate that realistic heuristic operation rules can be inferred from the results of applying the IDP models and SDP algorithm.

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GLOSSARY OF TERMS

Net Basin Supply:	Commonly used term in the simulation of lake levels defined as inflow minus net evaporation in the Lake. The term ‘net basin supplies’ is used frequently in the thesis and refers to net basin inflow.
Separable function:	An objective function is separable when it is a sum of terms, each depending on a different decision variable
Markov Process:	The fundamental elements which comprise a Markov process are a set of states, a set of actions for each state, a set of matrices of transition probabilities (one for each action). Reservoir operation can be described in terms of these elements, i.e., states as monthly storage levels, actions as monthly releases from the reservoir, transition matrices as mass balance equations plus stream flow characteristics, and rewards as benefits from use of water or sale of electricity.
First Order Markov:	A stochastic process, in which the current state of the process is dependent only on the state of the process in the preceding time period.

LIST OF ABBREVIATIONS

AC	Agreed Curve
ANN	Artificial Neural Network
BCM	Billion Cubic Metres
CGIAR	Consultative Group on International Agricultural Research
CPWF	Challenge Program on Water for Food
DM	Decision Maker
DP	Dynamic Programming
DSS	Decision Support System
DSS/M	Decision Support System – Management
DSS/P	Decision Support System – Planning
ED	Energy Driven release policy
ESKOM	South African electricity supply company
ESO	Explicit Stochastic Optimisation
EU	European Union
HEP	Hydro Electric Power
HYDROMET	Hydro-Meteorological survey of the catchments of Lakes Victoria, Kyoga & Albert
IDP	Incremental Dynamic Programming
IDPSA	Incremental Dynamic Programming with Successive Approximations
ISMO	Interactive analysis of dynamic water regulation Strategies by Multi-criteria Optimization
ISO	Implicit Stochastic Optimisation
IWMI	International Water Management Institute
IWRM	Integrated Water Resources Management
LVDST	Lake Victoria Decision Support Tool
LVEMP	Lake Victoria Environmental Management Project
MCDA	Multi Criteria Decision Analysis
MCM	Million Cubic Metres
MODDS	Multi-Objective Decision Support System
MW	Mega Watt
Nile DST	Nile Decision Support Tool

PIP	Participatory Integrated Planning
SA	Systems Analyst
SAA	Successive Approximations Algorithm
SDP	Stochastic Dynamic Programming
WMO	World Meteorological Organisation
WRAP	Water Resources Assessment Project
WREM	Water Resources Engineering & Management

1. INTRODUCTION

Contemporary management strategies for reservoirs often concentrate on technical solutions that consider only certain parts of the total system. For example, large dams built to provide urban water and electricity, have extensive impacts on rivers and aquatic ecosystems. These dams often modify ecological processes in the environments they are built and in such instances, may deprive those living in rural areas of ecosystem goods and services (Challenge Program on Water for Food, 2001). The wise and sustainable utilization of the water stored in large reservoirs requires consideration of a number of complex and inter-related issues, and poses intricate technical and political problems (Challenge Program on Water for Food, 2001). Reservoir releases must be optimized to take account of water uses upstream and downstream of the dam, including water supply to agriculture (i.e. irrigation and livestock), fisheries and power generation, as well as for the requirements of communities dependent on the natural resources of downstream ecosystems, and to meet the needs of downstream aquatic habitats and the possible impacts on human health. These considerations and linkages are summarised in Figure 1.1.

The large number of variables involved makes the management of reservoirs a very important task but also introduces considerable difficulties. The problem is compounded by the stochastic nature of future inflows, the nonlinearity of system dynamics and other uncertainties of reservoir systems. Complexity is further increased when attempting to combine multiple benefits arising from reservoir system operation (e.g., hydropower, irrigation, etc.), which are frequently competitive or even conflicting, together with a reduction of natural risks (e.g., flood control) and whilst simultaneously ensuring that environmental and ecosystem requirements are also satisfied. Frequently the management of large hydro-systems, especially when they span more than one catchment, raises conflicts between authorities or organizations with different interests e.g. water supply companies, power utilities, farmer organisations and ecologists (Koutsoyiannis *et al*., 2002).

Difficulties are intensified when system managers cannot easily perceive the trade-offs between the several objectives, given the existing and predicted conditions relevant to system operation. Moreover, such trade-offs may need to be modified if predictions are updated (Yeh and Becker, 1982). Unless legal or contractual priorities have been established, the usual refuge of the system manager is to assign priority to the objective (commonly hydropower) which realises the greatest monetary benefit for the operation. When this happens, water is extracted on an unsustainable basis, the quality is degraded or hydrological regimes are modified. Thereafter, the natural environment deteriorates, habitats may be destroyed and ecological functions could be lost (Challenge Program on Water for Food, 2001).

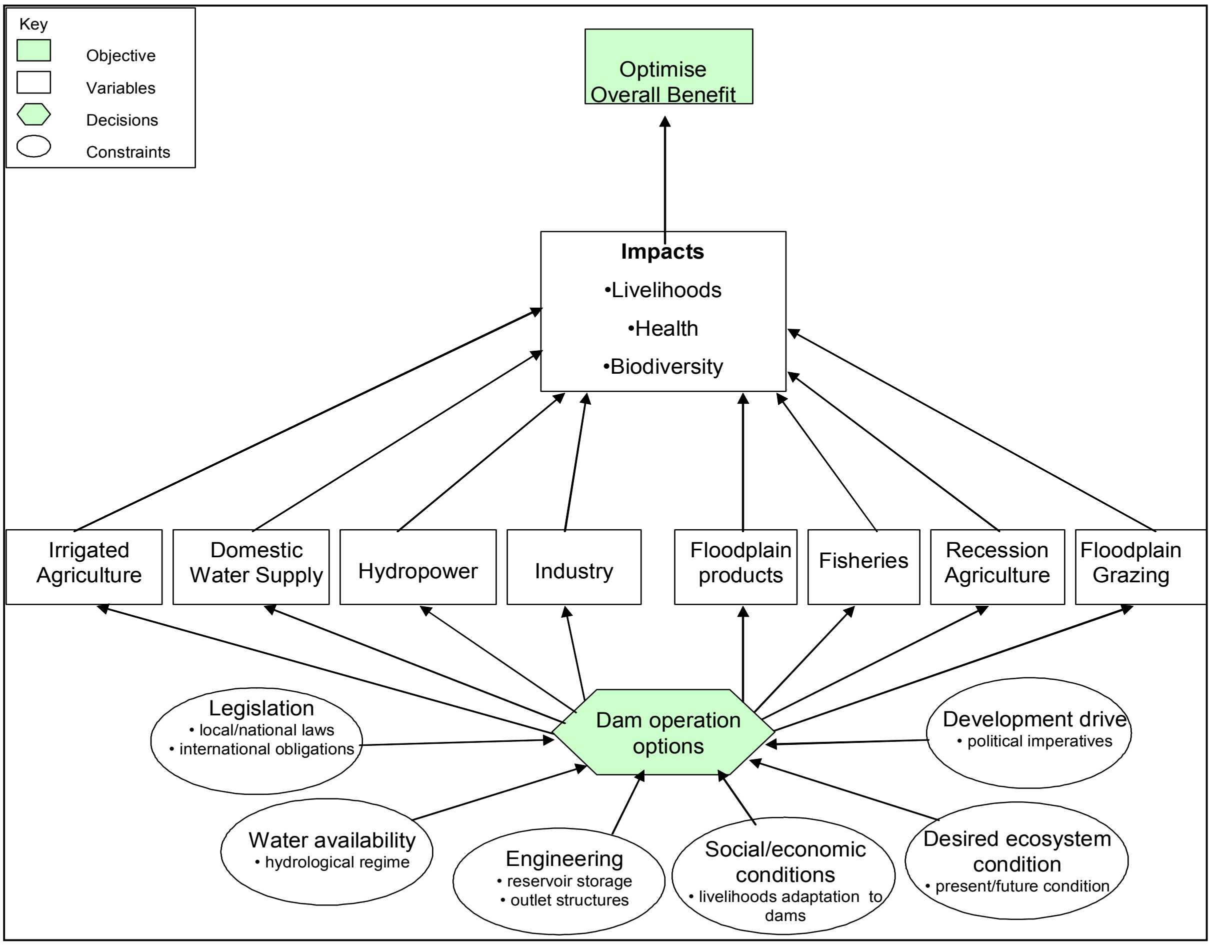


Figure 1.1 Complex web of interlinked issues and trade-offs that must be considered in planning dam operation (McCartney, 2007).

This thesis describes a case study, the Equatorial Lakes of the Upper Nile Basin, where many of issues that need to be to be considered in the planning and management of large dams are coming to the fore.

1.1 System description of the Equatorial Lakes of the Upper Nile Basin

The lake-river system that constitutes the case study area is illustrated in Figure 1.2. The dotted lines represent basin boundaries.

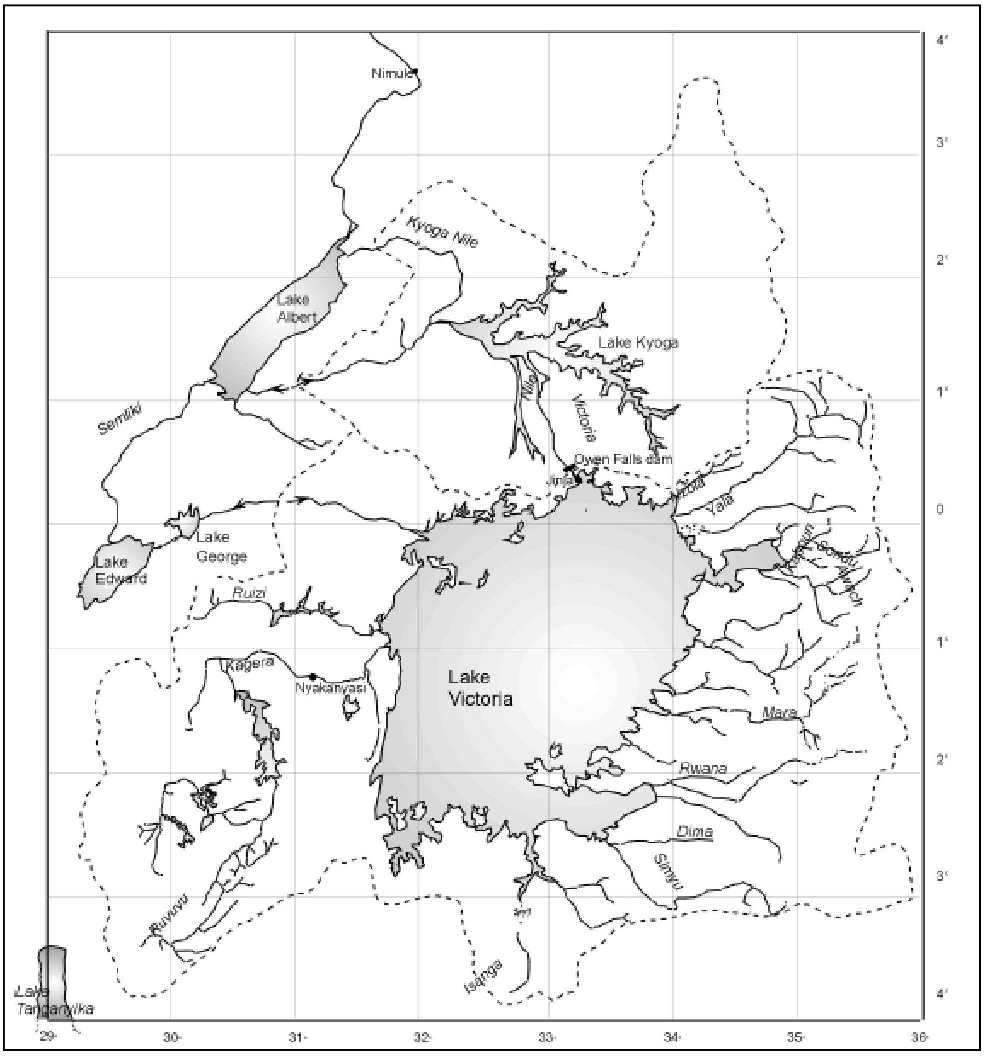


Figure 1.2 Equatorial Lakes Basin (Sutcliffe and Parks, 1999).

Lakes Victoria, Kyoga and Albert are the three largest lakes in the region that are interconnected through the Victoria and Kyoga Nile Rivers. Lake Victoria, with a surface area of 68,800 km^2 and an adjoining catchment area of 184,000 km^2 (Agriculture and Environment Operation Division, E.A.D., Africa Region, 1996) is the largest hydrologically dominant Lake in the basin. The two smaller lakes i.e. Lake George and Lake Edward are not part of the Lake Victoria catchment. They ultimately drain into Lake Albert through the Semliki River. The hydrology of these lakes is discussed in Chapter 4 and 5.

Lakes Victoria, Kyoga and Albert contain an estimated 3200 km^3 of fresh water (Kite, 1984). There is an elevation difference (fall) of approximately 107 m over a distance of approximately 125 km along the Victoria Nile as the river cascades over a series of rapids, over several more rapids along the Kyoga Nile and large falls closer to Lake Albert. Consequently, a series of hydropower dams are planned to be built along the Victoria and Kyoga Nile as illustrated in Figure 1.3.

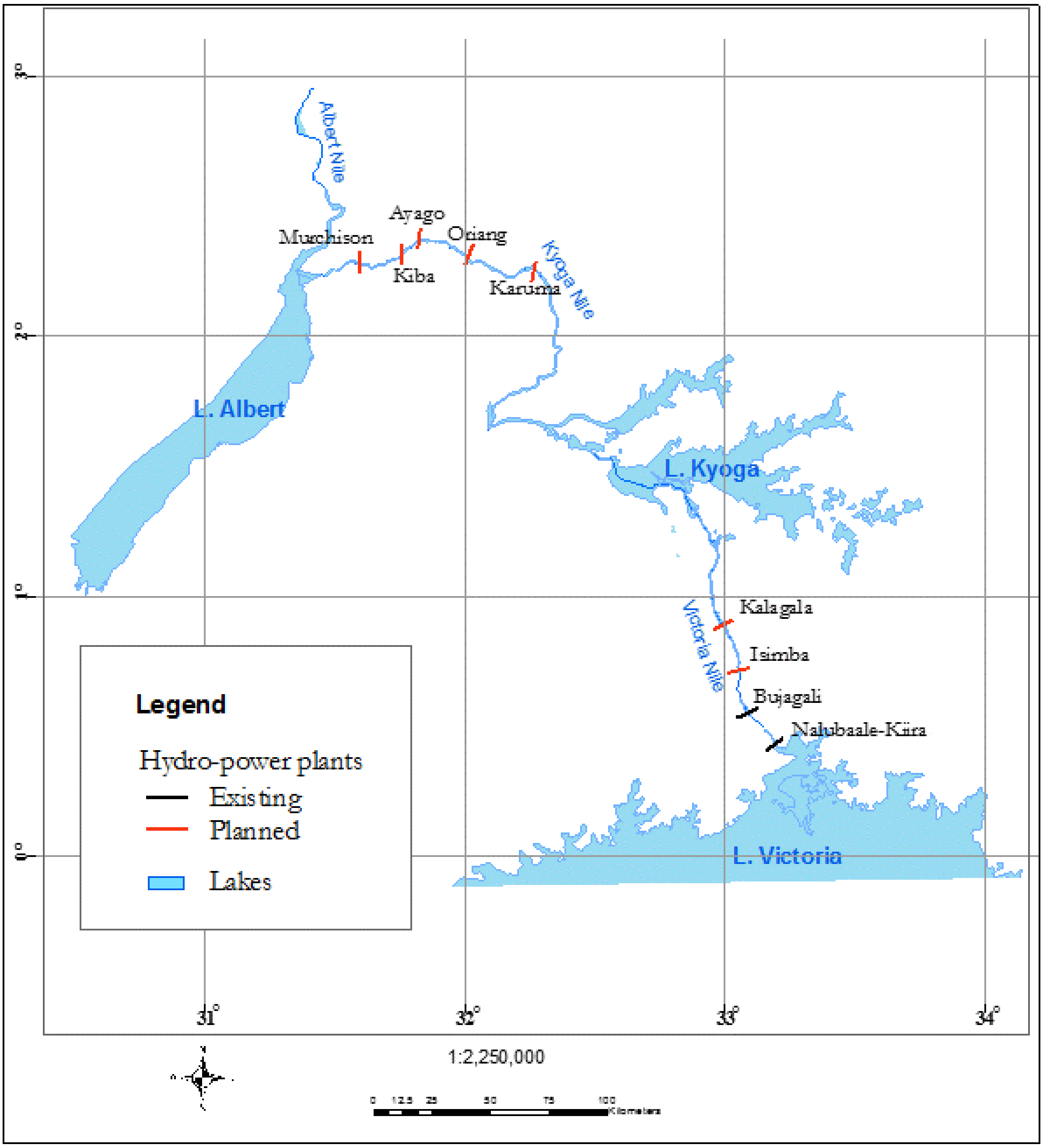


Figure 1.3 Existing and planned dams.

As shown in Figure 1.3, two projects currently exist. These are Nalubaale - Kiira and Bujagali hydro-power plants. Other candidate sites are also shown in Figure 1.3 and these were evaluated under the Master Plan on Hydropower Development (JICA, 2010) in which the potential power plants at Isimba, Karuma and Ayago were confirmed as prospective projects. Figure 1.4 is a schematic diagram which illustrates the vertical profile from the Owen Falls Dam to Lake Albert and the location of the planned hydropower projects in each reach of the Nile Rivers. In Figure 1.4, Owen Falls Dam and Nalubaale – Kiira refer to the same power plant.

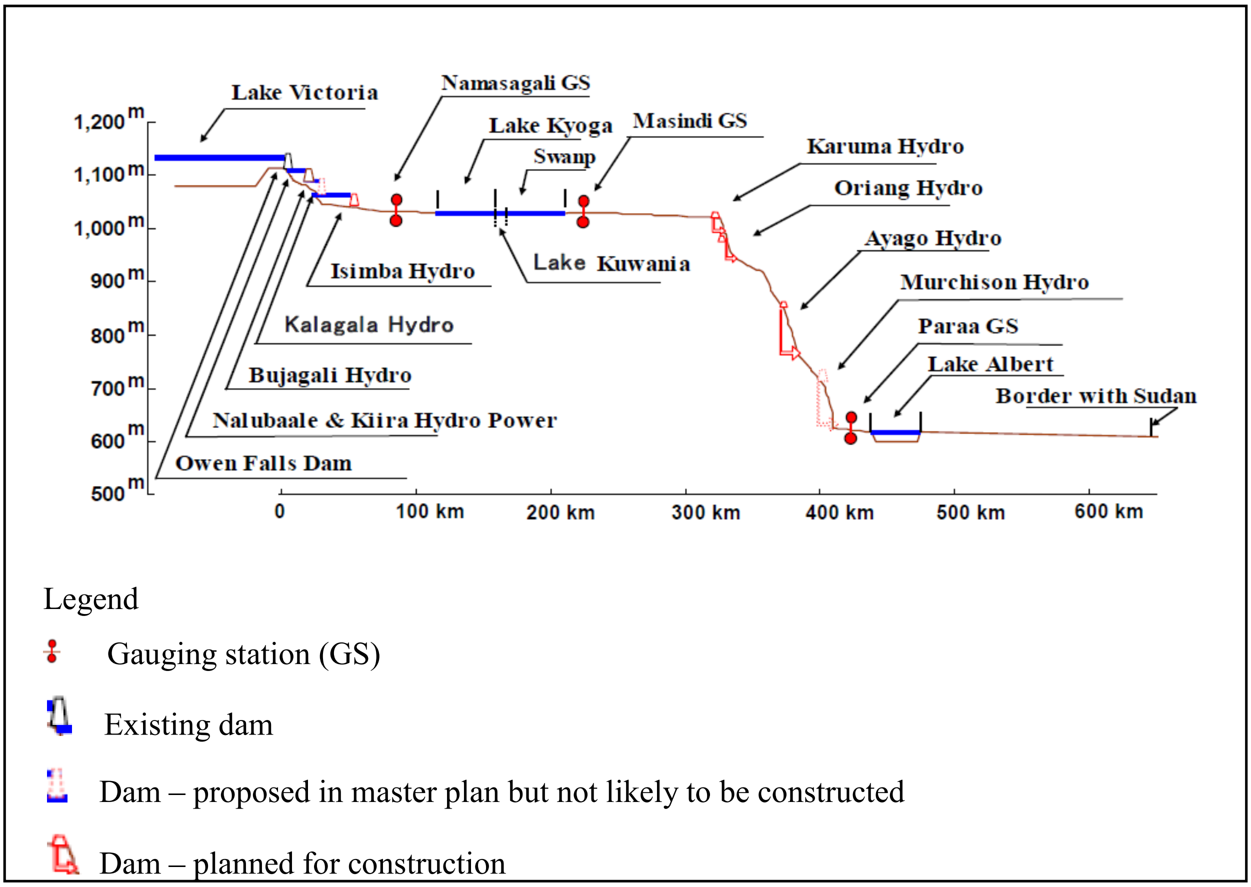


Figure 1.4 Schematic profile (JICA, 2010).

1.2 Description of the problem

The case study is located in the Equatorial Lake Basin of the Upper Nile catchment where a series of dams are planned to be built along the Victoria and Kyoga Nile to satisfy demand for electricity that has been increasing at an annual rate of approximately 8.5 % in Uganda (Kennedy and Donkin, 1996). Recent, estimates of annual power demand growth have been stated to be 8% (Adeyemi and Asere, 2014). Prior to construction of the Owen Falls Dam

(Figure 1.2), the natural barrier of the Rippon Falls, some 3 km upstream of the dam, controlled the outflow from Lake Victoria. Following completion of the dam and hydro-electric power station in 1954, Rippon Falls was submerged and hence outflow was controlled by a combination of releases through turbines and sluices in the dam. According to the Nile Waters Agreement of 1959 (Abdallah, 1971), the dam is to be operated as if natural conditions govern the outflow.

The natural condition relationship between outflow and lake level is known as the Agreed Curve. The Agreed Curve was established based on observations of the stage-discharge relationship with the falls in their natural state during the period 1939 and 1950. The stage observations were taken as the water level in Lake Victoria at a point located about 1 km upstream of the falls while the discharges were measured at Namasagali, 64 kms further downstream. A curve through the plotted observations was accepted by the riparian countries and is referred to as the Agreed Curve.

The Owen Falls Dam scheme was designed based on an average discharge of 505 $m^3.s^{-1}$ (Kennedy and Donkin, 1996). Since Lake levels remained relatively high after 1960 and natural outflow never dropped below 750 $m^3.s^{-1}$, the question of what would happen if lake levels eventually declined was not resolved. The state of affairs was complicated by the design of an extension to Owen Falls Dam which was named Kiira while the old dam was renamed Nalubaale. These two dams will now be referred to as the Nalubaale – Kiira for purposes of clarity (Figure 1.3). The combined Nalubaale – Kiira dams were designed based on an average flow of 1200 $m^3.s^{-1}$ and commissioned as a combined unit in the year 2001, thereby creating the possibility of drawing in excess of 2000 $m^3.s^{-1}$ at the outlet of the lake. The existing engineering facilities have the capacity to enhance hydropower generation by facilitating increased storage in Lake Victoria but also create the possibility to draw down Lake Victoria levels than would have occurred naturally since they submerged the natural control that previously existed at Rippon Falls.

The two dams (Nalubaale-Kiira) are the principal source of Uganda's Hydro-Electric Power (HEP) and combined releases through their turbines and sluices now represent outflow to the Victoria Nile. Figure 1.5 is an aerial overview of the configuration of Kiira (left) and Nalubaale (right) at the outlet of Lake Victoria.

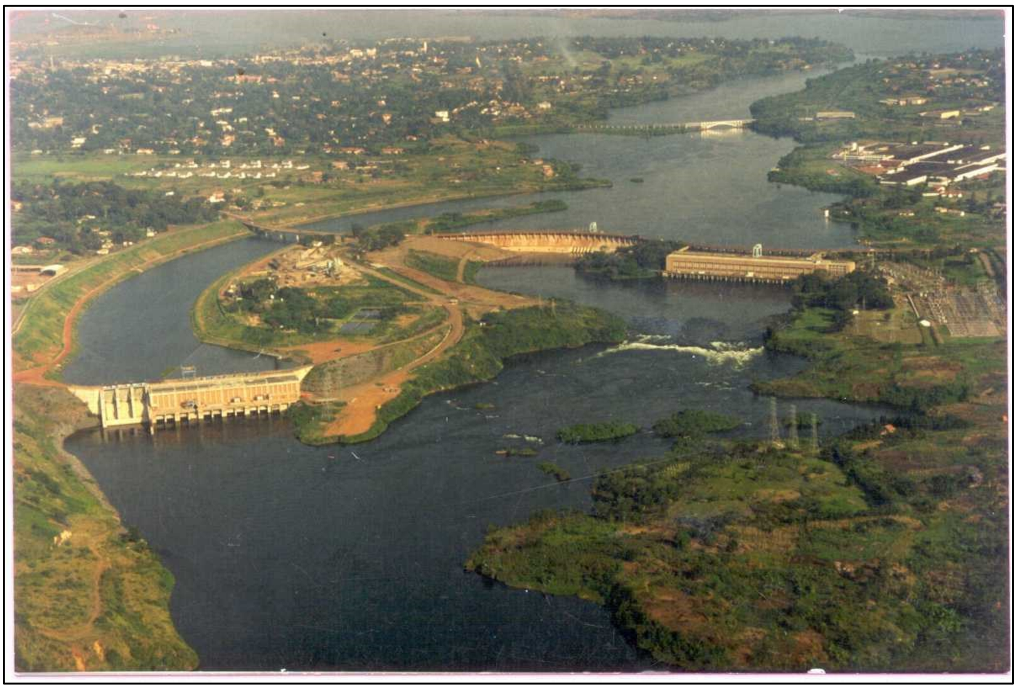


Figure 1.5 Aerial view of the Nalubaale-Kiira Dam complex.

The operation of Nalubaale - Kiira Dams in tandem, implied that more energy could be generated. However, this required passing more water through the turbines than is consistent with the operation of the Agreed Curve. At the time the extension was constructed, it was generally held that there would be enough water to drive the extra units without causing excessive draw-down of the lake levels. The situation five years after commissioning Nalubaale- Kiira was markedly different. There was a clear accelerated decrease in lake levels that was partly linked to the excessive water (i.e. above that dictated by the Agreed Curve) that was being let through the new turbines at the Nalubaale-Kiira power station (Sutcliffe and Petersen, 2007).

Lake levels continued to recede in the period up to February 2006 to 10.49 m at the local datum lake level, a state established to be the lowest recorded level in the past 82 years. The lowest historical level recorded in March 1923 was 10.34 m. Thus Lake Victoria levels reached a point where the level was less than half a metre from the lowest historically recorded level. Figures 1.6 and 1.7 illustrate the excessive releases between the years 2000-2006.

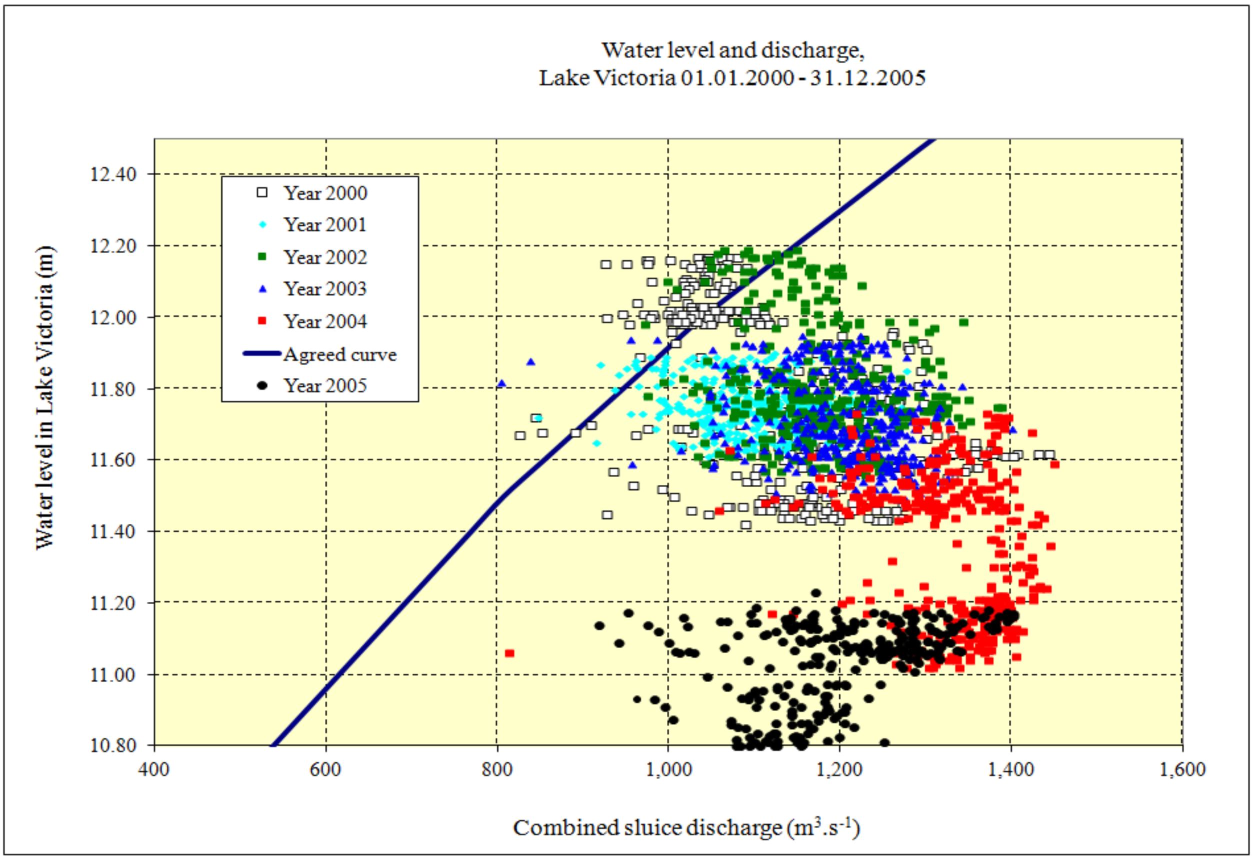


Figure 1.6 Excessive release practices at Nalubaale-Kiira Dams.

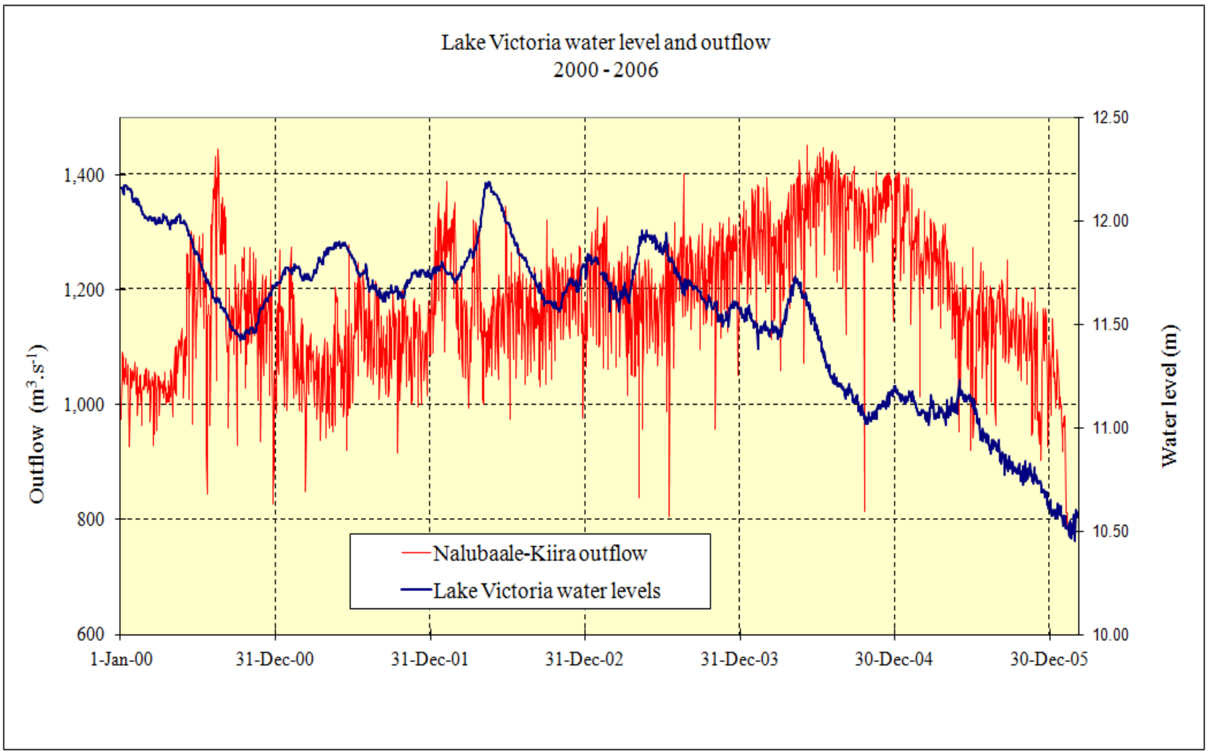


Figure 1.7 Declining water levels in Lake Victoria.

A study on the water management of Lake Victoria utilised the Lake Victoria Decision Support Tool (WREM Inc. & Norplan (U) Ltd, 2004) and investigated the Energy Demand (ED) driven release policy and the policy of following the Agreed Curve (AC). The results obtained noted that the installed power capacity has fallen far behind power demand and that the ED policy, which is still currently being followed, is releasing increasingly higher discharge rates, thus drawing the lake levels closer to unprecedented lows. To meet power demand, an average release rate of 113 MCM.day^{-1} was applied during the year 2004, a rate 55 % higher than the Lake Victoria average net basin supply recorded over the past 100 years, with the potential to deplete the lake to a historically unprecedented low level within a year or two. This release rate corresponded to the 79th non-exceedance percentile of net basin supply frequency distribution, indicating that the present release pattern is unsustainable in the long-term, regardless of hydrologic drought.

The Lake Victoria basin supports a population of 25 million people whose income ranges from US $ 90 to US $ 270 per capita per year and, although it is not possible to put a single estimate to the global value of the lake in sustaining the regional economies of Uganda, Kenya and Tanzania, over exploitation of the water resources and resulting deterioration results in an annual loss of productivity of the order of US$ 150 million (Agriculture and Environment Operation Division, E.A.D., Africa Region, 1996). The riparian countries that constitute the Lake Victoria Basin derive several socio-economic benefits that are dependent on the maintenance of a reasonable range of Lake Victoria levels. Seasonal fluctuation of lake levels is critical for the maintenance of shoreline ecosystems and wetland areas including the satellite lakes which are the breeding grounds for fisheries for over 50 endemic species (Centre for Ecology and Hydrology, 2008). The fishing industry employs local fishermen and contributes significantly to the economies of Kenya, Uganda and Tanzania due to the introduction of several fish processing factories which export their catch to Europe.

Over the years significant settlement has occurred around the lake and there are now several major towns and cities along the lake shore. The growth of these town and cities led to investment in infrastructure such as lake ports, navigation facilities, landing sites, recreation areas and intakes for water supply plants. The functionality of these facilities is sensitive to extreme occurrence of high or low Lake Victoria levels.

If lake levels continue to recede, extensive wetland areas could potentially be lost (i.e. dried up) in addition to many other beneficial functions (e.g. agriculture, fisheries, pollution abatement, harvesting of craft and construction materials). Very low lake levels adversely affect the ecosystems that support fish and bird life. Destruction of these fragile ecosystems would drastically reduce fish catches and affect the breeding grounds for many forms of aquatic life. Likewise, landing sites, navigation facilities and shoreline industries and settlements will experience severe interruptions and a range of socio-economic impacts will result.

The study on the Water Management of Lake Victoria (WREM Inc. & Norplan (U) Ltd, 2004) also confirmed that at the prevailing (2006) lake levels, the channel hydraulic capacity could not support the operation of all turbine units at the Kiira-Nalubaale complex. At such low lake levels, hydropower generation is greatly curtailed and needs to be supplemented with very expensive thermal power.

The new challenge for Uganda and upstream countries that share Lake Victoria is that energy planning needs to be coordinated with sustainable water management in order to avoid negative impacts for Uganda as well as the downstream and upstream countries. Significant departures from historical lake levels are bound to introduce adverse impacts while, conversely, establishing tight control of the levels of fluctuation, as a means to protect and support upstream water uses, or transferring significant amounts of water outside the Lake Victoria Basin, as currently under consideration by Kenya and Tanzania, will have significant impacts on power plant feasibility and commissioning and could cost Uganda millions of US dollars (WREM Inc. & Norplan (U) Ltd, 2004).

The ED driven policy that has been followed by Uganda since 2003 has proven to be unsustainable in the face of persisting and frequent droughts within the Upper Nile Basin. It is also apparent that the Agreed Curve policy is not sensitive to the demands of the energy sector. The planned cascade development program of dams along the Victoria and Kyoga Nile presents operational challenges related to the need to regulate the lake for sustained benefits to both downstream and lakeside communities. There is thus an urgent current need to re-evaluate operating policies within the framework of the current hydropower master plan (JICA, 2010). Attention must focus on improving operational effectiveness and efficiency of the Nalubaale-Kiira complex and other planned hydropower facilities along the Victoria and Kyoga Nile by considering the systems of Lakes Victoria, Kyoga and Albert as multi-facility reservoirs in a fully integrated manner. Expanding the scope of the working system to more integrated analysis significantly increases the potential number of operational policies.

The research problem is to optimise releases from the Equatorial Lakes to maximise hydropower production. However, the interests of various water uses upstream and downstream of the Nalubaale-Kiira Complex, including water supply, navigation, agriculture, fisheries, as well as the requirements of communities dependent on the natural resources of downstream ecosystems and the needs of aquatic habitats must be taken into account by maintaining constraints on upper and lower limits of lake levels and outflows. The problem essentially comprises the definition of monthly releases, hydroelectric generations and end of planning period storage levels for a three-lake system in series that can be harnessed for several purposes. The research was therefore conducted to deliver a set of improved planning reservoir operation models, which will assist the water management agencies to propose appropriate regulation policies.

By aiming to improve the operational effectiveness and efficiency of the Nalubaale-Kiira complex and other planned hydropower facilities along the Victoria and Kyoga Nile through a process of conceptualising the systems of Lakes Victoria, Kyoga and Albert as multi-facility reservoirs, this study contributes significantly towards identification of operational policies that maximise hydropower production. The study also enhanced understanding of how such policies would affect the historically observed natural lake levels.

1.3 Research questions

The three key questions that were addressed by the research are the following:

(i) What are the contemporary components/modules of a Decision Support System (DSS) that are suitable for managing large multi-dam operation along the Victoria and Kyoga Nile?

(ii) How can such a DSS be applied to a real world case study such as the Equatorial Lake Basin so as to define appropriate operational policies?

(iii) What is the nature of alternative operational policies defined by the DSS and how can they be implemented by decision makers to derive multipurpose benefits?

1.4 Objectives of the study

The objectives of the study include the following:

(i) Develop and demonstrate the applicability of a methodology and DSS to a real world case study where the objective is to develop alternative operating rules for a multi-reservoir system.

(ii) Define reservoir operating rules in the form of end of planning period storage guide curves for Lakes Victoria, Kyoga and Albert which maximise the energy production of power plants along the Victoria and Kyoga Nile subject to constraints on maximum and minimum lake levels and outflows.

(iii) Analyze the historical operation of the foreseeable dam infrastructure development structure along the White Nile. Explore and evaluate the reliability of the re-operation options or proposed rules and quantify, where possible, the benefits of adopting the proposed operating rules.

1.5 Research hypothesis

The basic premise of the proposed case study is that the Agreed Curve has proven to be insensitive to the demands of increased energy generation and therefore inappropriate for long term multiple reservoir operation. Application of contemporary tools and techniques are therefore proposed to define alternative operating rules. The principal research hypothesis of this thesis is:

"*Application of an appropriately selected and customised DSS can play an important role in generating improved operating rules for enhancing hydropower generation of large dams along the Victoria and Kyoga Nile. Alternative operational rules can be defined and applied, without significantly modifying hydrological regimes.*"

The context for modification of hydrological regimes refers to alternation of natural lake levels and outflows. However, the degree of modification that is considered to be significant can be subjective depending on stakeholder perspective but can be quantified through visual or statistical methods.

1.6 Organisation of the thesis

The thesis is organised as follows. It is divided into 9 chapters plus references. The introduction consists of a background, a specific description of the study area, and outlines of the research questions, objectives of the study and a statement of the research hypothesis.

Following the introduction, Chapter 2 is a review of approaches to reservoir operation and optimisation. Chapter 3 formulates the research strategy and methodology for the case study. The hydrological data preparation and compilation process for the research is documented in Chapter 4 while Chapter 5 is devoted to the derivation of the net inflows or net basin supplies for each lake-reservoir and analysis of the stationarity of the historical time series.

Chapter 6 documents the process of analysing and generating synthetic net basin supplies for the lake- reservoirs. This analysis is utilised at a later stage to formulate the nature of the Stochastic Dynamic Programming algorithms and also to select the most suitable type of model that can be utilised to generate synthetic data series which are indicative of future basin hydrology and also have potential for use in evaluation of various operational policies that are prescribed by the optimization models in the regulation studies for the Lakes.

Chapters 7 and 8 are deal with the application of Dynamic Programming techniques to derive alternative operating rules for the lakes. The derived operating policies are evaluated within these two Chapters. Finally, Chapter 9 presents and discusses the major findings and conclusions of the research.

2. REVIEW OF APPROACHES TO RESERVOIR SYSTEM OPERATIONS

The problem of finding operating procedures to optimally plan and manage a reservoir network has challenged many analysts and continues to be the subject of extensive research and periodic review of existing approaches (Yakowitz, 1982; Yeh, 1985; Labadie, 2004; Soncini-Sessa *et al.*, 2007b; Rani and Moreira, 2010; Singh, 2012). The task has often been formulated such that the control problem for an existing system of reservoirs is a sequential decision making problem in which release decisions (r_t) are made sequentially at different time steps (t = 1,2,…T) and stages (s_t), where T is the end of the planning horizon. Each stage is associated with a set of reservoir inflows (q_t) and stage returns or rewards in the form of benefits from use of water or sale of electricity. These returns are a function of the initial storage (stage), release, final storage at each time period and are denoted by f_t (s_t,r_t, s_{t+1}) in Figure 2.1.

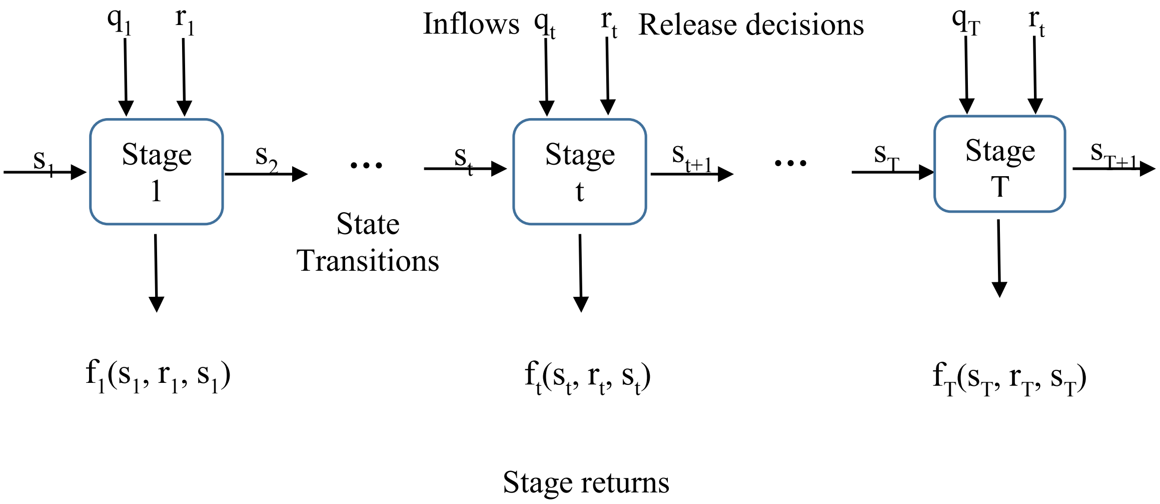


Figure 2.1 Reservoir operation as a sequential decision making process (Labadie, 2004).

The aim of the control problem is to find operating rules that minimise the total expected cost of all the stages, from the selected time period onwards. Reservoir operations can therefore be classified as either long-term or short to medium-term operations. Beyond distinguishing according to the time scale, reservoir operation may be further categorized by the number of reservoirs and the objectives to be pursued (single or multiple). In addition to these classifications, deterministic and stochastic planning and operation may be utilised (Huang, 1996). This chapter is intended to serve as a broad introduction to the various concepts, approaches and terminologies in reservoir operation or policy design.

2.1 Release plan

Release schemes i.e. sequences of m_1, m_2, $m_3 \ldots . m_t$ volumes to be released at successive time periods (e.g. one for each month) are usually proposed to manage reservoir systems. These sequences of releases are referred to as a release plan. Within the framework of a simple release plan, a decision maker/regulator often chooses to arbitrarily or intuitively release water at a given time to satisfy downstream or upstream demands. In such a case, the reservoir is known to be controlled according to an open loop scheme. Simple open loop schemes were a typical historical approach to reservoir management where regulators found it hard to establish when or how much to deviate from release plans when ‘conditions were not normal’. To assist the regulator, starting from the end of the 19th century, analysts thought to associate a nominal trajectory S_t^*, also termed the rule curve or storage guide curve, with the release scheme (Soncini-Sessa *et al.*, 2001). The rule curve specifies either reservoir (target) storage volumes or desired (target) releases based on the time of year and the existing storage volume in the reservoir. Figure 2.2 represents a typical example of such a rule curve for a dam on the Kafue River in Zambia.

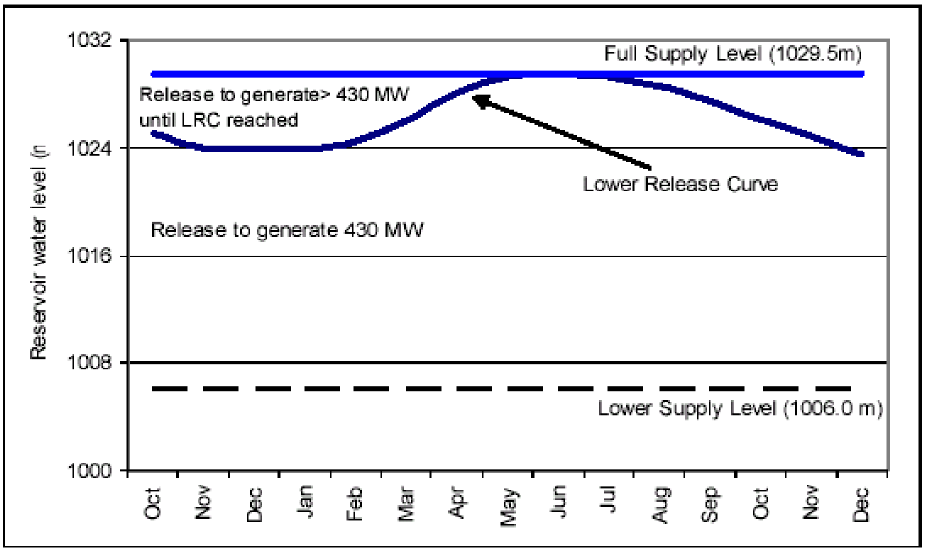


Figure 2.2 Rule curve for Itezhi-tezhi Dam on the Kafue River, Zambia (McCartney, 2007).

The rule curve takes on the form of a trajectory of releases, generally defined by a set of end-of-month target levels or storages. It is of particular use when long-term planning is undertaken in the absence of reliable knowledge of future flows and can be computed by a simple simulation. Given the rule curve, in a given month of a given year, the release decision u_t can be defined as that release which allows the end of month storage S_{t+1} to get as close as possible to what is specified by the *rule curve*. In doing so, Mass (1962) ironically remarked, that "the Decision Maker (DM) spills water when the storage $S_t$in the reservoir exceeds the quantity specified by the rule curve and hopes for rain when it falls below".

A variety of techniques to devise release plans have been formulated. Initially, DMs resorted to empirical or heuristic methods based on experience, common sense or rules of thumb. Lund and Guzman (1999) review a variety of empirically derived release plans for single purpose reservoirs operating in series or parallel, where a typical example is given as the "space rule" which seeks to leave more space in reservoirs whenever greater inflows are anticipated (Bower *et al.,* 1966).

More advanced techniques of deriving the rule curve have been devised in which the classification is according to the manner in which the hydrologic information is utilised. According to Roefs and Bodin (1970), there are three different classes: a simulation approach, an implicit stochastic approach and the explicit stochastic approach.

2.1.1 Simulation approach

In the simulation approach, effects of an operating rule are simulated on the basis of a sequence of reservoir inflows. Hence simulation models that approximate the behaviour of a system on a computer, where the characteristics of the system are represented by a mathematical or algebraic description have found favour with reservoir managers. The model simulates the response of a system for specified inputs, which include decision rules, and through a formal search procedure, an operating rule that achieves the desired objectives is found. Therefore simulation models assume special significance because they help define and evaluate predefined rules to ensure that they satisfy various constraints on system operation (Oliveira and Loucks, 1997; Nicklow, 2000; Labadie 2004; Soncini-Sessa *et al.*, 2007b). When the length of the historical flow is insufficient for a reliable estimation of the effects of the rules to be investigated, it is commonly extended or replaced by a synthesized sequence. Many simulation models are customised for particular systems (Emery and Meek, 1960; Hall and Dracup, 1970; WREM Inc. & Norplan (U) Ltd, 2004; Soncini-Sessa *et al.*, 2007a). The MIKE 11 model (Ngo *et al.*, 2008) is another example of a simulation software which employs the Shuffle Complex Algorithm to guide the releases of reservoir systems based on current reservoir level, hydrological conditions, water demands and the time of the years. The Shuffle Complex Algorithm (Duan *et al.*, 1992) is an optimization method that was initially designed for calibration of hydrologic models. A specific advantage of the method is that it adopts a parallel rather than a point by point search strategy to determine a global optimum once given a population of potential solutions.

Simulation models can accurately represent system operations and are useful in examining the long-term reliability of operating systems but when used independently are not suited to prescribe the best or optimum strategies when flexibility exists in coordinated system operations (Labadie, 2004). Prescriptive optimization models, coupled to a simulation model, have therefore been proposed by various researchers to systematically select optimal solutions, or families of solutions, under agreed upon objectives and constraints.

2.1.2 Implicit stochastic approach

In the implicit stochastic approach, sequences of historical or synthetically generated stream flow are used to determine optimal rules with the help of a suitable deterministic optimisation model. Figure 2.3 illustrates the implicit stochastic approach.

Linear Programming (LP) and Non-Linear Programming (NLP) are some of the deterministic optimisation models that have been employed in the implicit approach. The utilisation of LP has been reported to be associated with a number of advantages such as ease of problem setup and availability of low cost solvers but the major drawback is that to formulate LP models, the objective function and constraints have to be linear or linearizable (Labadie, 2004). In contrast to LP, the use of NLP techniques for reservoir system operation has received relatively little attention in the literature. Most applications of NLP have been in the field of hydropower optimisation of systems of several large-scale reservoirs (Barros *et al.*, 2003). From the literature surveyed for LP and NLP techniques, it is apparent that their application to reservoir systems optimisation necessitated too many simplifying assumptions and showed significant limitations related to excessive computational effort (Yeh, 1985; Labadie 2004).

Mixed integer linear programming (MILP) is an adequate approach that can overcome the limitations associated with application of LP to solve large scale multi-reservoir operation optimisation (Srinivasan *et al.*, 1999; Guo *et al.*, 2011; Heidari *et al.*, 2015). This is due to the fact that model formulation allows combining real, integer, and binary variables. This renders the method to be very useful for purposes of describing nonlinear and non-convex statements in the objective function and the constraints. Software packages are available that can be utilized to solve large scale optimisation problems with MILP (Moraga *et al.*, 2007).

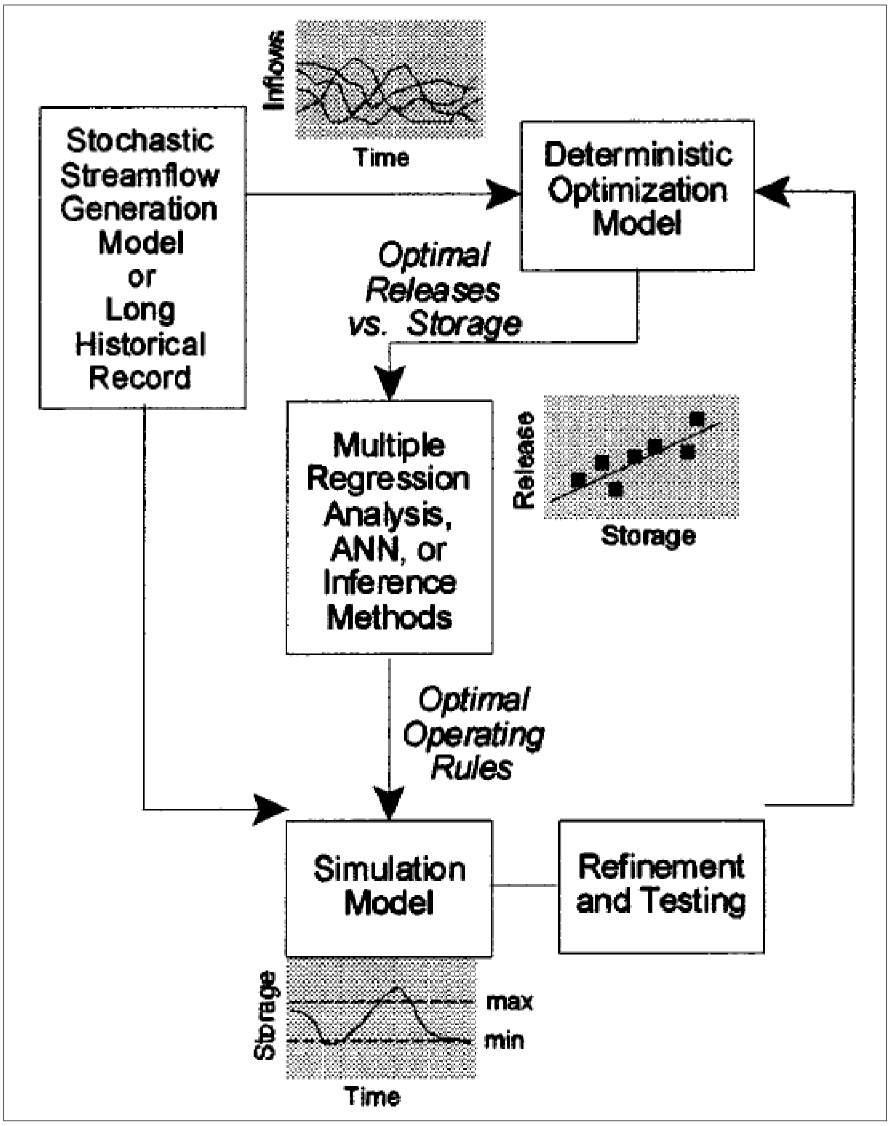


Figure 2.3 Implicit stochastic approach (Labadie, 2004).

Deterministic DP reservoir optimisation models have been widely applied in reservoir system optimisation (Nandalal and Borgardi, 2007). Utilization of these solvers within the implicit stochastic approach involves application of Multiple Regression Analysis or Artificial Neural Networks (ANNs) techniques to the optimisation results for purposes of developing seasonal operating rules conditioned on observable information such as current storage levels, inflows during the previous period, and/or forecasted inflows (Young, 1967; Roefs and Bodin, 1970; Bhaskar and Whitlatch, 1980; Karamouz and Houck, 1982, 1987; Willis *et al*., 1984; Hiew *et al*., 1989; Raman and Chandramouli, 1996; Chandramouli and Raman 2001) . The rules derived using this process are then refined and tested using a simulation model.

2.1.3 Explicit stochastic approach

Explicit stochastic optimisation is performed without the perfect foreknowledge of future events and optimal policies are determined without the need for inferring operating rules from results of optimisation. The approach uses probabilistic distributions of random stream flow instead of deterministic hydrologic sequences as shown in Figure 2.4.

A stochastic optimisation tool is a key component of the explicit approach. Several optimisation methods have been applied to reservoir operation and these include Extended Linear Quadratic Gaussian Control (Georgakakos, 1989), Stochastic Dynamic Programming (SDP), and other stochastic control methods (Yakowitz, 1982; Labadie, 2004; Rani and Moreira, 2010). According these literature surveys, Stochastic Dynamic Programming (SDP) methods and their variants or extensions have generally been the most widely applied techniques in the field of stochastic reservoir optimisation.

The Extended Linear Quadratic Gaussian Control Algorithm (ELQGC) algorithm has been applied in real time reservoir operation optimisation studies along the White Nile (WREM Inc & Norplan (U) Ltd, 2004). The framework of the algorithm offers significant computational advantages over SDP methods but it is a real time control scheme. Real-time reservoir operation models often use as input, target parameters established by the planning model (e.g. desired ending storage targets and/or reliability levels) and are designed to not only conform to directives that were defined at the long term planning level but also uses the resources in an effective way in the short to medium term by taking into account contingent and unforeseeable situations that may occur. This two-level approach, i.e. strategic planning first with later sequential update is widely prevalent in the management of reservoir systems by state and federal agencies in the United States (Loaiciga *et al*., 1987; Soncini-Sessa *et al*., 2007a).

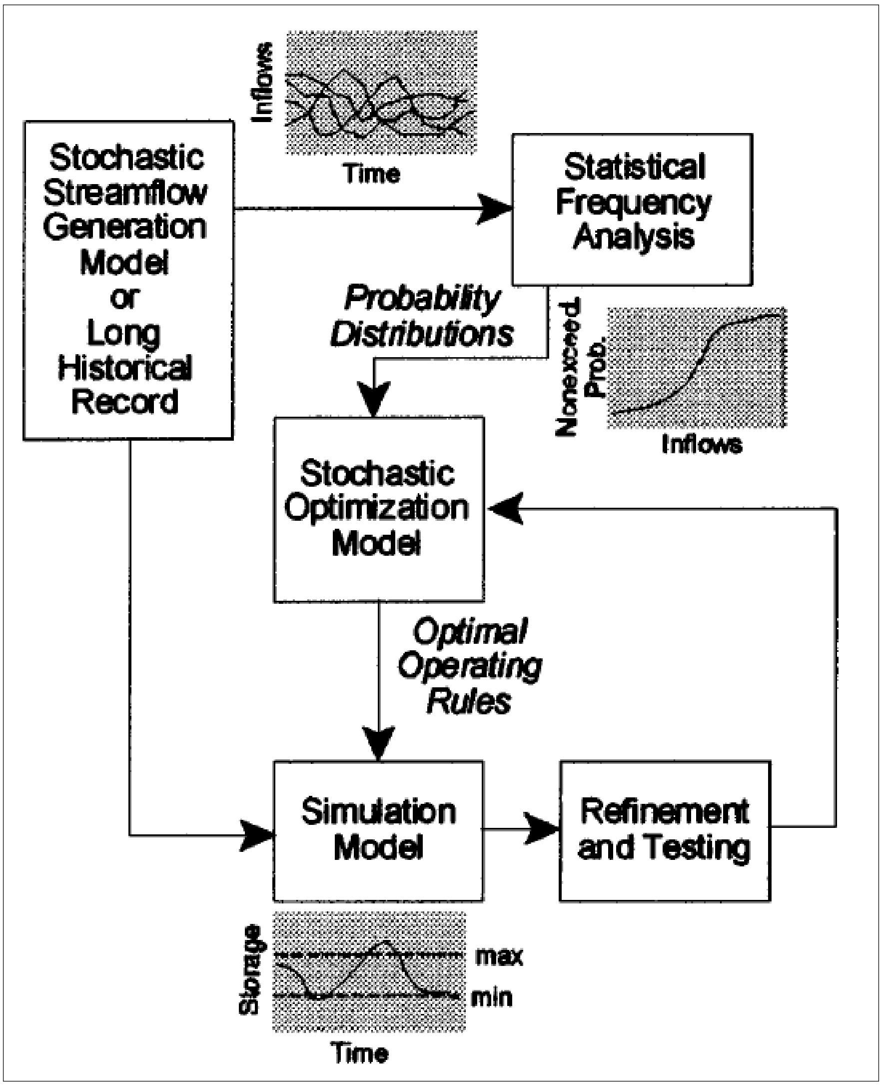


Figure 2.4 Explicit stochastic approach (Labadie, 2004).

The objective of this study is to define long guide curves or storage targets and for this purpose DP is more attractive due to its sequential nature and non- restrictive handling of objective functions. The formulation of SDP algorithms usually requires dense discretization of the reservoir storage space, inflows and release variables to guarantee solution accuracy. Where correlated inflows are taken into account, a probabilistic definition of reservoir inflows is also necessary as illustrated under Figure 2.4. For a complex three cascade lake – reservoir optimisation problem such as the White Nile case study, the computational burden associated with a discrete SDP formulation would be expected to be significantly greater than the implicit approach (Lee and Labadie, 2007) and would ultimately overwhelm even the fastest CPU processors (Malinowski and Sadecki, 1990; Piccardi and Soncini-Sessa, 1991; Sadecki 2002, 2003). Chuntian *et al.* (2014) have recently implemented a classical Discrete Differential

Dynamic Programming (DDDP) algorithm with multi-core computer processors to enhance computing efficiency.

Various methods to overcome or cope with the dimensionality problem so as to produce computationally tractable solutions have been designed by reservoir research scientists. The remedies, or combinations thereof, belong to the field of approximate dynamic programming (Powell, 2011) and can be identified as follows:

(i) Decomposition of a multiple reservoir system into single reservoir units and subsequent use of iterative procedures to optimise the single reservoir systems one at a time by SDP or its extensions. (Turgeon, 1981; Nandalal and Sakthivadivel, 2002; Nandalal and Borgardi, 2007; Barty *et al.*, 2010).

(ii) Aggregation of the system of reservoirs or parts thereof, in into an composite reservoir thus allowing a straight forward application of the optimisation procedure and the subsequent disaggregation of the derived composite operating strategy into control policies of individual reservoir elements (Saad *et al.*, 1994; Archibald *et al.*, 1997; Turgeon and Charbonneau, 1998; Nandalal and Borgardi, 2007).

(iii) Variants of SDP or its extensions that do not require discretization of the storage space. Examples of such applications with Stochastic Dual Dynamic Programming (Tilmant and Kelman, 2007; Tilmant *et al.*, 2007; Goor *et al.*, 2010) do not provide the traditional release policy tables but rather, a set of piecewise linear cost to go functions which are used to manage mixed hydrothermal systems. Another distinction between SDP and SDDP is that the former can handle a large number of stages while the latter is best suited to handle a larger state space. Hence the claim that SDDP actually mitigates the curse of dimensionality should be viewed within this context since its computational complexity can increase with increase in the number of state variables (Shapiro *et al.*, 2012). For these is reasons, Lee and Labadie (2007) contend that SDDP is incapable of finding optimal closed loop or feedback operating policies over long operational horizons and requires special care when applied in the context of highly non-convex problems such as hydropower system optimisation.

(iv) Solving the problem with another variation of SDP known as Neuro Stochastic Dynamic Programming (NSDP), as proposed by Bertsekas and Tsitsiklis (1996). NSDP reduces algorithm complexity by approximation of the Bellman functions via Artificial Neural Networks (ANNs). An ANN is a nonlinear mathematical structure which is capable of representing complex nonlinear processes that relate the inputs and outputs of any system. Castelleti *et al*. (2007) applied the NSDP algorithm to a multi-objective problem in the Paive catchment in Italy which had 3 three reservoirs. They found NSDP to be 450% faster than an equivalent SDP.

(v) Adoption of a heuristic approach or algorithm that exploits knowledge of the approximate form of the optimal policy of the multi-reservoir systems to simplify the calculations and obtain efficient descriptions of the optimal release rules (Archibald *et al*., 2001).

Disaggregation/Aggregation techniques are attractive but pose certain difficulties related to loss of interconnectivity modelling detail between reservoirs. It is also cumbersome to disaggregate the composite policies and the results may not meet the accuracy requirements for real-world case study applications (Nandalal and Borgadi, 2007). Almost all the approximate dynamic programming approaches only alleviate the dimensionality problem to some degree and none actually removes it. The challenge in this study will therefore be to devise creative methods of working with a suitable approximate dynamic programming method to yield acceptable results.

In a review of optimal operation of multi-reservoir systems, Labadie (2004) indicates that implicit and explicit stochastic approaches have been useful in determining long-range guide curves and operating policies over weekly, monthly or seasonal time increments but have proven to be of limited use because the release plans they define are unique to the assumed time series (long historical record or stochastic stream flow generation). Consequently, many schemes operated with long-range guide curves continue to be function below their potential. To remedy such short-comings, long range guide curves are often regarded as planning models that must be complemented by real-time operation models designed to track long-term guidelines over shorter time horizons.

The release plan/rule curve can be categorized as an *off-line* policy determined *a priori* for all possible occurrences of the state resulting from analyses of a long historical period or stochastically generated inflows.

2.2 Genetic Algorithms

An evolutionary method of deriving reservoir operating rules for complex reservoirs that is practical and robust is the Genetic Algorithm (GA). Application of the method to multi-reservoir systems is reported by Oliviera and Loucks (1997), Wardlaw and Sharif (1999) and Sharif and Wardlaw (2000), Reddy and Kumar (2006), Momtahen and Dariane (2007), Jothiprakash *et al.*, (2011), etcThe method seeks solutions through a process analogous to "the mechanics of natural selection and natural genetics" in the biological sciences. Excellent introductions to GAs are given by Goldberg (1989) and by Michalewicz (1992). GAs have been shown to derive optimal reservoir operating schedules for single multi-purpose reservoirs that are advantageous or superior to those derived using traditional methods such as DP (Chang and Chang 2001; Ahmed *et al.*, 2005; Dariane and Momtahen, 2009). The multi-objective evolutionary algorithm NSGA-II (Deb *et al.*, 2002) has been widely employed for optimizing the operation of multi-reservoirs systems where trade-offs are sought by decision makes (Chang and Chang, 2009; Scola *et al.*, 2014). The algorithm has been modified and improved to allow better constraint handling and improve computation efficiency (Hossain and El-shafie, 2013).

Noori *et al.* (2013), applied a GA model to determine the optimal operation of two reservoirs in series on the Ghezel Ozan's river. The two objectives investigated were the production of hydroelectric power and controlling of probable floods. Their deterministic model of genetic algorithms was written in the Matlab programming environment. The application of GAs to solve large-scale and complex water reservoir system problems can sometimes be difficult due to premature convergence of the algorithm (Chun-Tian *et al.*, 2008). In such cases, the optimization method may get stuck at a local optimum. It can also take a large number of iterations to reach the global optimal solution. They adopted a novel chaos genetic algorithm (CGA) based on the chaos optimization algorithm (COA) and genetic algorithm (GA) to improve convergence speed and solution accuracy.

Methods combining traditional methods (LP or DP) and GAs have also been adopted to determine operational decisions for reservoirs (Reis *et al.*, 2005)

2.3 Regulation policy

At the beginning of the 1970's, two control schemes evolved in the fields of Optimal Control Theory and Operations Research as rational solutions to the DM's problem. Both are based on the principle that a decision must be taken at every time instant on the basis of information available at that time. Adopting the notational convention from Soncini-Sessa *et al.* (2001), it follows that if a storage S_t is observed at time *t*, the release decision should have the form

$$u_t = m_t(s_t) \tag{2.1}$$

where, $m_t(.)$ is a succession, generally periodic of *t*, of monotone non-decreasing functions in s_t (the control laws). The regulation policy (*p*) is therefore defined by the succession $[m_0(\cdot), m_1(\cdot), \ldots, m_{T-1}(\cdot)]$ of *t* control laws each of which specifies for a given time *t*, the release decision u_t as a function of the current storage s_t of the reservoir. In this way the decision taken is not determined *a priori* for time *t*, regardless of the conditions that might occur (as in the release plan), but depends on the current conditions (the storage, s_t) which depends in turn on the decision taken at the previous time step, and thus there is a recursive feedback loop (Soncini-Sessa *et al.*, 2001; 2007a). Therefore, the control scheme is said to be closed loop as shown in Figure 2.5. The element which closes the feedback loop is therefore a regulation policy, composed of a sequence of "control laws" in Control Theory terminology and which are also be termed "operating procedures" in Hydraulic Engineering terminology.

In the closed loop control scheme shown in Figure 2.5, I_t represents hydro-meteorological information (e.g. rainfall measurements over the catchment). The resultant inflow volume to a reservoir over a time period *t* is denoted as a_t while w_t is taken to be the downstream users water demand.

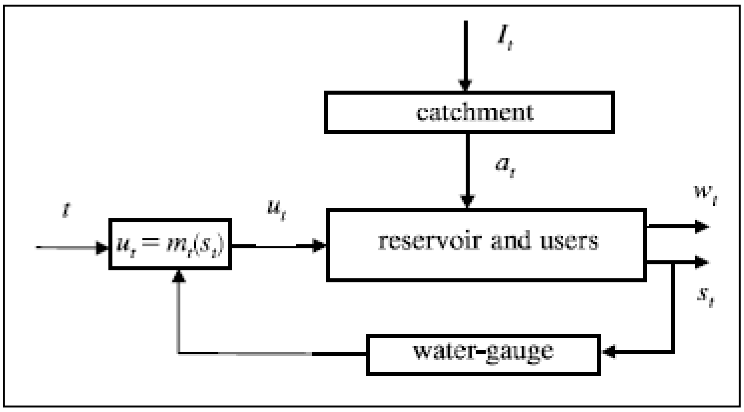


Figure 2.5 Closed loop scheme (Soncini-Sessa *et al.*, 2001).

From Figure 2.5 it is evident that the management system could be more effective if the net catchment outflow a_t (a stochastic quantity) into the reservoir, were known before hand. This is clearly impossible, but the effects of the outflow can be anticipated by utilizing the hydro-meteorological information I_t. In this way the release decision u_t is a function of the storage and hydrological information given by

$$u_t = m_t\left(s_t, \mathrm{I}_t\right) \tag{2.2}$$

The closed loop control scheme can be improved by inserting a feed forward compensation component by installing a telemetry system as shown in Figure 2.6.

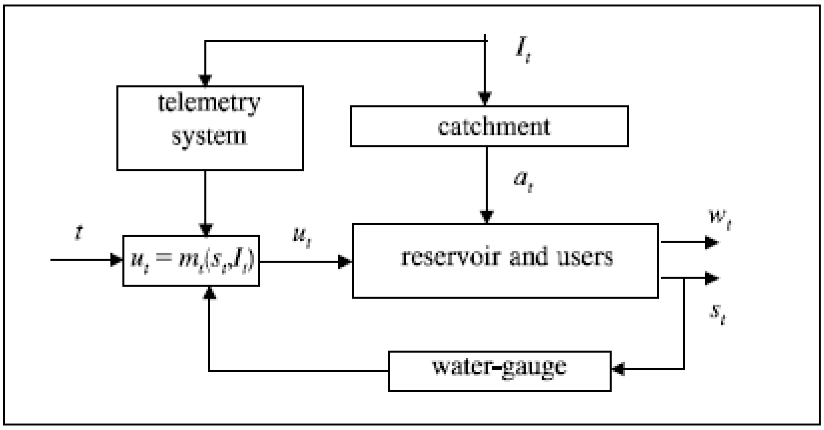


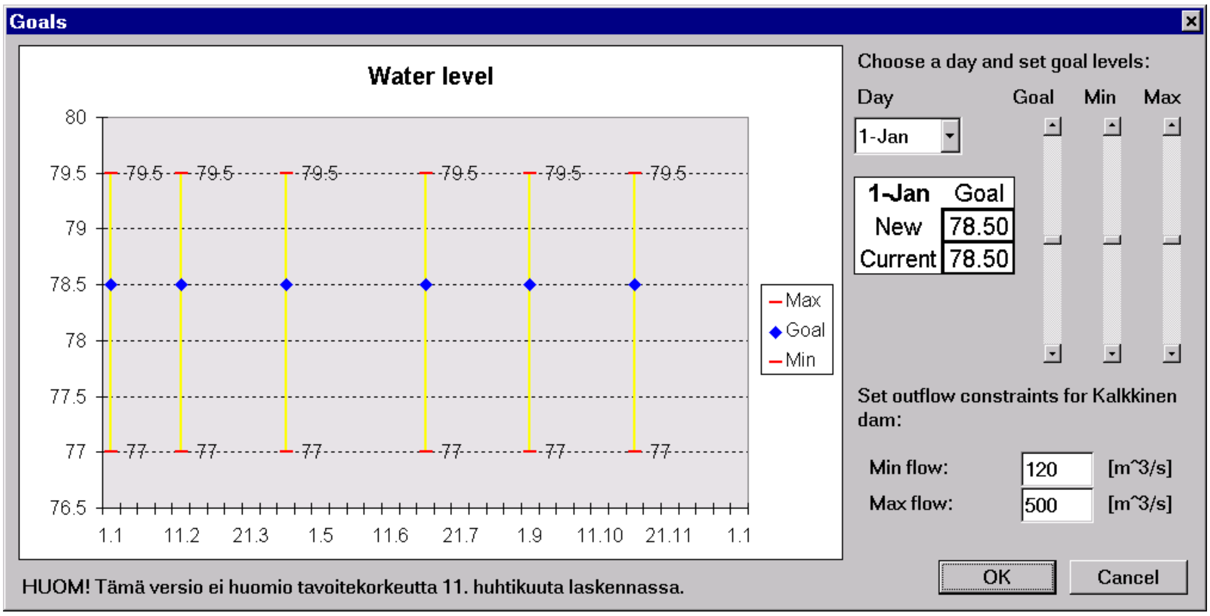
Figure 2.6 Closed loop scheme with feed forward compensation (Soncini-Sessa *et al.*, 2001).

In place of the telemetry system, a forecasting model (at an appropriate time step) could be used for many reservoir operation decisions. By proceeding in this way, a sequence of controls is determined which are not fixed *a priori* but are established during the life of the system (*Adaptive Control*) and is referred to as an *Online Policy*. Feedback approaches have been applied in past studies having a similarity to the research problem outlined under this study by, for example, Su and Deininger (1972, 1974), Alarcon and Marks (1979), Loaiciga and Marino (1985), Kitanidis and Foufoula-Georgiou (1987), Stedinger *et al*. (1984), Bras *et al*. (1983) and Kelman *et al*. (1990). Current application of such feedback approaches to real world case studies are extensively documented by Soncini-Sessa *et al*. (2007b) and Nandalal and Borgadi (2007). Hydrological forecasting models are an important component of real-time reservoir operation. To underline this importance, Yang *et al*. (1995) recommended that forecasting and decision making should be construed as single unit, implying that the linkage between the hydrological forecast model and the operational method should be as strong as possible.

2.4 Decision Support Systems based operation of reservoirs

External influences such as required for IWRM result in the shift from optimisation of reservoirs as independent units to consideration of the whole basin, while taking into account the interest of all involved stakeholders (World Commission on Dams, 2000) implies that policy design should be based on estimates of the effects of operating policies for each of the stakeholders involved. In practice, individuals often do not know what questions they want answers for before some exploration and comprehension of the impacts of some of their ideas for plans and policies (Loucks *et al*., 1985). The outcome of this exploration often leads to new questions and the need for additional exploration.

Over the past decade, applications of Multi-Objective Decision Support Systems (MODSS) have been documented in the literature as a new holistic approach to take decisions in a way that is coherent with the requirements of IWRM. A Decision Support Systems (DSS) is broadly defined by Booty *et al*. (2001) as a specific decision information system that integrates a hierarchy of tools which are seamlessly linked to one another in a single system and are used, for example, for real-time monitoring, database, modelling, visualization and management scenario analysis. Several other researchers such as Loucks *et al*. (1985) and Simonovic (1996) offer slightly varying definitions but essentially emphasize the importance of a built-in capability in a DSS that allows decision makers to combine personal judgment with computer output, in a user–machine interface in order to produce meaningful information for support in a decision making process. Examples of application of MODSS to develop regulation policies have been widely reported in regulated river-lake systems mainly in Finland and Italy. For example, Hämäläinen *et al.* (1999) report on the testing of an approach for multi-criteria modelling and support of multi-stakeholder decision making in the development of a new water level management policy for a regulated lake-river system known as Päijänne-Kyimijoki in Finland. Alternatives for the regulation policy were generated using DSS software known as ISMO (Hämäläinen and Mantysaari 1998a, 1998b, 2001). In this software, the decision variables, which are used to define the regulation policy alternatives, are target water levels at different times of the year (Figure 2.7).



Choose a day and set goal levels:

Day: 1-Jan

1-Jan	Goal
New	78.50
Current	78.50

Set outflow constraints for Kalkkinen dam:

Min flow: 120 [m^3/s]

Max flow: 500 [m^3/s]

HUOM! Tämä versio ei huomio tavoitekorkeutta 11. huhtikuuta laskennassa.

Figure 2.7 Setting of goal points and acceptability levels in the ISMO spreadsheet program (Hämäläinen and Mantysaari, 2001).

Hämäläinen and Mantysaari (1998a, 1998b) demonstrated that regulation can be attained by formulating a dynamic multi-criteria problem which minimizes deviations from set goals for given inflow data over the planning period. In ISMO, inflow forecast to the system is updated periodically resulting in a series of dynamic rolling horizon goal programming problems that are solved in an EXCEL spreadsheet with a graphical user interface. In order to have meaningful connections between values and criteria decision levels, Hämäläinen *et al.* (1999) proposed that analytical value functions, for example an impact model expressing target water levels in terms of annual flood damages, power generation, vegetation loss, be constructed to facilitate stakeholders to express their preferences over different regulation policy alternatives. In that way the socio-economic and ecological impacts of selected regulation policies were tested using a simulation model of the river-lake system.

Similarly, Marttunen and Suomalainen (2006) document experiences and lessons learnt through a process of reviewing regulation policies for a system of four interconnected lakes and a river course within the watershed of Kokemäenjoki River in Finland. The existing regulation policy for the lakes prior to the review process was designed to minimize flooding around lake-shores and maximize hydropower production during the winter period when tariffs were highest.

Castelletti *et al*. (2004) document the application of a DSS to resolve conflicting objectives in the utilization of Lake Verbano, located on the Swiss-Italian border, as a multipurpose reservoir. A Multi-Objective DSS known as *TwoLe* (Soncini-Sessa *et al*., 1990, 1999, 2007b) was used to support stakeholders involvement in the decision making process. *TwoLe* is designed for a two tier decision making level i.e. one for Planning (P) and another for Management (M).

The separation of roles in *TwoLe* is designed to make it attractive to use by water agencies where policies are designed at planning level and decisions taken at the management level, thus allowing the decision makers to have an active part in planning the policies embedded in the DSS. The planning module, *DSS/P* deals with the choice of alternatives and its outputs are planning decisions, management policies and models. All of these constitute inputs to the management module, *DSS/M*. The interaction among the Systems Analyst (SA), the Decision Maker (DM) and stakeholders takes place in the *DSS/P* at the planning level and in the *DSS/M* at the management level. This scheme is illustrated in Figure 2.8.

Dynamic programming algorithms were utilised as the optimisation tools at the planning level as described in Orlorvski *et al*. (1983, 1984), Guariso *et al*. (1984), Piccardi and Soncini-Sessa (1991), Nardini *et al*. (1992) and Aufiero *et al.* (1995, 2001, 2002). These algorithms were constructed and applied to facilitate stakeholders to generate a diverse range of alternatives. *TwoLe's* architecture allowed a rapid prototyping of various modelling situations both at planning and at management levels via a user friendly interface (Soncin-Sessa *et al*., 1999, 2007b). The Decision Maker was facilitated to use the *DSS/M* to produce forecasts, compute the daily release decision and simulate the effects of a release decision in the short term.

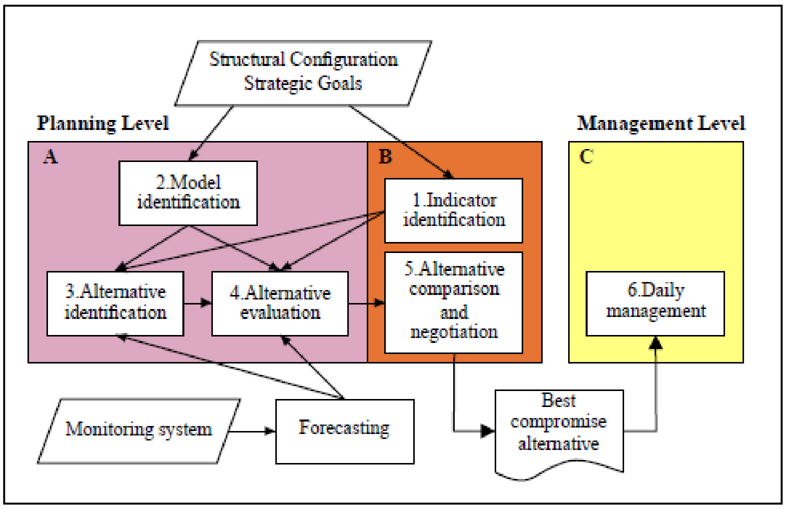


Figure 2.8 Phases of the two level decision process (Soncini-Sessa *et al.*, 2002).

2.5 Previous regulation studies in the Equatorial Lake Basin

The possibility of using Lake Victoria to regulate flows in the Victoria and Kyoga Nile for the benefit of riparian states has been considered on many occasions. Kite (1984) summarises investigations made in the regulation of the Equatorial Lakes. Initial studies were undertaken in the late 1940s at the time of planning Nalubaale Dam development. Further studies were undertaken in 1958 and 1960 by a technical consultant to the Egyptian Ministry of Irrigation (Bakhiet, 1996) and later, by the Uganda Water Development Department in 1968 (WMO, 1974), the Egyptian Organisation for the Nile Waters in 1972 and as part of the Hydro-Meteorological (HYDROMET) survey project of the catchments of Lakes Victoria, Kyoga and Albert in the mid-1970s (WMO, 1974). This project established the first hydro-meteorological instrumentation network for the Equatorial Lake basin and processed hydrological and meteorological data during the period 1975-1981. Individual and system wide patterns of lake regulation were proposed and studied with the help of the Upper Nile Catchment Model, (Nemec and Kite, 1979). According to WMO (1982), proposed regulation of the Equatorial Lakes was intended to achieve the following objectives;

(i) to maximise power output at Owen Falls dam,
(ii) to maximise power potential in the Kyoga Nile,
(iii) to meet foreseeable water resource requirements of riparian countries of the Upper Nile Basin and to minimise the negative impacts on people utilizing the riparian ecosystems of the Equatorial Lakes Basin (Nemec and Kite 1979; Kite, 1984).

All the conceived regulation plans involved setting discharge criteria within different zones in each of the Lakes. These plans lacked economic and environmental data, but a set of computer programs were written so that economic information could be included when the necessary data became available. Following completion of this project in 1982, it was recommended that:

(i) Historical regulations plans should be considered for application or developed further to include, for example, studies of economic and environmental aspects.

(ii) Consideration be given to modification of the mathematical model to incorporate optimisation routines.

More recent studies have considered regulation of Lake Victoria as a means to enhance hydropower production (Acres, 1990; Mott MacDonald, 1998; WREM Inc & Norplan Ltd, 2004). Simulation models are now available through which the impacts of alternative regulation rules on hydropower production can be assessed. These models represent Lake Victoria, Lake Kyoga and Lake Albert, and include provision for the calculation of hydropower production at Owen Falls and at other potential downstream sites. All models are driven by historical net basin supplies to each of the three lakes, and were run using historical data from 1899 to 1997 (Mott MacDonald, 1998; Wardlaw *et al.*, 2005). Outputs from these models include time series of simulated levels and discharges from each of the three lakes, and time series of potential power production at each hydropower installation. The time step of the models is monthly. The impact of any other consumptive uses of water and constraints on environmental flow on forecasted hydropower production are not explicitly taken into account in the simulations. For example, LVDST (WREM Inc & Norplan (U) Ltd, 2004) includes four modelling layers, three of which pertain to operational planning and management of the Hydropower facilities at Kiira and Nalubaale and a fourth to assessment. Figure 2.9 illustrates the LVDST design concept.

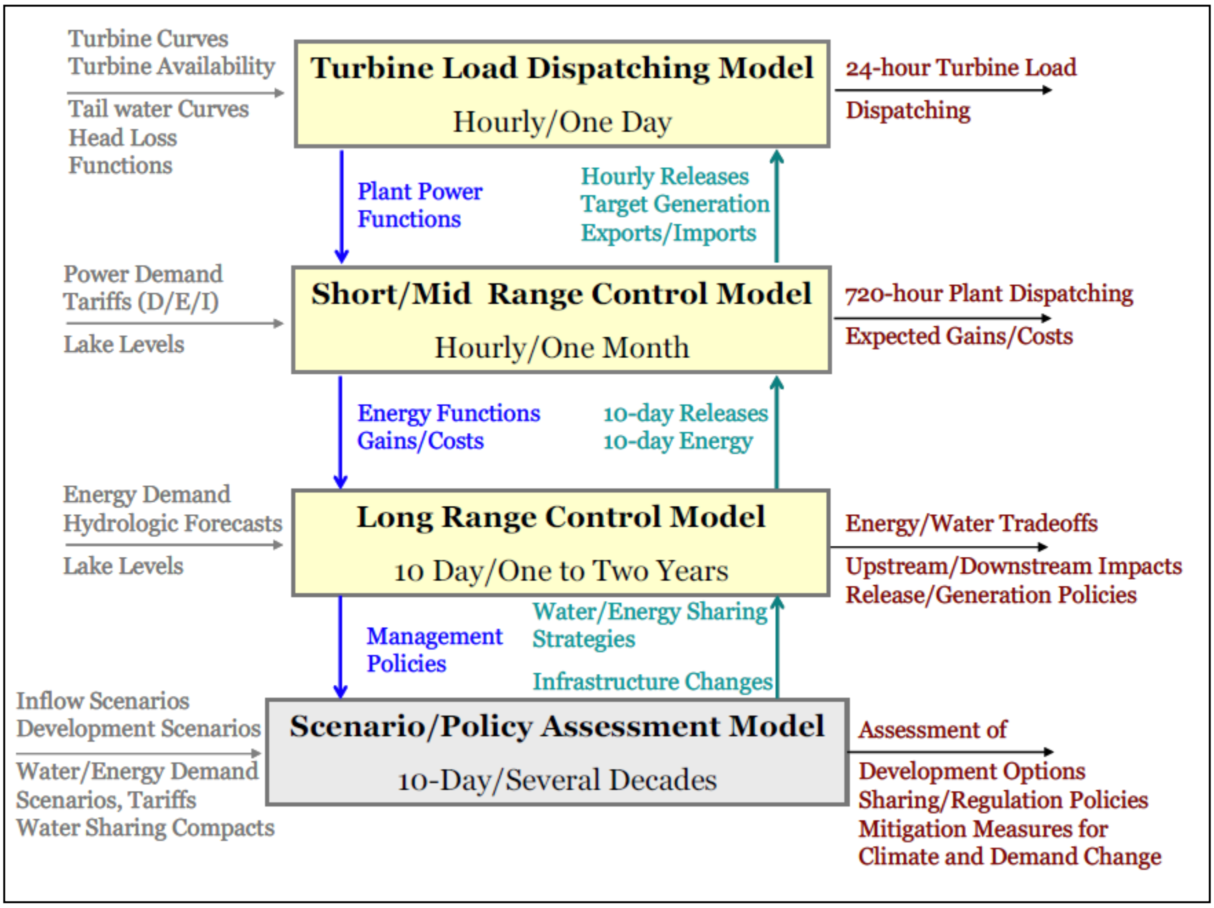


Figure 2.9 LVDST design concept (WREM Inc & Norplan (U) Ltd, 2004).

The turbine load dispatching model identifies the most efficient turbine operation that meets a certain power target. The short/mid-range model considers the integrated operation of power plants over a horizon of one month while the long range planning model prescribes the release targets to be utilised by the first two models and derives the benefits accruing to power and assess impact on the Sudd wetlands in Sudan on ED release policies or Agreed Curve (AC) policies.

The long range control model utilizes hydrologic and demand forecasts with a 10 day resolution and quantifies tradeoffs through a process of setting storage, release and energy targets. More specifically, in its application, storage targets can be used to maintain high lake levels while release targets are used to implement the Agreed Curve. Energy targets are used to satisfy a desirable energy generation sequence, such as a projected energy demand. In the case of the Equatorial Lakes, the tradeoffs that can be derived by the LVDST are energy generation vs. lake level or energy generation vs. releases. LVDST applies the Extended Linear Quadratic Gaussian (ELQG) control method (Georgakakos, 1989) to identify the release sequences for all reservoirs such that system objectives and constraints are met successfully. Extended Linear Quadratic Gaussian (ELQG) control is a stochastic real time reservoir control method with both open-loop and feedback features. The feedback element results from ELQG's sequential character, suggesting controls which depend on the current system conditions. However, at each decision time these controls are obtained from an open-loop solution process. The focus is more on management at daily, monthly or annual management rather than formulation of long range guide curves. However, the solution process is computationally very efficient since the solution process involves no discretizations.

A similar initiative under the Nile Decision Support Tool (Nile DST) developed a river simulation and management model of the Equatorial Lake Basin capable of simulating the flow of water through the various system nodes, reaches, and lake reservoirs (Georgakakos and Yao, 2003). In it, two types of single reservoir regulation rules are included:

(i) Simple static rules, for example releases are governed by the ‘’Agreed Curve” for Lake Victoria and the natural unregulated outflow-lake level relationships for Lakes Kyoga and Albert.

(ii) Simplified release-elevation rule curves that divide lake elevations into three zones as shown in Figure 2.10: Zone 1 ($H_{min} – H_1$), Zone 2 ($H_1 – H_2$) and Zone 3 ($H_2 – H_{max}$). If the elevation is in Zone 2, the release equals a constant Q_0; if the elevation is in Zone 1, the release decreases linearly slides to a minimum value; and if the elevation is in Zone 3, the release increases linearly to a maximum value. The boundaries of the zones, the constant value Q_0, and the minimum and the maximum values are all user specifiable.

(iii) Simple coordination built upon the single release rule but aimed at keeping the reservoirs fluctuating uniformly.

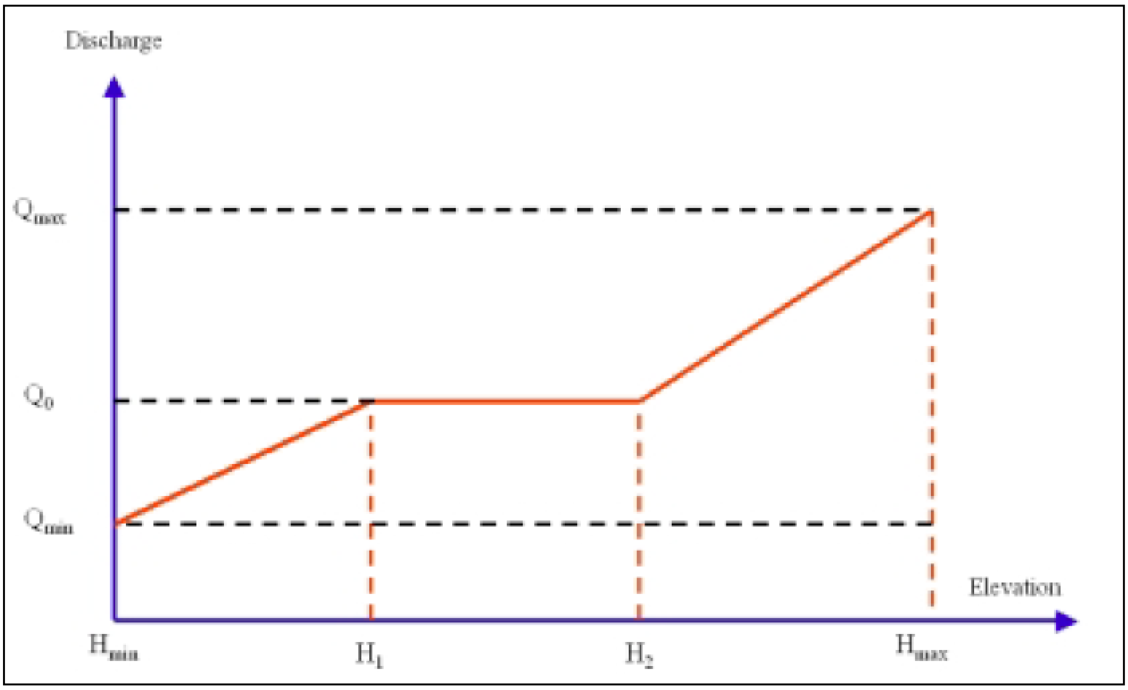


Figure 2.10 Simplified release-elevation rule curve (Georgakakos and Yao, 2003).

However, it is interesting to note that in over 50 years, no progress has been made towards implementing any of the identified plans (Wardlaw *et al.*, 2005). It could be argued that the lack of a consultative basin wide framework to support the consideration and adoption of new regulation strategies has impeded progress.

Within the framework of the regulation studies under HYDROMET, the potential for utilisation of Lake Albert as a reservoir had been considered over many years (Hurst and Phillips, 1938) on the basis that the relatively steep shores make it more suitable than Lake Victoria for intra-year storage to control the supply of water to Egypt. The effect of flooding around Lake Albert was studied in 1956 to assist Uganda in possible negotiations (Sutcliffe *et al.*, 1957) and also as one component of control for the Nile under the HYDROMET Project (WMO, 1982). The completion of the High Aswan Dam has since satisfied Egypt's storage requirements but it may be useful to reconsider historical regulation plans in a manner that reconciles the need for Uganda to optimize the hydroelectric potential of the Nile below Lake Victoria, and to take into account the interests of other riparian countries that share Lake Victoria.

3. METHODOLOGY

In the preceding chapter, a review of approaches to reservoir operation indicated that the most promising approach for deriving reservoir operating rules for the case study would involve the application of a MODSS. The literature revealed that such a MODSS must contain several modules that perform different but complementary functions. Labadie (2004), specifically identified these modules as a deterministic and stochastic optimisation model, a stochastic stream flow generation model, regression tools, a simulation model and a supporting database with a good user interface.

A review of past initiatives in the Upper Nile Basin confirmed that various simulation models capable of evaluating the impact of alternative operating rules to hydropower generation are available. Therefore a core element of the methodology that was adopted for the research was to assemble, adapt and customise a suitable MODSS from several existing contemporary components and then determine how to apply and link the models in order to derive the operation rules. This chapter contains a discussion of the methodologies utilised and applied to design regulation policies for the Equatorial Lakes.

3.1 Preparation of basic data for the study

Various types of data are required to derive regulation alternatives. These include system data for the power plants, and components of water balance which represent the lake tributary inflows, rainfall, evaporation losses and abstractions. System characteristics are readily available and were extracted from existing decision support tools such as LVDST (WREM Inc & Norplan (U) Ltd, 2004) and Nile DST (Georgakakos and Yao, 2003). However, acquisition and utilization of components of the water balance of the lakes required water balance modelling to understand the system dynamics over a common period for each lake-reservoir.

Two approaches to estimating the water balance can be considered. One is a direct modelling technique where each individual component of the water balance is presented, such as performed by Sene (2000). This approach was not selected in this study due to the difficulty of accurately determining each component over a relatively long common time period for each lake. The difficulty is a consequence of either the lack of concurrent hydro-meteorological data in each of the constituent sub-basins or the lack of sufficient data necessary to derive the components to a realistic level of accuracy in any of the basins at a given time period of analysis. The available time series data that represent the various components of the water balance equation for each lake, as derived from literature, are presented in Chapter 4. The difficulties associated with this approach are discussed and a justification is presented as to why an alternative approach which utilises a concurrent period of lake levels and measured outflows along the Victoria, Kyoga and Albert Nile was favoured. In Chapter 4, it is shown that the record of lake levels and outflows are available over a longer period than the records of rainfall, tributary inflows and evaporation for all the lake-reservoirs.

3.2 Application of the Equatorial Lake Model and analysis of stationarity of derived net lake-reservoir inflows

The Equatorial Lake Model (Mott MacDonald, 1998), adapted from the Hydrologic Model of the Upper Nile Equatorial Lake Basin (Nemec and Kite, 1979) was applied to compute the net inflows or net basin supply time series to each lake reservoir in each month for a given common time period of analysis utilizing the end of period lake levels, observed outflows and lake characteristic curves as the input data. The Equatorial Lake model is essentially a water balance of the lakes accounting for net inflows, measured outflows and change in storage with provision for application of various operational rules and it is therefore capable of simulating the hydrologic regime of the Upper Nile Basin. A detailed description of the method of application and results obtained showing the comparison in terms of verification of reproducing observed and measured lake levels is presented separately in Chapter 5.

In the area of stochastic hydrology and water resources systems analysis, investigation of the stationarity of the historical net basin supply time series is important in modelling studies designed to generate synthetic net basin supplies that are often utilised to either design or evaluate alternative reservoir operating rules. The historical net basin time series was examined for stationarity by applying a segmentation algorithm (Hubert, *et al.*, 1989) so as to partition the original non stationary time series into several stationary segments whose means are significantly different from each other by means of a statistical test referred to as the Scheffe test of contrast (Scheffe, 1959). Each of the resulting homogeneous segments constitutes a contiguous block of data, where the goodness of segmentation is evaluated by the sum squared deviation of the data from the means of the respective segments.

3.3 Statistical analysis of the data and stochastic modelling

The historical net basin supply time series was analysed to determine their underlying statistical characteristics by application of a suitable statistical modelling and simulation software. The statistical properties of the net basin supplies are required to formulate the nature of the Stochastic Dynamic Programming (SDP) algorithm and also to determine the most appropriate form of the model to generate synthetic net basin supplies for the case study. The Stochastic Analysis Modelling and Simulation (SAMS) software (Sveinsson *et al.*, 2007), was adopted to study the statistical properties of the inflows, determine whether they can be reasonably be assumed to follow a 1st order Markovian process and generate appropriate synthetic series. The SAMS model is preferred as it is essentially an improved version of the LAST software package (Lane and Frevert, 1990) developed in 1977-1979 by the United States Bureau of Reclamation. The LAST software package has been widely applied in stochastic analysis and synthetic generation of reservoir inflows for purposes of simulating reservoir operation by, for example, Harboe and Ratnayake (1993).

SAMS is particularly attractive for application to this case study as it is capable of generating non stationary time series and analyzing complex river basin systems. SAMS is written in the C++ programming language and runs under the Windows operating systems.

3.4 Selection of the Dynamic Programming optimisation algorithms

Dynamic programming, (DP) has been one of the most popular techniques applied to water resources planning and management in general, and reservoir operations in particular (Yakowitz, 1982; Rani and Moreira, 2010). Yeh (1985) attributes the success and popularity of DP to its capability to support non-linear and stochastic features that characterize water resources systems and it has an additional advantage of effectively decomposing highly complex problems with a large number of variables into a series of sub-problems, which are solved recursively over each stage. As originally developed in its general form by Bellman (1957), DP is a procedure for optimising a multi-stage process (Bertsekas, 2005; Bertsekas, 2007). This property enables DP to effectively exploit the sequential decision structure of reservoir systems optimisation problems.

Application of DP to reservoir operation in this case study was explored in the deterministic context with algorithms that have continuously been refined to enable their application to systems of multiple reservoirs (e.g. Larson, 1968; Hall *et al*., 1969; Heidari *et al*., 1971; Mousavi and Karamouz, 2003) and broadly classified as IDP by Nopmongcol and Askew (1976). Computational aspects of IDP related to ease of convergence to an optimal solution have been improved though successive approximations and termed as Incremental Dynamic Programming with Successive Approximations (IDPSA) (Trott and Yeh, 1973; Giles and Wunderlick, 1981; Yakowitz, 1983).

Application of Stochastic Dynamic Programming (SDP) models is the second option selected to define probabilistic rules. Solution algorithms for SDP adopted are those that have been applied to regulate large lakes (Su and Deininger, 1974), optimize multiple reservoir systems (Ratnayake and Harboe, 2007) and determine trade-offs for operation of large dams such as the High Aswan Dam on the Nile (Oven-Thompson *et al*., 1982). These algorithms derive stationary policies based on two state variables, namely the storage and the previous periods' inflow. In all DP models, the storage and inflow is discretized. The requirement to discretize the state space in SDP involves considerable computational difficulties when extended to multi-reservoir and multi-purpose applications. For a multi-reservoir model with k state variables and N discrete levels of each state variable, on line storage requirements for the class of SDP algorithms are proportional to N^k (Tejada-Guibert *et al*., 1993). This problem was named the "curse of dimensionality" by Bellman (Bellman, 1957; Bertsekas, 2007; Nandalal and Borgadi, 2007; Powell; 2011) and it prevented the application of the SDP methodology to real world water systems consisting of more than two or three reservoirs. To circumvent these difficulties, the decomposition algorithm suggested by Nandalal and Sakthivadivel (2002) could be considered. Their approach is a decomposition method that optimises the reservoirs sequentially so as to alleviate the dimensionality problems of large scale reservoir analysis but tends to reach a local rather than global optimum.

A generalized dynamic programming software package known as Colorado State University Dynamic Programming (CSUDP) model (Labadie, 2003) is readily available and was utilised to facilitate the application of the proposed dynamic programming algorithms for the optimisation process. CSUDP supports the method of Incremental Dynamic Programming IDP and SDP by the method of successive approximation. The current version of the software is written in the C Programming language, with incorporation of a Windows interface written in

Visual Basic. CSUDP has been applied elsewhere to solve reservoir operation problems e.g. Allen and Bridgeman (1986), Labadie (1993), Abdelkader *et al.* (1994), Jaeeung *et al.* (2003), Labadie *et al.* (2007) and Räsänen *et al.* (2012).

3.5 Identification of efficient reservoir operating rules

The beneficial and adverse effects of a regulation project are not all commensurable and may therefore be difficult to combine into a single objective. To have a clear definition of optimality in such situations, solutions to non-commensurable multi-objective problems are classified as either 'inferior' or 'non-inferior', (Vemuri, 1974; Cohon and Marks, 1973; Haimes *et al.*, 1975). Roughly defined, an inferior solution to a maximisation problem is one that has an objective whose level of attainment is increased without necessitating a decrease in the level of attainment of any other objective. Conversely, a non-inferior solution is one where no objective's level of attainment can be increased without another objective's attainment level decreasing. Figure 3.1 illustrates the various terminologies associated with multi-objective optimisation. In this case, the problem considered is the minimisation of a function with two objective, f_l and f_2, i.e. max (f_1, f_2), subject to a constraint set in the decision space that defines the feasible and infeasible regions. The non-inferior solution set is a sub-set of the feasible region and it can alternatively be referred to as the set of non-dominated solutions.

The method of generating non dominated solutions for large scale multi-reservoir operation through application of constraints on allowable releases and storage targets was applied in this study since it has been shown to be superior over other approaches, such as the weighting method (Cohon and Marks (1975); Ko *et al.*, 1992). This approach is suitable for generating non-dominated solutions for a reservoir where the number of objectives and constraints is small in order to avoid prohibitive dimensionality (Tauxe *et al.*, 1979a, 1979b; Georgakakos, 1993). Objectives other than the primary objective were treated as constraints. By varying the minimum acceptable levels of the secondary objectives a set of trade-offs may be generated between all of the objectives. The hierarchy of primary and secondary objectives were defined in a participatory stakeholder consultative process (Zaake and McCartney, 2008).

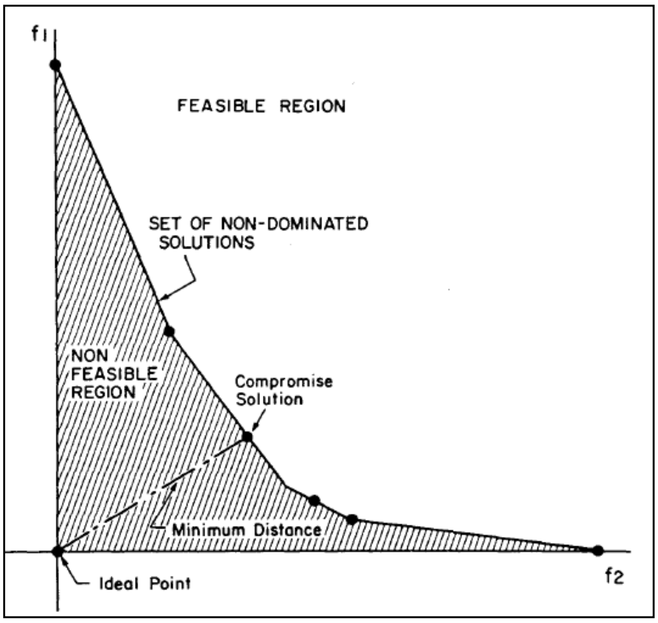


Figure 3.1 Search for pareto-optimal solutions (Duckstein and Opricovic, 1980).

Since it is acknowledged that it is not possible to consider all the relevant management objectives within the scope of a single study, the objective was to define operating rules that are only a plausible alternative but not a compromise solution. In this case, a primary objective of maximising expected energy generation was investigated subject to satisfying historically observed minimum and maximum lake levels and outflows. Secondary objectives such as flood control around the lake shorelines, limiting the range of lake level variation to support navigation and water related infrastructure, minimum flows to support freshwater ecosystems etc., were taken care of within the imposed constraints. The consumptive water demands for other sectors such as ecosystems, irrigation, and domestic water supply were indirectly accounted for through the utilization of net inflows or net basin supplies to each lake reservoir. The process of searching for efficient lake-reservoir operating rules was supported by application of the LVDST, Equatorial Lake Model, SAMS and CSUDP in a complimentary fashion where output from one or more models is utilised by another in a hierarchy illustrated by the flow diagrams shown in Figure 3.2 and 3.3. The method for deriving deterministic operating rules is shown in Figure 3.2. Similarly Figure 3.3 illustrates a slightly different method used for deriving stochastic operation rules.

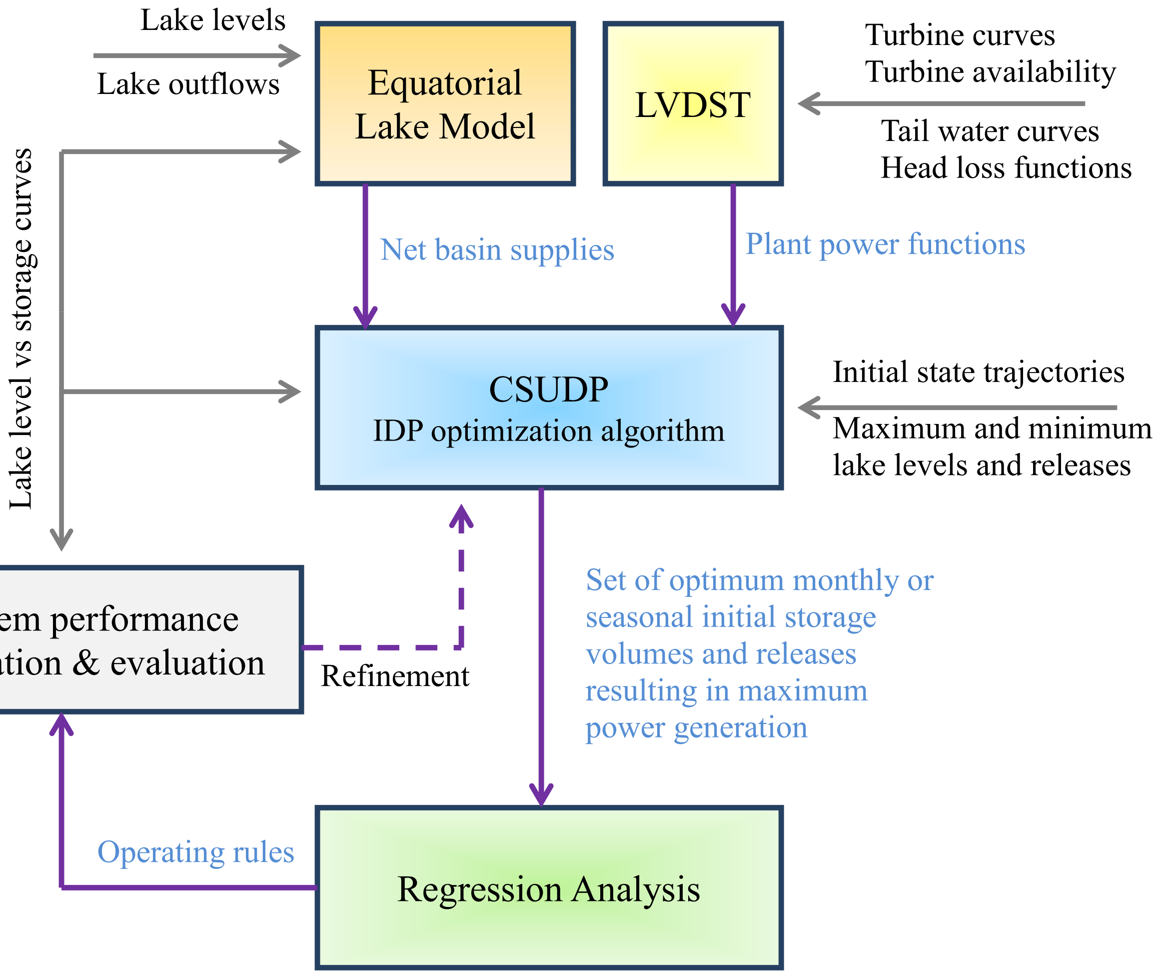


Figure 3.2 Deterministic derivation of operation rules for the case study.

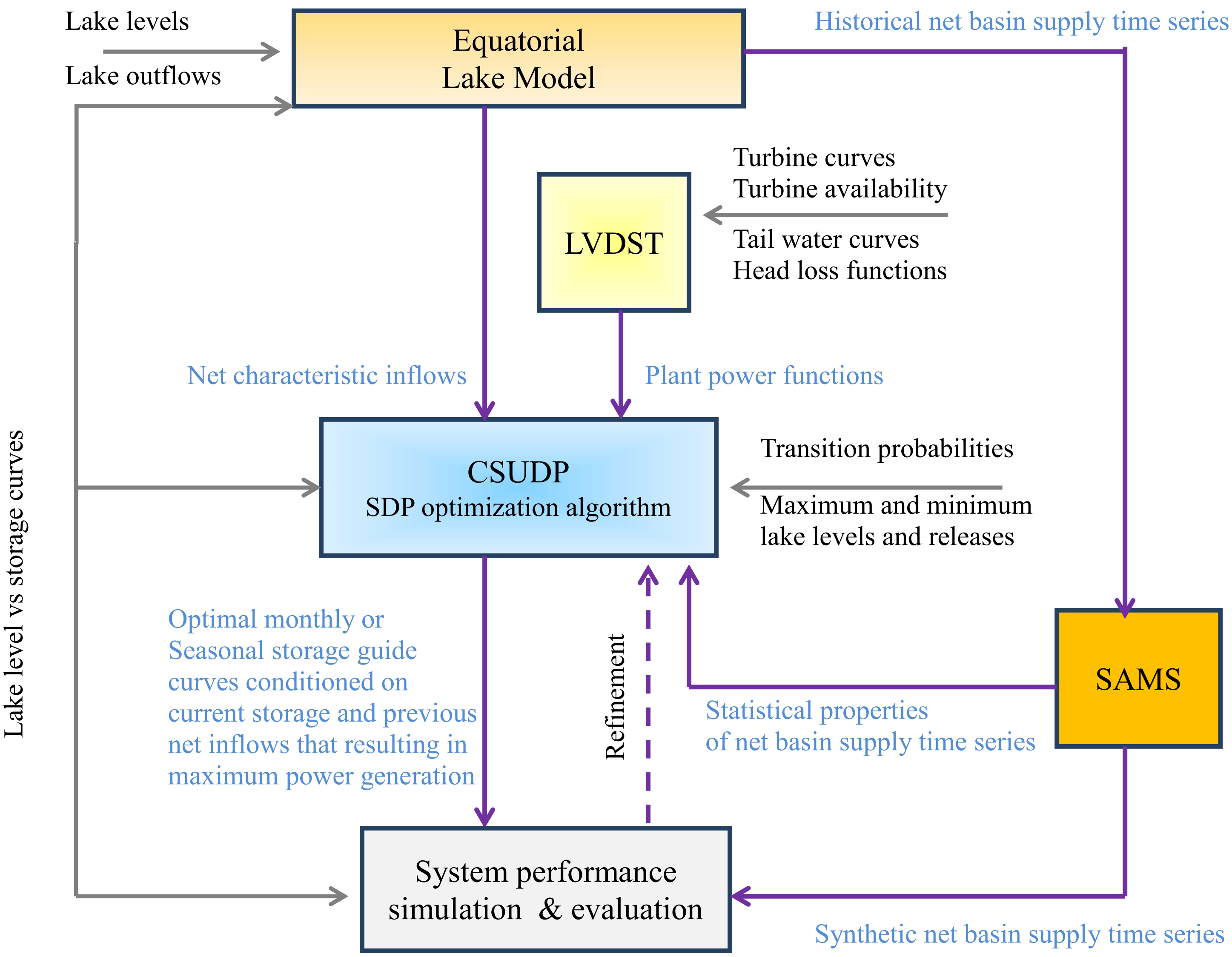


Figure 3.3 Stochastic derivation of operation rules for the case study.

In Figures 3.2 and 3.3 the basic data input to the Equatorial Lake Model are lake levels, outflows and lake level vs. storage curves. The output from the Equatorial Lake Model are the net basin supply time series. The LVDST yields optimum plant power functions based on plant characteristic input data. In both cases, operating rules are prescribed with the support of the generalised dynamic programming tool i.e. CSUDP. The method of utilisation of statistical features of the net basin supply in CSUDP is described in detail in Chapter 8. The prescribed operating rules are associated with a certain level of performance of the system. Evaluation of the performance of the system is discussed in the next section.

3.6 Evaluation of the defined operating rules

Once a non-dominated set of reservoir operating rules had been obtained, they were evaluated for purposes of determining whether they are superior to the historical performance of the system and for providing an assessment of their economic benefits in terms of total expected hydropower generation. This evaluation has been carried out by comparing their effect on lake levels against the Agreed Curve. Rules can be refined based on extensive simulation with historical or generated net basin supply sequences. The refinement process can be iterative.

Having described the methodology to be applied to the case study, the preparation of data that is to be utilised for analysis within the framework of the proposed methodology is discussed in the next chapter.

4. COMPILATION OF DATA FOR THE CASE STUDY

The focus of this chapter is to review previous studies on estimating the water budgets of the Equatorial Lakes of the Upper Nile Basin, and analyze all data available with a view to determine the nature and adequacy of data and to assess how to best to compile and utilise the data within the proposed methodological framework for the study.

4.1 General climate of the Equatorial Lake Basin

The climate within the Equatorial Lake Basin is of a tropical nature. It is highly influenced by the Inter-tropical Convergence Zone (ITCZ), a phenomena caused by the convergence of northwest and southwest trade winds near the equator. This effect within the basin is to cause two rainy seasons each year in the months March to May and October to November. Annual spatial variability of rainfall (Figure 4.1) generally varies between 500 mm and 2500 mm while maximum daily temperatures range from 15^0C to 30^0C.

The spatial patterns of annual rainfall variation within the Equatorial Lake Basin have been attributed to the interaction between orographic and thermodynamic effects (Nicholson and Yin, 2002; Anya and Semazzi, 2004). The orographic effects are induced by the flow of wind currents over the Rwenzori mountain ranges to the West of Lake Victoria, the Kenya Highlands in the East and the Mt Elgon mountain ranges to the North East. Thermodynamic effects are attributed to humid Westerly and South Westerly moving winds across Lake Victoria that significantly boost convection and enhance the deposition of rainfall over the Western and North Western parts of Lake Victoria (Nicholson 1996).

The El Niño Southern Oscillation (ENSO) global phenomena exerts an influence on the inter annual and seasonal variability of rainfall in the region. ENSO exerts this influence as a result of the periodic oscillation of sea surface temperature, atmospheric pressure and rainfall on the eastern and western coasts of the Pacific Ocean coast. ENSO is characterized by two different phases known as El Niño and La Nina.

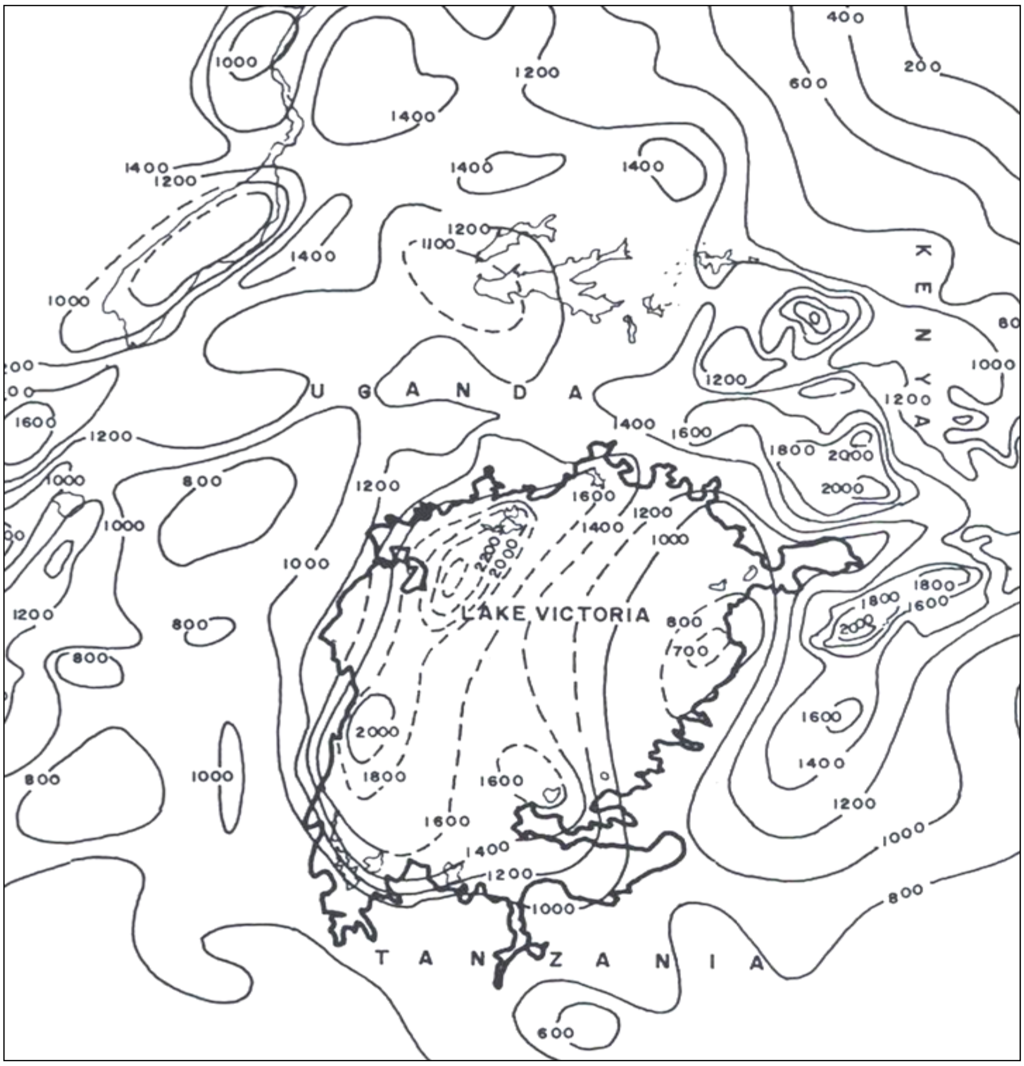


Figure 4.1 Annual rainfall (mm) over the Equatorial Lake Basin (Asnani, 2009).

El Niño episodes of ENSO are usually associated with above normal rainfall amounts between October and April in the region (Wardlaw *et al.* 2007; Indeje *et al.* 2000; Ntale and Gan, 2004). Episodes of El Niño have been shown to occur every 3 – 5 years. Other studies have assessed the temporal variability of rainfall in the region on seasonal and annual time scales (Kizza *et al.*, 2009) and noted that over the twentieth century, rainfall over Lake Victoria experienced a predominantly positive change.

4.2 Drainage system and key long term monitoring stations

Figure 4.2 shows the locations of the long term lake level and flow monitoring stations in the Semliki sub-basin The figure also indicates the major tributaries in the drainage network and the locations of the major towns. Table 4.1 lists the lake surface areas of all the major lakes in the basin and the adjoining catchment areas that they drain. The figures are compiled from WMO (1974).

Table 4.1 Basin area statistics

Sub-basin	Lake Surface Area (km^2)	Adjoining Catchment area (km^2)
Victoria	68800	184000
Kyoga	6270	57669
Albert	5300	40576

Lake Kyoga is a relatively shallow lake surrounded by extensive wetlands. The net effect of Lake Kyoga is to cause a delay of outflow due to lake storage of approximately one month (Sutcliffe and Parks, 1999). Outflow from Lake Victoria is therefore modified as it flows through Lake Kyoga.

Natural outflow from Lake Kyoga to Lake Albert is through the Kyoga Nile while the stretch of the river flowing out of Lake Albert to Nimule in Sudan is known as the Albert Nile Figure 4.2). The adjoining catchment area to Lake Albert is shared between Uganda and the Democratic Republic of Congo (DRC) and it includes Lake Edward and Lake George. Lake George is connected to Lake Edward through the Kazinga Channel. The combined surface area of lakes Edward and George is 2,590 km^2 and they drain a total area of 26,828 km^2 measured from the outlet of Lake Edward at Ishango. Outflow from Lake Edward to Lake Albert is through the Semliki River.

Table 4.2 contains a summary of the time periods during which lake levels and flows along the White Nile have been observed at the key locations. Other than Figure 4.2, additional supplementary figures showing the locations of the key stations in the other sub-basins are to be found in latter sections of the chapter for ease of cross reference. Measurements at these key stations were initially made by the Physical Department of Egypt during the period 1904 to 1957 (Sutcliffe and Parks, 1999). Discharge measurements were established with the aid of cableways, and rating curves were derived to convert records of river stages to discharges. The data were published in successive volumes and supplements of the *Nile Basin* (Sutcliffe and Parks, 1999).

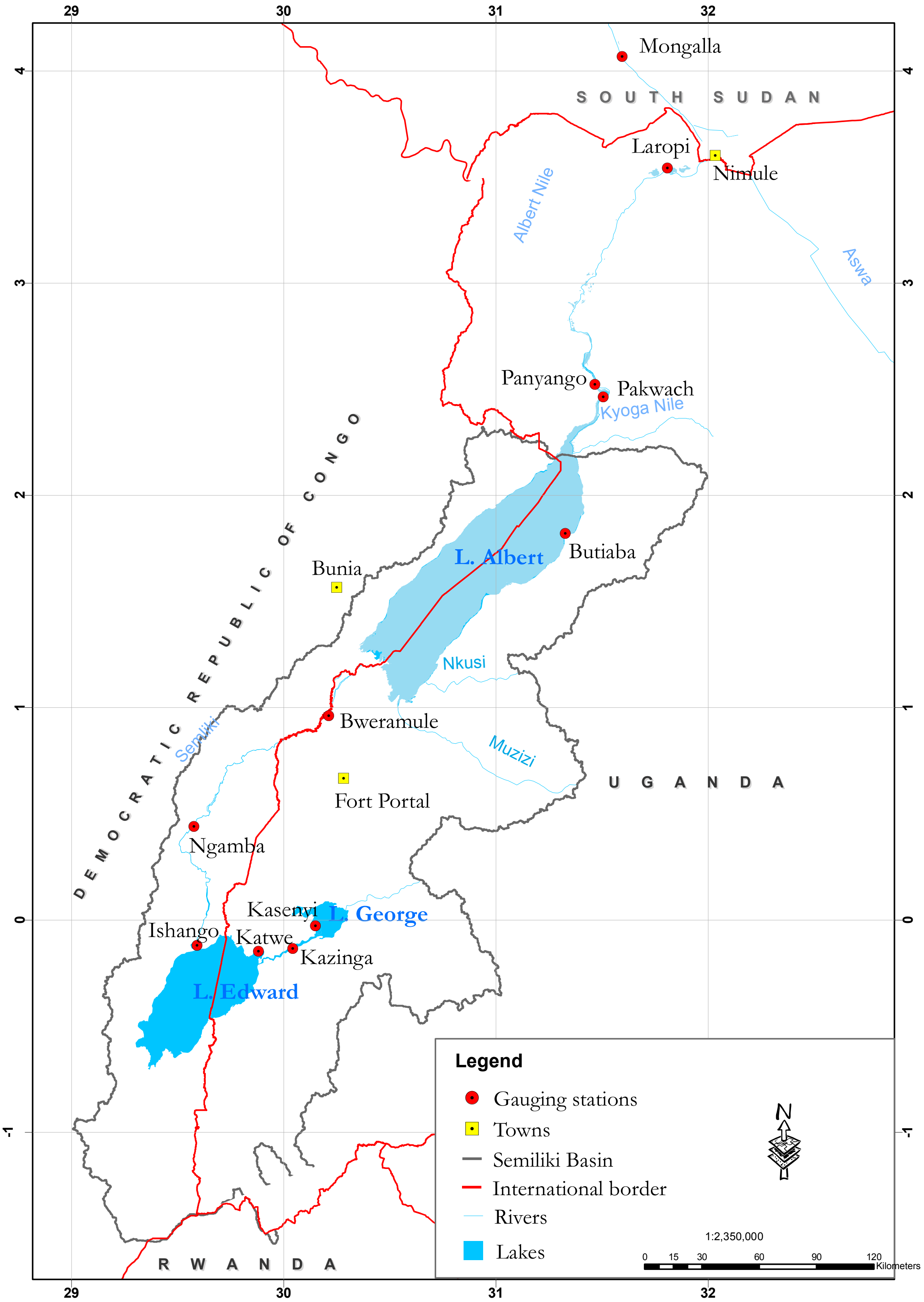


Figure 4.2 Long term lake levels and flow monitoring stations – Semliki basin.

Table 4.2 Summary of data available at key long term monitoring stations

Location	Nature of observations	Period of record available
Mongalla	Flow monitoring	1905 – 1983
Laropi		1958 – 1971; 2000 – to date
Panyango		1948 – 1978; 1996 – to date
Packwach		1956 – 1970
Paraa		1963 – 1971; 1979 – 1981; 1997 – to date
Kamdini		1940 – 1979; 1997 – to-date
Namasagali		1940 – 1952
Mbulamuti		1956 – to date
Rippon Falls		1896 – 1942
Bweramule		1940 – 1957
Ishango		1940 – 1957
Owen Falls		1954 – to date
Masindi Port	Flow and lake level monitoring	1912 – 1978; mid 1989 – to date
Butiaba	Lake level monitoring	1904 – to date
Katwe		1965 – 1978; 1998 to date
Kasenyi		1965 – 1978; 1998 to date
Katunguru		1942 – 1978
Bugondo		1948 – 1977; 1978; 1980; 1994, 1995 - todate
Kachung		1965 – 1977; 1981 – 1983; 1997 – 2002
Jinja		1913 – to date
Entebbe		1896, 1899 – to-date

From the historical monitoring records available it was established that only 30 % of the land area of the Lake Albert Basin is gauged (WMO, 1974). The entire area covered by the Semliki basin in the Democratic Republic of Congo also remains ungauged to date. Although the Semliki River contributes the second largest inflow to Lake Albert after the Kyoga Nile River, measurements along the Semliki River are only available for the period 1940 – 1978. Lack of representative long term tributary inflow data to Lake Albert, is identified as of the key constraints in the formulation of a consistent lake-reservoir modelling framework which is inclusive of the linkages between Lakes Albert and the Lake George-Edward system.

Although approximately 25 major rivers flow into Lake Victoria, the fraction of the gauged basin was below 40 % in 1956 until the implementation of the Hydro-meteorological Survey Project (WMO, 1974; 1982) between 1969 and 1978. This project increased the gauged area to about 80 % of the total basin area. After 1978, gauging declined drastically until the onset of the Lake Victoria Environmental Management Program (LVEMP) in 1998. Consequently, the time series of tributary inflows to Lake Victoria are riddled with many missing segments of data. The most reliable estimates of monthly inflows to the lake have been derived for the period 1925-1990 using measured flows wherever possible, with missing flows estimated using conceptual rainfall runoff models (Sene & Plinston, 1994).

Other data sets other than long term records of lake levels and outflows can be obtained. For example, a record of net annual rainfall over Lake Victoria has been published by Tate *et al.* (2004) for the period 1925 – 2000 and also extended for the period 1903 – 2006 by Kizza *et al.* (2009). Brown and Sutcliffe (2013) assembled a record of Lake Kyoga basin rainfall from a set of 22 stations selected to provide a reasonable coverage for the period 1902 – 1985. Sutcliffe & Parks (1999) have quantified rainfall over Lake Albert and presented the results as components of the monthly water balance for the period 1951- 1960 and 1966 – 1975. However, they conceded that the accuracy of the estimates is low since rainfall over Lake Albert was estimated based on observations at a single station at Butiaba. This illustrates the reality that concurrent estimates of net rainfall over the lakes are not available.

Rainfall in the Equatorial Lake basin has in the past, been monitored using manual rain gauges. However, station coverage has been steadily decreasing due to political instability in the riparian countries and due to lack of sufficient resources and appropriate institutional frameworks to consistently operate and maintain hydro-meteorological monitoring infrastructure (Sene and Fuquarson, 1998; Kizza *et al.*, 2009; Brown and Sutcliffe, 2013). There are large periods of missing rainfall data since the late 1970s to date hence more recent studies have tended to utilize satellite derived rainfall with a large spatial resolution for national or regional rainfall estimation (Nicholson *et al.*, 2000; Petersen *et al.*, 2008; Asadullah *et al.*, 2008; Swenson and Wahr, 2009). In some of these studies the lack of coincident ground gauged rainfall data has rendered direct comparison with satellite derived rainfall to be of limited practical value. Extensive calibration to the ground gauged values would still be required prior to the utilization of satellite derived rainfall estimation in the transfer of gauged-rainfall occurrence and amount statistics from gauged to ungauged catchments.

Satellite derived rainfall estimations reported in the literature are also not available for overlapping time periods or same regional location. For example, Diem *et al.* (2014) assessed the accuracy of satellite based rainfall estimates in Western Uganda for the period 2001 – 2010 and reported a reasonably good estimation of mean monthly and annual rainfall totals. However, data obtained from the available satellite products rarely correctly identified more than 80% of the observed rainfall days. Furthermore, their estimation of rainfall at stations in the vicinity of complex topology, or rain shadow areas around Lake Albert and Lake Edward was found to be poor. Similar analysis conducted by Asadullah *et al.* (2008), for Lake Victoria region, Central Uganda, Mt Elgon and North Eastern Uganda, reported better performance of satellite derived rainfall for low lying areas around Lake Victoria with higher rain gauge density for the period 1960 – 1990 than other localities.

In most of the existing water balance studies, average monthly lake evaporation has been estimated using very limited pan evaporation observations, a water balance for the period 1970-1974, a heat budget method and models using global solar radiation (WMO, 1974; Nicholson *et al.*, 2000). Difficulties in the accuracy of the estimates were also cited due to the large lake surface areas.

Given the above overview of the basin drainage features, location of key long term flow and lake level monitoring stations, analysis of the long term lake levels and outflows is presented in greater detail for each sub-basin in the subsequent sections. In the subsequent analysis, the limitations related to lack of availability of concurrent data sets of other measurements such as tributary inflow, rainfall and evaporation in each sub-basin are reiterated. A justification to compile a continuous record of concurrent lake levels and outflows for each lake is presented and a detailed method of how the data was compiled is presented.

4.3 Lake Victoria long term lake levels and outflows

Interest in Lake Victoria’s water balance can be traced back to the study by Brookes (1923). Since then, numerous subsequent studies have evaluated and successively updated the lake’s water balance, for example, Hurst (1952); Balek (1977); Kite (1981, 1982); Hastenrath and Kutzbach (1983); Sene and Plinston (1994); Spigel and Coulter (1996); Yin and Nicholson (1998, 2002); and Tate *et al*. (2001, 2004). Consequently, the long term levels and outflows for Lake Victoria have been more precisely determined and assessed over a longer time period than any of the other Equatorial Lakes. Lake Victoria has also been shown by these studies to have a dominant effect on outflows of Lakes Kyoga and Albert.

4.3.1 Lake Victoria levels

Lake Victoria levels have been regularly measured at Entebbe and Jinja (Figure 4.3). The earliest measurements date back from 1896 at Entebbe, with a gap in 1897 – 1898. Early records at Entebbe and later records at Jinja have been converted into levels at the Jinja gauge. Historical observations of Lake Victoria levels have been extensively published, for example by WMO (1982), Institute of Hydrology (1993), Acres (1990) and Kennedy & Donkin (1996). Recent observations are available from archives of the Directorate of Water Resources Management (DWRM) at Entebbe.

The historical record, often published as end-month levels above the zero of the Jinja gauge as shown in Figure 4.4, demonstrates a relatively steady regime from 1896 to 1961, within the limits of 10.2 and 12.0 m, followed by a conspicuous rise between 1961 and 1964, and an apparent gentle decline interrupted by rises with short durations. The sharp rise in Lake Victoria levels which occurred in 1961 generated a lot of debate and controversy when lake levels increased sharply in 1961, reaching a maximum in 1964 with a record outflow of over 1600 $m^3.s^{-1}$. Initially, researchers found it difficult to explain this abrupt shift in levels until Piper *et al*. (1986) attributed the rise to increased rainfall and resulting tributary inflows. Sene and Plinston (1994) more recently investigated trends in levels of Lake Victoria and outflows and concluded that the levels remained relatively high from the early 1960s to the early 1990s as a result of sustained increase in rainfall on the lake and on contributing catchments.

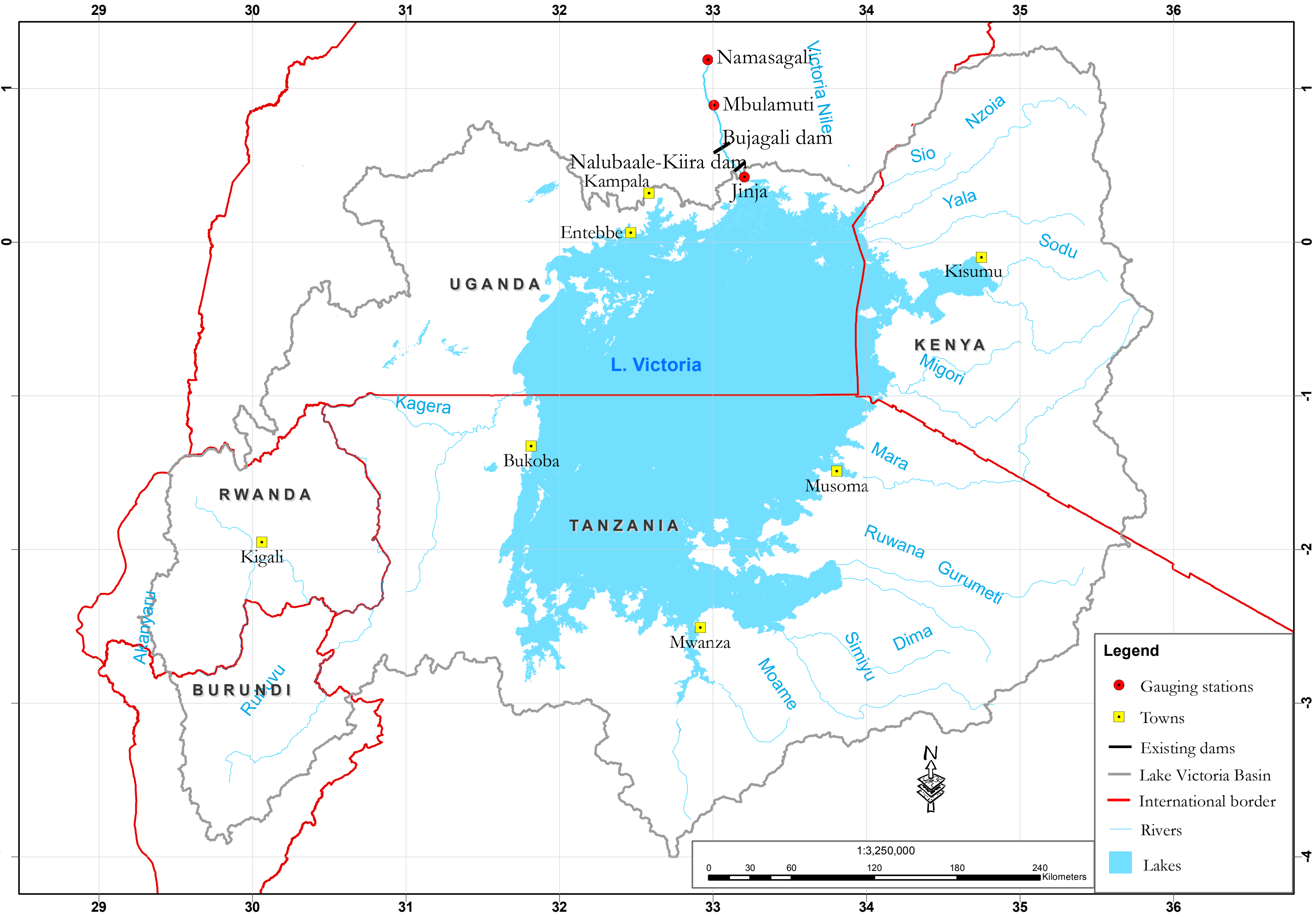


Figure 4.3 Long term lake levels and flow monitoring stations – Victoria basin.

Later studies by Tate *et al*. (2001) extended the nomograph of observed water levels of Lake Victoria back to 1870 by combining the historically observed records with statistically analysed downstream measurements. Their work demonstrated that high levels were also reached in 1878 and that comparatively rapid declines to lower levels also occurred then. Their findings are confirmed by early observations of lake levels by Lyons (1906), recounted by Sutcliffe and Parks (1999), where it is stated that levels were very high in August and September 1878, followed by declines between 1878 and 1892, then rises in 1892 to 1895 and continuous decline to the end of 1902.

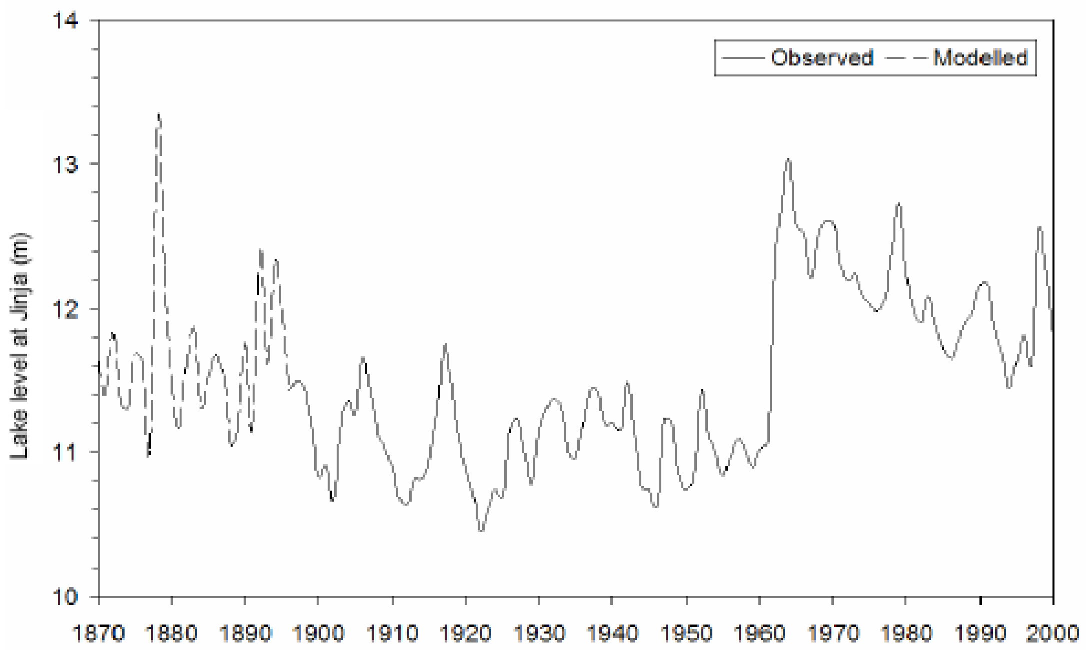


Figure 4.4 Lake Victoria levels, modelled (1870-1895) and observed (1896-2000) (Tate *et al*., 2001).

Nicholson *et al*. (2000) derived a model for Lake Victoria that simulates end-of–year lake level changes using only rainfall on the lake as input. The similarity between calculated and measured lake levels (correlation of 0.98) demonstrated the model was robust. Yin and Nicholson (2002) refined the model to estimate end-of-year lake level for a current year based on the previous end-of-year lake level and interim estimated annual rainfall. Such lake level predictor models have the potential for numerous applications in lake management. With any annual rainfall information obtained from other sources, the end-of-year lake level is easily estimated and utilised in the setting of storage targets for long-term planning.

4.3.2 Lake Victoria outflows

Outflows to the Victoria Nile River are the result of the balance between direct rainfall on Lake Victoria, tributary inflows, lake evaporation and releases at Nalubaale-Kiira dams. Before 1950, outflow from Lake Victoria was regulated naturally at Rippon Falls and during the period 1896-1939, outflows can be determined from lake levels using the Agreed Curve supported by simultaneous measurements at Namasagali. These data were published in various volumes and supplements of *The Nile Basin* (Hurst and Phillips, 1939; Hurst and Black, 1949, 1945; Hurst *et al.*, 1953, 1955, 1961; The Nile Control Department, 1962). From 1940-1956, it was generally held that the best estimate for the outflow record were the Namasagali discharge measurements. Until the rise in lake levels in 1961, the Namasagali discharge measurements agreed within about 5% with the turbine/sluice estimates of releases from the Owen Falls Dam, but after 1961, the Namasagali measurements were about 10% higher than the recorded releases and a decision was made to shift the gauging station further upstream to Mbulamuti in order to avoid back water influence from equally high levels in Lake Kyoga. Subsequent measurements at Mbulamuti were in close agreement with the turbine sluice releases. Hence in practice, after operations began at Owen Falls Dam from 1954 and prior to commissioning of the extension in 2001, releases largely followed the Agreed Curve (Figure 1.6) and where departures occurred, compensatory releases were made at a later date.

Later, analysis by Institute of Hydrology (1993) and Sene and Plinston (1994) following comprehensive studies on the water balance of Lake Victoria concluded that the Agreed Curve provides a reasonable basis for estimating monthly lake outflow up to 1954. Their study recommends that between 1951-1954 outflows be in-filled from interpolation of weekly Namasagali discharges made at the time and that recorded releases from turbine sluices are more representative of lake outflows after 1954.

A revised record of Lake Victoria outflows derived using these methods for the period 1896-1995 is available from Kennedy & Donkin (1996). It was originally adapted from Institute of Hydrology (1993) and has been extended in this study, to date, by obtaining data submitted from ESKOM to DWRM which pertains to the monthly releases from the turbines at Kiira-Nalubaale complex.

4.4 Lake Kyoga long term lake levels and outflows

The hydrology of Lake Kyoga has been less extensively studied. The most in depth assessment of the components of its water balance has been published by Sutcliffe and Parks (1999), Sene (2000) and Brown and Sutcliffe (2013).

4.4.1 Lake Kyoga levels

Lake Kyoga levels have been monitored at Masindi Port, Bugondo and Kachung (Figure 4.5).

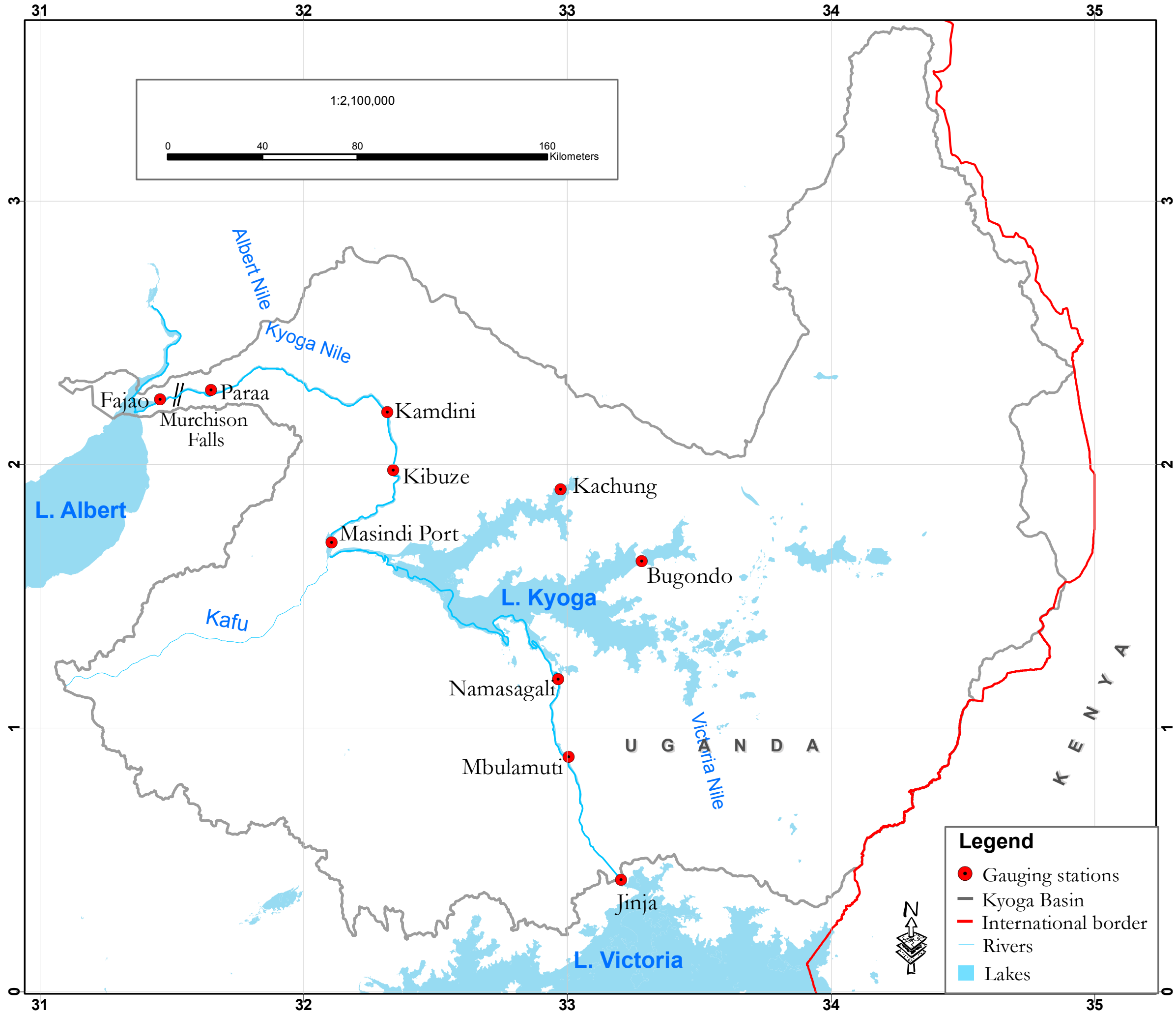


Figure 4.5 Long term lake levels and flow monitoring stations – Kyoga basin.

The record at Masindi port dates back from 1912 and Sutcliffe and Parks (1999) have derived a continuous record of lake level records from 10-day mean levels at Masindi Port for the period 1912-1977 as shown in Figure 4.6. This segment of the record is the most complete portion as later observations are riddled with gaps up until 1989.

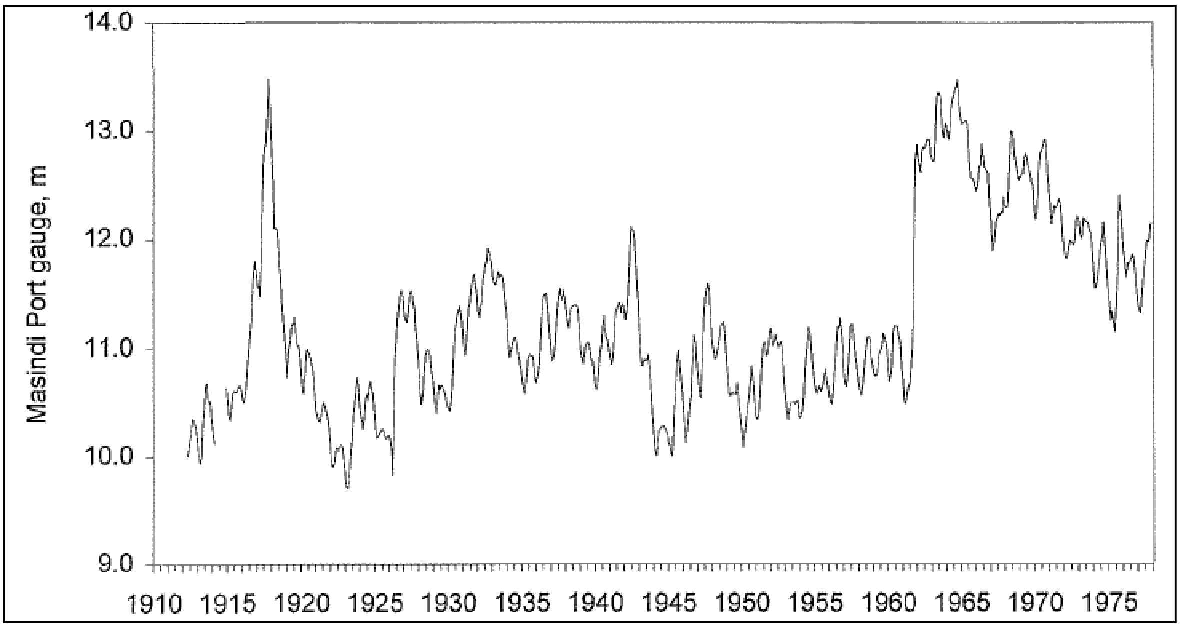


Figure 4.6 Lake Kyoga monthly levels at Masindi Port 1912- 1977 (Sutcliffe and Parks, 1999).

Figure 4.7 illustrates the variation of concurrently recorded daily lake levels in metres above sea level (m.a.s.l) at Masindi port and Bugondo during the period 1948 – 2008. Prior to 1998 the two readings are shown to be closely correlated with minor differences arising due to application of different datums. A few sections of the missing record at Masindi port can be in-filled using observations made at Bugondo. However there is a brief common period where readings are not available at either of the two stations.

In May 1998, heavy rains dislodged floating masses of papyrus which blocked the outlet of Lake Kyoga, and modified the hydraulic gradient between the station at Masindi Port at the mouth and the station at Bugondo further upstream. The blockage was removed using mechanical equipment between the years 2000 – 2005 and thereafter the original relationship between Masindi Port and Bugondo gauge readings seems to have been restored.

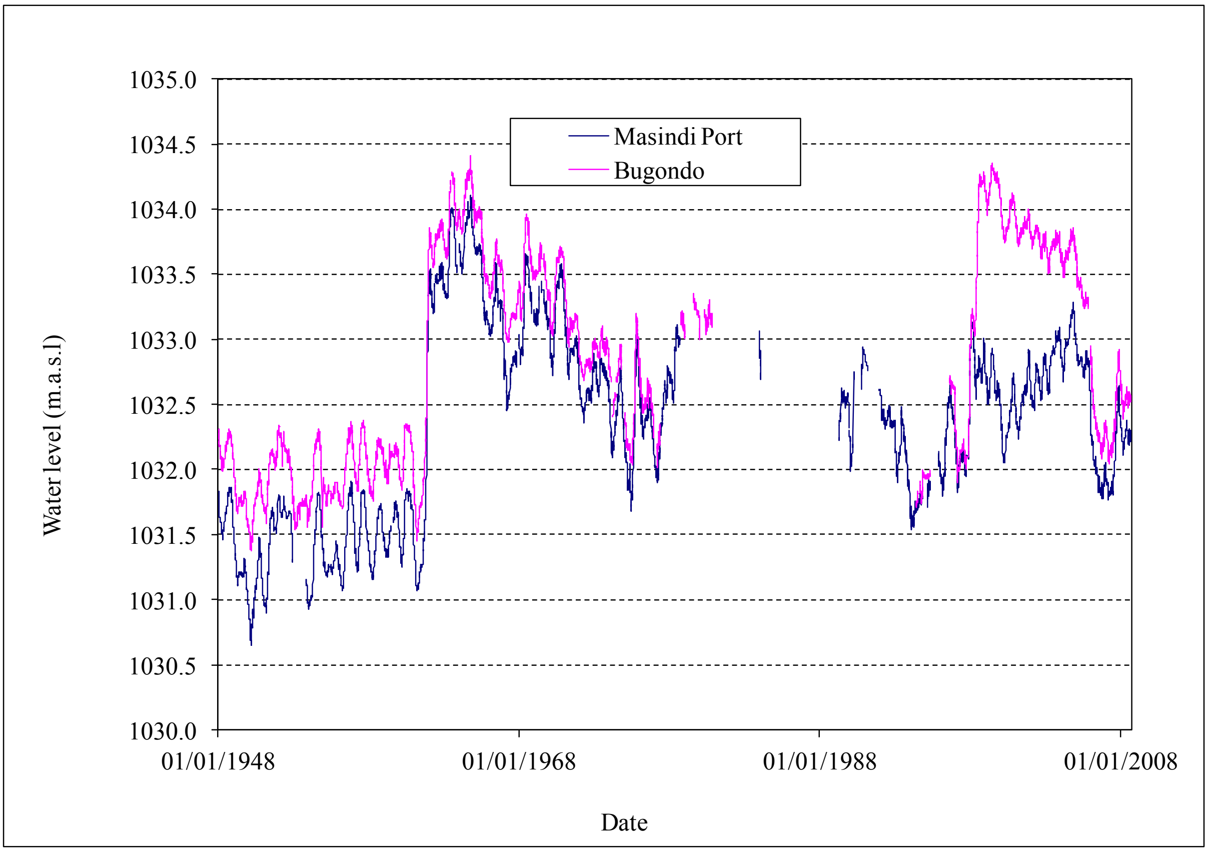


Figure 4.7 Masindi Port and Bugondo gauge readings (1948 – 2008).

4.4.2 Lake Kyoga outflows

Along the Kyoga Nile, flow measurements have been made at Masindi Port, Kibuze, Kamdini, Fajao and Paraa. The station at Masindi Port is situated near the outlet of Lake Kyoga while the river gauge at Kamdini is located about 80 km downstream from Masindi Port. The station at Fajao is 1 km below Murchison Falls. Paraa is located 15 km from the point where the Kyoga Nile flows into Lake Albert (Figure 4.2). Gauging at Kamdini and Fajao, commenced in 1940.

Flows at Masindi Port from 1912 -1944 published in *The Nile Basin* (Hurst and Phillips, 1939; Hurst and Black, 1945; Hurst *et al.*, 1953) are based on a rating curve for Masindi Port derived from gaugings made at Fajao between 1907 and 1935. This curve was published by Hurst and Phillips (1938), and it was noted that the observations were fairly consistent over a long period. The record before 1940 was based on few gaugings but these include measurements in 1922-1923 when river levels were at their lowest. Thereafter, it was noted that the rating was not stable and flow measurements were discontinued (Hurst *et al.*, 1946). From 1945-1951, the flow records are at Masindi Port were derived from a station at Kibuze located approximately

40 km downstream of Masindi Port as published in the fifth supplement to volume IV of the *Nile Basin* (Hurst *et al.*, 1957). The flow records at Kamdini for the period 1940-1955 published in *The Nile Basin* (Hurst and Phillips, 1939; Hurst and Black, 1945; Hurst *et al.*, 1953, 1957, 1961), were based on annual gaugings. The record at Kamdini is considered to be more reliable than at Masindi Port, as the rating curve is more stable (Sutcliffe and Parks, 1999).

Since gaugings along the Kyoga Nile at the various locations have taken place intermittently and for varying periods of time, previous researchers have aggregated these measurements for purposes of compiling the most reliable flow along this reach at Kamdini after determining that tributary inflows along the Kyoga Nile are estimated to be less than 1% of the Victoria Nile flows and can reasonably be neglected (Sutcliffe, 1986; Gibb, 1989; Gibb, 1996; Sutcliffe and Parks, 1999; Sene, 2000). This aggregated record of Kyoga Nile flows has been taken to be synonymous with inflows to Lake Albert and outflows from Lake Kyoga. Figure 4.8 is an extract from Sutcliffe and Parks (1999) and it illustrates how the gaugings taken at Kamdini, Fajao and Para are plotted against the gauge readings at Kamdini to derive an aggregated record of Kyoga Nile outflows for the period 1940 to 1979.

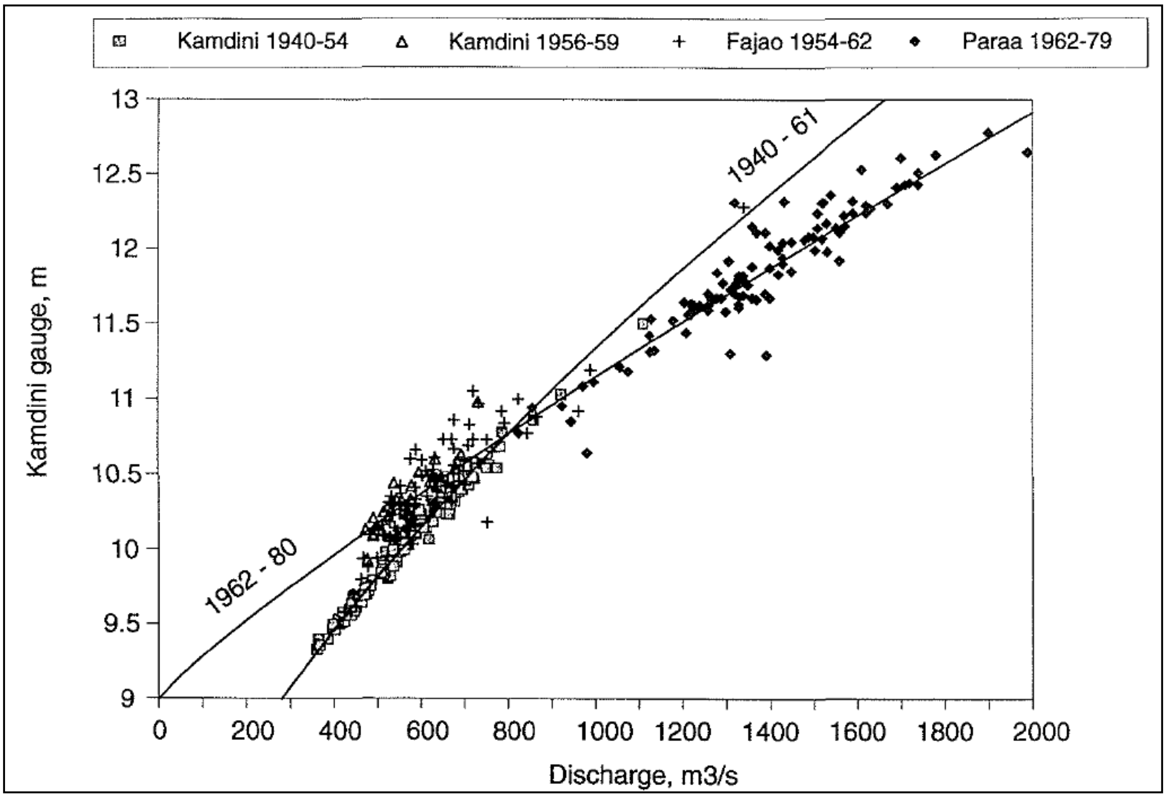


Figure 4.8 Gaugings at Kamdini, Fajao and Paraa, 1940 – 1979 (Sutcliffe & Parks, 1989).

Sutcliffe and Parks (1999) compared the derived monthly outflows at Kamdini with Lake Victoria outflows for the common period 1940 – 1977. The method of deriving Lake Victoria outflows for the common period has been described in Section 4.3.2. Table 4.3 contains an extract from their publication and it summarises the main results of their regression analysis. In Table 4.3, the tabulated parameters are defined after Sutcliffe and Parks (1999) as follows:

Coeff.	is the regression coefficient b in an equation of the form $Q_0 = a + bQ_i$,
Seb	is the standard error of b,
R, R^2	are the coefficients of correlation and determination,
See	is the standard error of estimate, and
Constant	is the Constant a in the equation.

Table 4.3 Regression of monthly outflows ($m^3 \times 10^6\ day^{-1}$) at Kamdini with Lake Victoria outflows, 1940-1977 (Sutcliffe & Parks, 1999)

Lag (t - months)	Coeff.	Seb	R	R^2	See	Constant
0	1.1319	0.0151	0.9620	0.9255	9.85	-8.03
1	1.1390	0.0139	0.9677	0.9365	9.09	-8.44
2	1.1336	0.0148	0.9633	0.9280	9.68	-7.92
3	1.1205	0.0169	0.9522	0.9067	11.02	-6.80

The results in Table 4.3 indicate that analysis with a lag of one month was the best fitting equation with an R^2 value of 0.9365. Thus inflow to Lake Kyoga from the Victoria Nile (Q_i) and outflow (Q_o) based on the record at Kamdini can be estimated as:

$$Q_0(t) = 1.139044\ Q_i\ (t - 1) - 8.44181 \tag{4.1}$$

In order to apply Equation 4.1, monthly flows have to be converted to units of $m^3 \times 10^6.day^{-1}$ in order to take account of the different month lengths. Assuming that the relationship in Equation 4.1 holds true during periods where outflow records from Lake Kyoga at Kamdini are not available, it can be applied to extend or infill the flow record for Lake Kyoga.

Gaugings along the Kyoga Nile resumed in 1996 and it is possible to deduce a new rating curve at Kamdini based on all available gaugings during the period July 1996 to June 2009 taken at Masindi Port, Kamdini and at Paraa, using the approach illustrated in Figure 4.6 as prescribed by Sutcliffe and Parks (1999). Two rating curves are discernible during this period as shown in Figure 4.9. There appears to be a significant shift in the rating in approximately 2000. The rating for the period March 2000 – June 2009 shows a wide scatter, indicating a large degree of uncertainty in estimation of the higher range of discharges. Changes in the rating curves in rivers without stabilised or lined channels are commonly observed in this region. They can be attributed to changes in cross section morphology of rivers due to the effects of sediment deposition, shifting papyrus movement and flooding (Petersen *et al.*, 2007). In this instance the change in rating was taken into account in subsequent water balance calculations. The two rating curves can be adopted for purposes of extending the Kamdini record from 1996 to 2008.

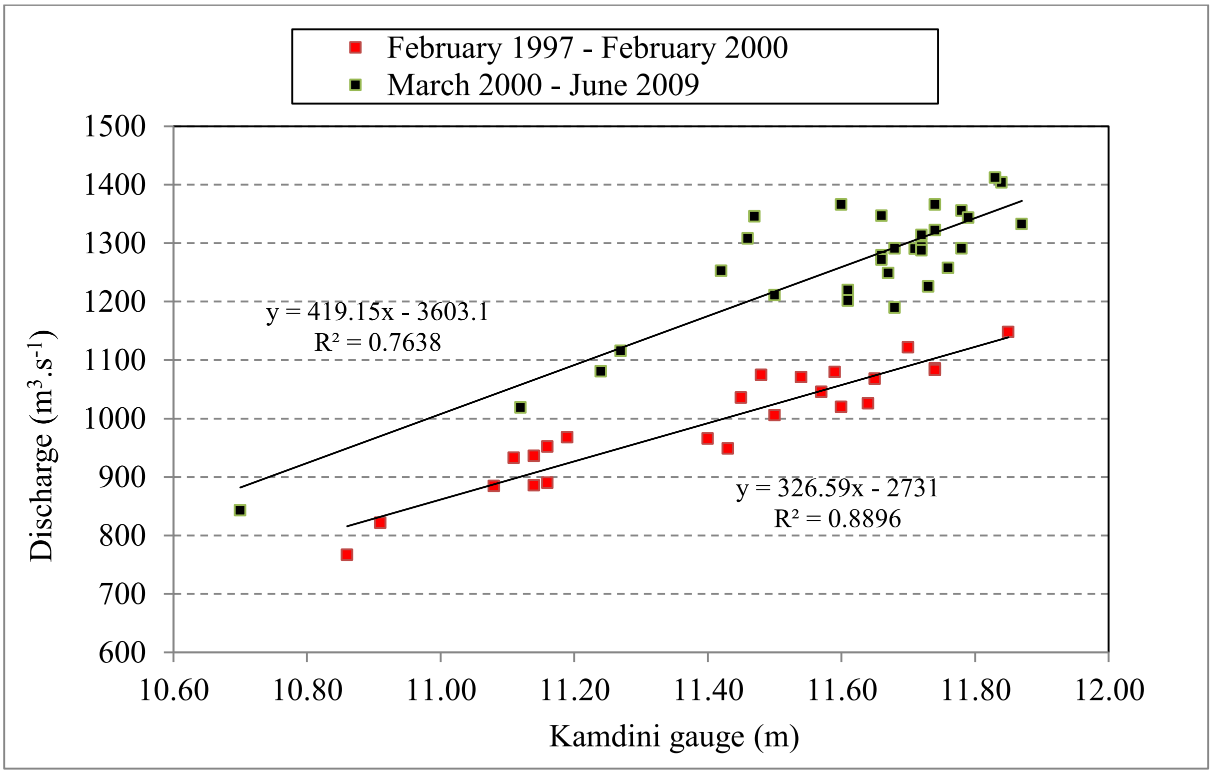


Figure 4.9 Updated rating curves at Kamdini (1996 – 2009).

A complete monthly record of Kyoga outflows is required for the period 1899 – 2008 for purposes of subsequent application of the Equatorial Lake Model. This record was derived by concatenating five segments defined as follows:

(i) Application of Equation 4.1 to derive a representative record at Kamdini for the period 1899 – 1911 based on Lake Victoria outflows for the same period derived using the method outlined in Section 4.3.2.

(ii) Adoption of monthly outflows recorded at Masindi Port for the period 1912 – 1939 (Hurst and Phillips, 1939; Hurst and Black, 1945; Hurst *et al.*, 1953).

(iii) Adoption of the monthly outflows recorded at Kamdini for the period 1940 – 1979 (Sutcliffe and Parks, 1999).

(iv) Application of Equation 4.1 to derive a representative record at Kamdini for the period 1980 – 1995 based on Lake Victoria outflows for the same period.

(v) Application of the rating curves illustrated in Figure 4.6 to derive outflows at Kamdini for the period 1996 – 2008.

Derivation of the long term Lake Kyoga outflows by concatenating different segments of data for purposes of analysing Lake Regulation was pioneered by Kennedy and Donkin (1996) and Mott MacDonald (1998).

Brown and Sutcliffe (2013) have assessed the suitability of utilizing the published early flows at Masindi Port (1915 – 1939) in a concatenation scheme designed to extend knowledge of Lake Kyoga outflows. The analysis utilized the insight gained from determining an updated annual water balance for Lake Kyoga for the period 1940 – 1977. The improved water budget estimates were realised to due quantification of net rainfall and tributary inflows. Thereafter Jinja annual outflow for the period 1915 – 1935 was adjusted based results of the improved water balance so as to obtain model derived estimates of Masindi Port outflow for the same period. To do so, the improved model was run with lake rainfall for the same period, evaporation based on a lake area of 4,700 km^2 and local runoff estimated from basin rainfall. The estimated flows were then compared with the published record at Masindi port (Figure 4.10).

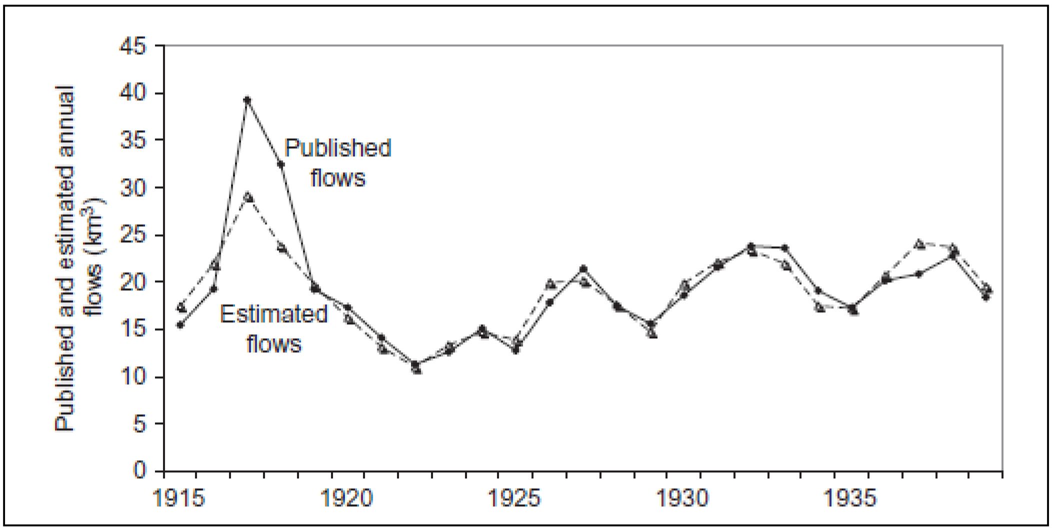


Figure 4.10 Masindi Port: published and estimated annual flows, 1915 – 1939 (Brown and Sutcliffe, 2013).

Apart from the mismatch when the flood in 1917 is not predicted, the small difference between the estimated and published flows, suggests that the published flows at Masindi Port are a reasonable estimate of the true historic flows (Brown and Sutcliffe, 2013).

4.4.3 Extension of Lake Kyoga level records at Masindi Port

In order to compute the net basin supply time series for Lake Kyoga, through application of the Equatorial Lake model, a complete record of Lake Kyoga levels at Masindi Port for the period 1899 to 2008 was required. Beginning of month gauge levels at Masindi Port published in WMO (1982) for the years 1912 – 1947 were adjusted to end of month gauge levels. For example, the beginning of month gauge reading level for February 1912 was taken to be the end of month reading for January 1912. Thereafter, end of month gauge readings were extracted from the archives of the Directorate of Water Resources Management at Entebbe from the lake level station at Masindi Port so as to complete the record from 1947 up to the year 2008. However, intermittent gaps still remained in this record from October 1978 – December 1997. These missing levels were estimated in two steps.

In the first step, observations from lake gauging stations at Bugondo and Kachung were utilised after deducing the relationships amongst all lakeside gauges during periods of concurrent observation. To estimate the remaining portion of the record, an equation, derived by Mott MacDonald (1998) was adopted. This equation is essentially a fitted rating relationship to the common period of mean monthly Masindi Port levels and monthly Kyoga outflows. The fitted equation is;

$$Q_k = 0.00067352 * H^{5.717553} \tag{4.2}$$

where, Q_k = Lake Kyoga outflow in ($m^3.s^{-1}$), and
H = Masindi Port mean monthly level (m).

Equation 4.2 estimates the lake level from available records of Kyoga outflow. It was also applied to estimate Lake Kyoga levels from 1899 to 1911 based on the representative record of Kyoga outflows derived using the approach described in Bullet (a) in Section 4.4.2.

Extension of the record of observed levels at Masindi Port from 1998 to the end of the year 2008 required a different approach. During the duration of the blockage, Masindi Port levels are not representative of the actual lake level. Koponen and Kummu (2004) noted that the net effect of the blockage was to cause an immediate rise of 1.5 m around the shoreline of Lake Kyoga and also a temporary decrease in the outflow. Koponen and Kummu (2004) also demonstrated that measured outflows along the Kyoga Nile did not correspond with the linear relationship that existed between water levels at Bugondo and Lake Kyoga yearly outflows prior to the blockage. Prevailing Lake Kyoga levels during the duration of the blockage, i.e. from 1998 up to the end of the year 2003, have therefore been estimated using actual gauge readings at Bugondo recorded during the same period. After the blockage was effectively removed at the end of the year 2003, end of month Masindi port gauge readings for the period 2004 to 2008 were adopted.

4.5 Lake Albert long term lake levels and outflows

The longest and most reliable record of lake levels and outflows below Lake Victoria is associated with the Lake Albert Basin where scientific observations of flows on the White Nile began in 1905 at Mongalla in Sudan (Sutcliffe and Parks, 1999) and where Lake Albert levels have been recorded since 1904 at Butiaba. The location of key reference gauge stations in the Semliki sub-basin are shown on Figure 4.2 at the beginning of the chapter. Early water balance studies by Hurst and Phillips (1938) of the lake basins for the period 1912 – 1932 demonstrated the dominant influence of Lake Victoria outflows on Kyoga Nile and Albert Nile outflows.

4.5.1 Lake Albert levels

Beginning of month gauge levels at Butiaba have been published in WMO (1982) for the period 1904 – 1978. Daily lake levels are available for the same station from the archives of the DWRM in Entebbe. These data are for the period 1938 to date with gaps in 1966, 1967 and from 1980 to 1998 as shown in Figure 4.11.

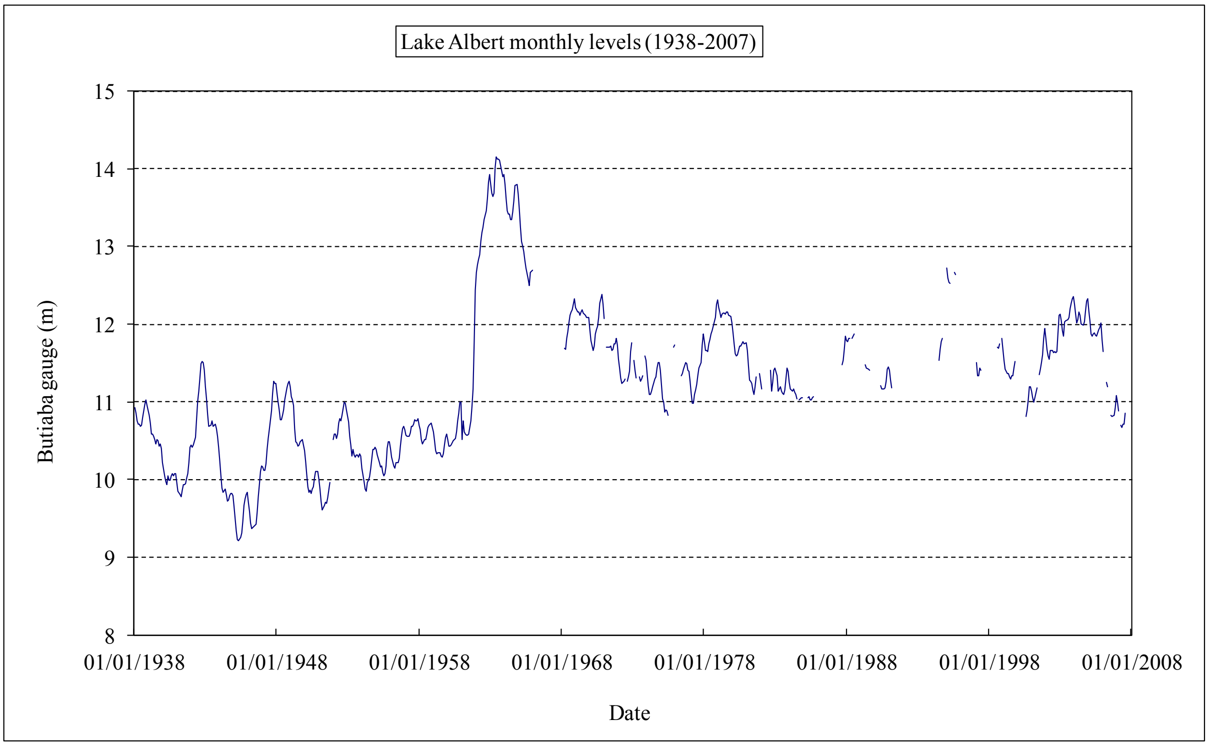


Figure 4.11 Lake Albert Levels, 1938-2007.

In order to compile a complete water level record for the period 1899 to 2008 for Lake Albert, the beginning of month gauge levels published in WMO (1982) for the years 1904 – 1978 were adjusted to end of month gauge levels in the same manner described in Section 4.4.3. Thereafter, end of month gauge readings were extracted from the archives of the DWRM in Entebbe to complete the record up to the year 2008. However, a few intermittent gaps still remained in this record from 1982 – 1994 and in 1996. These missing levels were estimated either by linear interpolation, in cases where only a few months were missing or by a correlation relationship established between total monthly Kyoga outflows and mean month Lake Levels at Butiaba during the period 1912 – 1965, when concurrent measurements are available and of good quality. The correlation relationship is illustrated in Figure 4.10. The fitted relationship is of the form;

Butiaba gauge level (m) = 8.475 + 0.0012 * (Kyoga outflow in million cubic metres) (4.3)

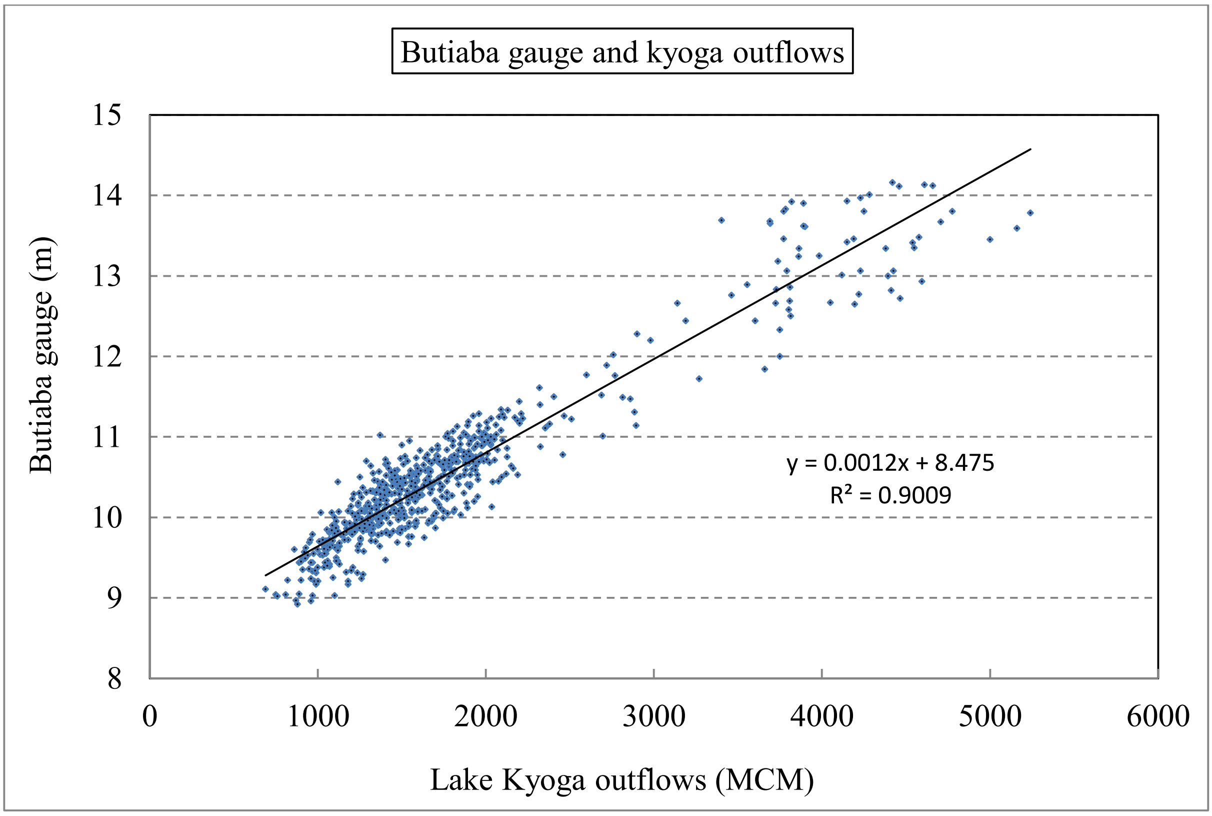


Figure 4.12 Correlation between monthly Lake Albert levels at Butiaba and Lake Kyoga outflows.

Equation 4.3 ($r^2 = 0.90$) was also used to estimate Butiaba levels for the period 1899 to 1903. Since Lake Kyoga outflows are only an estimate during this period, the derived Albert levels for this period are viewed as a plausible estimate. This method of estimating periods of missing Lake Albert records, using linear interpolation, and cross checking qualitatively with outflow data from upstream Lake Victoria was first suggested by Petersen *et al.* (2008).

4.5.2 Lake Albert outflows

The earliest record of flow measurements in the Lake Albert Basin date back from 1905 at Mongalla, which is 440 kilometres downstream of the lake. The flow at Mongalla has two components which are the contribution of direct outflow from Lake Albert and augmentation from the torrent flows. Torrent flows refers to the ungauged flow contributions in the area between Mongalla and the outlet of Lake Albert. The early records at Mongalla were taken to be representative of the outflow from Lake Albert by Hurst and Phillips (1938), who based their assessment upon a derived relationship between monthly dry season flows at Mongalla, increased by 5 % to allow for losses, and simultaneous Lake Albert levels at Butiaba. This data has been published in various volumes and supplements of *The Nile Basin* for the period 1904-1957 as “Discharges of Lake Albert at Mongalla” (Hurst and Phillips, 1939; Hurst and Black, 1945; Hurst *et al*., 1953, 1957, 1961). Monthly outflows from Lake Albert for the period 1905 – 1978 have also been published in WMO (1982) and this record is actually a concatenation of the early records derived from flow observations at Mongalla and subsequent measurements at Panyango for the period 1948 – 1978.

Later observations of Lake Albert outflow made during the implementation of the Hydromet Project directly at the mouth from Pakwach during the period 1956 – 1974, led to the conclusion that the rating curve was unstable due to the effects of invasive aquatic vegetation and lake level influence (WMO, 1974). Measurements were therefore transferred further downstream to Panyango in 1948. The station at Panyango continued to be regularly monitored until 1978 but the record of flows is discontinuous from then till 1995 due to the prevailing insecurity in Uganda at the time. The station at Panyango was restarted in 1996 but since then gaugings have been irregular and few. Observations of outflow further downstream at Laropi commenced in 1958 but these are also discontinuous during the period 1971- 2000.

Due to political instability in Southern Sudan in 1983, flow measurements at Mongalla were suspended. To address the lack of continuity of observations at Mongallla which is a key long term monitoring station from which outflows from Lake Albert have in the past been deduced, Petersen *et al.* (2008) were able to estimate missing flow data at Mongalla from the two components of Lake Albert outflow and also derived a new rating curve relating Lake Albert water levels at Butiaba to Lake Albert outflows at Mongalla, excluding estimated torrent flows. In their study, Petersen *et al*. (2008), simulated torrent flows by application of the Collaborative Historical African Rainfall Model (CHARM) to a rainfall data set, for the period 1961 – 1996, in the catchment between Lake Albert and Mongalla using GIS techniques. The CHARM derived torrent flow was validated based on a calibration process where the torrent flow was assumed to be the difference between observed flow at Mongalla and observed flow at Panyango during periods of overlapping data. Their results provide a reliable update of derived Lake Albert outflows, as a separate component of observed discharges at Mongalla for the period 1979 – 1983 and calculated discharges at Mongalla for the period 1984 - 1996.

Extension of the record of Lake Albert outflows from 1996 – 2008 requires updating and application of the rating curve at Panyango based on all gaugings available from 1971 – 2009. This rating curve is shown in Figure 4.13.

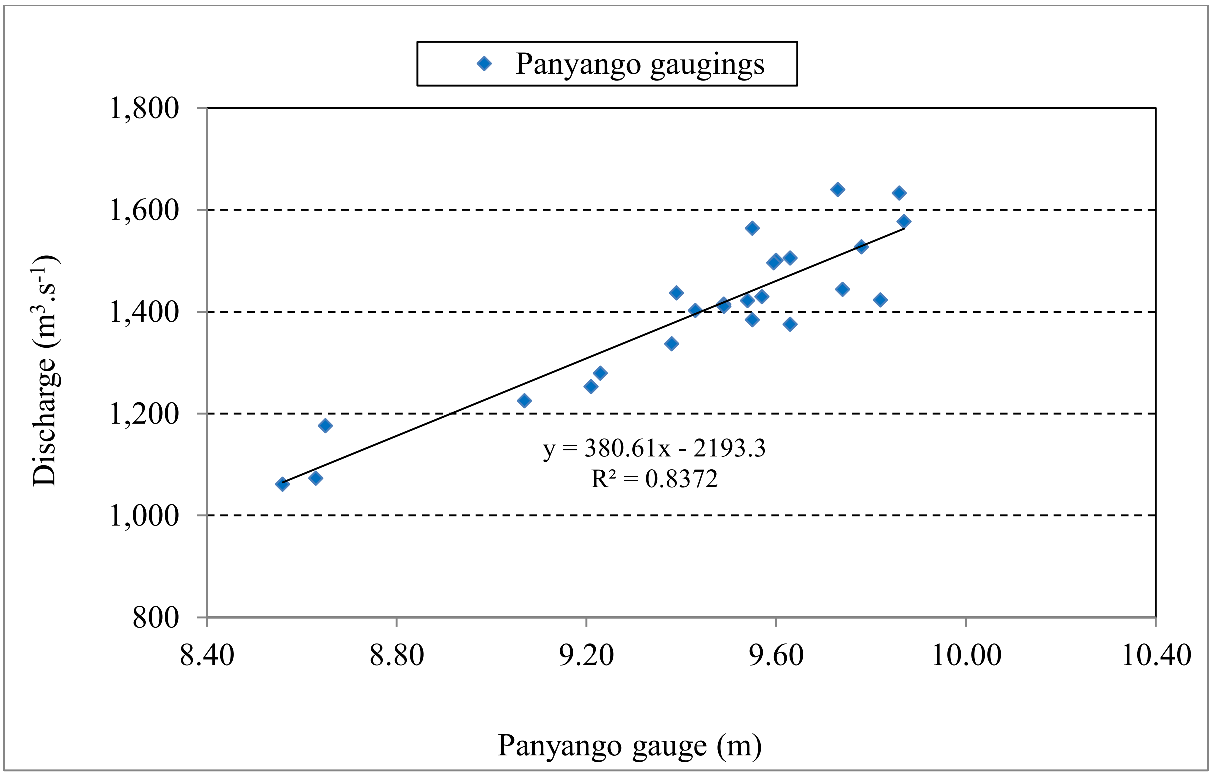


Figure 4.13 Rating curve at Panyango (1971 – 2009).

A record of Lake Albert outflows for the period 1899 – 2008 is required prior to application of the Equatorial Lake Model in the methodology that has been adopted in this case study. The required record was compiled by concatenation of four data sets that were constructed as follows:

(i) Lake Albert outflows for the period 1899 – 1904 were estimated using a derived lake level outflow relationship based on gauge readings at Butiaba and directly measured discharges at Panyango (Mott MacDonald, 1998). This relationship has been compared against recently observed gaugings and was found to still be valid (Figure 4.14).

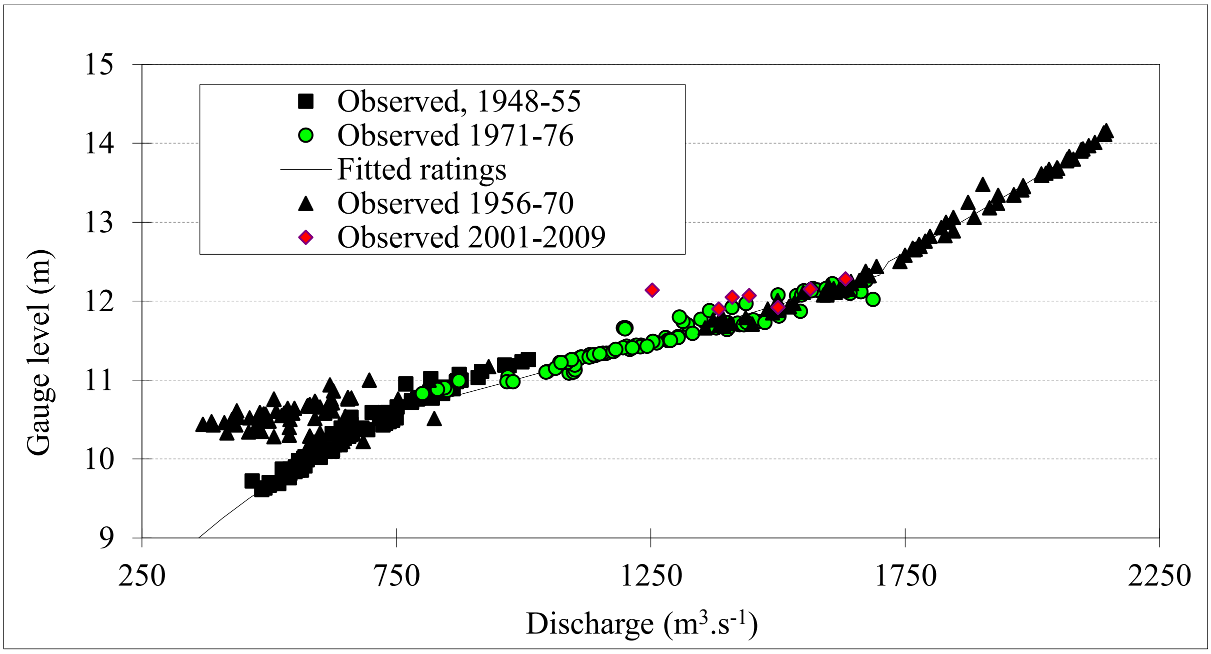


Figure 4.14 Rating used to extend Lake Albert discharge records (after, Mott MacDonald, 1998).

(ii) Adoption of the monthly outflows from Lake Albert for the period 1905 – 1978 (WMO, 1982).

(iii) Lake Albert outflows (Petersen *et al.*, 2008), derived as a separate component of observed discharges at Mongalla for the period 1979 – 1983 and calculated discharges at Mongalla for the period 1984 - 1996.

(iv) Most recent record of Lake Albert outflows for the period 1997 – 2008 derived following application of the rating curve at Panyango illustrated in Figure 4.10.

4.6 Discussion regarding data available and its limitations

A concurrent record of lake levels and outflows or inflows for the period 1899 – 2008 for Lakes Victoria, Kyoga and Albert has been constructed from various long term monitoring stations. This data set is preferred to other data sets such as rainfall, evaporation and tributary runoff to the Equatorial Lakes that are often not concurrent, are much more fragmented and are of shorter duration.

It is acknowledged that a significant margin of error is likely to arise during the utilization of the derived long term lake levels and outflows of Lake Kyoga and Albert for purposes of generating actual net basin supply time series. The sources of error are due to infilling of missing segments of record, unstable rating curves and attenuation due to storage effects. However, the compiled concurrent record of lake levels and outflows is considered to be the best available data set for the purposes of identifying and evaluating alternative regulation rules within the proposed methodological framework for this study.

Having compiled the basic data required to derive the net basin supply time series for each lake, the next chapter discusses how the net inflow series to each lake are computed using the Equatorial Lake Model.

5. DERIVATION OF NET BASIN SUPPLY TIME SERIES FOR THE EQUATORIAL LAKES

An indirect method that utilises measured lake levels and natural outflows without estimating the total water balance for each lake has been adopted so as to compute net basin supplies for each lake. Details are given in this chapter. Net basin supply for a lake is defined as the net inflow arising from tributary inflows, rainfall on the lake surface, losses due to lake evaporation and ground water seepage into or out of the lake. The record of net basin supply is required for purposes of simulating the natural behaviour of the lakes and for application in optimisation models where various lake regulation alternatives are investigated.

A modified version of the Hydrologic Model of the Upper Nile Equatorial Lake Basin (Nemec and Kite, 1979), referred to herein as the Equatorial Lake Model has been adopted to simulate the lake levels and compute the net basin supplies. Preliminary results from statistical analysis of the stationarity of the net basin supply time series is also discussed in this chapter as it has a bearing on the method of generating operating rules. The time series of computed annual net basin supplies have been examined to determine if they are stationary. A computer program that segments a time series into sub-series that are stationary (Hubert, 2000), is applied to detect change points in the records.

5.1 The Equatorial Lake Model

The water balance of a lake requires that the total inflow to the lake should be equal to the sum of the outflow and the change of storage. Assuming that subsurface inflow and seepage can be neglected (Kite, 1984), the water balance can be determined using Equation 5.1 where each component is expressed in millions of cubic metres. The lakes are taken to be in series.

$$I + R + P = O + E + \Delta S \qquad (5.1)$$

where: I = is the inflow from the upstream catchments,

R = is the runoff from the catchment of the lake excluding the catchment of the upstream lake,

P = is the rainfall over the lake surface,

O = is the outflow from the lake,
E = is the evaporation from the lake surface, and
ΔS = is the change in storage i.e. storage at the end of the time period minus the storage at the beginning.

The direct method of obtaining the Net Basin Supply (NBS) involves computation of the stream inflows to the lake, estimating the direct rainfall over the lake surface from rain gauges which, typically, are distributed around the shoreline and measurement of the lake evaporation as:

$$NBS = R + P - E \tag{5.2}$$

There are many difficulties associated with determining the NBS directly for the equatorial lakes due to the lack of sufficiently long records of rainfall and evaporation. Tributary inflows to the lakes are also poorly estimated as many contributing catchments are un-gauged. These limitations have been discussed in detail above. Since concurrent records of lake levels and outflows of the lakes are available over longer periods than the meteorological data, it is therefore easier to estimate the net basin supply indirectly as follows:

$$NBS = \Delta S + O - I \tag{5.3}$$

Hence the net basin supply can be derived from change in storage, which can be obtained from the lake levels using the lake capacity curves and from the lake outflow (which is also inflow to the subsequent lake). Lake capacity curves or tables indicate the variation of lake level or elevation with volume.

A long term lake level – outflow discharge relationship is derived by plotting the mean monthly discharges against the mean lake levels. Such a curve is readily available for Lake Victoria i.e. Agreed Curve. Under WMO (1977), similar relationships were established for Lake Kyoga and Albert, by plotting mean monthly discharges against the lake water levels and fitting up to 5th order polynomials to the data points. There was considerable scatter of points for lakes Kyoga and Albert. Owing to the large magnitudes of individual outflows from the Equatorial Lakes, inaccuracies in gaugings and water level – outflow relationships at key gauging stations along the Kyoga and Albert Nile, the simulation of levels at Lakes Kyoga and Albert are likely to be susceptible to a significant level of uncertainty. Notwithstanding the above limitations, a number of studies have attempted to simulate the behaviour of the Equatorial Lakes by solving the water balance on either a monthly or annual timescale using either the observed or simulated net basin supplies (WMO, 1982; Kite, 1984; Kennedy & Donkin, 1996; Wardlaw *et al.*, 2005).

In order to compute the net basin supply, a simulation model that had previously been set up for the Equatorial Lake system was used (Mott MacDonald, 1998). The model simulates each lake in turn in the sequence of Victoria, Kyoga and Albert and is very similar to the Lake Model component of the Hydrologic Model of the Upper Nile Equatorial Lake Basin. The Equatorial Lakes are represented in Figure 5.1 as a series of three individual reservoirs in series subject to inter-basin flows (Q_i) and net basin supplies (N_i). The inter basin flows are conveyed along the Victoria Nile (Q_1), Kyoga Nile (Q_2) and Albert Nile (Q_3).

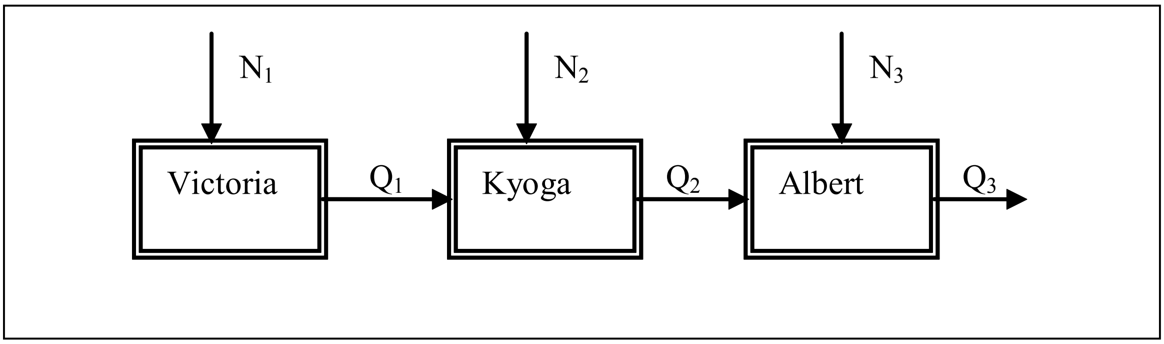


Figure 5.1 Inter basin flows and net basin supplies at the Equatorial Lakes.

The modelling framework adopted in Figure 5.1 is largely motivated by the work of Sene (2000), who applied a similar approach to develop his theoretical model which was used to estimate the impacts of changes in Lake Victoria levels on river flows, lake levels and swamp areas in the White Nile basin. The basis of this simplified method is the consideration that there are no significant tributary inflows along the Victoria and Kyoga Nile (Sutcliffe & Parks, 1999). Only the major lakes (Victoria, Kyoga and Albert) are considered as they are linked by the connecting rivers through which the dominant flows are routed. All other inflows such as those arising through the Semliki River which drains Lakes Edward and George are accounted for through the net basin supply for each major lake.

To simulate the behaviour of the Equatorial Lakes or to simulate a regulation plan, recorded lake levels and outflows are converted to net basin supplies using the capacity curves. The long term record of lake levels and outflows for Lake Victoria, Kyoga and Albert derived in Chapter 4 for the period 1899 – 2008 were utilised as the primary data input for the Equatorial Lake Model. The net basin supplies were then used as input to the regulation plan which estimates regulated lake levels and outflows. If natural conditions are specified as the regulation plan, for example the Agreed Curve, then the estimated lake levels and outflows should be equal to recorded lake levels and outflows.

5.2 Segmentation of the net basin supply

A number of studies have indicated the existences of abrupt shifts in the annual net basin supply for Lake Victoria (Bruk, 1975; Salas, *et al.*,1982; Sene and Plinston, 1994) and have tried to predict the future behaviour of the lake. It has been suggested that the net basin supply time series for the Equatorial Lakes are characterized by multiple stationary states, which only differ from each other by having different means that vary around the long term mean of the process. Such time series are now commonly referred to as "shifting mean processes" and the models that simulate their behaviour are termed "shifting mean" models (Sveinsson *et al.*, 2003). These models can be utilised to simulate and generate long sample records of net basin supply series that can be utilised in regulation studies for the Equatorial Lakes. It is therefore appropriate to detect and identify the times when abrupt changes occur in the derived net basin time series with the aid of statistical testing procedures. Hence segmentation algorithms for detection of multiple change points (Hubert, 1997; Hubert, 2000) were adopted in this study.

The segmentation procedure involves dividing the time series into several optimal segments, in such a manner that the arithmetic means of the contiguous time series are statistically different from each other. The procedure utilises the Sheffe test of contrasts (Sheffe, 1959) to ensure that the means of successive segments are significantly different. Identification of abrupt shifts in the mean, trends and long term periodicities can be construed to be confirmation of non stationarity of the net basin supply time series if such statistical properties are shown to vary with time (Chen and Rao, 2002).

5.3 Results from application of the Equatorial Lake Model and segmentation algorithm

The Equatorial Lake Model was run, with the long term record of lake levels and outflows for Lake Victoria, Kyoga and Albert as basic data inputs. The model computed the historically observed net basin supply time series as the output. The time step of application considered was monthly, for the period 1899 – 2008. The resulting net basin time series were subjected to the segmentation algorithm and the results are discussed in the next sub sections.

5.3.1 Lake Victoria

A continuous record of end of month levels at Jinja for the period 1899 – 2008, constructed from published end-month levels at the Jinja gauge and data from the archives of the DWRM in Entebbe, was compiled prior to application of the Equatorial Lake Model. A similar dataset for the period 1899 – 1995 has previously been utilised in studies by the Institute of Hydrology (1993) and Kennedy and Donkin (1996). It is considered to be of very good quality and was found to be consistent with the record published by Mott MacDonald (1998) for the concurrent period. Lake Victoria outflows utilised to run the model were compiled using the method outlined in Section 4.3.2.

The Equatorial Lake model was run to simulate operation according to the Agreed Curve with this data set. The model iterates to compute a mean monthly discharge corresponding with an average monthly water level determined from start and end of month levels. It utilises the elevation – storage characteristics for Lake Victoria (WMO, 1982) in order to compute changes in storage from changes in level and then finally computes the net basin supplies by summing the change in storage and the outflow in the Victoria Nile. Figures 5.2 and 5.3 contain simulated and observed average monthly levels and discharges respectively for Lake Victoria. From Figure 5.2 it is evident that there is very close agreement between the simulated and observed levels, particularly prior to completion of the Owen Falls dam in 1954.

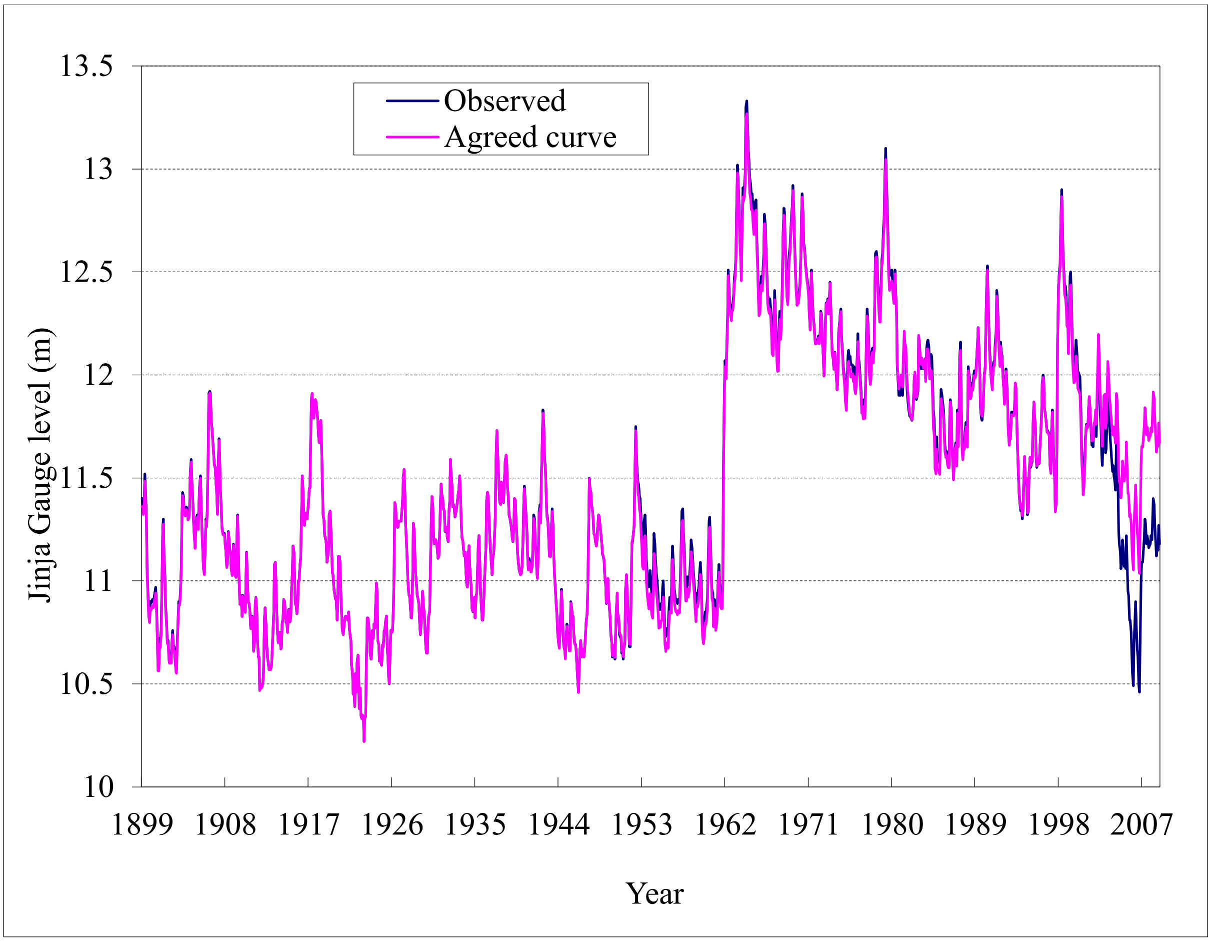


Figure 5.2 Model simulation of Lake Victoria levels.

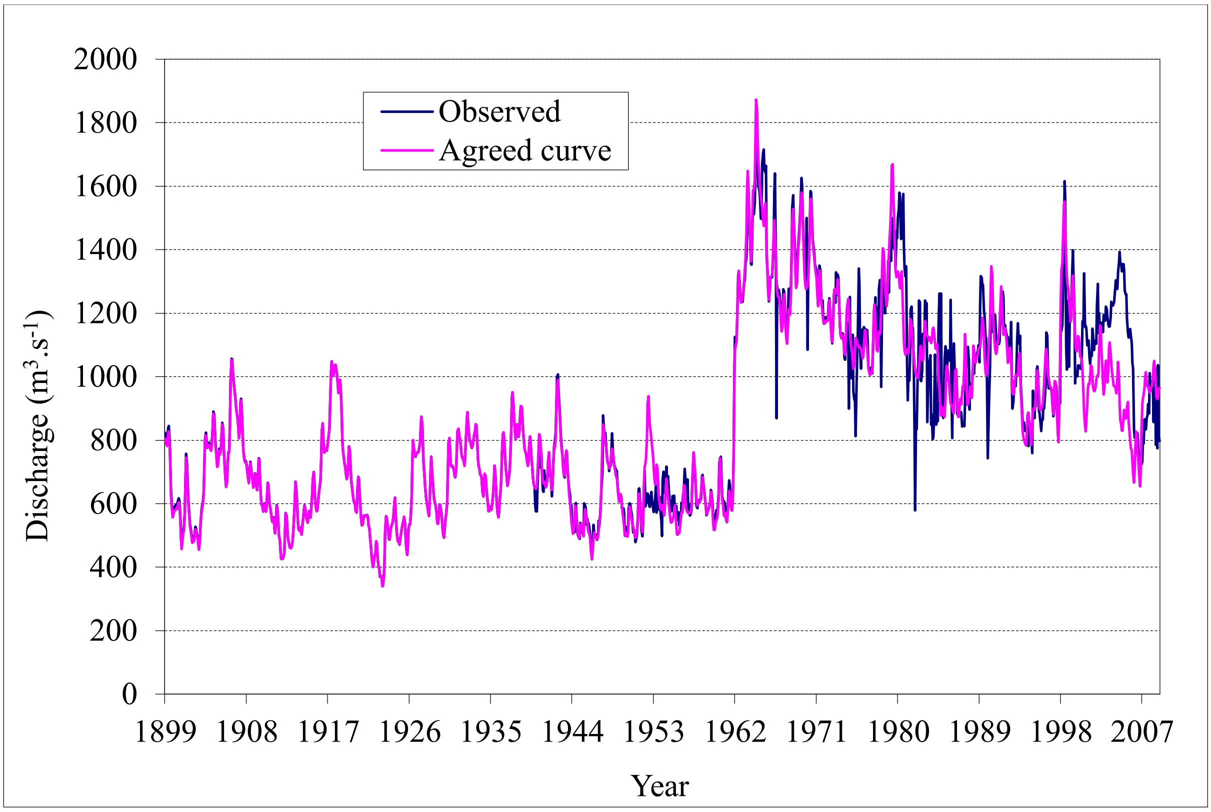


Figure 5.3 Model simulation of Lake Victoria discharges.

As shown in Figure 5.3, the outflows used in this simulation for the period 1889 - 2008, correspond to the actual dam releases from the Nalubaale-Kiira Dams and it is noticeable from Figure 5.3 that releases continued in the period 1954-2004 to follow the Agreed Curve with minor deviations followed by compensatory releases. After 2001 there is a marked difference between the observed and simulated levels and outflows due to sustained departure from the Agreed Curve release policy.

Sutcliffe and Petersen (2007) compared measured lake levels, outflows according to the Agreed Curve and actual dam releases for the period up to 2006 and have derived a corrected natural level series which would have resulted had releases been based on the Agreed Curve. Comparison of this naturalized series with actual measured levels revealed that the impact of recent over-abstraction on declining levels was of the order of 0.6 m.

The resulting annual net basin supply time series obtained through application of the Equatorial Lake Model were subjected to the segmentation algorithm developed by Hubert (1997, 2000) and the results are illustrated in Figure 5.4.

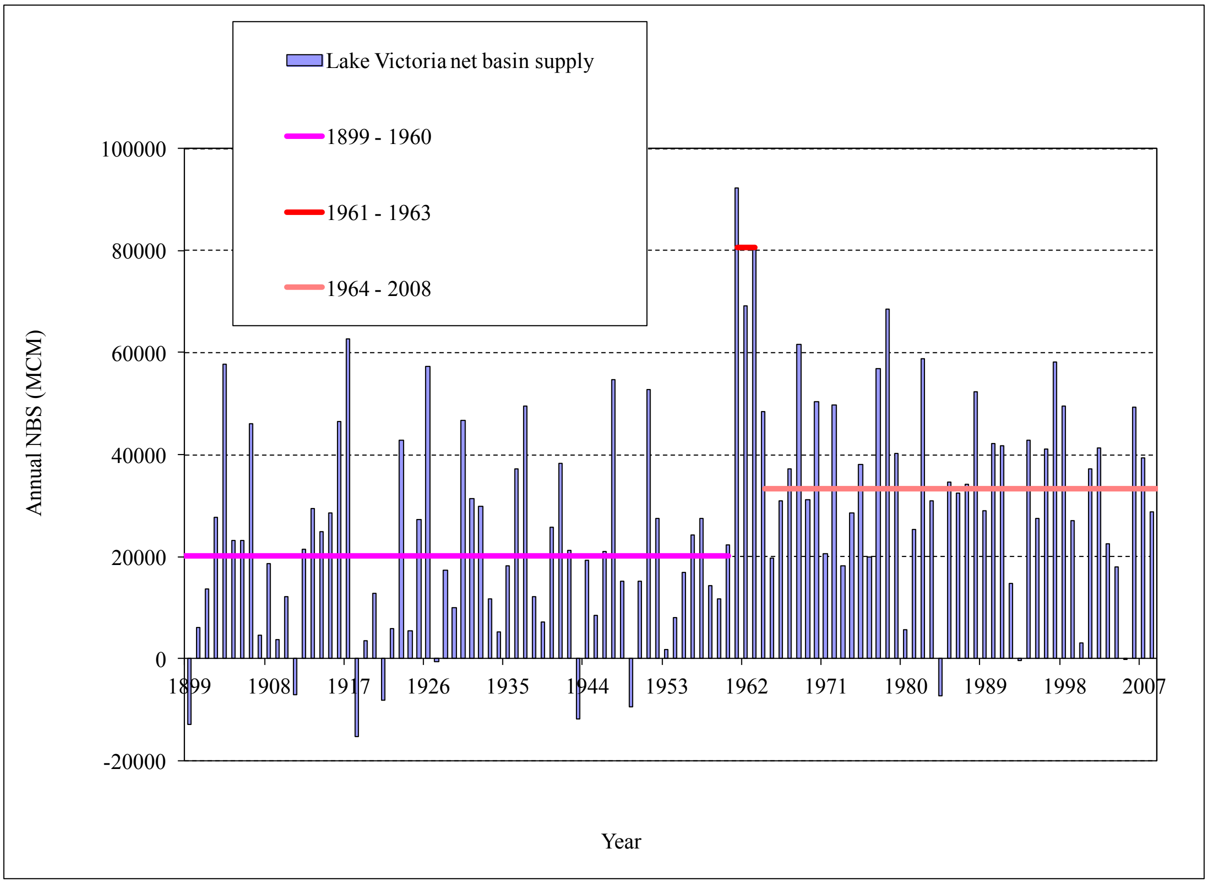


Figure 5.4 Historical annual net basin supply computed by the model (1899-2008).

Figure 5.4 shows that application of the segmentation algorithm to the derived annual net basin supply time series of Lake Victoria for the period 1899 – 2008 produced three segments with different means at a 0.05 significance level of the Scheffe test. The three contiguous periods are 1899 – 1960, 1961 – 1963 and 1964 – 2008. Abrupt shifts occur in 1961 and 1964. The mean net basin supply during the three successive periods rises from 20,040 MCM (Million Cubic metres) to a short lived high of 80,558 MCM during three years and then declines to 33,325 MCM. From this preliminary analysis, the time series of Lake Victoria net basin supply can be construed to be non-stationary from the point of view of significance of occurrence of homogeneous segments with significantly different means.

The year 1918 was particularly dry and characterised by a negative value of net basin supply. The net basin supply for the year 2005, which is one of the years during which the lake releases were not conforming to the Agreed Curve following the commissioning of Kiira dam, was also negative.

The observed variation of annual net basin supply in Figure 5.4 is similar to the findings in a study for development of a new lake Victoria water release policy (Centre for Ecology and Hydrology, 2008), where the values were derived from 108 years of record (Sept 1899 – August 2008) and the difference is in their definition of a hydrological year i.e. September to August as opposed to the calendar year definition of January to December that is utilised in this study.

|The Institute of Hydrology (1993) evaluated the accuracy of net basin supply time series derived using the indirect approach (Figure 5.4) against those derived using a conventional water balance approach i.e. with lake rainfall and evaporation inputs for the period 1925 to 1990. It was concluded that there is reasonable agreement for both inflow models but the conventional water balance approach particularly provides a better representation of the increase in net basin supply during the 1961-64 period. The errors in net basin supply vary randomly in many periods, and are typically in the range 10,000-20,000 MCM/year. These error magnitudes were established to translate into about 0.15 - 0.30 m per year in terms of depth over the lake surface.

An assessment of the sensitivity of lake levels to variations in lake rainfall or land use change was also undertaken by the study conducted by Institute of Hydrology (1993). The findings demonstrated that Lake Victoria water balance is about 5 times more sensitive to long term changes in rainfall than to changes in basin runoff coefficient.

5.3.2 Lake Kyoga

A record of lake levels and outflows for Lake Kyoga pertaining to the period 1899 – 2008, derived using the methods described in Sections 4.4.2 and 4.4.3 was utilised as input to the Equatorial Lake Model.

The Equatorial Lake Model was run to simulate operation according to the natural Kyoga lake level-outflow relationship utilised in the LVDST (WREM Inc & Norplan (U) Ltd, 2004). The model iterates to compute a mean monthly discharge corresponding with an average monthly water level determined from start and end of month levels at Masindi Port. It utilises the elevation – storage characteristics for Lake Kyoga (WMO, 1982) in order to compute changes in storage from changes in level and finally computes the net basin supplies by application of Equation 5.4:

Lake Kyoga NBS = Kyoga Nile Outflow + Change in Storage – Victoria Nile outflow (5.4)

Simulated and observed water levels for Lake Kyoga are shown in Figure 5.5.

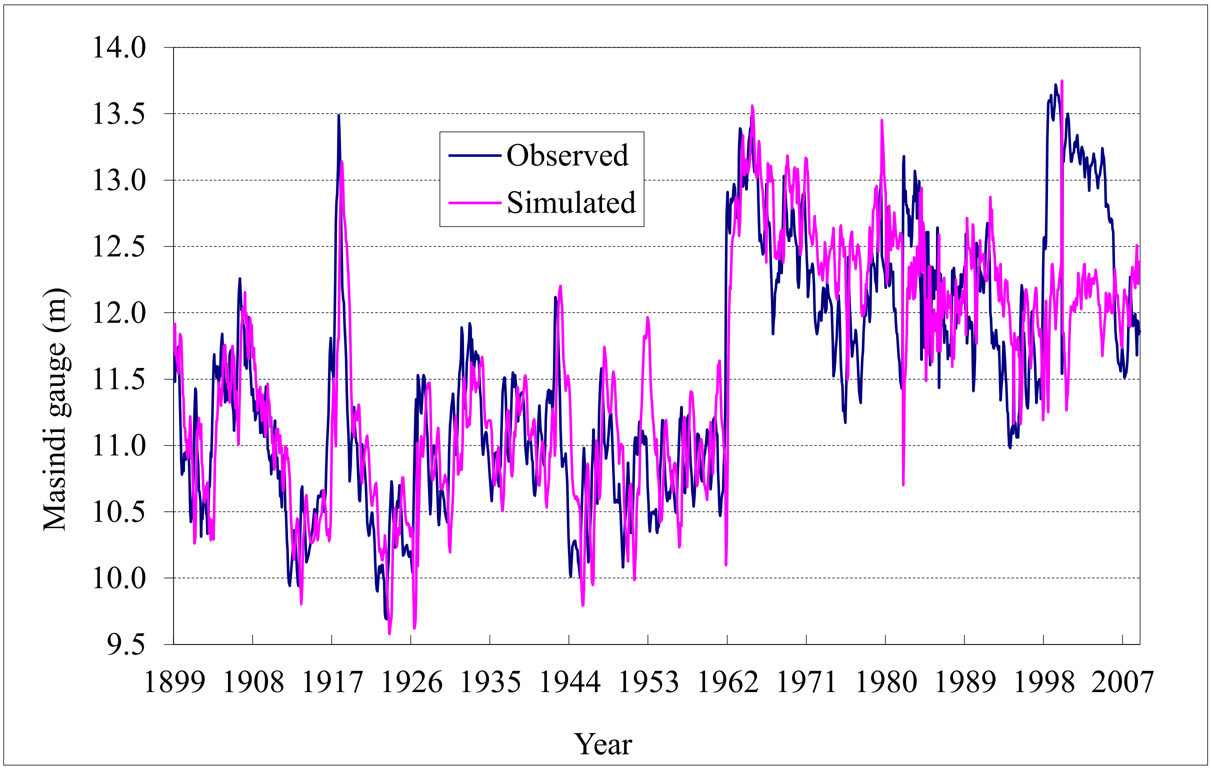


Figure 5.5 Model simulation of Lake Kyoga levels.

The results are similar to those obtained by Mot Macdonald (1998). It appears that observed water levels lag simulated water levels by approximately one month, but the magnitude of the simulated levels matches the observed closely from 1899 to 1979. After the year 1980 and particularly from 1978 to 1984 and in the early 1990's, simulated levels clearly exceed the observed. The discrepancies arise due to the fact that during extension of the data, some water levels were estimated using a rating relationship between mean monthly levels at Masindi Port and monthly Lake Kyoga outflow data. This relationship is expressed as Equation 4.2 in Section 4.4.3. Where the levels for in-filled periods are mean monthly rather than end of month, but are treated by the model as end of month, a shift will be evident.

During the duration of the blockage of Lake Kyoga, the model is unable to match the observed and simulated levels due to distortion of the natural level-outflow relationship after the blockage and during the remedial dredging works that took place to remove the blockage. Figure 5.6 illustrates model simulation of Lake Kyoga discharges.

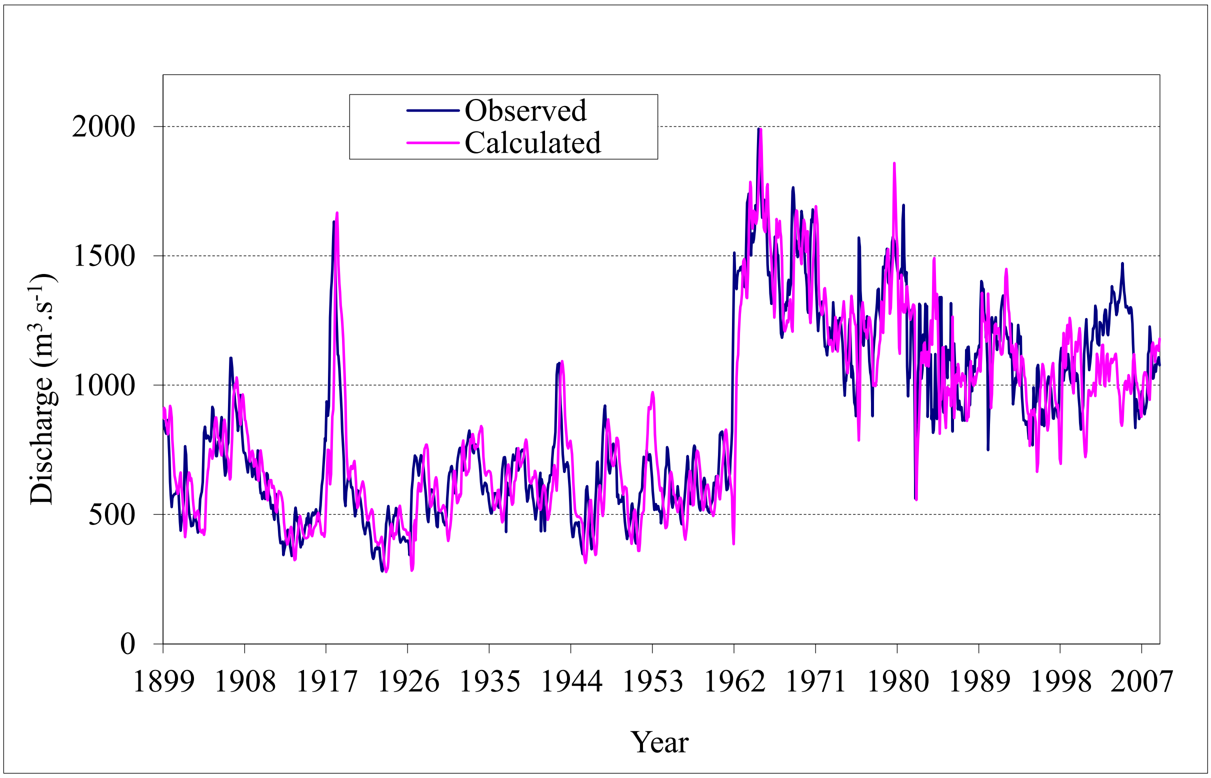


Figure 5.6 Model simulation of Kyoga discharges.

In Figure 5.6, the simulated discharges also appear to be slightly ahead of the observed discharges, with a reasonably good match until the onset of the blockage in May 1998. After the removal of the blockage in 2005, observed discharges increase but are not reproduced by the model due to unsteady flow conditions at the time of the dredging works.

Another contributing factor to the failure of the model to match observed and calculated discharges is the considerable scatter inherent in plots of long term lake level – out flow rating relationship at Masindi Port (WMO, 1977). All periods of the historic discharge record do not match the rating curve used by the model in computing lake discharge. Figure 5.7 shows the Kyoga outflow rating based on the observed data input to the model, and that used by the model to compute outflows. Clearly this is partly the source of differences between simulated and observed discharges.

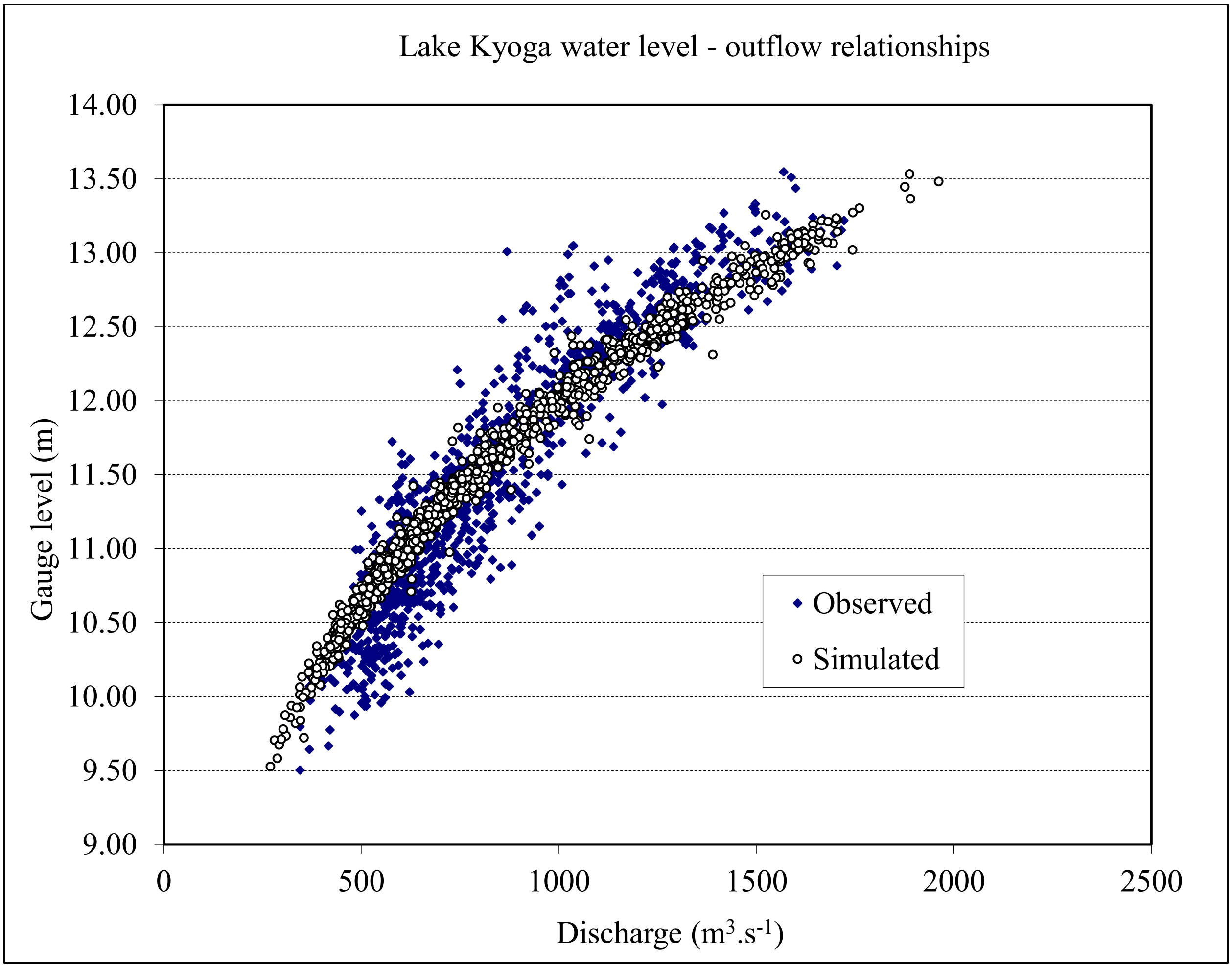


Figure 5.7 Lake Kyoga outflow relationships.

This indicates the need to regularly review and update the lake level-outflow and elevation area curves for Lake Kyoga since they are prone to alteration arising from both flood events and floating papyrus movements. The resulting Lake Kyoga annual net basin supply time series obtained through application of the Equatorial Lake Model were subjected to the segmentation algorithm developed by Hubert (1997, 2000) and the results are illustrated in Figure 5.8.

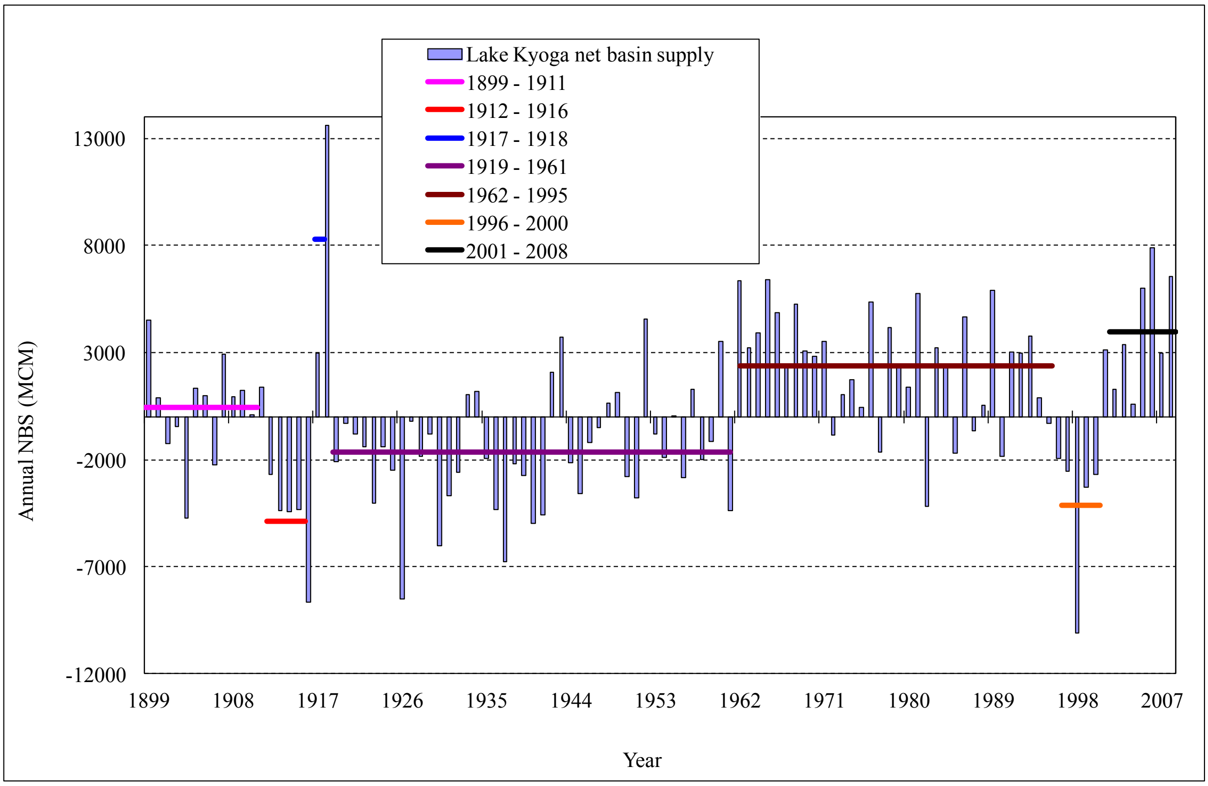


Figure 5.8 Historical variation in net basin supply to Lake Kyoga.

Application of the segmentation algorithm to the derived annual net basin supply time series of Lake Kyoga produced seven contiguous segments with different means at a 0.05 significance level of the Scheffe test. Several shifts occur in the averages of the dominant phases, and it appears that the time series exhibit alternating periods of net gains and net losses, where the duration of contiguous mean of net gain or net loss appear to be a random variable. The long term average for the period 1899 – 2008 is 157 MCM.

The alternating episodes of net gain and net loss in the various segments presents a markedly different pattern when compared against the results for Lake Victoria, where the change points in 1961 and 1964 do not correspond to the change points identified in the Kyoga data, particularly in 1962 and 1996. It appears that the sudden increase in lake rainfall in 1961 that occurred in Lake Victoria basin does not coincide in time over Lake Kyoga basin. It appears that the increase occurred a year later in 1962, and from then until 1995, there were net gains in inflow. It is not expected that the hydrological response time of the Lake Kyoga and Lake Victoria basin is similar owing to large differences in basin size and the significant influence attributed to the existence of extensive wetlands around Lake Kyoga. The Lake Victoria net basin supply has been shown to be more sensitive to net rainfall over the lake while Lake Kyoga is more susceptible to the effects of attenuation caused by the large surrounding wetlands (Sene, 2000).

The unique pattern of variation of the annual net basin supply time series over Lake Kyoga clearly illustrates the net effect of Lake Kyoga on the Nile flows, which is to cause net losses in dry years and net gains in wetter years (Hurst and Phillips, 1938). Extreme net gains in net basin supply are recorded in 1918, 1962, 1965 and in 2006 while the largest net losses occurred in 1916, 1926 and 1998. The segment for the period 1996 – 2001, coincides with the period when the blockage at the mouth of Lake Kyoga raised lake levels and increased the total surface area of the lake. It is associated with net loss in net basin supply. The reason as to why the net basin supply during the entire period is negative can be attributed to excessive evapotranspiration. The general pattern of net basin supply variability up to the year 1997 is similar to the results obtained by Mott MacDonald (1998) where data was analyzed for the period 1899 - 1997.

Brown and Sutcliffe (2013) have assessed the accuracy of net basin supply calculated from the difference between outflow and inflow, allowing for changes in lake storage for the period 1940 – 1977 when precise measurements are available. The assessment was conducted by comparing net basin supply with basin rainfall (Figure 5.9).

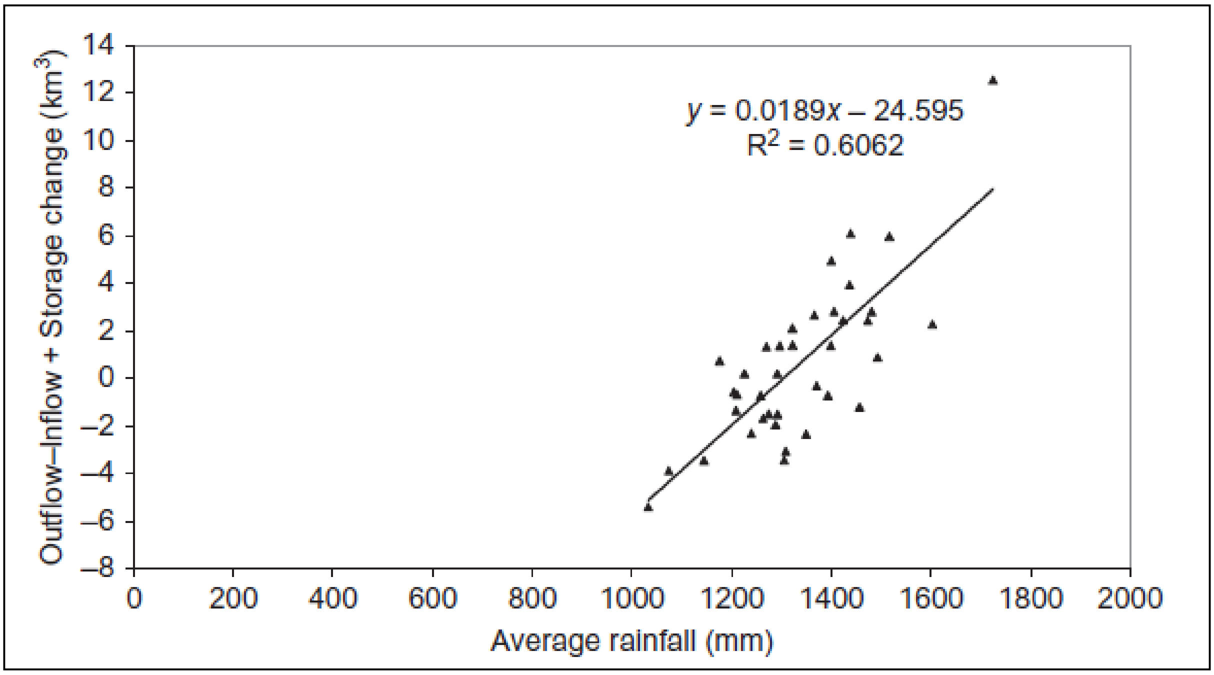


Figure 5.9 Lake Kyoga net basin supply vs basin rainfall (Brown and Sutcliffe, 2013).

The moderate precision of the derived relation between the two can be explained by errors inherent in the method of deriving the two datasets. There is a standard error introduced by utilizing measurements at Kamdini and Masindi Port to determine Lake Kyoga outflows. It can be deduced by computing the standard deviation of the differences over the periods 1940–1950 and 1971–1977 and was determined to be 1.30 km^3, or 5% of the average flow of 26.0 km^3 (Brown and Sutcliffe, 2013).

Lake Kyoga annual basin rainfall time series were estimated based on the average of annual totals at all available stations. The availability of stations varied throughout the assessment period (1902 – 1985) from 5 to 22. The standard error of basin rainfall estimate was quantified as the standard deviation of the station rainfall annual totals divided by the square root of the number of observations. The magnitude of the stand error was found to be high in the early years, reaching a fairly steady value of about 50 mm, and then increasing because of the decreasing station coverage after 1977 (Brown and Sutcliffe, 2013).

5.3.3 Lake Albert

The record of lake levels and outflows for Lake Albert pertaining to the period 1899 – 2008, derived using the methods described in Sections 4.5.1 and 4.5.2 was utilised as input to the Equatorial Lake Model. The Equatorial Lake model was run to simulate operation according to the natural Albert lake level-outflow relationship at Butiaba (Figure 4.12). The model iterates to compute a mean monthly discharge corresponding with an average monthly water level determined from start and end of month levels at Butiaba gauge. It utilises the elevation – storage characteristics for Lake Albert (WMO, 1982) in order to compute changes in storage from changes in level and then finally computes the net basin supplies by application of Equation 5.5:

Lake Albert NBS = Albert Nile Outflow + Change in Storage – Kyoga Nile outflow (5.5)

Figures 5.10 and 5.11 present simulated and observed average monthly levels and discharges respectively at Lake Albert. Observed and simulated lake levels for Lake Albert are similar in shape and range but with displaced timing of the peaks as evident in Figure 5.10.

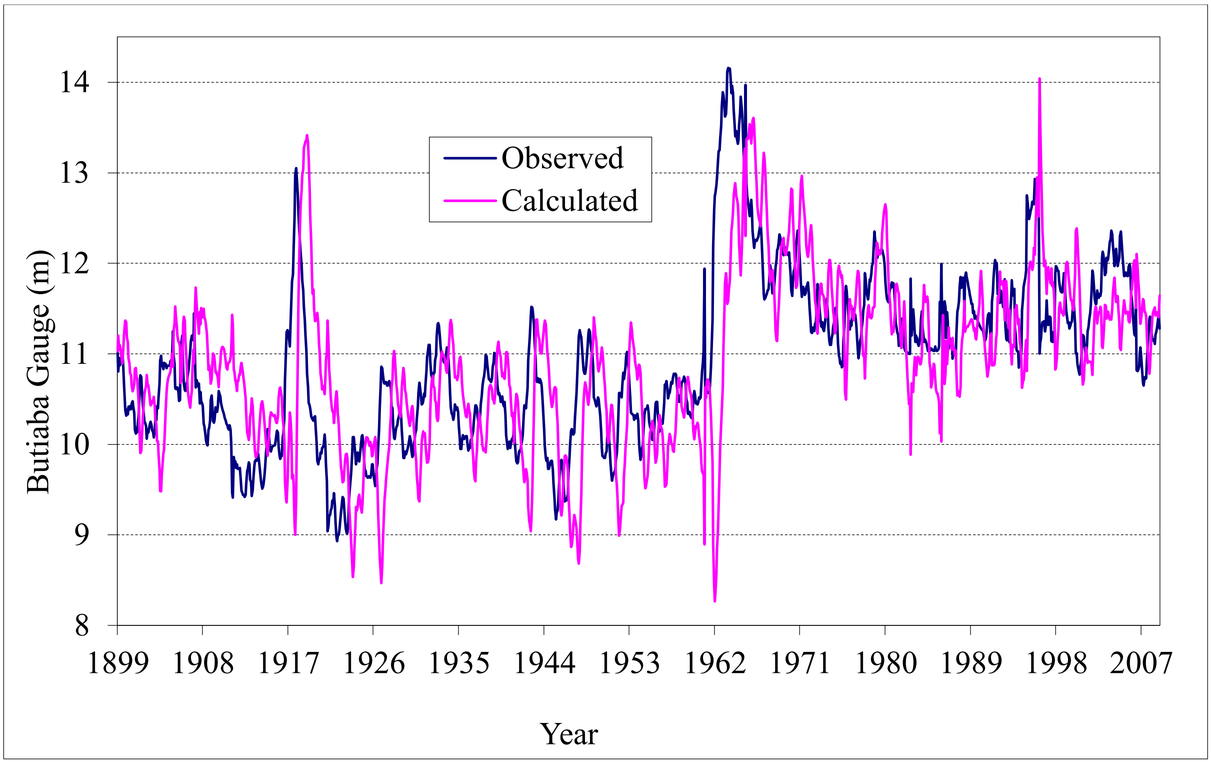


Figure 5.10 Model simulation of Lake Albert levels.

Simulated levels are over-estimated between 1905 and 1929, and underestimated in 1961 – 1964 and 1998 – 2005. A lag of 4 months can be discerned between the simulated and observed lake levels in 1918 but it appears to increase to 18 months from June 1963 to February 1966 although it appears to revert back to 3 – 4 months thereafter. Comparison of observed and calculated discharges shown in Figure 5.11 shows a similar pattern to the behaviour of the simulated levels but the range of simulated flows is closer to the observed.

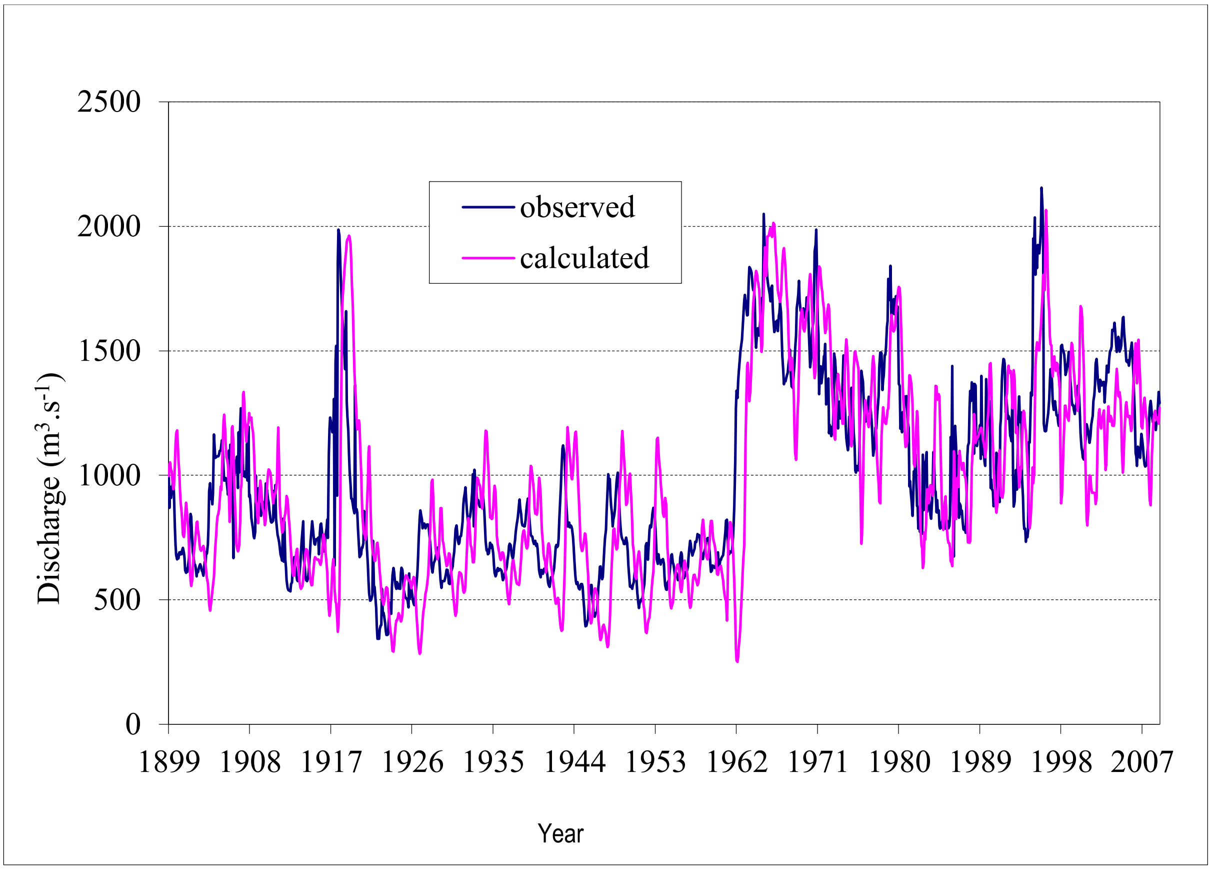


Figure 5.11 Model simulation of Lake Albert discharges.

The lack of correlation between the simulated and observed Lake Albert levels and discharges can be attributed to errors introduced by the estimation of missing segments of lake levels and outflows as outlined in Sections 4.5.1 and 4.5.2. In order to emphasize this argument, it is noted that particularly during the periods 1899 – 1904 and 1982 – 1994, the estimates of Lake Albert levels and outflows utilised in the application of the Equatorial Lake Model are more uncertain as the missing segment of lake levels were derived indirectly from correlation with long term lake Victoria outflows, while the representative outflow time series for Lake Albert was derived from rating curves that convert mean monthly lake levels at Butiaba to either measured discharges at Panyango (MottMacDonald, 1998) or dry season flow at Mongalla (Petersen *et al.,* 2008). Due to the considerable uncertainties inherent in the accuracy of these records, the implied lag between simulated and observed lake levels that could be attributed to the effects of storage in Lakes George and Albert and is difficult to quantify. Consequently the net basin supply time series obtained through application of the Equatorial Lake Model in Figure 5.11 is considered to be uncertain.

Application of the segmentation algorithm to the derived annual net basin supply time series for Lake Albert produced six contiguous segments with significantly different means from each other at a 0.05 significance level of the Scheffe test.

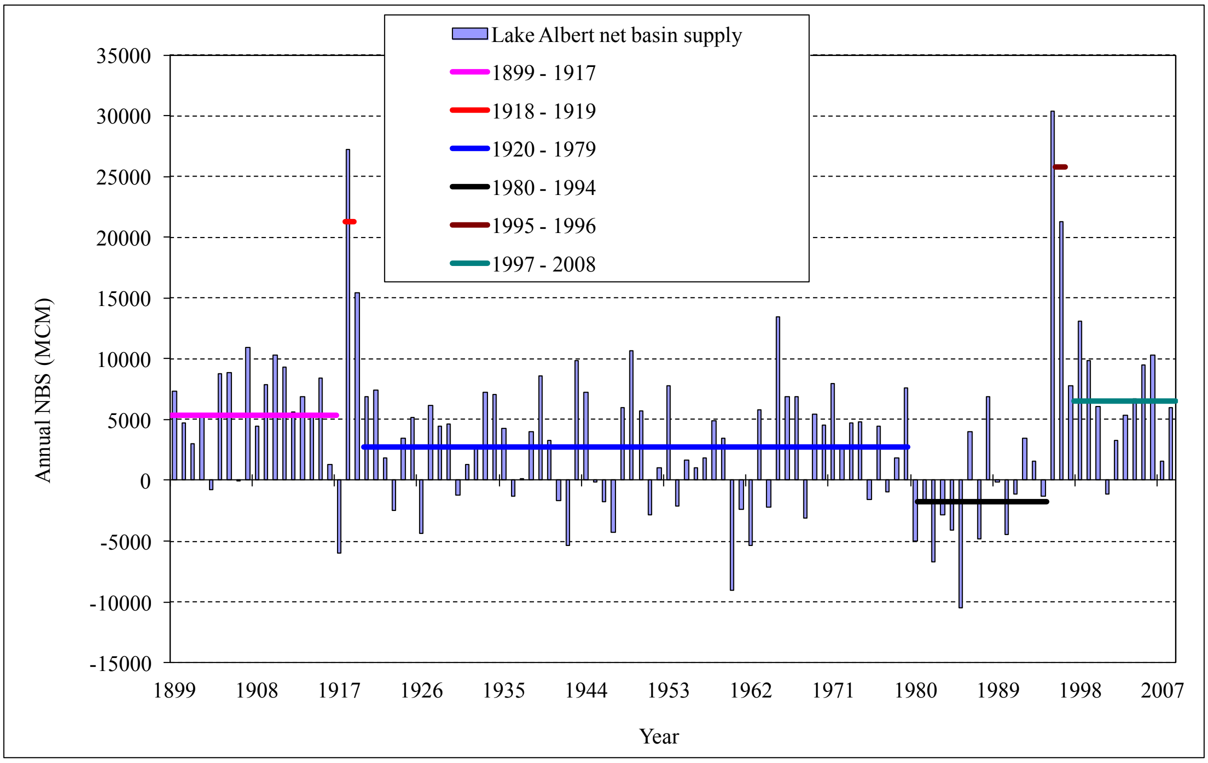


Figure 5.12 Historical variation in Net basin supply to Lake Albert.

In Figure 5.12, the Lake Albert net basin supply long term average for the period 1899 – 2008 is 3,755 MCM. The shifts in the patterns of net basin supply obtained for Lake Albert appear to be different from those observed for Lake Kyoga. The shifts in the means of the contiguous periods are smoother, either upwards or downwards but in the same direction. The exception to this occurrence is the period 1980 – 1994 where the mean net basin supply was negative.

Extreme net gains in net basin supply are recorded in 1918-1919, 1964 and in 1996 while the largest net losses occurred in 1960, and 1985. The general pattern of net basin supply variability is different from the results obtained by Mott Mac Donald (1998), whose analysis was based on the period 1899 – 1997. This is because significantly different data sets for observed outflows and lake levels were utilised. It is important to deduce how net basin supply derived as outflows from Lake Albert at Mongalla and storage change minus inflow relates to lake rainfall. In this case the comparison for the period 1940 – 1976 (Figure 5.13), only serves to indicate the marginal relevance of lake rainfall estimates established from a single station at

Butiaba. The scatter is considerable owing to the measurements errors in lake outflows, inflows and the use of a single rainfall station (Sutcliffe and Parks, 1999).

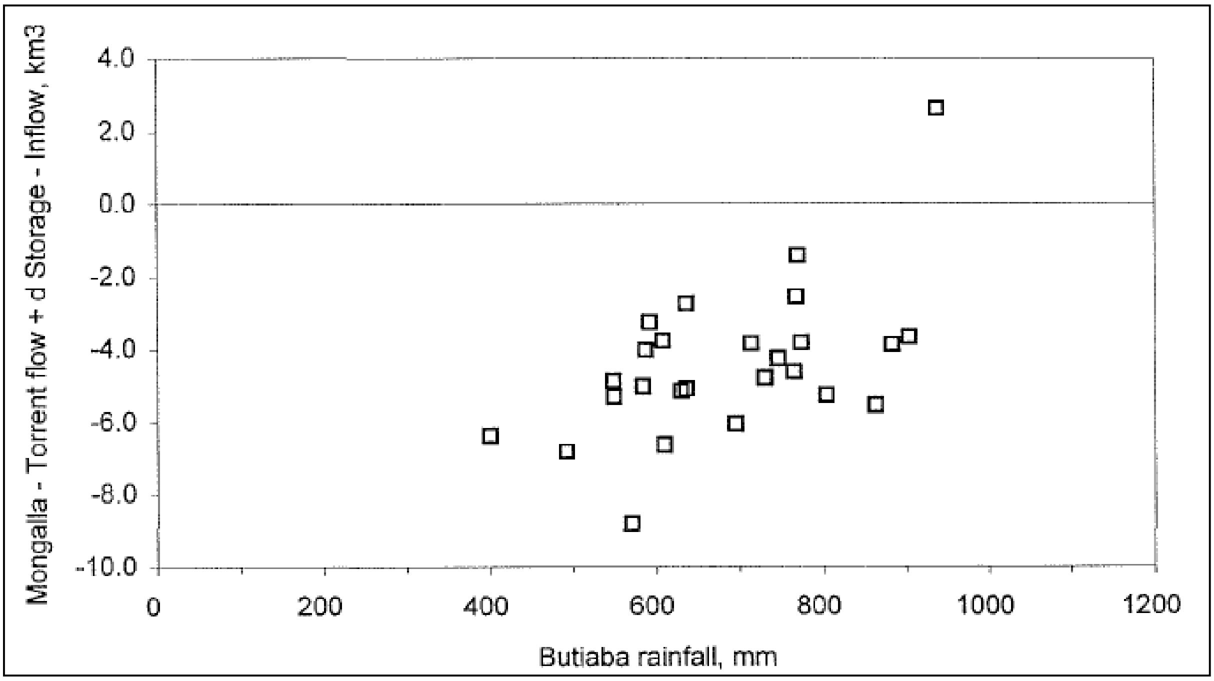


Figure 5.13 Lake Albert net basin supply *vs*. rainfall: 1940 -1967 (Sutcliffe and Parks, 1999).

5.4 Concluding remarks

The Equatorial Lake Model has been applied based on the assumption that Lakes Victoria, Kyoga and Albert are unregulated for the period 1899 – 2008. The concurrent record of lake levels and outflows for each of the lakes that was derived in Chapter 4 was utilised as the basic data to run the model. This data is taken to be representative of the hydrological regime during the same period. The analysis showed excellent agreement between observed and simulated lake levels and outflows for Lake Victoria but exhibited less accuracy in reproducing the historical variation of natural lake levels and outflows for Lakes Kyoga and Albert. The reasons for the observed discrepancies with regard to Lake Kyoga and Lake Albert can be attributed to uncertainties inherent in the derivation of their long term lake levels and outflow relationships and the fact that missing segments of lake levels and outflows were estimated using various methods. The net basin supply values for Lake Victoria are considered to be accurate due to the reliability of the lake level outflow relationship and the availability of a concurrent long term period of observed lake levels and outflows for the period 1899 – 2008, which forms the basis for the computation.

The overall consistency and accuracy of net basin supply time series derived in a similar manner for Lake Kyoga and Albert is also more difficult to ascertain due to the effects of attenuation induced by the surrounding wetlands and storage in Lake George and Edward which were ignored in the modelling framework.

The existence of strong temporal persistence, long term periodicities and evidence of abrupt changes in statistical parameters such as the mean have been demonstrated in the time series. A possible cause of the non-stationarity of in the time series can be attributed to changes in basin rainfall and the effects of the ENSO phenomena within the region.

Time series with such characteristics are associated with poor possibilities to fit classical autoregressive models for purposes of further stochastic analysis. A segmentation algorithm which enables the detection of multiple change points in the means of contiguous segments of a time series was therefore applied to the derived net basin supply time series for each lake. The findings confirmed the presence of abrupt shifts in the mean of contiguous time segments of the net basin time series, which occur in certain years, although not necessarily for the same periods for each lake. The pattern of alternating periods of high and low values is unique to each lake for the common period considered, i.e. 1899 – 2008. The results seem to suggest that the basin hydrological regimes are not consistently similar during the period considered, from the point of view of net basin supply at an annual time scale. For example, the cyclic and alternating pattern of positive net gain and net loss in Lake Kyoga contiguous segments of net basin supply time series is unique to this basin and not applicable to Lake Victoria and Albert basins. The extremely wet period registered from 1961 - 1963 in Lake Victoria basin was not experienced as significantly in the Kyoga and Albert basins, whereas the year 1918 is one of the most extreme wet years recorded concurrently in these two basins.

Despite the documented reservations about the reduced accuracy in matching observed levels, outflows, and computed net basin supply for Lakes Kyoga and Albert, it is considered that the reference set of indicative historical net basin supply time series that were utilised as basic data by the deterministic dynamic programming models were sufficient for purposes of generating alternative operating rules for the Equatorial Lakes

6. STOCHASTIC ANALYSIS, MODELLING AND SIMULATION OF EQUATORIAL NET BASIN SUPPLY TIME SERIES

The net inflows to the Equatorial Lakes have been represented as net basin supplies in the modelling framework adopted in the previous chapter to simulate lake levels and outflows under unregulated conditions. The net basin supplies were derived from an indirect water balance computation approach for each lake and they represent the aggregation of water gains due to rainfall over the lakes, basin runoff into the lake, water losses resulting from lake evaporation and groundwater outflow.

The annual net basin time series for the Equatorial Lakes have also been shown in the previous chapter to exhibit abrupt shifts from one stationary state into another. Salas and Boes (1980) discussed the potential of applying shifting mean models to such hydrological processes whose means shift upwards or downwards at random intervals. Sveinsson *et al.* (2003) provided a probabilistic framework for modelling the temporal dynamics of abrupt shifts in hydro-climatic time series. The methods suggested in their framework are particularly suitable for simulation and generation of long sample records. Sveinsson and Salas (2006) expanded the previous studies of the shifting mean models to develop univariate and multivariate Contemporaneous Shifting Mean (CSM) models and applied them successfully to model the annual net basin supplies of the Great Lakes System in North America, where some of the lake time series showed evidence of shifts, spatial correlation and autocorrelation.

These examples suggest the need to further analyze and model the net basin supply time series of the Equatorial Lakes based on stochastic techniques. Currently available methodologies (Salas *et al*., 2009), indicate that the activities involved in the analysis and construction of a stochastic model for generating synthetic net basin supplies are generally as follows:

(i) Extract fundamental information about the annual and monthly series of net basin supply.

(i) Select and fit an appropriate model to the data that is capable of reproducing temporal variability and cross correlation structure between inflows to the lakes.
(ii) Estimate the model parameters.

(iii) Test the model and verify it by comparing statistics obtained from the generated data with those determined from the historical data.

This chapter contains a description of the statistical analysis of the underlying nature of the derived historical net basin supply series for the Equatorial Lakes, which is the basis for the formulation and application of the dynamic programming algorithms and generation of synthetic net basin supply series. The synthetic series are often required as input to optimization models or are applied at a later stage to test and evaluate derived operating rules in lake regulation studies. In order to facilitate the application of these methods the Stochastic Analysis, Modelling and Simulation (SAMS) computer software package for hydrologic time series developed by Colorado State University and the US Bureau of Reclamation (Sveinsson *et al*., 2007), has been adopted. Univariate Shifting Mean models fitted to the annual historical data with a disaggregation model for temporal disaggregation of annual to monthly net basin supplies are utilised within the software to generate the synthetic series which are compared against the historical data set.

6.1 Analysis of statistical characteristics

According to Salas and Pielke (2003), the most commonly used statistical properties for analyzing stationary or non-stationary time series are the sample mean ($\bar{y}$), variance (s^2), coefficient of variation (cv), skewness coefficient (g), lag-k auto correlation coefficient (r_k), the cross correlation coefficient at lag zero and the spectrum, $g(f)$. These statistics can be defined for both annual and seasonal data and the equations to define them are available in many standard textbooks and implemented computer software for mathematical and statistical computations. In this study, the formulae and notation for these basic statistics are as defined by Sveinsson *et al*. (2007).

A key task in the construction of a stochastic flow generation model is to determine the record of historic NBS time series and extract the fundamental characteristics of the multivariate stochastic process that represent it. The temporal and spatial properties of the historical record of NBS time series were analyzed at annual and monthly time steps and the results are presented in the following sections.

6.1.1 Annual net basin Supplies

The Equatorial Lakes annual NBS time series were segmented into contiguous sequences of statistically different means in the previous chapter. Several occurrences of non-stationarity were revealed and periods during when major shifts occurred were identified. Table 6.1 contains a summary of the temporal properties of the annual NBS for Lakes Victoria, Kyoga and Albert. In the table Acf (1) and Acf (2) refer to the autocorrelation lag-1 and lag-2 coefficients. Mean net inflows to Lake Victoria are considerably larger than the values from lakes Kyoga and Albert as expected due to differences in basin size.

Table 6.1 Annual sample statistics (1899 -2008)

Lake	Mean (MCM)	Standard deviation (MCM)	Coefficient of variation	Coefficient of skewness	Acf (1)	Acf (2)
Victoria	27125	20860	0.77	0.36	0.27	-0.04
Kyoga	169	3590	21.29	0.32	0.29	0.22
Albert	3757	5988	1.59	1.10	0.30	0.14

The coefficient of variation values indicate a very high degree of variability of Lake Kyoga annual net basin supply. The coefficients of skewness are relatively low for Lakes Victoria and Kyoga indicating near normality of the distribution while the values for Lake Albert are slightly greater than 1.5 showing that this data is non-normal and highly skewed. The plot of the autocorrelation coefficient at various lag times is known as a correlogram or Auto Correlation Function (ACF) and it provides information about the degree of persistence in the structure of the time series. The correlograms for each of the lakes are presented under Figures 6.1 – 6.3. The dashed lines in the correlograms represent the confidence intervals and correspond to the limits 0.2 and -0.2.

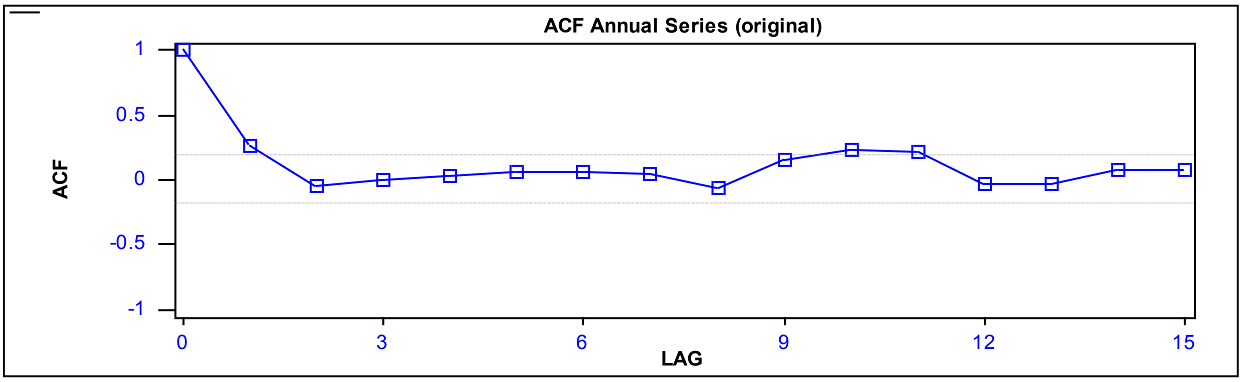


Figure 6.1 Correlogram – Lake Victoria annual series.

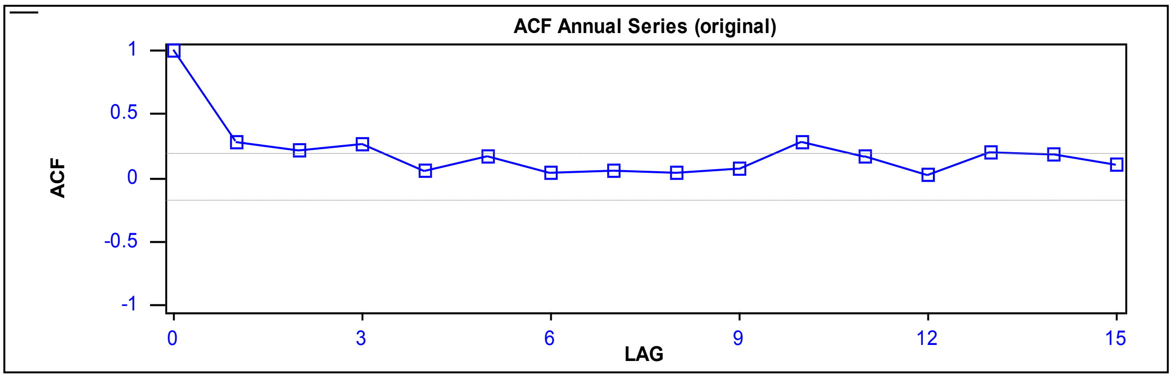


Figure 6.2 Correlogram – Lake Kyoga annual series.

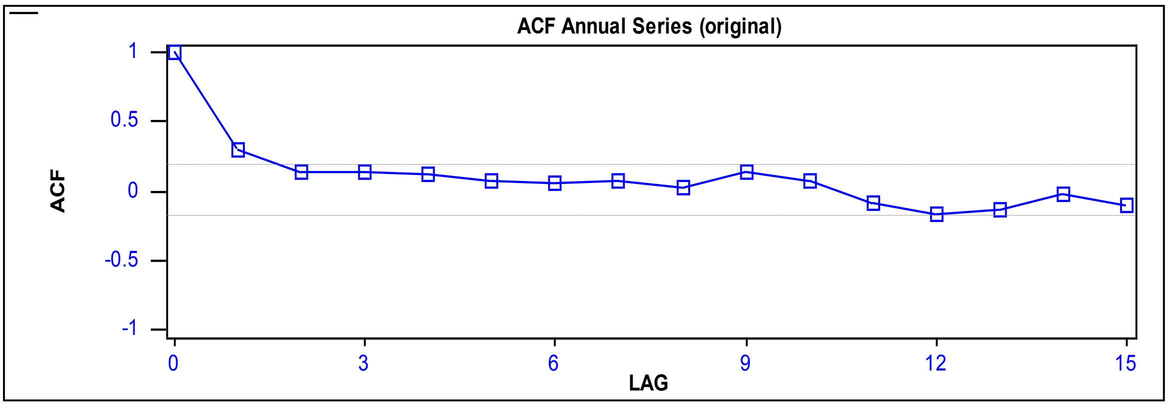


Figure 6.3 Correlogram – Lake Albert annual series.

The autocorrelation functions for all three lakes at the annual time scale do not cut off abruptly and vary irregularly with increasing lag, indicating a degree of persistence or memory. The lag-1 correlation coefficients for Lake Victoria and Lake Albert are low but still significant at a 5 % significance level while the lag-1 to lag-3 coefficients for Lake Kyoga are low but still significant at the 5 % level. The structure of an autocorrelation function is an important consideration in the process of choosing the type of stochastic model to be adopted to represent the time series (Bras and Rodriguez-Iturbe, 1985).

The cross correlation coefficients at lag zero are another important statistic to consider when analyzing the three time series of the lakes jointly. The cross correlation at lag-zero for Lakes Victoria vs Kyoga and Kyoga vs Albert were -0.19 and 0.18 respectively. The values are insignificant at the 5 % level while the cross correlation at lag-zero between Victoria and Albert is -0.36, i.e. significant at the 5 % level, but low.

6.1.2 Monthly net basin supplies

The time series of monthly net basin supply for each lake, for the number of years of record (1899 – 2008), has also been studied in detail. Their auto-correlation functions or correlograms with the lag in months, up to 36 months are displayed in Figures 6.4 to 6.6.

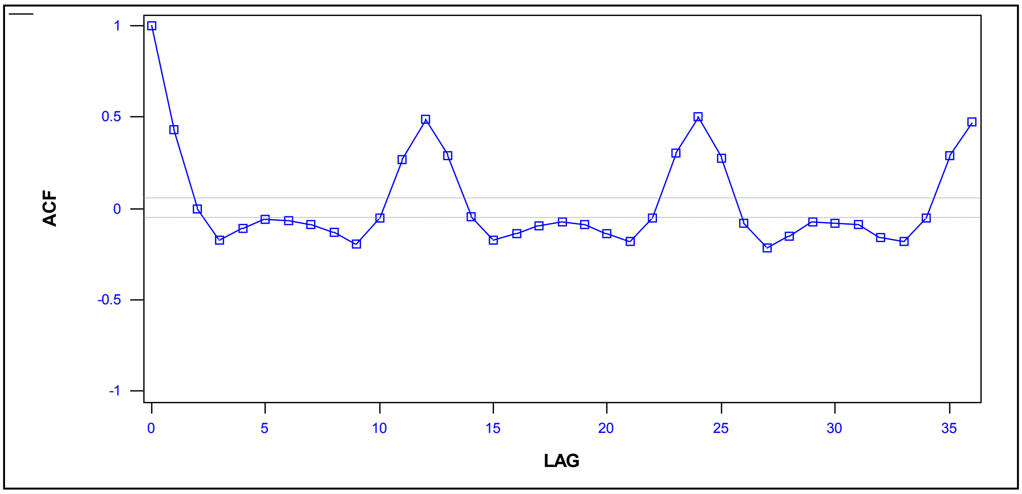


Figure 6.4 Correlogram – Lake Victoria monthly series.

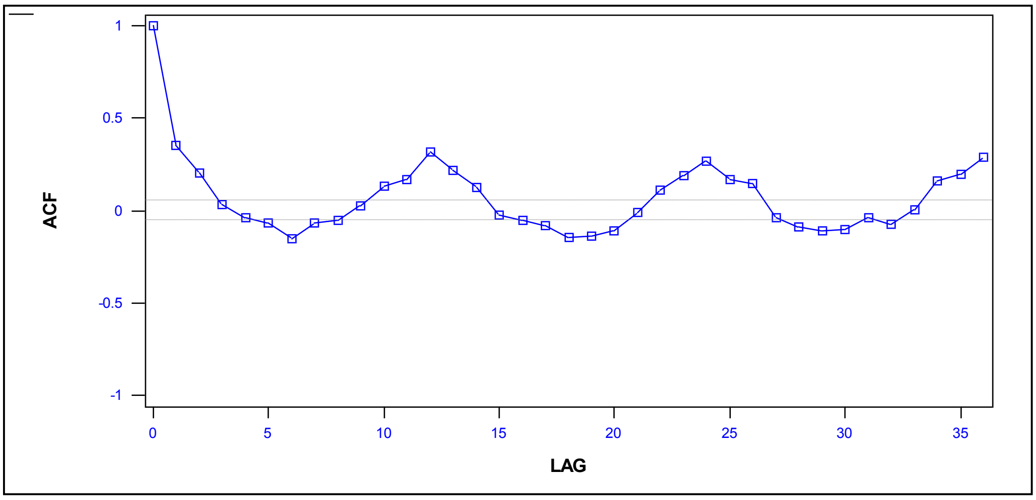


Figure 6.5 Correlogram – Lake Kyoga monthly series.

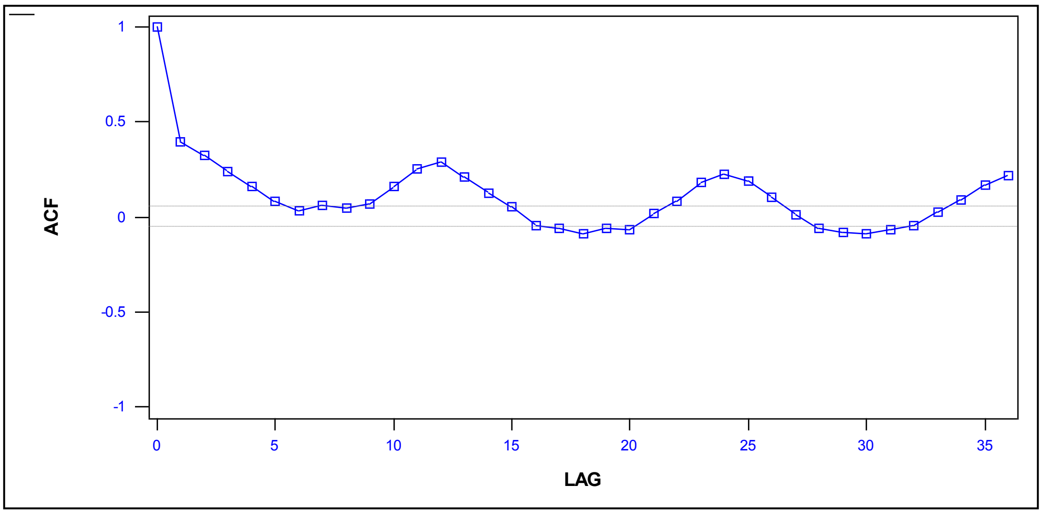


Figure 6.6 Correllogram – Lake Albert monthly series.

The correlograms for each lake possess a unique signature shape but in all three, the autocorrelation function is cyclic and symmetric, of similar amplitude, and is non-decaying, essentially indicating a stochastic seasonal process with long term dependence and with an almost perfect correlation between net inflows with a 12 months lag.

The shape of the correlograms in Figures 6.4 – 6.6 indicate the presence of periodicity which can be confirmed quantitatively by analyzing the Fourier transform of the autocorrelation functions. This exercise, also known as spectral analysis, involves the separation of the variance of a time series of record into its components parts at different frequencies (Wastler, 1969). Spectral analysis was performed on the individual time series of monthly NBS for each of the three lakes to yield a spectrum of variance or spectral density plots as shown in Figures 6.7 – 6.9.

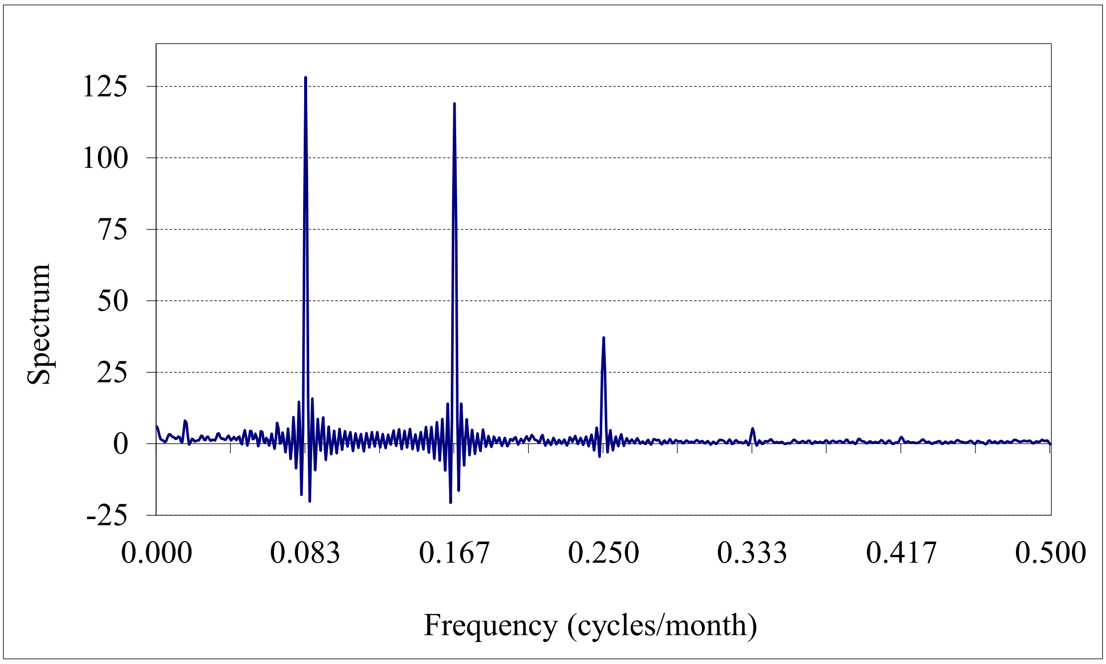


Figure 6.7 Spectral density plot – Lake Victoria.

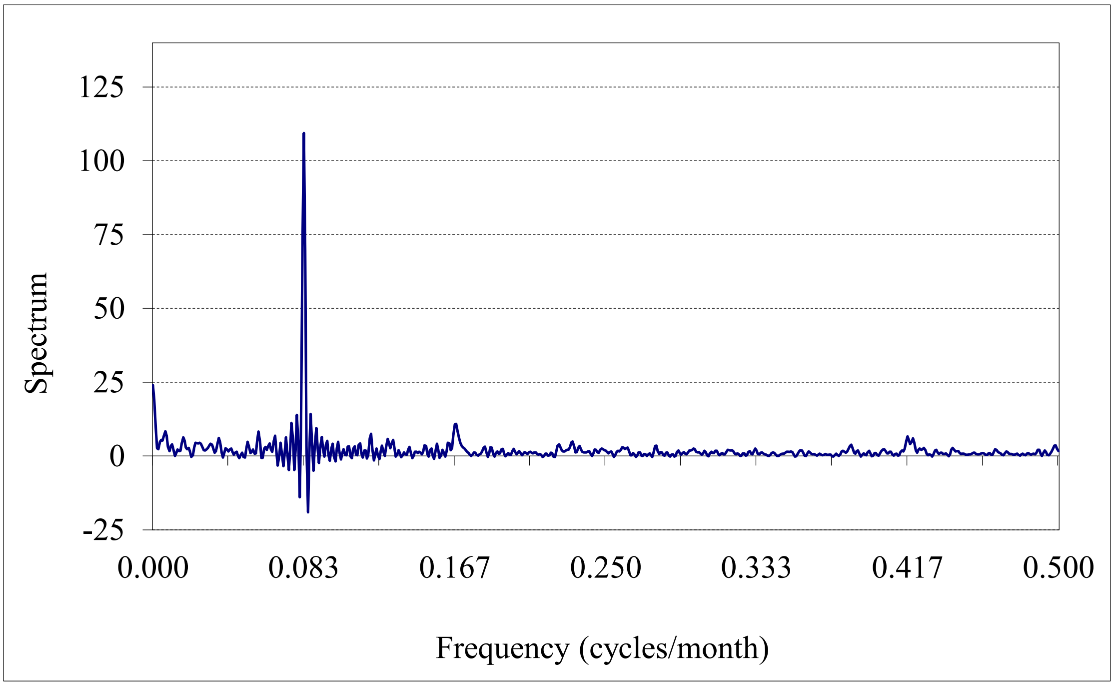


Figure 6.8 Spectral density plot – Lake Kyoga.

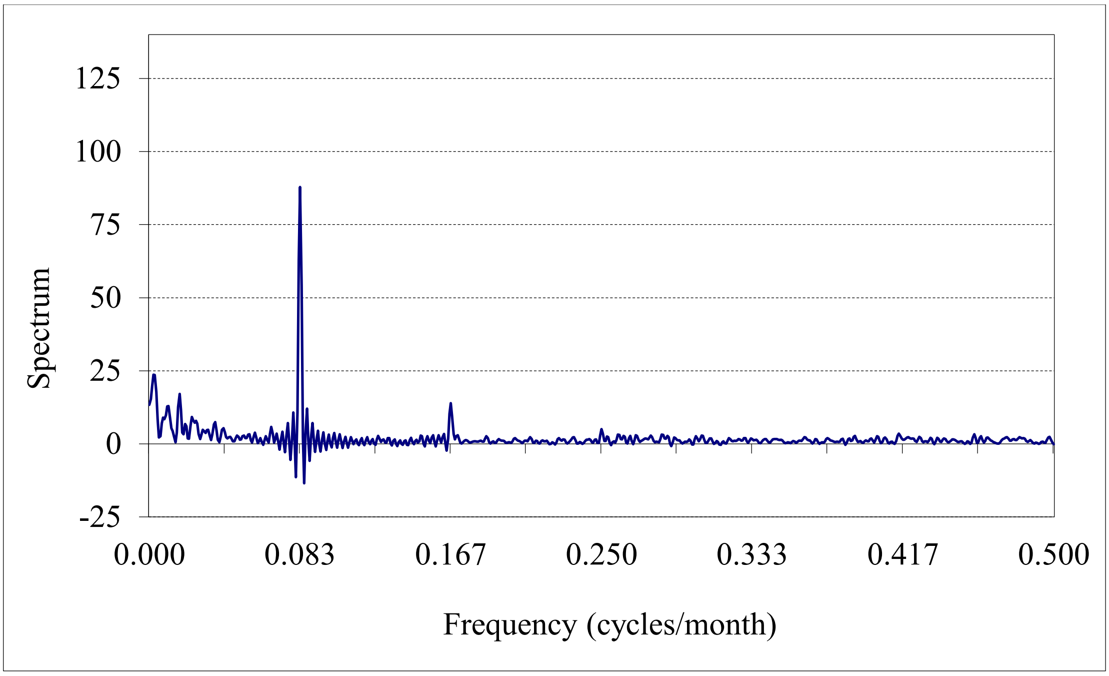


Figure 6.9 Spectral density plot – Lake Albert.

The spectral density plots for all the three lakes show that a strong peak density lies in the frequency band of 0.083 cycles per month which is equivalent to 12 months per cycle. This evidence strongly indicates that the hydrologic process of the lakes can be assumed to be periodic. In the case of Lake Victoria, the 6 month cycle at a frequency of 0.167 is also significant but the variance spectrum of the 3 month cycle at a frequency of 0.25 is small and can be considered insignificant. The correlation coefficients between the inflows of a particular month and its preceding 12 months for each lake are tabulated in Tables 6.2 – 6.4.

Table 6.2 Correlation coefficients between the net inflows of a particular month and its preceding 12 months for Lake Victoria

	Preceding Month											
Current Month	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Jan.	0.02	0.07	0.14	0.13	0.15	0.10	0.06	0.10	0.04	0.08	-0.07	0.08
Feb.	-0.01	-0.14	0.08	-0.08	0.20	0.11	-0.11	0.02	-0.08	0.03	0.06	0.01
March	-0.02	0.15	0.06	-0.04	0.10	-0.03	0.03	-0.12	0.00	0.02	-0.07	-0.09
April	-0.04	-0.12	-0.03	-0.12	0.25	0.13	-0.05	-0.07	0.01	-0.05	-0.11	-0.03
May	0.00	-0.26	-0.03	-0.12	-0.07	0.02	0.09	-0.02	-0.13	-0.02	-0.03	0.10
June	0.17	0.02	0.00	-0.11	0.00	-0.11	0.15	0.16	0.00	0.02	-0.17	0.10
July	0.16	-0.15	-0.12	0.05	0.17	0.11	-0.07	0.02	-0.09	0.14	0.08	0.01
Aug.	-0.09	0.04	0.00	-0.09	-0.08	0.17	-0.05	0.07	-0.09	0.00	-0.13	0.06
Sept.	-0.01	0.02	0.00	-0.06	-0.20	-0.02	0.03	0.21	-0.06	-0.08	-0.24	-0.07
Oct.	0.18	0.24	0.00	0.21	0.27	0.16	0.19	0.00	0.17	0.06	0.33	0.12
Nov.	0.14	0.01	-0.01	0.03	0.16	0.10	0.09	-0.03	0.21	0.01	0.10	0.12
Dec.	-0.14	0.27	-0.01	-0.15	0.15	-0.03	0.11	0.00	0.04	0.00	-0.25	0.07

Table 6.3 Correlation coefficients between the net inflows of a particular month and its preceding 12 months for Lake Kyoga

	Preceding Month											
Current Month	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Jan.	-0.18	-0.07	0.05	0.04	-0.09	0.04	-0.09	0.09	-0.16	-0.01	0.07	0.05
Feb.	0.22	-0.09	0.17	0.13	0.01	0.02	-0.13	-0.19	-0.10	-0.16	0.14	0.07
March	0.04	0.30	-0.21	-0.09	0.13	0.06	-0.25	0.00	0.20	0.20	0.19	0.18
April	0.25	0.03	0.07	-0.04	0.06	0.10	0.20	0.09	-0.02	0.09	0.29	0.10
May	0.20	0.08	0.06	0.19	0.03	-0.01	0.04	0.07	-0.09	-0.01	0.05	0.22
June	0.17	0.30	0.25	0.32	0.33	-0.01	0.16	0.16	0.19	0.00	0.13	0.19
July	0.00	-0.02	0.05	0.23	0.16	0.19	0.03	0.11	0.04	0.02	-0.03	-0.05
Aug.	0.10	-0.02	-0.17	0.09	0.19	0.10	0.08	0.04	-0.06	0.26	0.07	-0.10
Sept.	0.18	0.01	0.00	0.00	0.09	0.11	0.15	0.30	-0.09	-0.15	-0.16	0.02
Oct.	0.05	-0.06	0.01	0.12	0.15	-0.01	0.14	-0.03	0.05	0.07	0.07	0.08
Nov.	0.07	-0.17	0.00	-0.09	0.01	-0.05	0.10	-0.15	0.04	0.11	0.12	0.08
Dec.	0.01	-0.03	0.12	-0.02	0.13	0.10	0.03	0.10	0.04	0.04	0.04	0.05

Table 6.4 Correlation coefficients between the net inflows of a particular month and its preceding 12 months for Lake Albert

	Preceding Month											
Current Month	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Jan.	-0.05	-0.06	0.13	-0.03	-0.03	-0.06	0.02	0.02	0.17	-0.11	0.04	-0.18
Feb.	0.05	-0.12	-0.12	-0.03	0.13	-0.12	0.19	-0.01	0.12	-0.11	0.06	0.11
March	0.26	0.31	-0.12	0.01	0.05	-0.05	0.12	0.17	0.19	0.14	0.10	0.25
April	0.00	0.05	0.19	-0.03	0.01	0.04	-0.02	0.06	-0.04	0.01	-0.13	0.06
May	-0.01	-0.15	-0.02	0.04	0.03	-0.06	0.07	0.05	-0.04	0.00	0.02	-0.03
June	0.03	-0.04	0.07	-0.09	-0.08	0.07	-0.05	-0.02	0.08	-0.14	-0.05	0.18
July	0.15	0.09	0.20	0.17	0.21	0.21	-0.07	0.01	0.06	0.23	0.06	0.09
Aug.	0.11	0.11	0.06	0.18	0.17	0.18	0.15	-0.06	0.00	0.12	0.20	0.07
Sept.	0.05	0.09	0.03	0.05	0.06	0.15	0.12	0.31	-0.10	-0.03	-0.05	0.05
Oct.	0.05	-0.09	-0.12	0.08	0.05	-0.05	0.03	0.02	0.07	-0.15	0.04	0.12
Nov.	0.14	-0.07	-0.09	-0.08	0.05	0.08	0.04	-0.03	0.14	0.20	-0.12	-0.05
Dec.	-0.14	0.04	0.09	-0.03	0.04	0.08	0.16	0.14	0.15	-0.09	0.22	0.01

For all three lakes, it is observed that generally the correlation coefficients between net inflows for any two months are very low, often less than 0.2 and not more than 0.33. Correlation between Lake Victoria net inflows are higher when a comparison is made between the months April-May, May-February, October-May, October-December, December-February and December-November. In the case of Lake Kyoga, the highest correlations between net inflows of any two months are obtained for the month of June (up to a time lag of four months) and in consecutive months particularly March-February and September-August. The highest correlation coefficients between net inflows of any two months for Lake Albert occur when a comparison is made between the months of March-February and September-August.

In a situation where the correlation between the inflows in consecutive months is generally stronger than the correlations between non-consecutive months, Su and Deininger (1974) argue that the stochastic process of the monthly inflows can be reasonably assumed to be a first-order Markovian process. This assumption is an important consideration when formulating the optimization approach in a series of reservoirs.

6.2 Model identification

Stochastic time series models have been extensively applied in water resources management to generate long synthetic time series that have subsequently been used as input to management models for reservoirs. Traditionally, Autoregressive Moving Average (ARMA) type of models were considered but have since proven to be inadequate under circumstances when modelling long term persistence is important or if there are shifts in the long term series (Sveinsson *et al.*, 2005). Other classes of models such as the fractional Gaussian models, and broken line models that are capable of modelling long term persistence have been cited to have a number of weaknesses such as the difficulty of parameter estimation (Koutsoyiannis, 2000), and have not been implemented in the commonly available stochastic hydrology software such as SAMS, LAST (Lane and Frevert, 1990) and SPIGOT (Grygier and Stedinger, 1990).

The models mentioned so far are often referred to as parametric methods for stochastic data generation. Non-parametric modelling alternatives have also been suggested in literature. These include block boot-strapping (Vogel and Shallcross, 1996) and k-nearest neighbours re-sampling (Lall and Sharma, 1996; Buishand and Brandsma, 2001). Issues associated with the choice and application of either a parametric or non-parametric approach have been reviewed by Rajagopalan *et al.* (2009). Non-parametric methods are robust, easier to understand and have fewer challenges with parameter identification when compared to parametric approaches. However, non-parametric methods tend to generate flow patterns that may be repetitive or too identical to the historical sequences (Prairie *et al.*, 2007). Generating similar or identical values and patterns is not desirable (Maheepala and Perera, 1996).

A class of Markov Switching (MS) models, that are capable of generating annual time series under the assumption that the climate is varying between various states, and that the state sequence is a Markov chain, have been investigated by Akintuğ and Rasmusses (2005). One of their key observations was that the MS model possesses close links with the Shifting Level (SL) model originally proposed by Salas and Boes (1980). Fortin *et al.* (2004) has shown that the SL model is actually a formulation of the MS model. The statistical properties of the Equatorial Lakes NBS annual time series, with shifts and long term persistence, has resulted in the choice of appropriate model for data simulation to be a univariate or multivariate Shifting Mean model.

The general form of the Shifting Mean (SM) model (Sveinsson and Salas, 2003; Sveinsson *et al.*, 2005) is defined by Equation 6.1.

$$X_t = Y_t + Z_t \tag{6.1}$$

where X_t is a sequence of random variables representing the annual series of NBS; Y_t is a sequence of independent and identically distributed (iid) variables with mean μ_Y and variance σ_Y^2; and Z_t is a sequence with mean zero and variance σ_Z^2. The sequences Y_t and Z_t are assumed to be mutually independent of each other. Process X_t is characterized by multiple "stationary" states each of random length N_i, i = 1,2.. as shown in Figure 6.10.

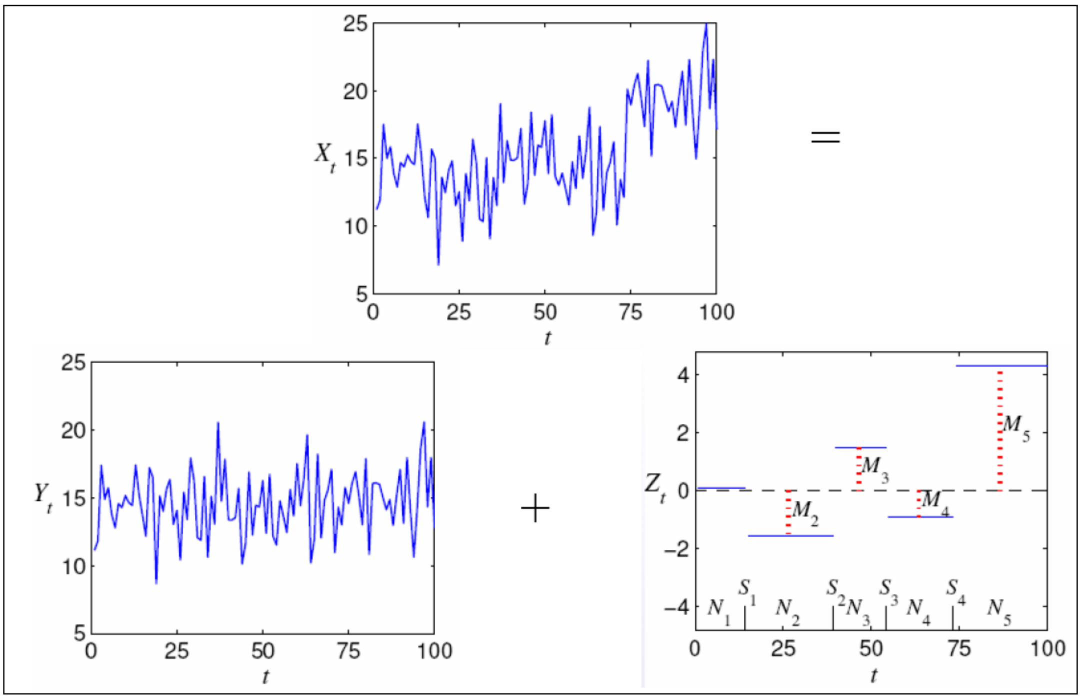


Figure 6.10 A schematic representation of the shifting mean process (Sveinsson *et al.,* 2007).

The stationary states are assumed to be different from one another but only vary around the long term mean of the stochastic process. The patterns of sudden shifts in the long term mean of the process from one state to the other are represented by Z_t. The sudden shifts are responsible for autocorrelation in the process and are also referred to as noise levels. The noise level process Z_t is defined by Equation 6.2:

$$Z_t = \sum_{i=1}^{t} M_i I_{(S_{i-1},S_i)}(t) \tag{6.2}$$

where $S_i = N_1 + N_2 + \ldots + N_i$ with $S_0 = 0$, and $I_{a,b}(t)$ is the indicator function equal to one if *t* $\in$ *(a,b)* and zero otherwise. Sveinsson *et al.* (2003) further explain that the noise levels $M_1, M_2, \ldots$, are zero mean random variables assumed to be iid normal with $\sigma_M^2 = \sigma_Y^2$, and $N_1, N_2, \ldots\ldots$, are positive geometric random variables with probability mass function given by

$$P(N = n) = p(1-p)^{n-1} I_{\{1,2\ldots\}}(n) \tag{6.3}$$

Parameter *p*, takes on a value of between 0 and 1. Thus the average length of each state of the process is computed as the inverse of the parameter *p*. The SAMS software package provides a number of options for fitting the SM models to a time series in the univariate or multivariate domain. Contemporaneous Shifting Mean (CSM) models are appropriate in situations where it is required to model multiple time series that are correlated in space. A necessary condition for the application of CSM models is that the shifts in the multiple time series of the hydrologic variable should coincide (Sveinsson and Salas 2006).

In this study, analysis of the cross correlation coefficients indicated the presence of non-significant coefficients at lag-zero between Lakes Victoria/Kyoga and Kyoga/Albert. The lag-zero cross correlation coefficient between Lake Victoria and Albert was significant but low. Detailed analysis of the shifts in the net basin supplies of the three lakes in the previous chapter, indicate that prevalent shifts do not necessarily coincide in time. Other variations in the pattern of the shifts and dependence structure (correlograms and spectral plots) are unique to each lake. These observations have therefore limited the experimentation in this study to the univariate domain of SM models.

6.3 Parameter estimation

Parameter estimation involves transformation of the time series to the normal distribution prior to estimation of the parameters of the univariate SM model for each lake. The two activities are described in the following sections.

6.3.1 Transformation to Normal

The coefficients of skewness of the annual net basin supply time series for the Equatorial Lakes are greater than zero (Table 6.1), indicating that the underlying data are not normally distributed and needs to be corrected for skewness using an appropriate normalizing transformation. The SAMS software provides a number of options to transform data. The procedure involves the estimation of the non-exceedance probabilities of the annual series of the net basin supply using the Cunnane unbiased plotting position formula (Cunnane, 1978). The non-exceedance probabilities are plotted against the normalized dataset on normal probability paper to produce probability plots. Probability plots are utilised as a graphical aid to assess the goodness of fit

of the data to the normal distribution. If the data has been successfully transformed to be normally distributed, then the plot of the transformed data against the non-exceedance probabilities is expected to be linear and a probability plot correlation coefficient is frequently used as a measure of linearity of the probability plot.
Transformation of data to the normal domain is subjected to two tests of normality. These are the skewness test (Salas *et al*,. 1980) and the Filliben probability plot correlation test (Filliben, 1975). Both are applied at the 10% significance level.

Given a series of annual net basin time series for each lake (X), the best goodness of fit results were obtained in the case of Lake Victoria and Lake Kyoga when the normalized variables (Y) were computed by applying the Wilson-Hilferty transformation (Loucks *et al*., 1981) which gives the quantiles of the gamma distribution in terms of the quantiles of the standard normal distribution.

Application of the logarithmic transformation Y = ln (X + a), with the transformation coefficient a = 24971.65 produced the best fit with the Lake Albert data. Figures 6.11 to 6.13 illustrate the probability plots for the three Lakes.

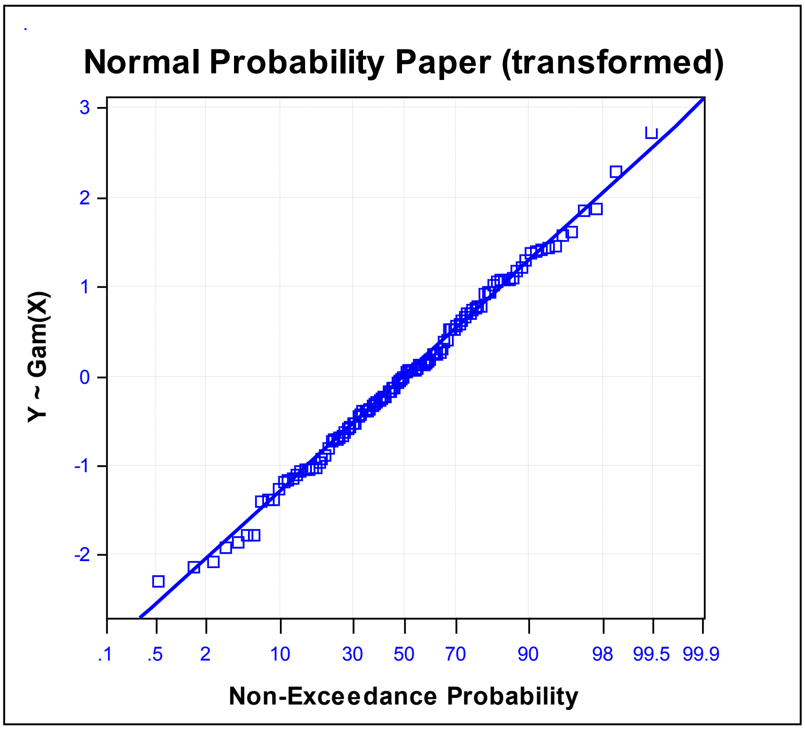


Figure 6.11 Probability plot – Lake Victoria

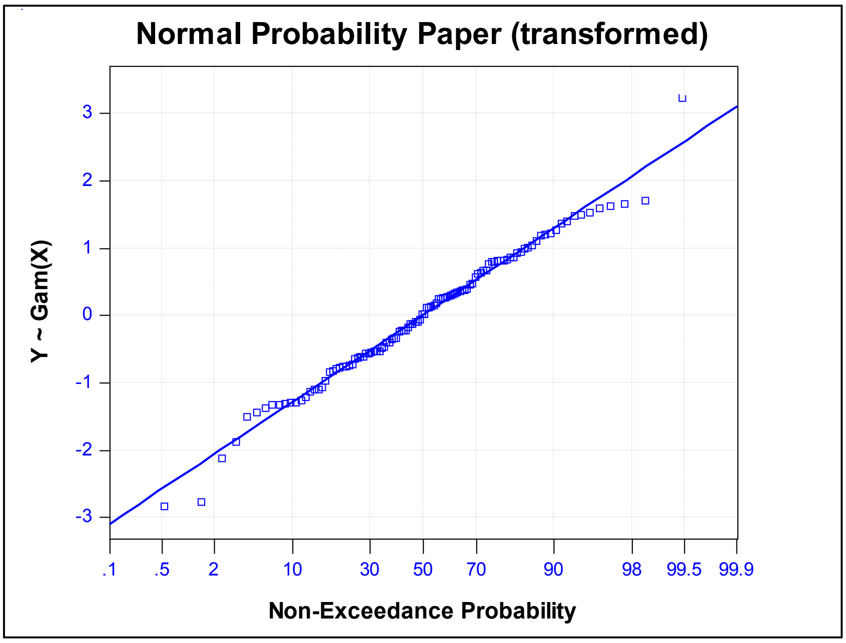


Figure 6.12 Probability plot – Lake Kyoga.

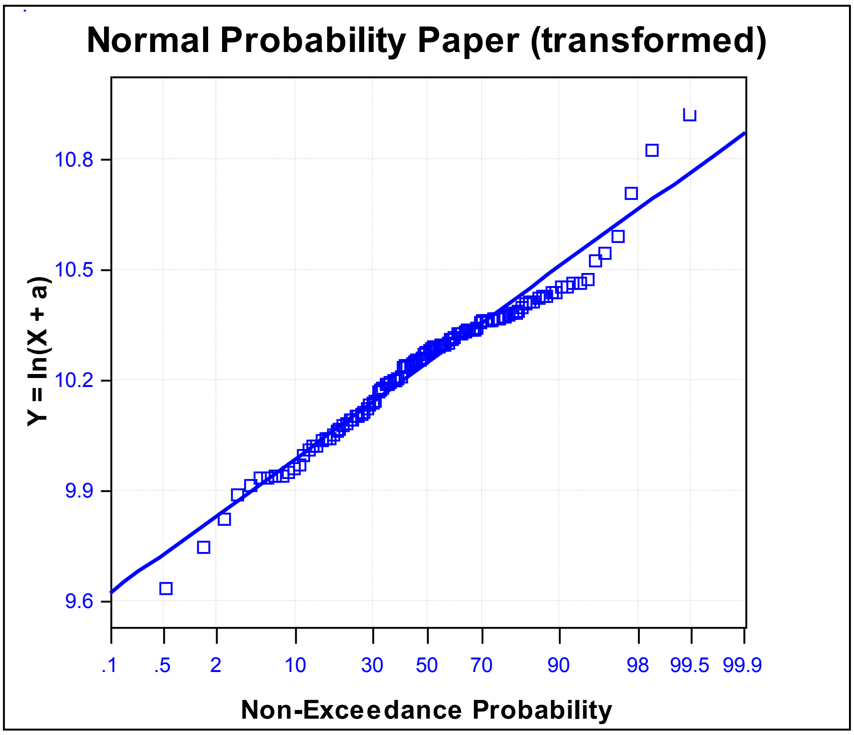


Figure 6.13 Probability plot – Lake Albert

The skewness test of normality was accepted in all three cases. The Filliben probability plot correlation test was accepted for Lakes Victoria and Kyoga but marginally rejected with regard to Lake Albert.

6.3.2 Parameter estimation

There are four parameters that are required to be estimated in order to fit a univariate SM to the annual net basin supplies. These are μ_Y, σ_Y, σ_M, and p. The relationships between the model parameters and the population statistics X_t in Equation 6.1 are defined after Sveinsson *et al.* (2003) as:

$$\mu_X = \mu_Y \tag{6.4}$$

$$\sigma_X^2 = \sigma_Y^2 + \sigma_M^2 \tag{6.5}$$

$$\rho_k(X) = \frac{\sigma_M^2 (1-p)^k}{\sigma_Y^2 + \sigma_M^2}, \text{ k = 1,2..} \tag{6.6}$$

where μ_X, σ_X^2, and $\rho_k(X)$ are the mean, variance and the lag-k autocorrelation coefficient. Boes and Salas (1978) state that the autocorrelation function of the SM model in Equation 6.1 takes on the same form as an ARMA (1,1) process i.e. it is always positive and falls exponentially towards zero. Sveinsson *et al.* (2003) suggest that one way of fitting parameters using Equation 6.5 is to ensure that the goodness of fit between the sample and model correlogram is good up to two different significant lags greater than zero. This method was adopted and the parameters of the most promising SM model, when fitted to the standardized data are summarized in Table 6.5.

Table 6.5 Model Parameters – fitted to standardized data

Statistic	Lake Victoria	Lake Kyoga	Lake Albert
μ_Y	-7.31738E-018	-0.000253708	1.23326E-014
σ_Y^2	0.00491704	0.787236	0.45245
σ_M^2	0.995083	0.21882	0.54755
P	0.77	0.46	0.40

Detailed comparison of the performance of this model against the others that were considered less promising is presented in Section 6.5 where model testing and verification is discussed.

6.4 Model testing and verification

The objective of stochastic data generation is to provide alternative scenarios of net basin supplies all equally likely to occur and utilise them as input to a deterministic dynamic programming optimisation model. For valid results it is necessary that the selected generating scheme should be able to preserve both the monthly and annual statistics. Disaggregation models (Valencia and Schaake, 1973; Mejia and Rousselle, 1976; Lane, 1979; Grygier and Stedinger; 1990) have been widely applied to produce monthly data sequences by disaggregating annual data that have been generated by a suitable annual generation model such as the SM model. The temporal Lane model (Lane and Frevert, 1990) and the SM model were selected as the suitable generating scheme. The Lane model ensures that generated monthly NBS sum to the annual NBS total and preserves the monthly serial correlations and the lag-1 correlation between the first month of a given year and the last month of the previous year (Sveinsson *et al.* 2007).

For purposes of analyzing the suitability of the selected scheme with regard to preservation of the sample statistics, goodness of fit with the sample correlogram and capacity to mimic the shifting patterns in the historical data, 1000 samples of annual and monthly time series were generated for each lake. The length of each time series was the same as the historical record i.e. 110 years. Sensitivity tests were conducted based on the assumption that the parameter p is known. From the results of several visual goodness of fit comparisons between the sample model correlograms for each of the lakes with up to two different significant lags greater than zero, it was indicated that the most promising model was that fitted in accordance to the parameter p as illustrated in Table 6.5. Table 6.6 contains a summary of the properties of the 1000 samples of annual time series data generated with this adopted scheme.

Table 6.6 Generated data statistics (1899 -2008)

Lake	Mean (MCM)	Standard deviation (MCM)	Coefficient of variation	Coefficient of skewness	Acf (1)	Acf (2)
Victoria	27140	20590	0.76	0.32	0.21	0.03
Kyoga	161	3544	44.17	0.30	0.34	0.17
Albert	3717	5824	1.65	0.57	0.30	0.17

A comparison of the historical sample (H) and the generated time series (G) is provided under Table 6.7 below.

Table 6.7 Generated data statistics (1899 -2008)

Parameter	Lake Victoria		Lake Kyoga		Lake Albert	
	(H)	(G)	(H)	(G)	(H)	(G)
Mean (MCM)	27125	27140	169	161	3757	3717
Standard deviation (MCM)	20860	20590	3590	3544	5988	5824
Coefficient of variation	0.77	0.76	21.29	44.17	1.59	1.65
Coefficient of skewness	0.36	0.32	0.32	0.30	1.10	0.57
Acf (1)	0.27	0.21	0.29	0.34	0.30	0.30
Acf (2)	-0.04	0.03	0.22	0.17	0.14	0.17

The comparison shows that the model is capable of preserving the mean and standard deviation of the sample statistics when the values of *p* in Table 6.5 for each lake were left unchanged. The skewness and autocorrelation functions are also relatively well matched except in the case of Lake Albert where the skew is not. The coefficient of variation for Lake Kyoga is also higher for the generated series.

The performance of the preferred model was also compared against others that were deemed to have performed less favourably judging by goodness of fit with the sample correlogram. This was done by visual comparison of box and whisker plots of the annual net basin supply time series generated by the candidate models. These plots are considered to be useful since they provide a pictorial visualisation of important characteristics of the generated data sets such as measures of central tendency and dispersion determined by percentile rank analysis without necessarily assuming an underlying statistical distribution (Banacos, 2011). The plots are favoured due to their graphically compact nature which allows side by side comparisons of the multiple generated datasets for each lake in the sensitivity analysis with regard to parameter *p* of the SM model. The box plots are a graphical 5-number summary of the generated data sets, which includes the median, inter-quartile range, and the outer range. For comparisons purposes, the statistics of the historically observed annual net basin supply for each lake (Table 6.1) are represented as an additional reference tic mark on the Y-axis of a given thematic plot. Figures 6.14 – 6.16 illustrate the comparisons for each lake.

Similarly, Figures 6.17-6.19 illustrate comparisons of historical and generated annual net basin supply. Owing to the difficulty of plotting and visualizing 1000 time series on a single graph, the average of the generated series is shown on the plots. Figures 6.17 – 6.19 confirm that the generated data is consistent with the historical time series.

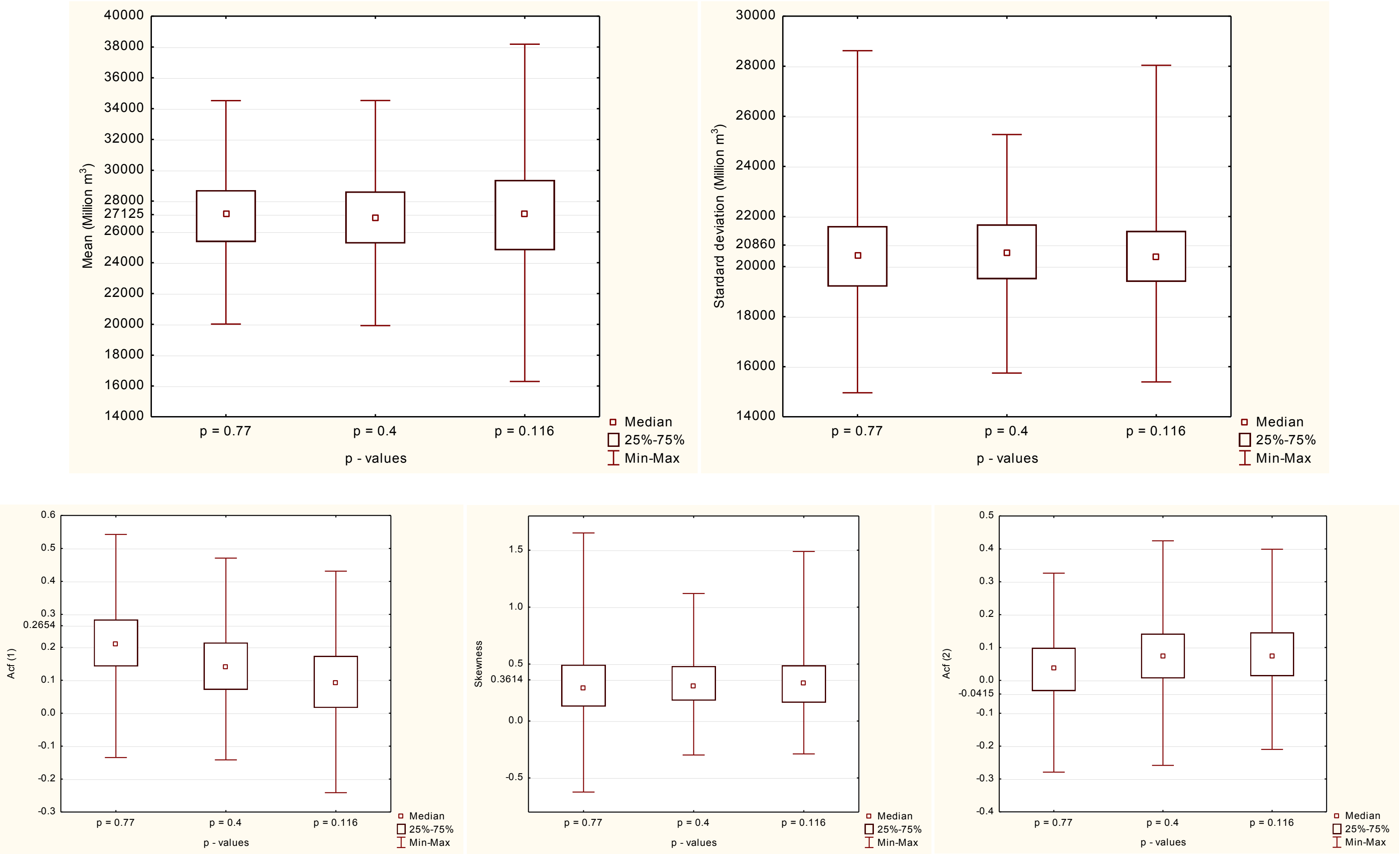


Figure 6.14 Box plot comparisons of generated data statistics for Lake Victoria with various SM models

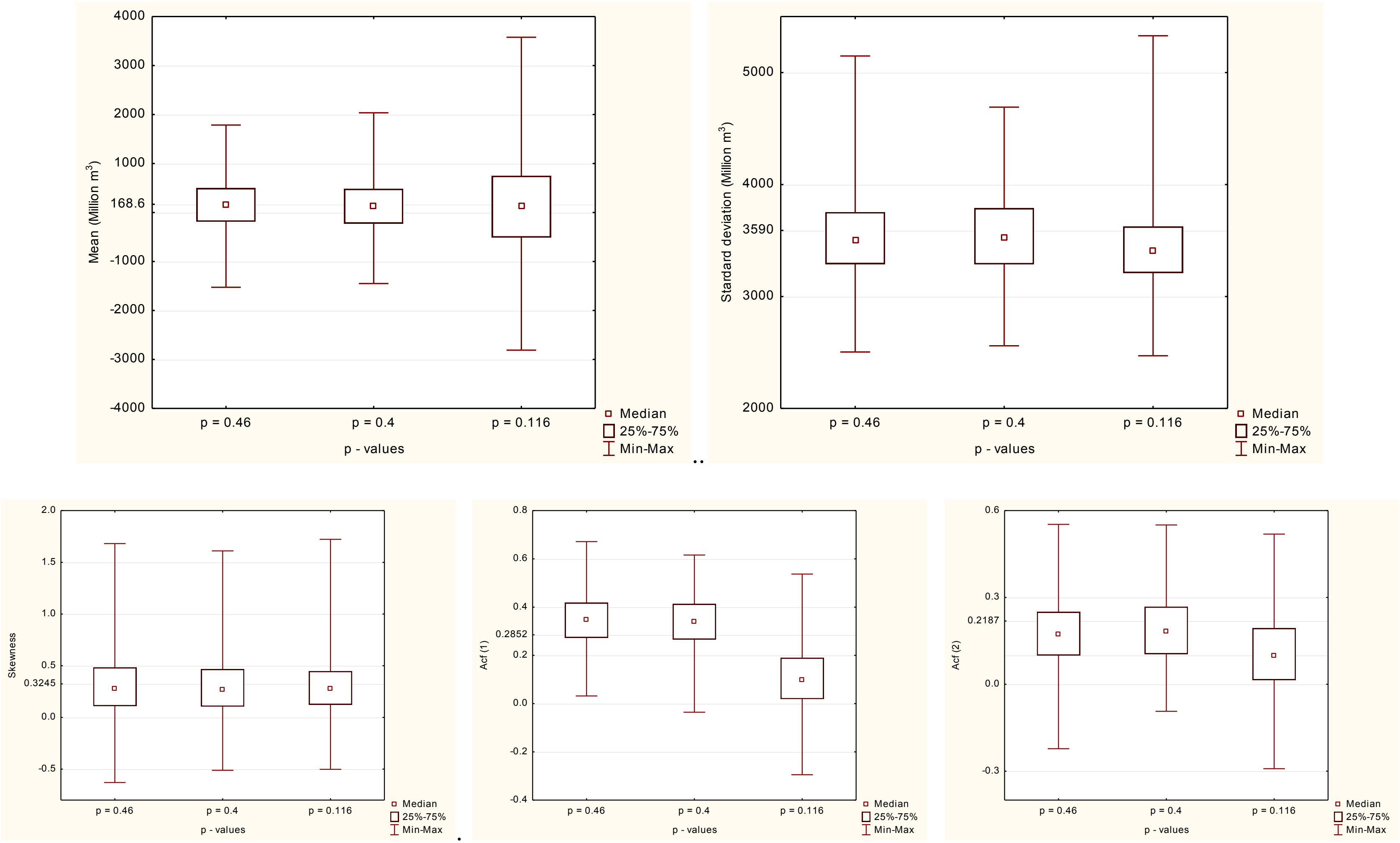


Figure 6.15 Box plot comparisons of generated data statistics for Lake Kyoga with various SM models.

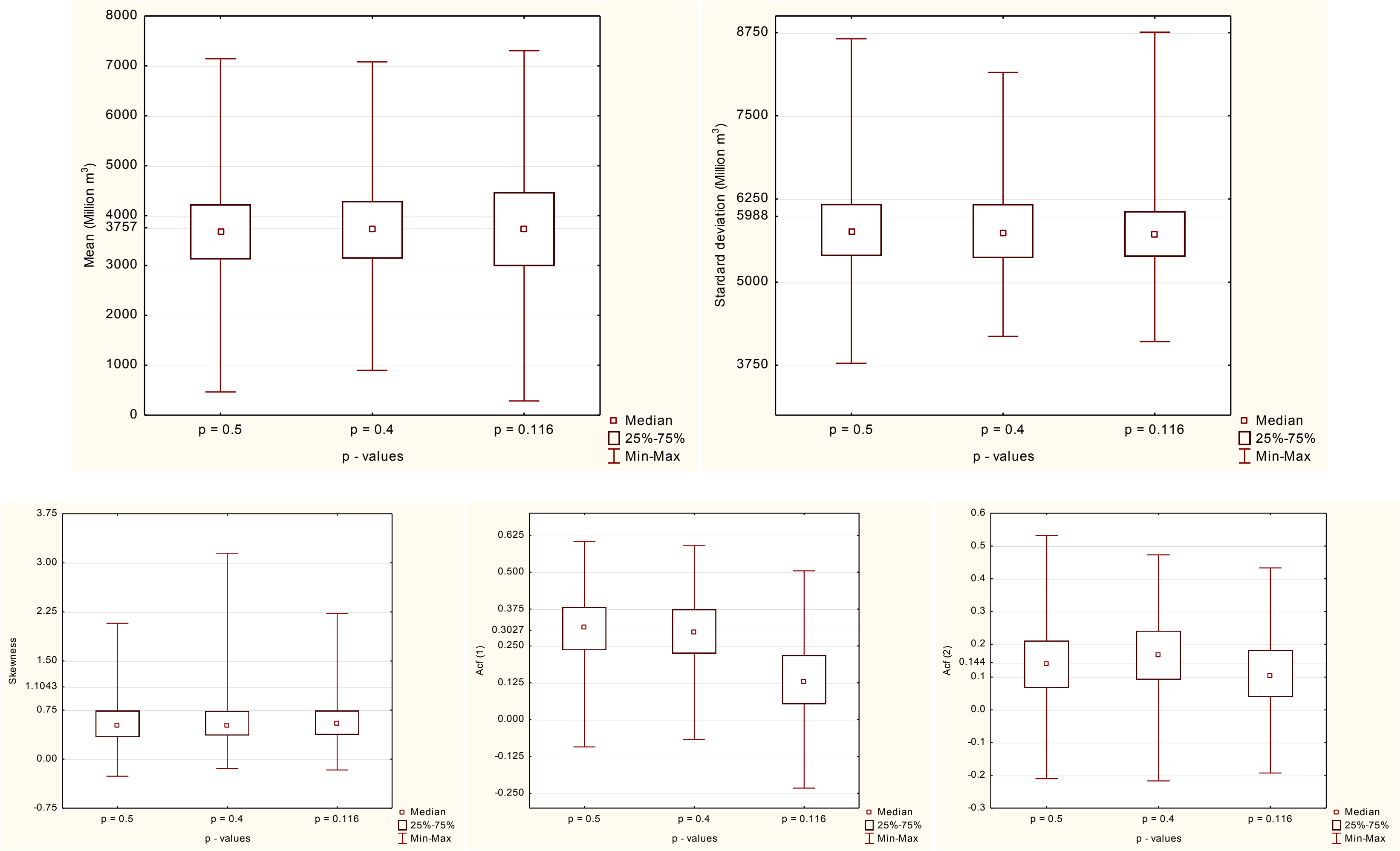


Figure 6.16 Box plot comparisons of generated data statistics for Lake Albert with various SM models.

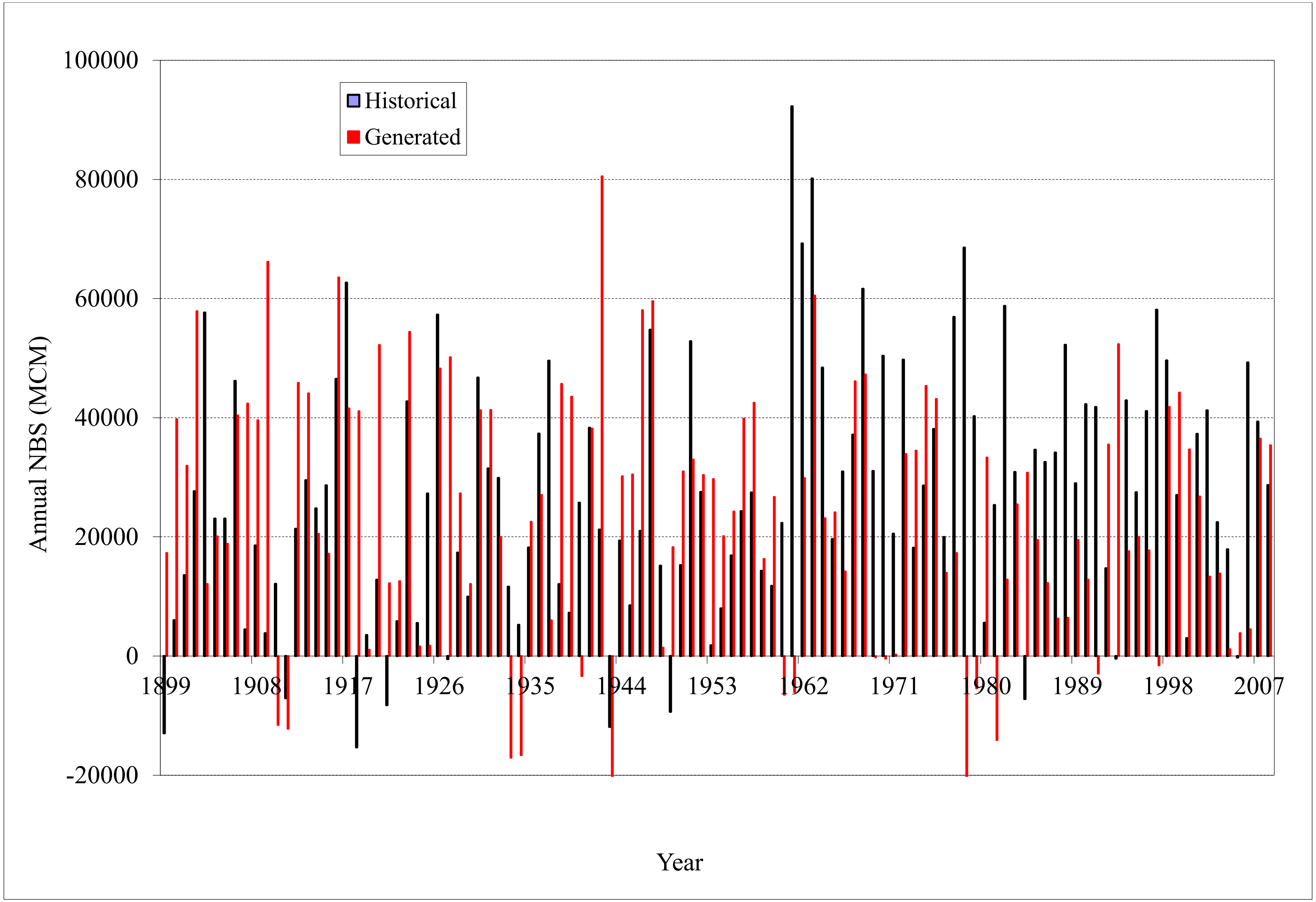


Figure 6.17 Comparison of historical and generated data for Lake Victoria.

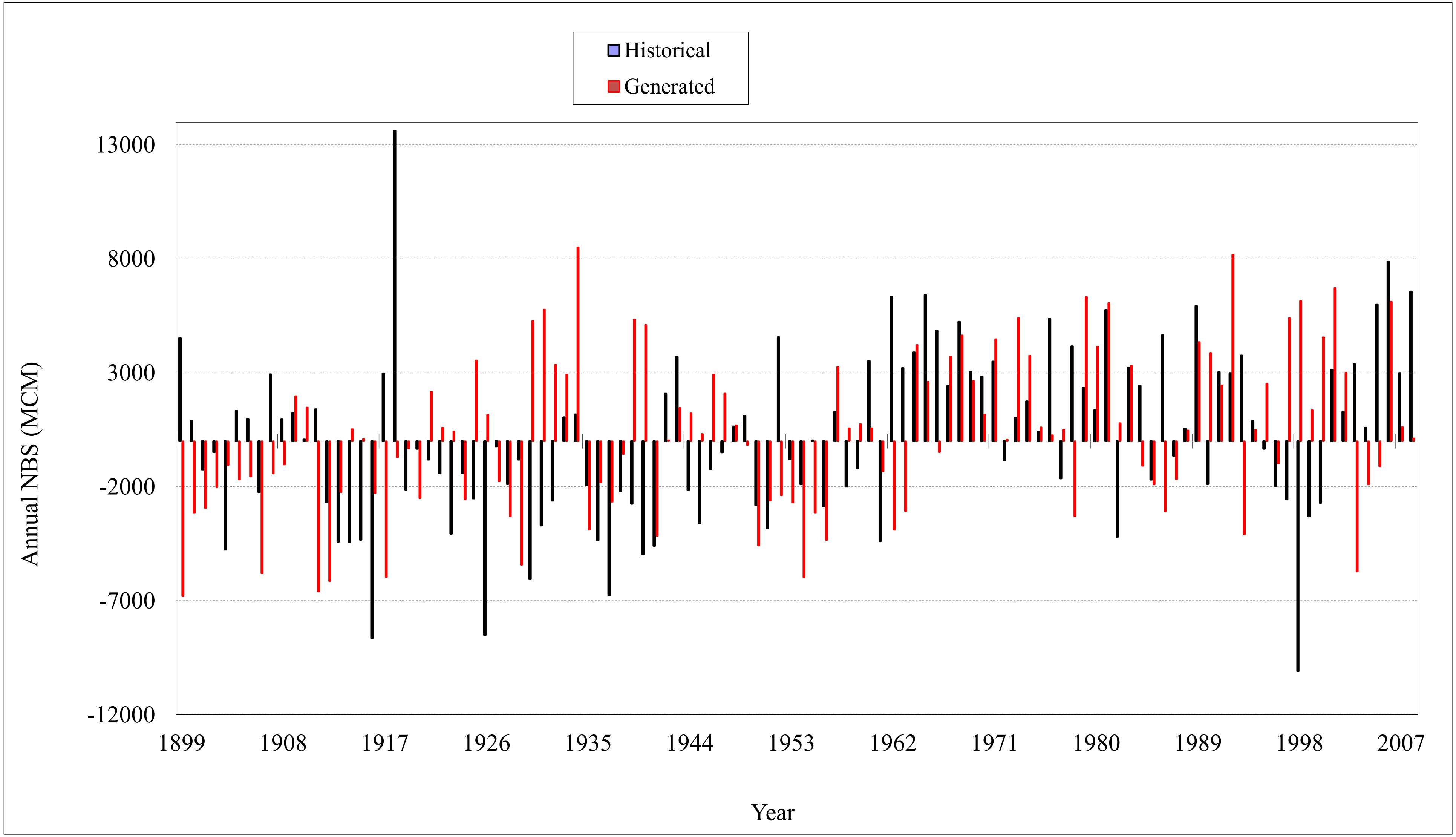


Figure 6.18 Comparison of historical and generated data for Lake Kyoga.

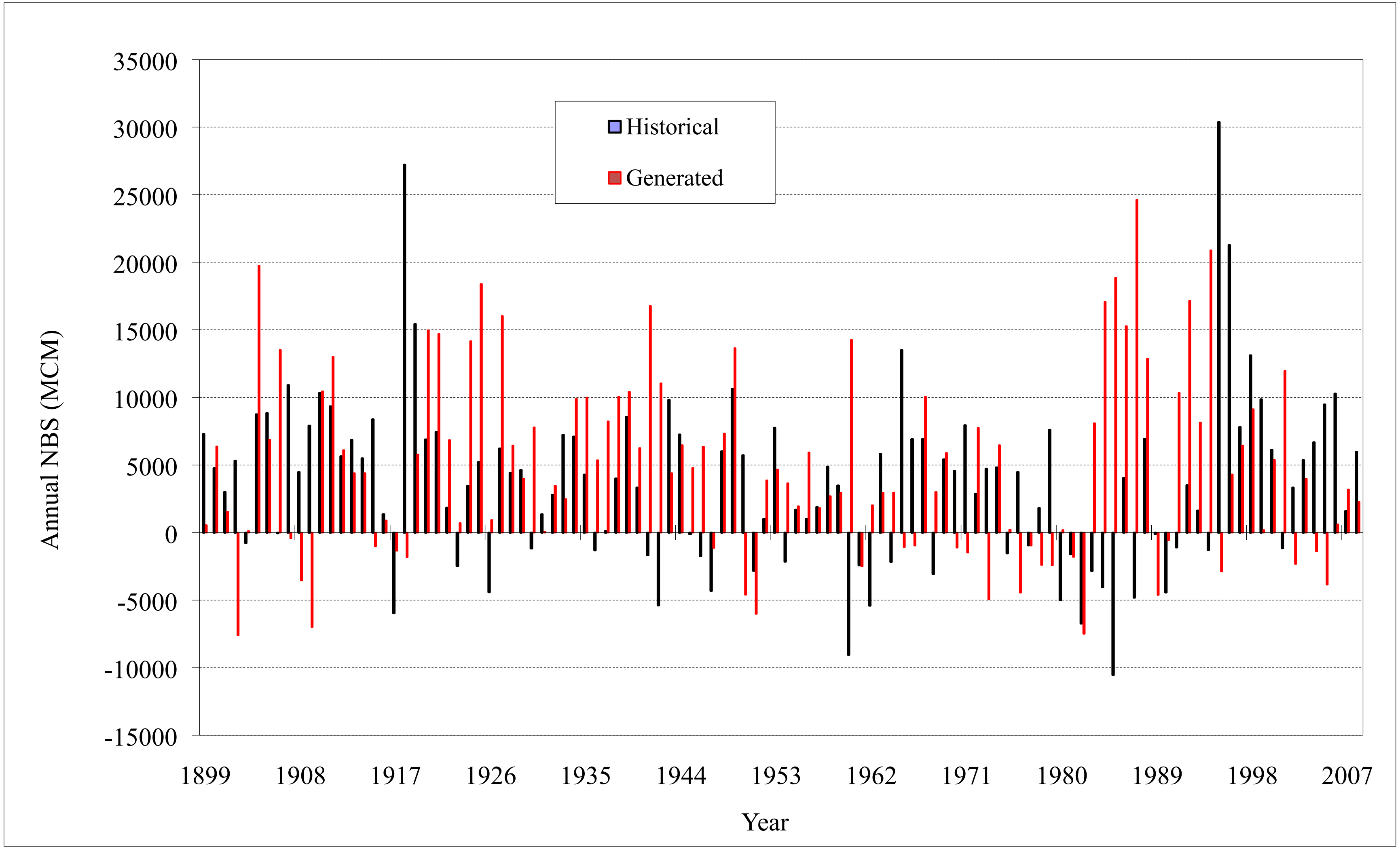


Figure 6.19 Comparison of historical and generated data for Lake Albert.

6.5 Summary and final remarks

In this chapter, the statistical properties of the historically observed net basin supply time series for Lakes Victoria, Kyoga and Albert have been analyzed and based on the results, a univariate shifting mean modelling frame-work with temporal disaggregation using a Lane Model has been applied to generate synthetic net basin supply time series for Lakes Victoria, Kyoga and Albert in the Upper White Nile basin. The model performed well in terms of preserving most of the statistical parameters of the historical sample of the time series. The generated data series can be applied to generate reservoir operating rules for the Lakes within a deterministic dynamic programming framework.

A number of features unique to each lake, in the correlograms and spectral plots of the monthly time series have also been illustrated as part of the statistical analysis. For all three lakes, it has been established that most of the correlation coefficients between inflows of any two months are low. A justification to model the stochastic process of the monthly inflows as a first-order Markovian process in an optimization model was formulated.

7. APPLICATION OF A DETERMINISTIC DYNAMIC PROGRAMMING OPTIMISATION METHOD TO THE EQUATORIAL LAKE BASIN CASE STUDY

Dynamic Programming (DP) optimization methods have been widely applied to reservoir operation (Nandalal and Borgadi, 2007). This chapter contains a detailed description of the application of a deterministic DP optimization technique implemented with a generalized dynamic programming software known as the Colorado State University Dynamic programming Model, CSUDP (Labadie, 2003) in order to derive alternative operating policies for the Equatorial Lakes. The limitations that lead to DP being used to derive alternative and not optimal policies are those related to the large dimensionality and stochastic characterization of the problem. The difficulty of handling the multi-objective aspects of the problem simultaneously coupled with the point by point iterative search method render the identification of a single optimal solution to be a challenging task. An evaluation of the computational performance and evaluation of the prescribed operational rules derived using the technique is also included.

7.1 System description

The main characteristics of the three lake-reservoirs in the system are tabulated under Table 7.1.

Table 7.1 Lake Reservoir characteristics in the system

Lake Reservoir	Average annual inflow (MCM)	Minimum level (m.a.s.l)	Maximum level (m.a.s.l)	Active storage (BCM)	Minimum observed outflow ($m^3.s^{-1}$)	Maximum observed outflow ($m^3.s^{-1}$)
Victoria	27125	1133.08	1136.28	215.55	347	1721
Kyoga	168	1030.31	1034.11	14.91	280	1991
Albert	3757	618.75	623.97	29.86	343	2074

Tabulated values of the lake level storage capacity curves for each lake reservoir are a key element of the mathematical model formulation for the dynamic programming model considered and these are included in Appendix “A” as extracted from WMO (1982). There are a number of existing and planned hydropower plants s along the Victoria and Kyoga Nile (Figure 1.3). However, not all the planned dams are likely to be constructed since some of the feasibility studies have not been favourable. Table 7.2 contains a list of the installed capacities and maximum turbine flows for the existing and planned dams that are considered in the current power master plan (JICA 2010) and in this case study.

Table 7.2 Existing and planned dams

Site	Location	Current Installed capacity (MW)	Proposed Installed capacity (MW)	Maximum turbine outflow ($m^3.s^{-1}$)
Nalubaale	Outlet of Lake Victoria	180	-	2150
Kiira	Outlet of Lake Victoria	200	-	
Bujagali	Victoria Nile	250	-	1375
Isimba	Victoria Nile	-	100	1375
Karuma	Kyoga Nile	-	250	799
Ayago	Kyoga Nile	-	550	607
Totals		630	900	

Future demand forecasts for Uganda indicate an increasingly widening gap between the available generation and the system demand. High scenario projections for the year 2025 indicate that the power demand will be 2,109 MW which is much larger than the planned installed capacity (SNC Lavalin and Parsons Brinkerhoff, 2011). In order to address the shortfall in current installed hydropower production, the Government of Uganda intends to have the planned power plants on line as soon as possible so as to plug deficits during peak and off peak hours. Therefore, it is evident that this case study presents a situation where the challenge is to maximise hydropower production while satisfying system constraints.

7.2 The objective function

In the adopted modelling framework, it is assumed that the system is in a steady state, that all power plants have been constructed and that the load is constant from year to year. Formulation of a mathematical model of this system involves representing the interconnected system of Lakes Victoria, Kyoga and Albert as a series of reservoirs, each with a storage capacity, inflows from upstream and releases to downstream and with run of the river hydro-power plants along the Kyoga & Victoria Nile as shown in Figure 7.1. All intermediate power plants along the Victoria and Kyoga Niles are treated as run of the river schemes although in practice, their design is associated with a head water level which has been taken to be negligible compared to the storage in the lakes.

In Figure 7.1, net inflows (net basin supplies) to the system are represented by $I_{1,t}$, $I_{2,t} \ldots I_{3,t}$ which denotes the net inflow in lake reservoir 1, 2 and 3 at time period $t = 1, 2, \ldots, T$ where t is a time interval that is typically 1 month and the total number of time periods T = 12 or the length of the planning period. Releases are made from each lake i.e. $R_{1,t}$, $R_{2,t} \ldots R_{3,t}$ in each time period to in order to produce power from the five power plants in the system.

The solution strategy involves a search for operating policies by traditional dynamic programming. The objective of the analysis is to derive the best achievable long-term operational strategy for the system to maximize hydro power production or meet foreseeable power demand while satisfying constraints related to water levels and flow magnitudes. The operational policy to be defined consists of 12 distinctive control rules defined for each month within an annual cycle.

In mathematical terms, the problem for the system illustrated in Figure 7.1 is to determine releases $R_{i,t}$, where $i = 1,2,3$ for all t, that maximise the total power generation of the system (Nandalal and Borgardi, 2007). Therefore the objective function (*OF*) of the dynamic programming model is to maximise hydro-energy generation from the five power plants over a pre-specified time period of time *t:*

$$OF = Maximise \sum_{j=1}^{5} \sum_{t=1}^{T} P_{j,t} \tag{7.1}$$

where:

$P_{j,t}$ = hydropower generated from power plant j at time $t\,(\mathrm{MW})$, and

j = index of power plants; $j = 1, 2, 3, 4, 5$.

The five (5) power plants in sequencing order are Nalubaale-Kiira, Bujagali, Isimba, Karuma, and Ayago. The power generated from each plant was represented in the form of plant generation functions that were input to the model as tabular functions of feasible hydropower at a given reservoir elevation and release. A two dimensional cubic spline interpolation scheme (Forsythe *et al.*, 1977) was then utilised to compute the hydropower generation at any intermediate head and release for Nalubaale-Kiira, Bujagali, Isimba, Karuma and Ayago power plants. The power generation functions are derived as described in the following sections.

7.2.1 Nalubaale - Kiira

The Turbine Load Dispatching (TLD) model of the Lake Victoria Decision Support Tool (LVDST) was used to determine power generation at the Nalubaale-Kiira dams as a function of Lake Victoria elevation and combined turbine discharge through both plants. In order to accomplish this task, the TLD model utilises the individual head loss functions, tail-water curves and turbine characteristics for each individual plant and then solves a dynamic programming algorithm which searches for the optimal discharge allocation for each power plant in order to maximize total power generation (WREM Inc. & Norplan (U) Ltd, 2004). Figure 7.2 shows the optimal discharge and power generation allocation for various Lake Victoria levels and total discharges for 5 units at Kiira (200 MW) and 10 Units at Nalubaale (180 MW). It is assumed that all turbine units are operational in the analysis. The aggregate power generation functions are included in tabular form in Appendix B.

7.2.2 Bujagali, Karuma and Ayago

Curves for the power generation functions for the existing power plant at Bujagali and the proposed plants at Karuma and Ayago were also extracted from the TLD module. The curves are derived for each power plant using the power generation load of each turbine, number of plant turbines, discharge through each turbine, tail-water level and fore-bay water level. These power generation functions are presented in Figures 7.3 – 7.5. According to the design reports for the Bujagali power plant (Burnside, 2006), the full supply level of the reservoir impounded by the dam at Bujagali is 1111 m.a.s.l and it corresponds to the Nalubaale dam tail water level elevation. Therefore the optimal generation function at 1111 m was selected as the reference curve. At Karuma and Ayago, curves corresponding to a gross head of 27 m and 60 m were selected respectively. These data are also included in Appendix B.

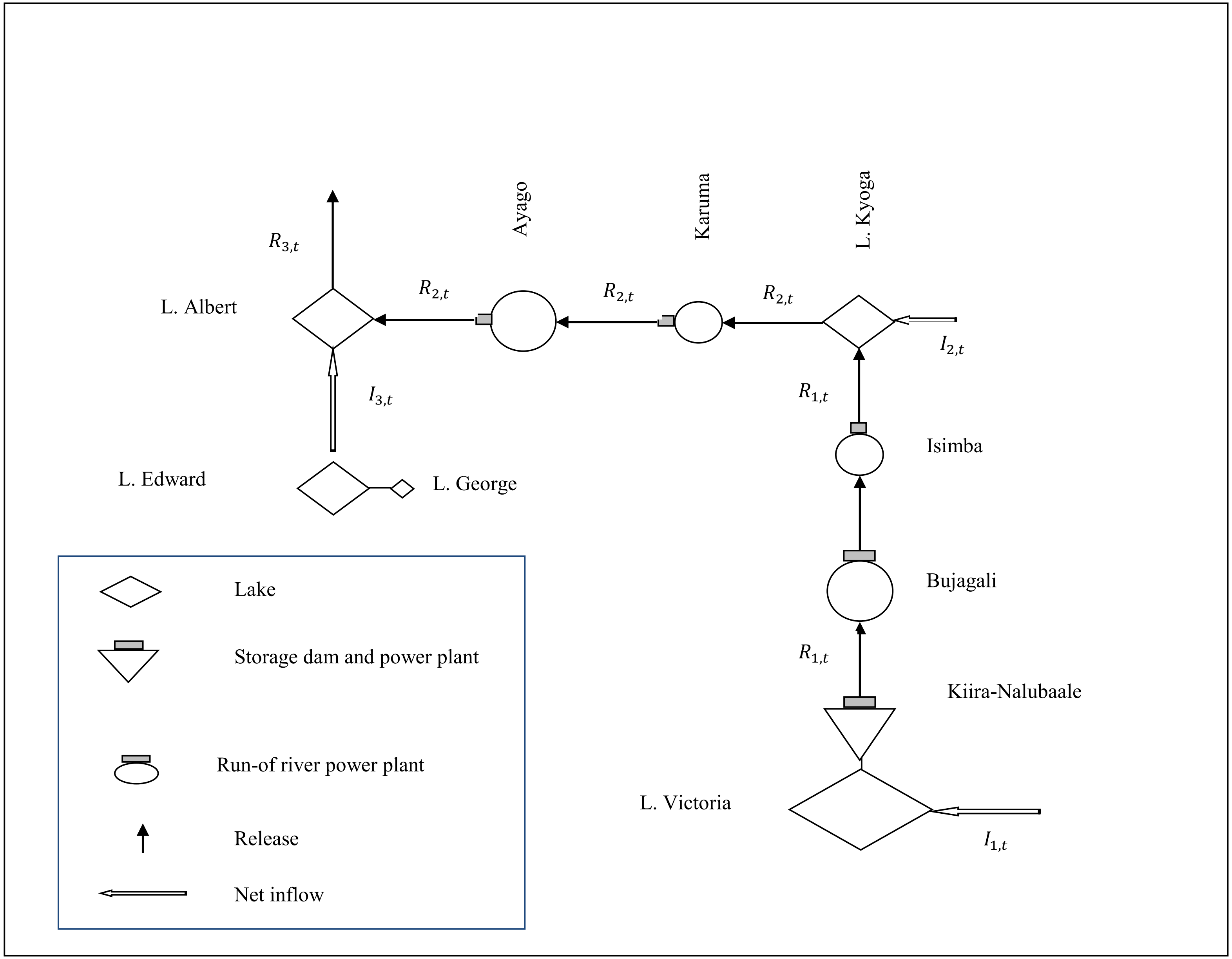


Figure 7.1 Schematic representation of lake reservoirs and power plants.

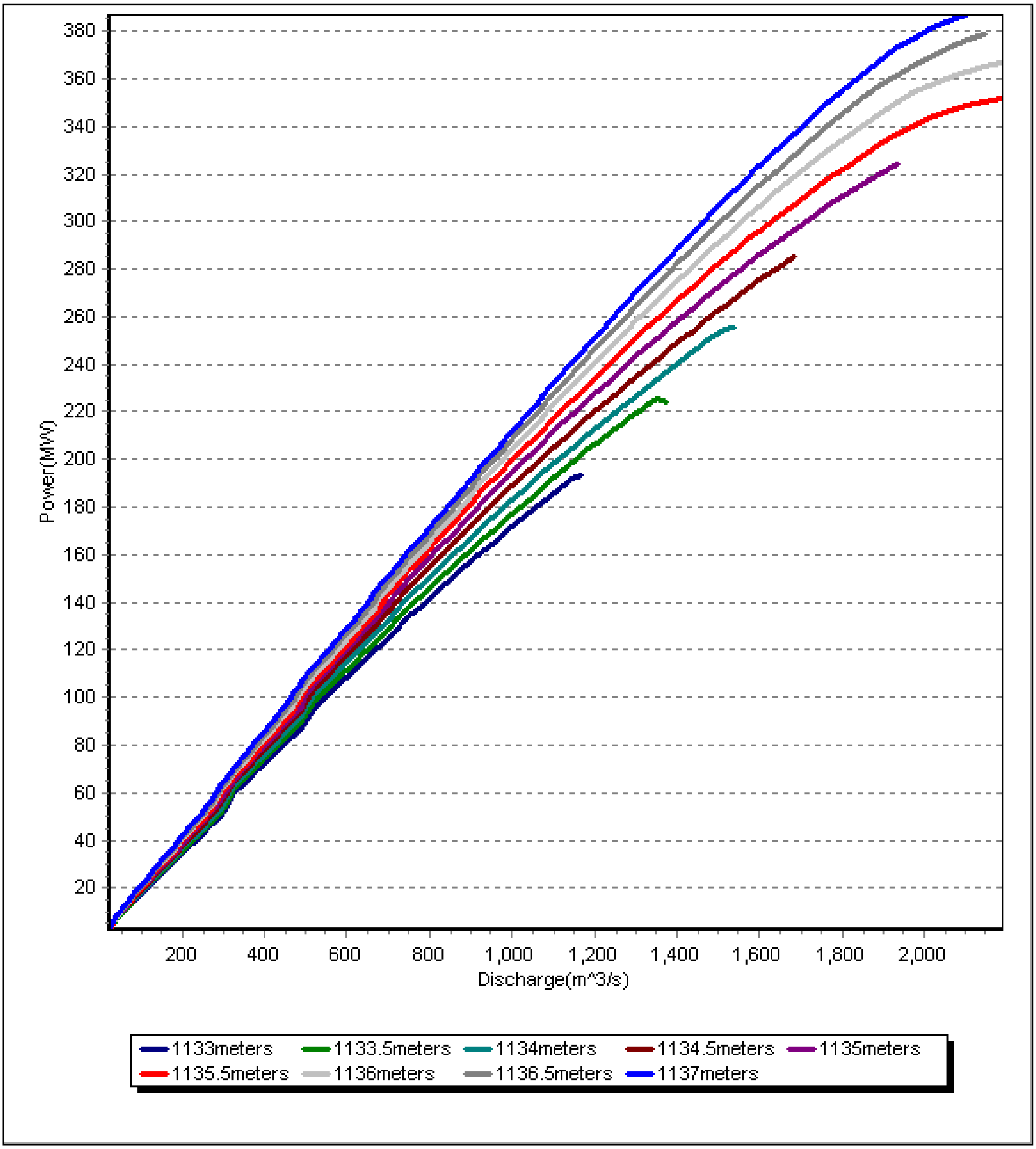


Figure 7.2 Power generation function for the Nalubaale (10 units) – Kiira (5 units) complex.

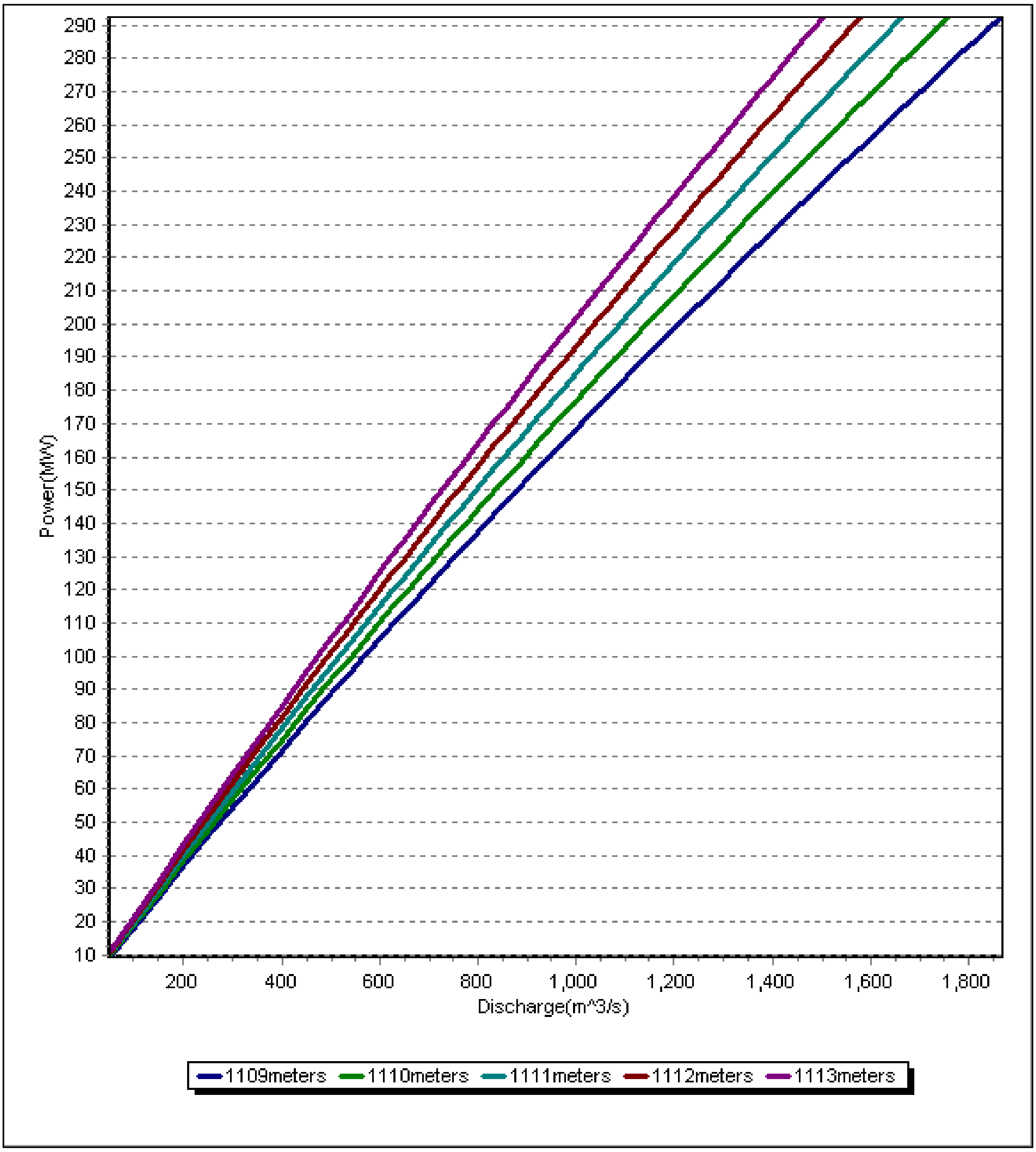


Figure 7.3 Power plant generation function for Bujagali (5 units).

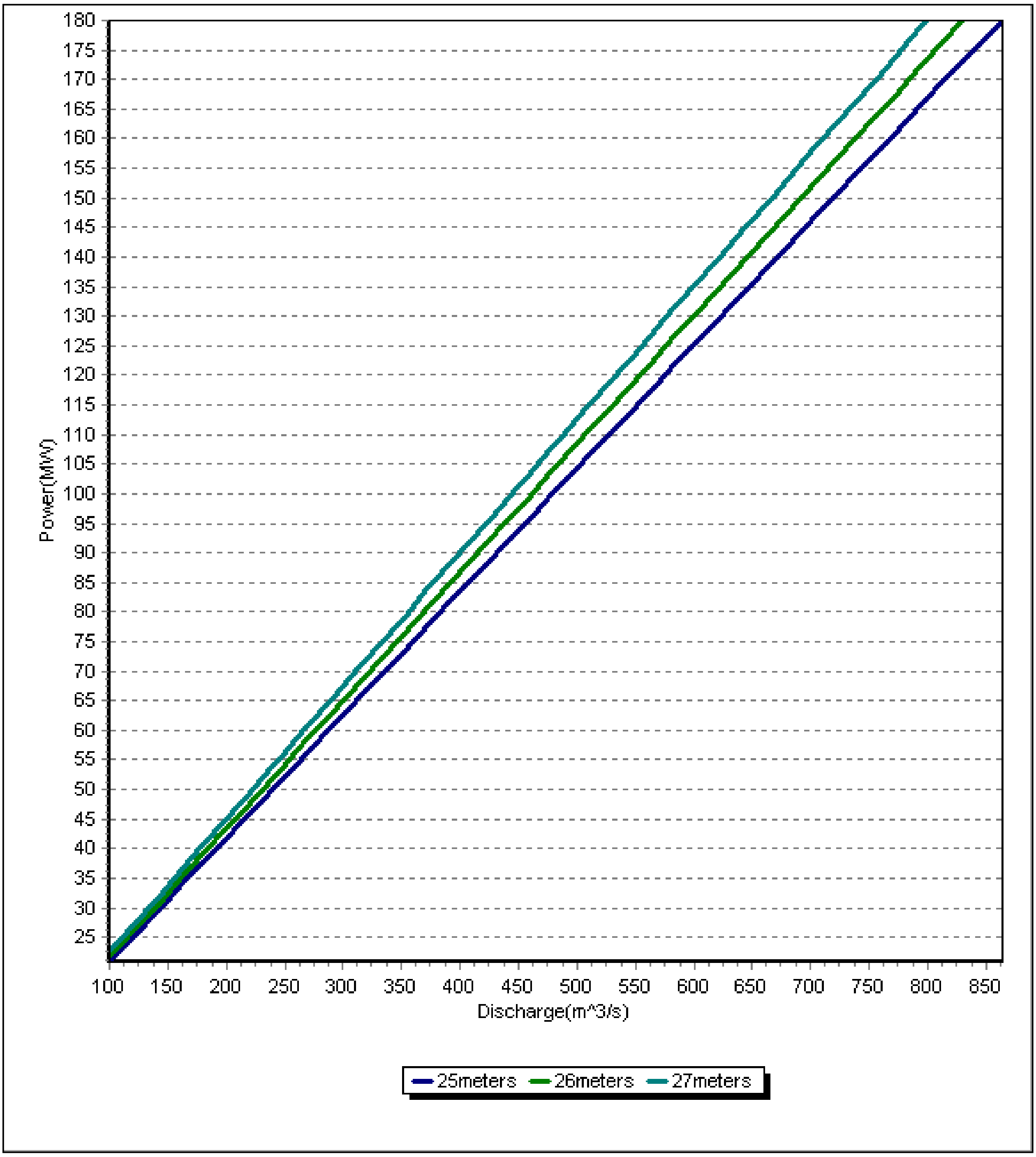


Figure 7.4 Power generation function for Karuma (4 Units).

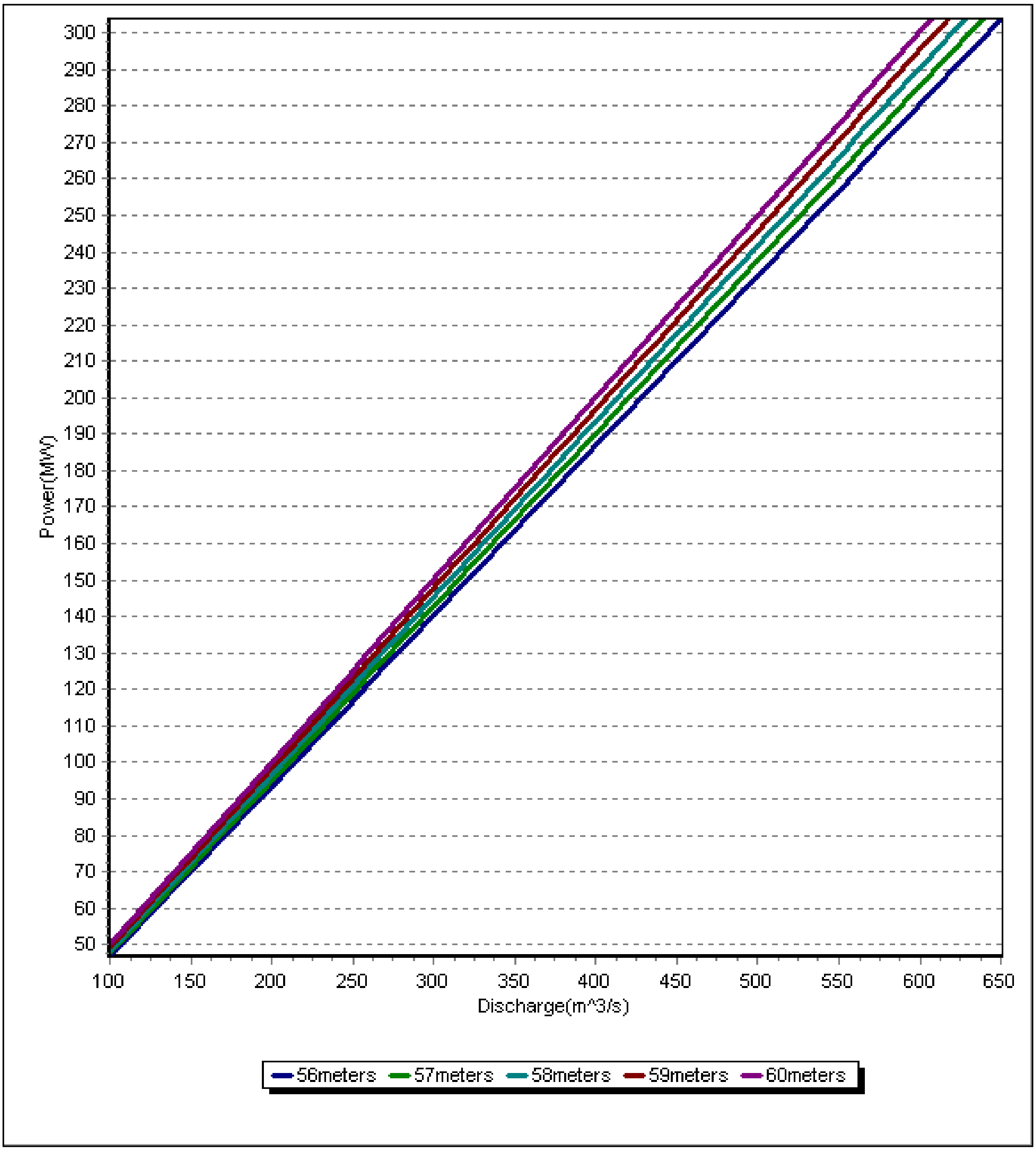


Figure 7.5 Power generation function for Ayago (8 Units).

Feasibility studies for the power plant have not been completed hence system data is not available. Therefore the potential power generation at Isimba was estimated using the formula

$$P = 9.81\ \eta\ Q\ H \qquad (7.2)$$

where: P = the power generation in kilowatts (KW),

9.81 = unit conversion coefficient,

η = overall generation efficiency, typically taken to be 0.85,

Q = is the turbine discharge in ($m^3.s^{-1}$), and

H = is the gross head in metres i.e. 16 m as determined from the feasibility studies.

7.3 Multiple reservoir IDP model formulation

A multiple reservoir discrete IDP algorithm was utilised to analyse the problem presented in Figure 7.1. The system is operated on a monthly or annual basis and the reservoirs begin and end their operational cycle with a given amount of water stored. Storage in the run-of-river power plants is assumed to be negligible. Complete fore-knowledge of monthly net basin supply time series for a given year is assumed, hence only very general operational guidelines for that particular specific set of inflows are yielded. The solution strategies within the deterministic multiple reservoir framework is in accordance with the method of Incremental Dynamic Programming (Larson, 1968).

The objective function of the IDP model is as defined in Equation 7.1. The state of the system is determined by the volume of water available in each of the three lake reservoirs at the beginning of the month or time period. The decision variables are the volumes of water to be released from each lake reservoir at a particular time step. Maximization of the hydro power generated at each time step is subjected to storage volume constraints corresponding to the maximum and minimum lake levels ($X_{i,max}$, $X_{i,min}$) and upper and lower limits on discharges ($R_{i,max}$, $R_{i,min}$) for i = 1, 2,3 from each lake reservoir as shown in Table 7.1. The backward moving Incremental Dynamic Programming recursive relation for estimating the maximum energy output is:

$$F_{t-1}^{*}\left(S_{1,t-1},S_{2,t-1},S_{3,t-1}\right)=\max\left\{r_t+F_t^{*}\left(S_{1,t},S_{2,\,t,}\,S_{3,t}\right)\right\},\ \text{for } t=\text{T, T-1,....1} \tag{7.3}$$

where

t = stage/time period = 1, 2, ……….T,

T = is the total number of stages/time periods,

F_t^* = are optimal objective functions from period *t* to the end of the cycle T, given the current state of the reservoir storage levels ($S_{i,t-1}$), and

r_t = is the immediate return (hydropower generated) during period *t* as defined by Equation 7.1.

In Equation 7.3, optimization begins at some point in the future (Stage T) and proceeds backwards in time to the present. The rewards associated with stage T+1 are a boundary condition taken to be zero. Equation 7.3 is solved recursively, subject to upper and lower limits on discretized reservoir storage levels and releases. State transformation equations for the lake reservoirs, which are governed by the principle of continuity are presented in Equations 7.4 – 7.6.

For Lake Victoria:

$$S_{1,t} = S_{1,t-1} + I_{1,t} - R_{1,t} \tag{7.4}$$

For Lake Kyoga:

$$S_{2,t} = S_{2,t-1} + I_{2,t} + R_{1,t} - R_{2,t} \tag{7.5}$$

For Lake Albert:

$$S_{3,t} = S_{3,t-1} + I_{3,t} + R_{2,t} - R_{3,t} \tag{7.6}$$

where:

$I_{i,t}$ = net basin supply or net inflow to reservoir *i* during period *t*, (*i* = 1, 2, 3) (MCM).

$R_{i,t}$ = release from reservoir *i* during period *t*, (*i* = 1, 2, 3) (MCM).

$S_{i,t-1}$, $S_{i,t}$ = beginning and ending period storage levels for reservoir *i* during period *t, (i* = 1, 2, 3) (MCM).

Upper and lower limits on storage levels and reservoir releases are imposed for purposes of safeguarding against damage to shoreline, river bank settlements, infrastructure and satisfaction of other riparian interests such as and navigation. The Incremental Dynamic Programming (IDP) model is an iterative method in which Equation 7.3 is used to search for an improved trajectory among discrete states in the neighbourhood of an initial trajectory. Figure 7.6 illustrates the procedure for a single reservoir (one dimension of the state space). It commences with selection of a trial trajectory in the state-stage domain chosen in such a way that the specified set of initial and final storage levels of the system yield a release that falls within the acceptable range of release constraints (R_{min}, R_{max}) of the system and then evaluates the return function (power generated) in the neighbourhood, or so called "corridor," of this trajectory. At the end of each iteration step a locally improved trajectory is obtained and then used as the trial trajectory in the next step. The step is repeated until a near optimal trajectory that determines a feasible operating policy of the system is found.

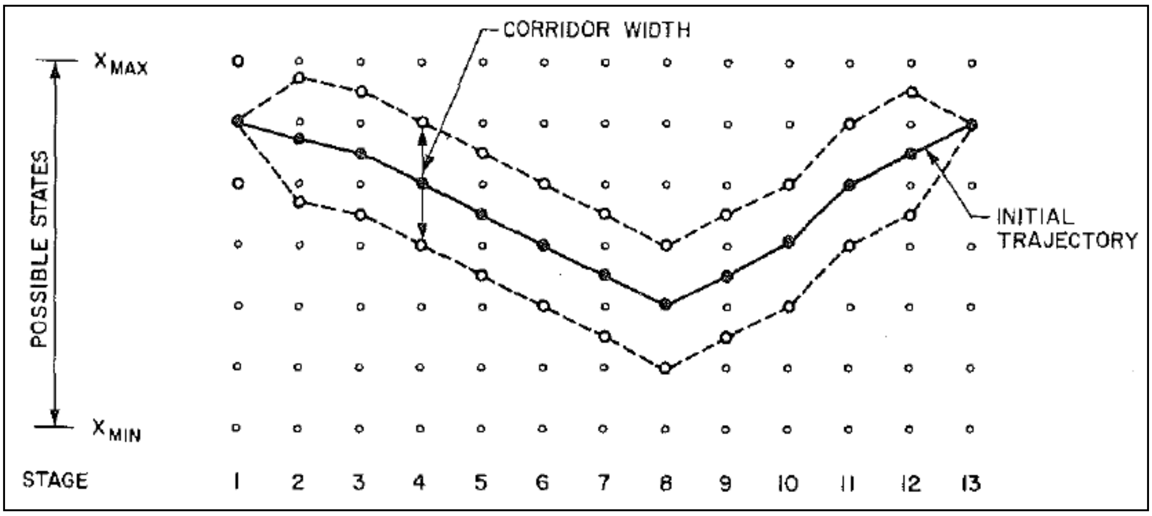


Figure 7.6 Illustration of the state increment, initial trajectory and corridor width concepts in one dimension for the IDP model (Allen & Bridgeman, 1986).

Thus instead of searching for the optimal operating policy over the entire state-stage domain as in the case of traditional dynamic programming, the IDP process circumvents the “curse of dimensionality” by narrowing down successive searches for the optimal rule. When implemented for a three lake-reservoir system the IDP procedure constructs a symmetrical corridor around trial trajectories of initial lake levels at each stage and subsequently searches for the optimal trajectory and corresponding objective function value within the corridor. Searching incrementally over the range of permissible storage levels, the backward moving recursive equation, finds the best initial storage volumes of the lake-reservoirs that maximizes the value of the hydropower generation over the planning period for feasible scenarios of the final storage volumes in each time period to complete a cycle. The computation steps for a conventional IDP as described by Nandalal & Bogardi (2007) are presented in Figure 7.7.

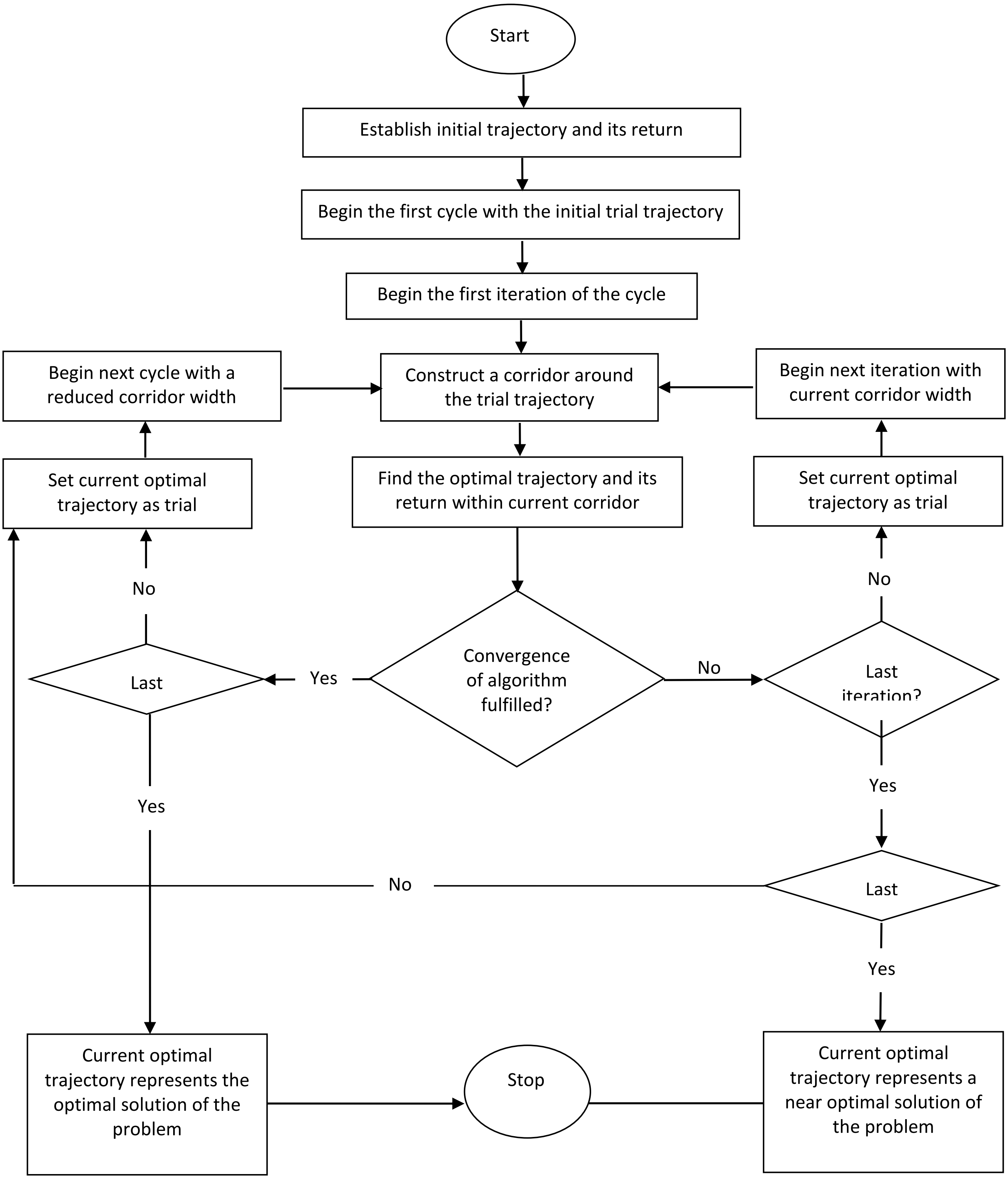


Figure 7.7 Incremental dynamic programming procedure (after Nandalal & Bogardi, 2007).

As the iterations are carried out, improvement in the objective function reduces. Since less superior trajectories are obtained as the iterations progresses for a given corridor width, a convergence criteria is set and computed upon completion of each iteration within the corridor. The reference to less superior trajectories here is to indicate that the improvement in trajectories reduces but the trajectories themselves improve. A maximum number iterations is also predefined which must not be exceeded within each corridor search. The maximum number of iterations is usually a multiple value of the number of time periods (months) for a given cycle (year). The convergence criterion that needs to be satisfied before a corridor width search can be changed is defined by Nandalal & Borgardi (2007) as:

$$\partial_i = \frac{\left|OBF_i^* - OBF_{i-1}^*\right|}{\left|OBF_1^* - OBF_0^*\right|}; \qquad i = 1,2,\ldots\ \ldots\ \ldots, I \tag{7.7}$$

where

OBF_i^* = return from the optimal trajectory for the i th iteration of a given cycle (I = 0,1,2,…), and

I = maximum number of iterations per cycle.

In a situation where successive values of δ_i, do not indicate a significant improvement on the value of the return function, the iterative process is terminated and the next cycle is begun with a reduced corridor width around the optimal trajectory of the completed cycle. Upon completion of the final iteration in each cycle, another convergence criterion is set to determine the convergence of the algorithm towards the optimal solution. Nandalal and Borgardi (2007), define this final convergence criteria as:

$$\lambda = \frac{\left|OBF_j^* - OBF_{j-1}^*\right|}{\left|OBF_{j-1}^*\right|}; \tag{7.8}$$

where

OBF_j^* = return from the optimal trajectory for the j th cycle (j = 1, 2, 3, ……)

λ = arbitrary value of the convergence criteria that terminates the IDP algorithm.

The final trajectory, i.e. the beginning of month reservoir storage levels that yield the optimum return, is identified as the solution of the optimization problem. The backward looking version of the dynamic programming evaluates many reservoir storage levels that are not attainable from the given initial storage levels, resulting in a large computational burden and slow convergence rates.

7.4 Multiple reservoir IDP model configuration with CSUDP

The multiple reservoir IDP algorithm that has been formulated in the previous section was configured within CSUDP which is a generalised Dynamic Programming software capable of solving Dynamic Programming algorithms for a wide range of sequential multi-dimensional problems. Within CSUDP, the user is required to develop customized functions in the C programming language which are then linked to the main program system through a Windows interface written in Visual Basic. The package also includes the public domain Gnu-C Compiler which is used to link the main C program and the user written C-functions for the specific problem. The main program developed for this particular application is based on the IDP algorithm in the backward looking solution procedure.

Labadie (2003) points out that the incremental search procedure inherent in the IDP method implies that it could in fact only converge to discrete local optima depending on the choice of initial trajectories and corridor widths. Nandalal and Bogardi (2007) have illustrated the importance of carrying out sensitivity tests where the effects of varying the corridor widths and choice of initial trajectory are quantified with a view to determining whether the optimum trajectory has been obtained.

7.4.1 Coding of the user supplied functions in CSUDP

A function denoted as **State** in CSUDP was prepared and coded in such a way as to simulate the behaviour of Lakes Victoria, Kyoga and Albert at each time period in such a manner as to easily determine the storage volumes and releases as required in the iterations of the IDP algorithm. This was attained by embedding the tabulated lake elevation vs storage data pairs (Appendix A) as static global arrays in function **State** and fitting a cubic spline function to the discrete storage data points for each lake. The algorithm prescribed by Forsythe *et al.* (1977) was adopted to approximate the function represented by the discrete lake elevation vs storage data pairs. Using this process, a series of unique cubic polynomials are fitted between each of the data points, with the stipulation that the curve obtained be continuous and appear smooth. The fitted spline function is then evaluated for any required lake level in order to determine the storage volume associated with that particular elevation. This is necessary because in function **State**, the live storage for the Lake reservoirs were discretized into intervals of levels spanning the permissible range of storage volumes. The scheme in CSUDP (Labadie, 2003) dictates that the discretisation intervals *delx,* for the range of permissible maximum and minimum lake levels $(X_{i,max}, X_{i,min})$, is selected such that:

$$\frac{\left[X_{i,\max}, \mathrm{X}_{i,\min}\right]}{delx} \leq 251; \qquad (i = 1,2,3) \tag{7.9}$$

The value 251 is imposed due to the current array dimensioning provisions in the software CSUDP. Adoption of a very fine discretisation scheme is extremely important since the reliability of the solution is enhanced. However, dense discretisation adversely affects computer execution times and memory storage hence, the value of *delx* was initially fixed at the permitted minimum value of 0.02 m for Lakes Victoria and Kyoga and 0.025 m for Lake Albert in order to comply with the requirements of Equation 7.9. The set value of *delx* corresponds to half of the "corridor width" around the initial trajectory of each lake in the search for the optimal trajectory in the IDP algorithm. Function **State** applies the inverted forms of Equations 7.4, 7.5 and 7.6 where the feasible releases $(R_{i,t})$ at each stage are computed once supplied with corresponding state vectors $(S_{i,t-1},\ S_{i,t})$, of beginning of month and end of month storages volumes and net inflows $(I_{i,t})$. Computed values of the decision variable, i.e. reservoir release, are rounded off according to a value corresponding to the desired accuracy of the solution.

A second function denoted as **Object** in CSUDP was prepared for purposes of computing the objective function value (*fobj*) for the current stage, and computed vector of release decisions. Function **Object** is called by the main program immediately after function **State** but in this case only if the calculated releases $(R_{i,t})$, returned by function **State** are within the admissible range ($R_{i,max}$, $R_{i,min}$) for i = 1, 2,3 for each lake reservoir (Table 7.1). Tabulated discharge vs power data pairs for each power plant (Appendix B) embedded as global arrays in function **Object** are evaluated in turn by the algorithm that returns cubic spline interpolated values of the power generated for the release magnitude considered along the Victoria Nile and Kyoga

Nile respectively within the current stage. Total power generated is taken to be the sum total of power generated from the individual units.

If no feasible releases are obtained by function **State** for that particular stage, the infeasible release is truncated to the bounds or limits specified. CSUDP continues with the iterations but assigns penalty terms to the objective function in order to encourage minimization of violation of the release constraints. Labadie (2003) specify a penalty term ($pntyu$), currently used in CSUDP as:

$$pntyu = w \times \left[\frac{\left[\max\left(0, R_{i,\min} - R_{i,t}\right) \right]}{delu} \right]^2 \qquad (7.10)$$

or

$$pntyu = w \times \left[\frac{\left[\max\left(0, R_{i,t} - R_{i,max}\right) \right]}{delu} \right]^2 \qquad (7.11)$$

where w = 1000 in the current code and the value of $delu$ = 0.001. $delu$ is the value to which computed releases are rounded off to in this particular application. The application of penalty terms is particularly useful in situations where the initial trajectory specified is poor resulting in the generation of infeasible states at the start. As the iterations proceed, feasible solutions are eventually found and the algorithm only continues to allow feasible solutions in further iterations.

A third function denoted as **Readin** in CSUDP was prepared and made available to read in the net inflows or net basin supply time series for each lake, and the maximum turbine capacities. The variable definitions used to store these arrays are globally shared within functions **State, Object** and **Readin** if they are required to process information. Function **Readin** is called by CSUDP at the beginning of the program.

7.4.2 CSUDP model parameter sensitivity analysis

For purposes of testing the performance of the configured CSUDP model, it is necessary to establish the sensitivity of the model to various parameters such as choice of initial trajectory, and corridor width. It is also important to establish the best combination of parameters that ensure that a global optimum can be reached in a given model run. In the application of the customised CSUDP model to the case study, sensitivity analyses to study the performance of the optimisation model was initiated by providing as input: net basin supply data for the year 1900 and a randomly chosen initial trajectory for each lake. The installed capacity of the hydro power plants was also randomly varied from 980 MW to 1530 MW. The value of *delx*, for the discretisation interval of lake levels was fixed at the permitted minimum value of 0.02 m for Lakes Victoria and Kyoga and 0.025 m for Lake Albert. The *splicing* option where an initially defined coarse interval of *delx* is tightened gradually to the desired value during subsequent iterations was not activated in this trial due to the fact that although it can significantly help to reduce execution time, there is a danger of not attaining the global optimum (Labadie, 2003).

During the search for the global optimum in the CSUDP model, a tie breaking option is also available for selection from the user interface for use in resolving situations where non unique optima exist. The program either saves the first optimal solution it encounters as it optimises over the discretized range of lake levels or saves the last non unique solution (Labadie, 2003). To select the first optimal solution encountered, the user must select the option “first tie value taken” from the user interface or “last tie taken” to return the last non unique solution found. Although the program is not capable of identifying all possible non unique solutions, by repeating the program execution for each tie breaking option, the user can determine whether a unique solution has been found (Labadie, 2003). For purposes of gaining experience with application of the model the option “first tie taken” was selected in this initial trial. The results in Table 7.3 illustrates the effect of varying the installed capacity on model output in the water year 1900 based on the selected CSUDP user interface parameters.

Table 7.3 Effect of varying installed capacity with the year 1900

Installed Capacity of Hydrower Plants (MW)	No. of iterations required for converging to optimal solution	Maximum Energy Generation (MWh)
980	262	90396144
1530	263	115000128

The results presented in Table 7.3 required approximately 4 days of computing time on an IBM Lenovo ThinkPad (T60p) Laptop fitted with an Intel Core Duo processor with clock speed of

2.33 GHz and 3GB of RAM. The model was then run with all the hydropower plants online i.e. with a total installed capacity of 1,530 MW and with the adopted CSUDP user inter face settings for *delx*, *splice* and *tie breaking* options left unchanged for the water year 1900, but with three different sets of initial trajectories specified for each lake. Model runs with trial initial trajectories denoted 1,2 and 3 are presented in Table 7.4.

Table 7.4 Effect of varying the initial trajectory with the year 1900

Trial trajectory number	No. of iterations required for converging to optimal solution	Optimum Annual Energy Generation (MWh)
1	263	115000128
2	219	113259605
3	243	113282162

In Table 7.4, Trajectories 2 and 3 were arbitrarily selected while Trajectory 1 corresponds to the median values of the historical net basin supply series in each month for each lake. Although models run with trajectory 1 required a slightly higher number of iterations to converge, it produced the highest annual energy generation.

Trial Trajectory 1, and all previous CSUDP user inter face settings for *delx* and *splice* for the water year 1900 were retained for the next sensitivity test where the objective was to investigate the effect of varying the *tie break* option. The results in Table 7.5 illustrates the effect of selecting either the "*first tie taken*" or "*last tie taken*" in the CSUDP user interface.

Table 7.5 Effect of varying the tie breaking option with the year 1900

Tie option	No. of iterations for converging to optimal solution	Optimum Annual Energy Generation (MWh)
First tie value taken	263	115000128
Last tie value taken	266	114957596

The effect of repeating program execution for each tie breaking option in Table 7.5 seems to indicate that non unique optima exist. However, the first optimal solution encountered (first tie taken) is only marginally higher than the last non unique solution (last tie taken) whose location is likely to be a "saddle point".

To study the effect of initial corridor width upon the convergence behaviour of the CSUDP model with the IDP process as the optimisation algorithm, the model was run for five different corridor width options, with all settings that yielded maximum annual generation in Table 7.5. Total energy production during the year 1900 and the number of iterations of the IDP model required to converge to the optimal result for the different *delx* settings are shown in Table 7.6. As indicated previously the *delx* setting can be related to corridor width by the relationship *delx* = 0.5 x corridor width.

Table 7.6 Effect of varying the *delx setting* on optimal energy generated for the year 1900

Corridor width option	*delx* settings (m)			No. of iterations required for converging to optimal solution	Optimum Annual Energy Generation (MWh)
	Lake Victoria	Lake Kyoga	Lake Albert		
1	0.10	0.10	0.10	49	-
2	0.05	0.05	0.10	85	-
3	0.02	0.20	0.20	79	114657552
4	0.02	0.10	0.10	101	114877152
5	0.02	0.02	0.025	263	115000128

In Table 7.6, corridor width Options 1 and 2 produced infeasible results since the discretisation intervals violate the provisions of Equation 7.9, hence no objective function results were returned. This experiment confirmed corridor width Option 5 as the one that yields the maximum annual energy generation for the case study. However it is also associated with a large number of iterations and therefore requires a lot of computing effort.

An attempt was made to run the IDP model with the settings that yield the optimal operation policies for a period of at least 80 years at a monthly time scale so as define monthly operating rules that relate release from any lake in a given month to the initial storage and net basin supply. At a later stage this approach would involve the determination of generalized lake-reservoir operating rules by multiple regression analysis. Unfortunately, insurmountable difficulties were encountered due to the excessive amount of computer time required for the IDP model to converge to the optimal solution. The length of computing time involved was in the order of several weeks. Due occasional interruption of power supply during these extended model runs, none of the trials was successfully concluded.

In order to reduce the computation times to reasonable time frames by reducing the dimensionality of the IDP model, subsequent analysis was confined to illustration of the prescribed optimal operating policies by the IDP model to a typical water year and evaluation of the defined operation rules of over an annual time step for period 1899 – 2008.

7.5 Trial operation policies for selected water years

The CSUDP model with the settings that yielded maximum energy generation in Table 7.6 was adopted to derive trial operation policies for three different years taken to be representative of a wet, average or dry year in the Lake Victoria Basin. The years were selected based on visual inspection of the computed annual net basin supply bar chart plots for each lake as illustrated in Figures 5.4, 5.7 and 5.10 in Chapter 5. The purpose of generating these trial policies was to confirm correct functioning of the code and model set up based on a wider range of scenarios than those considered in the sensitivity tests. Table 7.7 below shows the input inflow data for each lake and releases determined by the optimization model.

Table 7.7 Net basin supply input data and prescribed releases for three trial years

Reference Lake	Year	Net inflow (MCM)	Determined average releases ($m^3. s^{-1}$)
Victoria	1935 (average year)	18193	1267
	2006 (wet year)	49272	1246
	1900 (dry year)	5999	758
Kyoga	1935	-1939	1483
	2006	7877	1460
	1900	896	755
Albert	1935	4274	1022
	2006	10269	997
	1900	4758	372

The maximum energy generation obtained by the IDP model for each of the three selected years is shown in Table 7.8.

Table 7.8 Maximum energy generation for representative wet, average and dry years in the Lake Victoria basin

Water Year	Maximum Energy Generation (MWh)	No. of iterations required for converging to optimal solution
1935 (average year)	192527280	281
2006 (wet year)	189759120	319
1900 (dry year)	115000128	263

Generally, considerably less energy is generated in dry years, as expected. The trial operation policies to maximise hydropower generation without violating the system constraints for the three water years are illustrated in Figures 7.8 – 7.10.

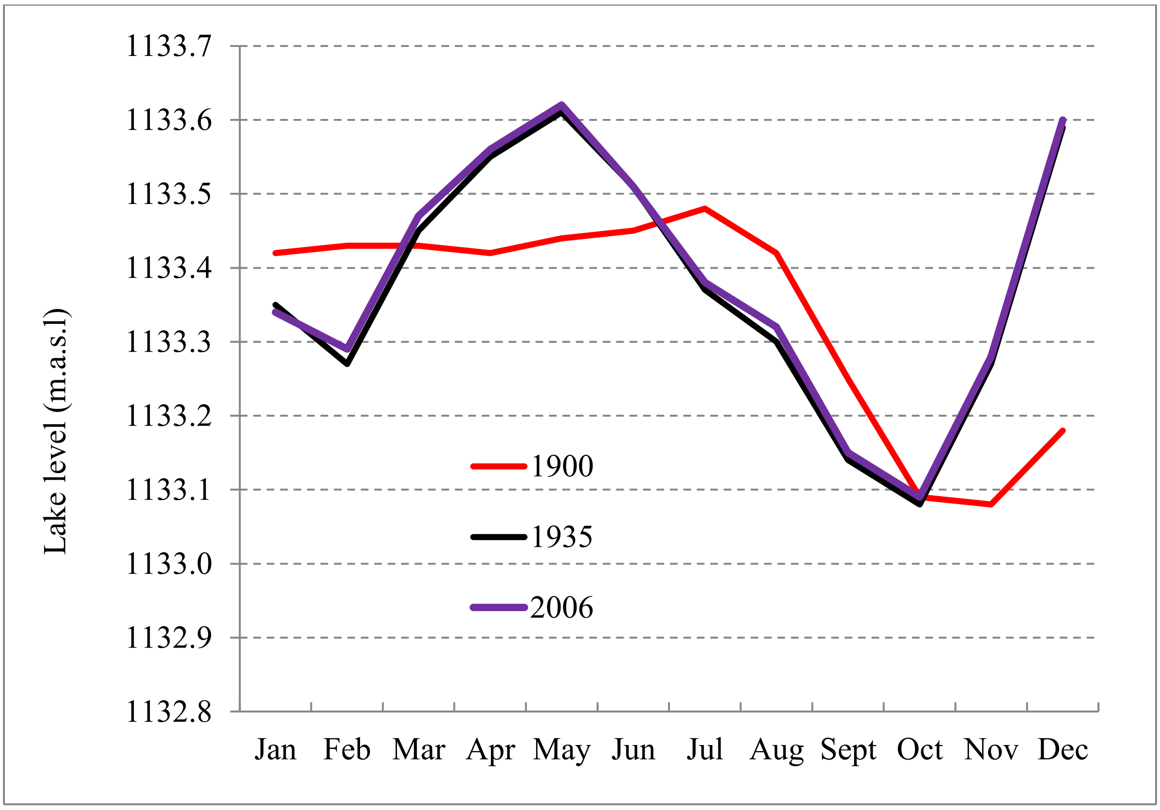


Figure 7.8 Beginning of month Lake Victoria Levels that yield maximum hydropower generation in typical water years.

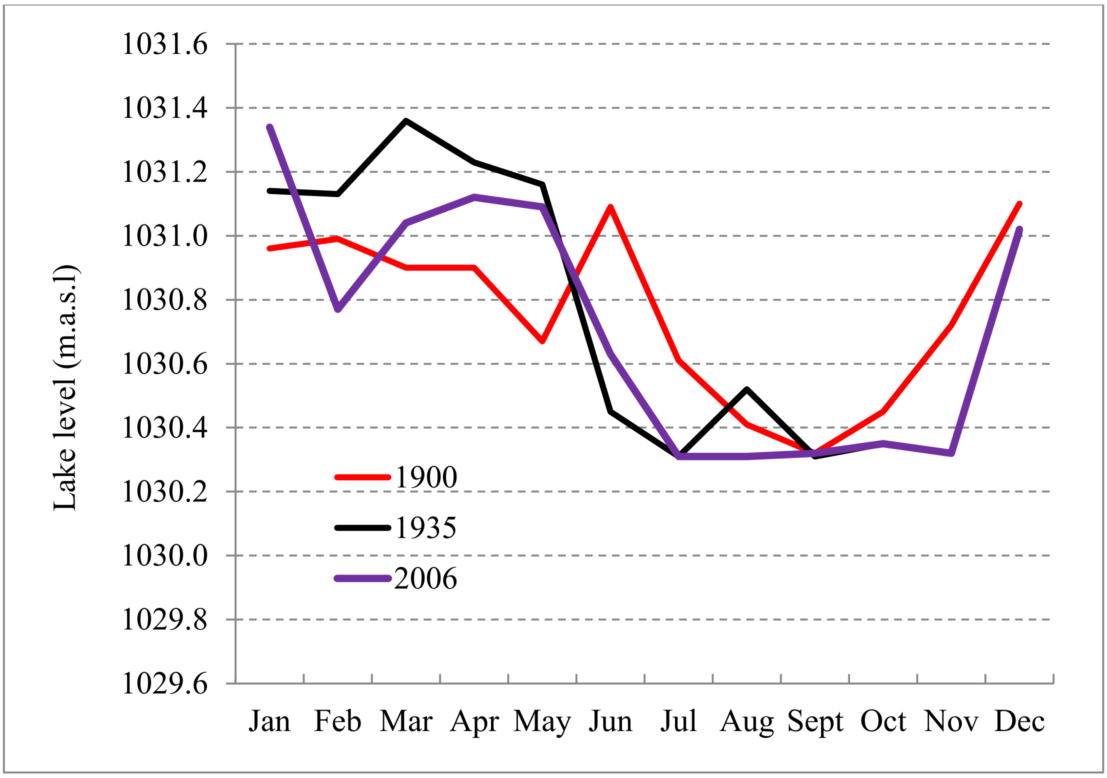


Figure 7.9 Beginning of month Lake Kyoga levels that yield maximum hydropower generation in typical water years.

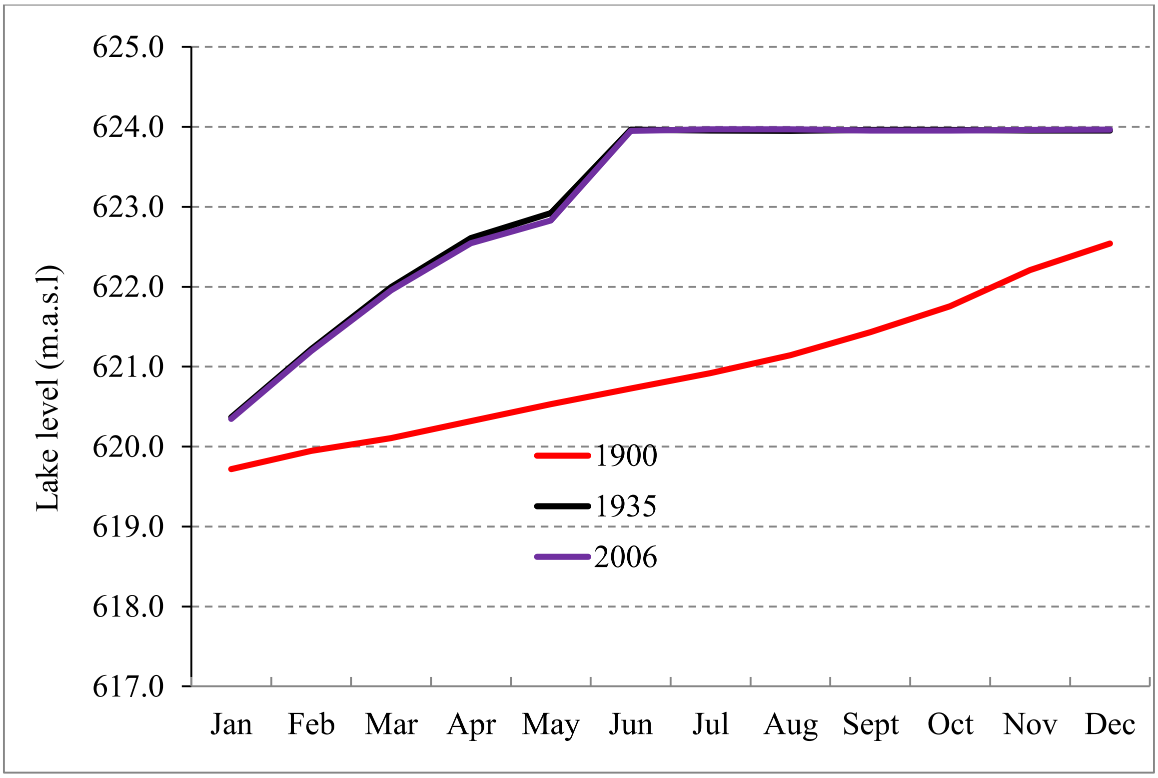


Figure 7.10 Beginning of month Lake Albert levels that are associated with maximum hydropower generation in typical water years.

In Figure 7.8, the beginning of month storage targets for Lake Victoria that are associated with maximum hydropower generation subject to satisfaction of system constraints, are similar in a typical wet or average year but different in a typical dry year. The prescribed beginning of month lake levels are the same in the month of October. Since the prescribed storage targets for the year 1935 and year 2006 are of similar magnitude with respect to Lake Victoria, and given that the year 2006 was a wet year, the simulation would be expected to indicate that more energy can be generated as compared to the year 1935, which is considered to be a dryer year (Table 7.7). This apparent discrepancy can be rationalised by referring to Table 7.7 where it is shown that enhanced energy generation in the case of water year 1935, is made possible by prescribed releases along the Victoria and Kyoga Nile that are 1.16% higher than those prescribed for the year 2006.

Releases of lower magnitude from Lake Victoria are generally provided to safeguard against flooding around the shoreline of Lake Kyoga, more especially when wet years in the Lake Victoria basin coincide with years associated with net gain in the Kyoga basin at high level. A typical example of such a scenario occurs in the year 2006 when wet years coincide and net inflows in the Victoria and Kyoga basins are 49,272 MCM and 7,877 MCM respectively.

A reverse scenario presents its self in 1935, considered to be an ‘average year’ in terms of inflows in the Lake Victoria basin (18,193 MCM) and a year associated with net loss in the Lake Kyoga basin (-1,939 MCM). When this happens and similar storage targets are feasible, then there is low risk associated with flooding around the shores of Lake Kyoga and higher releases along the Victoria Nile can be permitted.

The pattern for Lake Kyoga is different but it is noticeable that the prescribed beginning of month levels associated with maximum hydropower generation are within a narrow range of 1030.3 m i.e. the minimum allowable level, and 1030.5 m between July to October. The beginning of month Lake Albert levels associated with maximum hydropower generation in a typical wet or average year are approximately the same, levelling off to 623.97 m i.e. the maximum level allowable, in June to December. In a typical dry year, the pattern of beginning of month storage levels associated with maximum hydropower generation is almost linear, increasing from 619 m to 622 m in January to December.

However, the storage targets suggested by Figures 7.8, 7.9 and 7.10 can only be regarded as indicative and not representative of a situation where long term persistence is prevalent in annual time series such as Lake Victoria levels.

7.6 Optimal operation policies based on historical annual time series of net basin supply

The CSUDP model that was utilised to derive indicative optimal operating policies for a typical year (12 stages) in Section 7.5 was adapted to analyse 110 years of net basin supply (110 stages) for each lake for the period 1899 - 2008. The initial trajectory adopted for this model run were the observed end of year lake levels for each lake. All other CSUDP user interface options were left unchanged so as to ensure that maximum annual generation is returned. Each run of results required approximately 21 days of computing time on an IBM Lenovo ThinkPad (T60p) computer fitted with an Intel Core Duo processor with clock speed of 2.33 GHz and 3GB of RAM. Model execution was repeated for two different options that involved varying the system constraints as shown in Table 7.9.

Table 7.9 System constraints for annual net basin supply optimisation

Selection	Lake	Lake levels (m.a.s.l)		Flows ($m^3.s^{-1}$)	
		Minimum	Maximum	Minimum	Maximum
Option 1	Victoria	1133	1136	347	1721
	Kyoga	1030	1034	280	1991
	Albert	618.8	624	343	2074
Option 2	Victoria	1133	1136	347	2150
	Kyoga	1030	1034	280	2500
	Albert	618.8	625.9	343	2074

Option 1 is consistent with the maximum and minimum limits of lake levels and outflows observed in the historical data. In Option 2, the maximum lake level for Lake Albert is allowed to increase to 625.9 m while Lake Victoria and Kyoga outflows are allowed to reach 2,150 $m^3.s^{-1}$ and 2,500 $m^3.s^{-1}$ respectively. Option 2 allows Lake Victoria maximum outflow to reach the turbine outflow limits imposed by the existing Nalubaale-Kiira power plants so as to ensure generation of maximum power at appropriate lake levels. Option 2 permits Lake Kyoga outflows to exceed the historically observed limits, ostensibly to alleviate damage to shoreline infrastructure.

The rationale for experimenting with Option 2 is derived from a review of the work of Kite (1984) who utilised the Hydrologic Model of the Upper Nile Equatorial Lake Basin (Nemec and Kite, 1979) to simulate and test several previously designed regulation plans for Lakes Victoria, Kyoga and Albert. The regulation plans deemed to have been successful when evaluated in terms not violating dead storage constraints during the period 1912 – 1974, indicated that Lake Kyoga outflows should be allowed to exceed the historically observed limits so as to maintain the allowable limits on Lake Kyoga levels. These trial plans also permitted Lake Albert maximum recorded level to be exceeded. However, the plans tested by Kite (1984) were deemed successful in spite of the fact that the range of allowable levels prescribed were greater than the historical range in the case of Lake Victoria.

Within the context of the results obtained from the evaluation of historical regulation plans by Kite (1984), Option 2 is an attempt to draw lessons from these findings through specification of system constraints that avoid deviation from the historically observed range of lake levels for Lake Victoria and Lake Kyoga by permitting a wide range of releases and allowing Lake Albert to have a wider range of storage level variation since it can be utilised as a balancing reservoir in the system. Figures 7.11, 7.12 and 7.13 illustrate the beginning of period lake levels for the period 1899 – 2008 that result in maximum hydropower generation as prescribed by the IDP optimisation algorithm in the setup of the CSUDP model for the case study. The figures also illustrate the impact of the optimum operating policies on natural unregulated long-term lake levels i.e.. Agreed Curve end of year lake level records.

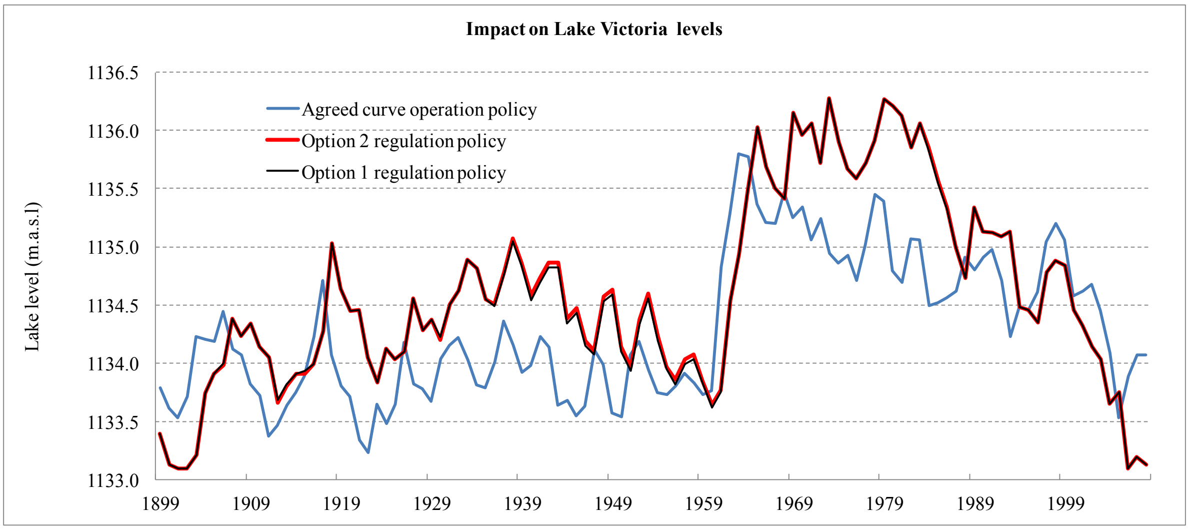


Figure 7.11 Optimal operating policies for Lake Victoria (1899 – 2008).

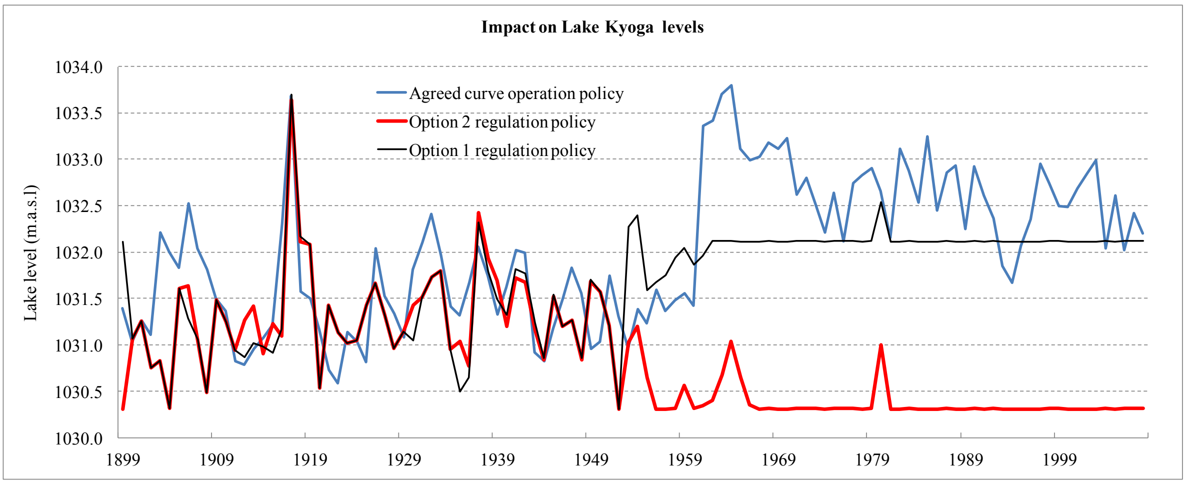


Figure 7.12 Optimal operating policies for Lake Kyoga (1899 – 2008).

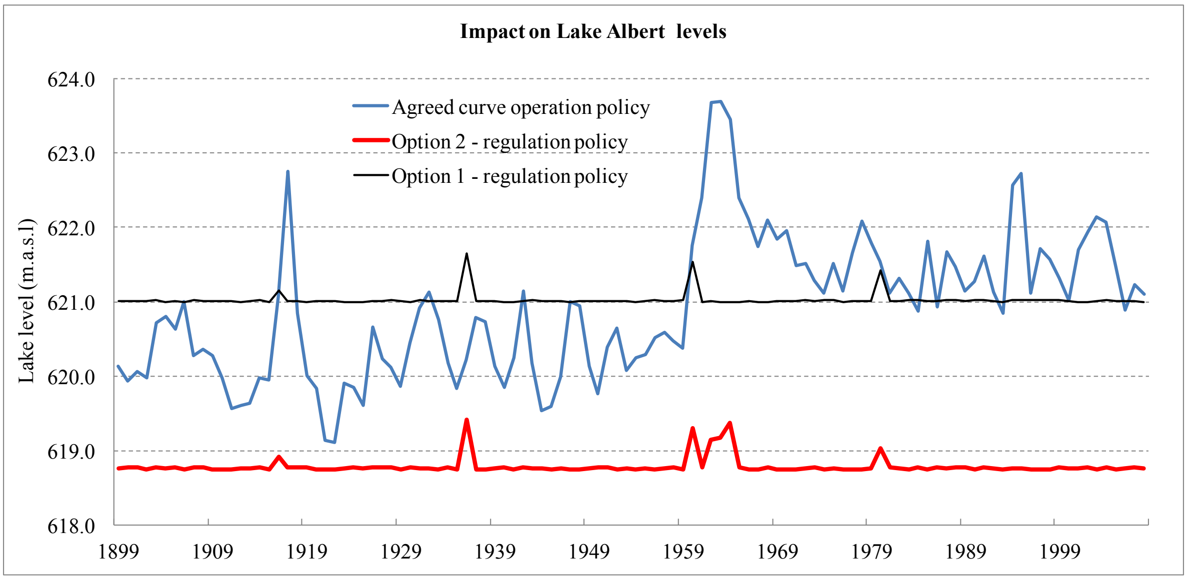


Figure 7.13 Optimal operating policies for Lake Albert (1899 – 2008).

In Figure 7.11, it is demonstrated that the magnitude of beginning of period Lake Victoria levels that would have yielded maximum hydropower generation is not significantly different under Options 1 and 2. As expected, in many instances the beginning of period lake levels prescribed by regulation with Option 1 or 2 are significantly higher than the natural lake levels that would have occurred. It is also striking to note that the beginning of period lake levels associated with maximum hydropower tends to mimic the shape of the variation of natural unregulated lake levels.

In Figure 7.12, it is evident that the beginning of period Lake Kyoga levels prescribed by regulation in accordance to Option 1 or 2 are approximately the same from the year 1900 up to 1952. After that, the beginning of period Lake Kyoga levels prescribed by Option 1 regulation are higher than those prescribed by Option 2. Both tend to suggest that Lake Kyoga should be maintained at a constant elevation of 1032.12 m.a.s.l after the year 1962 in the case of Option 1 and at 1030.31 after 1967 in the case of Option 2. Under both options, a deviation is evident in 1980 but it is short lived. In general Options 1 and 2 are associated with lake levels that are lower than the historically observed record with the natural variation being significantly altered, particularly after 1962. It is also interesting to note that some of the historical plans reviewed by Kite (1984) included trials that suggested that Lake Kyoga be regulated to maintain a constant elevation of 1031.62 m.a.s.l or 1035.23 m.a.s.l without being successful.

During the course of execution of the IDP optimisation algorithm, many more infeasible and/or inferior initial storage volume scenarios occur, in the case of Lake Kyoga, during the post 1961 hydrological regime. Constant lake level elevations tend to be prescribed by the optimisation model over this period as these are the transitions that result in feasible releases and superior hydropower generation capacity for a given set of release constraints. Sustained high regulated releases from Lake Victoria typically in the range of 1200 $m^3.s^{-1}$ tend to limit the range of existing feasible solutions. For example, an outflow of 1000 $m^3.s^{-1}$ would lower the level of Lake Victoria by 37 mm after one month, but the same inflow would raise Lake Kyoga by nearly 700 mm because of its smaller surface area (Swenson and Wahr, 2009).

This argument can also be extended to Lake Albert. Sene (2000) demonstrated that at high flow, a 1 m increase in Lake Victoria is capable of exerting a 1.57m rise in Lake Kyoga and a 1.7 metre increase in Lake Albert. Hence for any given lake reservoir, its upstream lake imposes extra constraints on the feasible region within which it has been designed to operate. In Figure 7.13, it is shown that regulation of Lake Albert would entail maintaining it at a constant elevation of about 621 m.a.s.l in the case of Option 1 and at a much lower elevation of 618.76 m.a.s.l in the case of Option 2. Clearly the variation associated with the unregulated natural lake levels would be drastically altered.

The pattern of total annual maximum hydropower generation over the period 1899 – 2008 that would have resulted if all hydropower plants considered were online is shown in Figure 7.14 below. It is approximately the same under Options 1 and 2. The simulation shows that annual hydropower generation in Options 1 and 2 is extremely variable prior to 1961 when lake levels were much lower in Lake Victoria and more stabilised thereafter when lake levels rose. Figure 7.14 clearly demonstrates the beneficial aspects of lake regulation in terms of enhancement of hydropower generation when compared against unregulated conditions i.e. Agreed curve operation. It also quantitatively illustrates the desirability of maintaining the post 1961 hydrological regime for the lakes if the objective is to maximise hydropower generation.

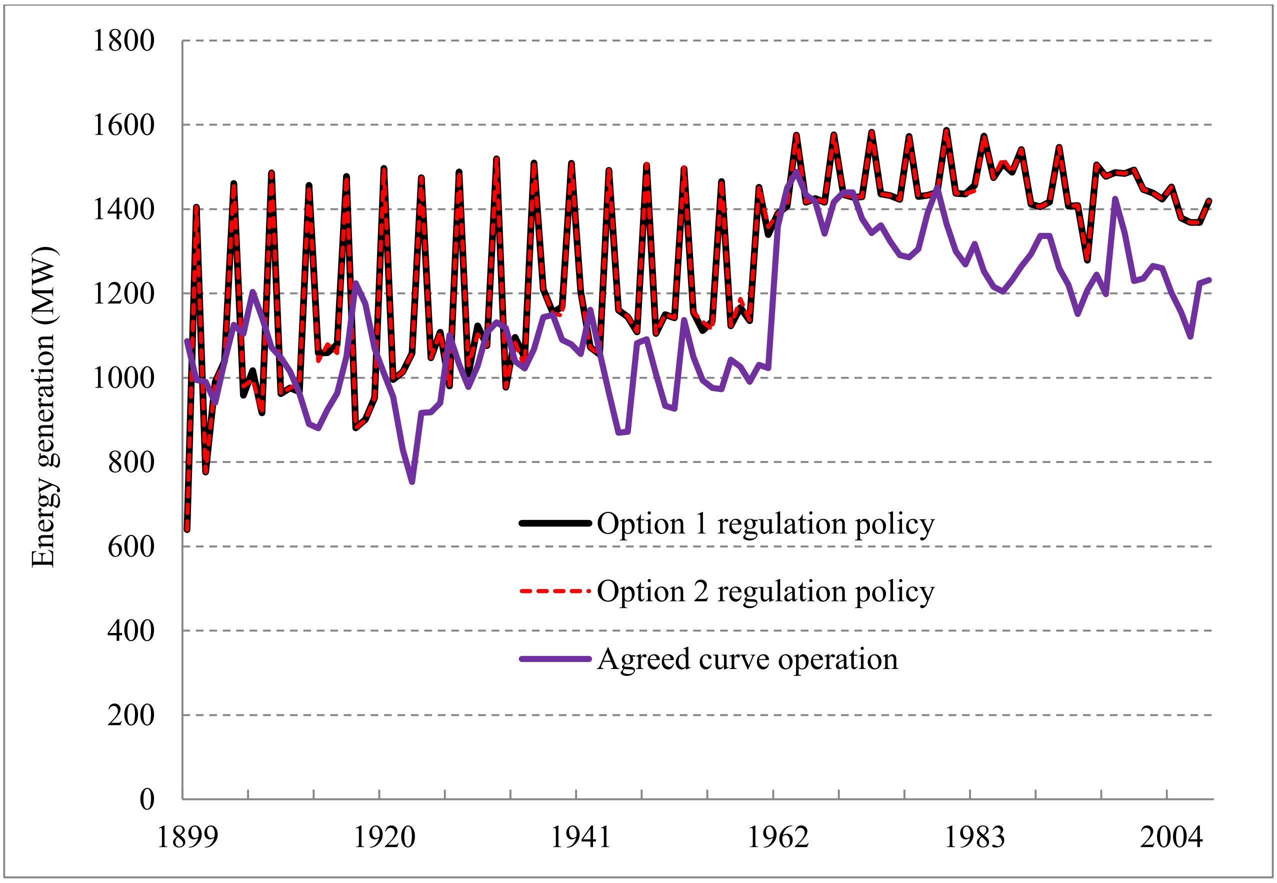


Figure 7.14 Variation of hypothetical annual hydropower generation (1899 – 2008).

Under regulated lake conditions, power generation can be enhanced in the short term by as much as 64% in certain years when compared against operation using naturalized lake levels or unregulated conditions. However, over the whole the planning period considered (1899 – 2008), the average gain in power produced under regulated lake conditions was a modest 13% (Table 7.10).

Table 7.10 Statistics of energy generation for the period 1899 – 2008 under various regulation options

Regulation policy	Mean annual energy generation (MW)	Total energy generation (MW)
Option 1	1287	141598
Option 2	1287	141596
Agreed curve	1144	125828

Table 7.11 contains a summary of the hydraulic statistics for regulation with Options 1 and 2. They are largely similar in terms of minimum and maximum values reached. However, the maximum withdrawals are significantly higher when the lakes are regulated with Option 2.

Table 7.11 Hydraulic statistics of flow ($m^3.s^{-1}$) for regulation Options 1 and 2

Limits	Option 1			Option 2		
	Victoria	Kyoga	Albert	Victoria	Kyoga	Albert
Minimum	261	280	343	261	280	344
Mean	861	864	981	861	866	986
Maximum	1718	1864	2057	1761	1908	2059

To attain convergence of the IDP algorithm in its application for Lake Victoria, the minimum flow constraint had to be relaxed for the initial two years of the model run i.e. in 1899 and 1900. In these two years the minimum flow constraint was relaxed from 347 $m^3.s^{-1}$ at all times to 261 $m^3.s^{-1}$ in 1899 and 274 $m^3.s^{-1}$ in 1900. Under these conditions, Options 1 and 2 violate the minimum flow constraint in Lake Victoria in the years 1899 and 1900. No violation of minimum flow constraints occurs in subsequent years of the near optimal trajectories. The reasons as to why minimum release constraints have to be violated in these years are related to the fact the initial lake reservoir conditions are very close to the minimum lake level.

Furthermore, years 1899 and 1990 were notably dry years. Year 1899 recorded the lowest net basin supply value of – 12,975 MCM in the Lake Victoria Basin.

7.7 Concluding remarks

In this chapter it has been demonstrated that the IDP algorithm can be utilised to generate operating rules using the implicit approach at an annual rather than monthly time scale. The monthly time scale is associated with prohibitively excessive computation times. The operating rules defined with this approach significantly enhance hydropower generation when compared against unregulated lake conditions. The option to derive generalized rules by considering several sequences of annual net basin supply which are all equally likely to occur, such as those generated synthetically in the previous chapter, should be explored further in future studies. In the next chapter, the viability of stochastic operation policies derived using probabilistic occurrences of inflow was investigated.

8. APPLICATION OF A STOCHASTIC DYNAMIC PROGRAMMING OPTIMISATION METHOD TO THE EQUATORIAL LAKE BASIN CASE STUDY

Regulation plans that perform best over the historical period of record (1899 – 2008) have been identified with the IDP algorithm and reported in Chapter 7. However, this period of record is only one of the many possible sequences of events. Other methods such as the explicit approach of deriving operating rules (Labadie, 2004), utilise the probability distribution of inflows derived from the historical record rather than a specific set of deterministic specific inflow sequences. In this chapter, the Generalised Dynamic Programming package: CSUDP (Labadie 2003) is used to explore operation policies in each time step for Lake Victoria which comprise of storage targets for every possible reservoir storage and inflow state derived using the SDP algorithm. The exploratory approach is adopted after considering it's known limitations. The large computational burden associated with application of SDP to large lake reservoirs in series with an implicit approach has already been illustrated in the previous chapter and it is recognized it could be significantly greater under the explicit approach. The other known challenge is the difficulty associated with identifying transition probabilities for each of the three lakes and simultaneously representing them within a 3 dimensional SDP algorithm.

Only one reservoir was studied initially for didactic purposes, with a view to understand the strengths and limitations of applying the procedure to a large lake such as Lake Victoria. Net inflows to Lake Victoria are treated as the stochastic random variable in the SDP model and are assumed to be correlated with the inflow of the preceding time period. The optimization objective is to find operating policies that maximize the expected undiscounted maximum power generated over a yearly time horizon. This, in essence, amounts to the determination of the amount of water to be released on the basis of annual intervals, by the reservoir operator, based on the information available i.e. the state of the system, in order to optimize net benefits. Discounting is the inclusion of an interest rate factor in the computation of the present values of the time stream of net benefits generated over a planning period. For these trials, however, a solution has been attempted without a discount rate.

8.1 Mathematical formulation of the single reservoir SDP Model

Typically the system of power plants along the Victoria Nile (Figure 7.1), is modelled within the framework of a periodic Markovian decision process. The SDP model employs the method of successive approximations originally developed by White (1963) and extended and applied by others to derive operation rules for a single multipurpose lake-reservoir systems (Su & Deininger, 1974; Oven-Thompson *et al*., 1982; Bras *et al*., 1983; Nandalal and Bogardi, 2007). This approach is particularly suited to the serially correlated nature of inflows or net basin supplies which have been analyzed in detail for Lake Victoria in Chapter 6. A key element of the solution procedure is to select the two state variables for which release decisions are sought. These are the reservoir storage at the beginning of a particular period and the total inflow realized in the preceding period. This strategy recognizes the reality of not being able to predict, at present, the exact inflow into Lake Victoria at the beginning of each period due to the large basin size involved and underlying complexity of its hydrological regime.

Similar versions of the procedure that consider storage at the beginning of the month and an inflow or forecast for the same month have been applied elsewhere (e.g. Alarcon & Marks, 1979; Tejada-Guibert *et al.* 1993; Kim and Palmer, 1997; Castelletti *et al.* 2005, 2007; Soncini-Sessa *et al*., 2007b) but were not pursued due to the limitations cited under this case study.

The mathematical formulation of the single reservoir/lake model begins with the variable definitions described in Table 8.1.

Table 8.1 Variable definitions of the SDP mathematical formulation

Variable	Definition
T	number of time periods per cycle.
t	index showing the time intervals in a cycle in the real time direction (t = 1) i.e. one cycle per year
N	is a stage counter in the successive approximations procedure. The total number of stages in the algorithm is denoted by *N*. Generally, the value of N is a multiple of cycles i.e. one cycle per year in this case. The cycles are repeated several times in the sequential decision process hence *N* = t**L* where *L* = the number of cycles to be evaluated in the stochastic dynamic programming calculations. In a backward moving SDP algorithm, *N* takes on the values *N*, *N*-1,…,1.
S_i^t	storage state variable representing the lake-reservoir volume at the beginning of period t. This variable can assume the value of *M* discrete values $i = 1, \ldots, M$.
Q_j^{t-1}	inflow state variable representing the net inflow or net basin supply to the lake-reservoir during the period t -1. The net inflow takes on *N* discrete values $j = 1, \ldots, N$.
$f_t\left(S_i^t, S_i^{t+1}, R^t\right)$	is the function of the SDP model for any period *t* which represents the energy generated downstream of a lake-reservoir during stages n = 1,….N. It is a function of the beginning and end of period discrete reservoir storages S_i^t, S_i^{t+1}, respectively and R^t ,which is the total volume of release from the reservoir during period *t.*
$F^n\left(S_i^t, Q_j^{t-1}\right)$	is the objective function of the SDP model which takes into account the accumulated expected energy generation by optimal operation of the system over stages n, n + 1,…,N, assuming reservoir storage is at current discrete level S_i^t and previous period net inflows were Q_j^{t-1}.
$P\left[Q_k^t / Q_j^{t-1}\right]$	is a transition probability which represents the probability of the *k*th discrete value of inflow event Q_k^t occurring during period *t*, conditioned on the previous period inflows Q_j^{t-1} occurring within discrete class *j*.

To obtain a current release policy for a single lake-reservoir, the optimization procedure begins at some known point in future and works backwards in time, over stages N, N-1,….., 1, searching for an optimal release decision that maximizes the total annual hydropower generated from that point to the end of the horizon. Although the operational horizon is theoretically infinite, the algorithm is initiated with an arbitrarily large value of annual cycles hence increasing finite values of N are tried until the algorithm converges to a stationary operating policy.

For example, at the end of the horizon, it is assumed that the expected power generated from that point on i.e. F^{N+1} (..) = 0. This means that at this point in time the power plants downstream of the lake reservoir are not usable any more. Based on a number of trials with varying number of years, it was established that the SDP algorithm requires a maximum of 5 years to assure convergence. Adopting a notation similar to Labadie (1994), the generalized DP formulation is:

$$F^N\left(S_i^t, Q_j^{t-1}\right) = \max_{R^t} \sum_{Q_k^t} P\left[Q_k^t / Q_j^{t-1}\right]\left[f_t\left(S_i^t, S_i^{t+1}, R^t\right) + F^{N+1}\left(S_i^{t+1}, Q_k^t\right)\right] \tag{8.1}$$

where:

$$R^t = S_i^t - S_i^{t+1} + Q_k^t \tag{8.2}$$

Equation 8.2 is the inverted form of the reservoir/lake mass balance relationship and with it, optimization is performed directly over the end-of-period volume with releases being treated as the random variables.

Strict bounds are maintained on reservoir storage levels in the optimization process but there is a potential risk of failure to satisfy constraints on release. Should releases exceed the allowable limits, a penalty term is subtracted from the objective function to discourage violation of release constraints (Labadie, 1993, 2003). Alternatively, program CSUDP can allow violations up to a pre-specified maximum risk of failure to exceed downstream release constraints.

The SDP optimization algorithm proceeds by aggregating the total expected value of the objective function at each stage until it reaches the accumulated value at the end of the first year (e.g. when $t = 1$). This marks the end of the first iteration for the hypothetical example. It then sets the value of the objective function for the beginning of the 2nd cycle to the accumulated value computed during the previous iteration. An outline of the procedure is illustrated in Figure 8.1. Convergence of the algorithm can be determined once one or both of the following two criteria are satisfied:

a) When the best final storage volume, given an initial storage volume does not differ for each season of the year in each of the successive iterations. In addition stabilization of the expected annual increment of total power generated from operation of the system must be demonstrated as the backward moving iterations proceeds (Loucks, *et al.*, 1981, 2005). This implies that $F^{n}\left(S_i^t, Q_j^{t-1}\right) - F^{n+1}\left(S_i^t, Q_j^{t-1}\right) = a\, constant\, value,$ regardless of the storage volume and time period.

b) Once the derived operation policy does not change from year to year (Chow *et al.*, 1975). It has been demonstrated by Ross (1983) that if discounting is not considered in the application and the algorithm converges then the solution must be optimal.

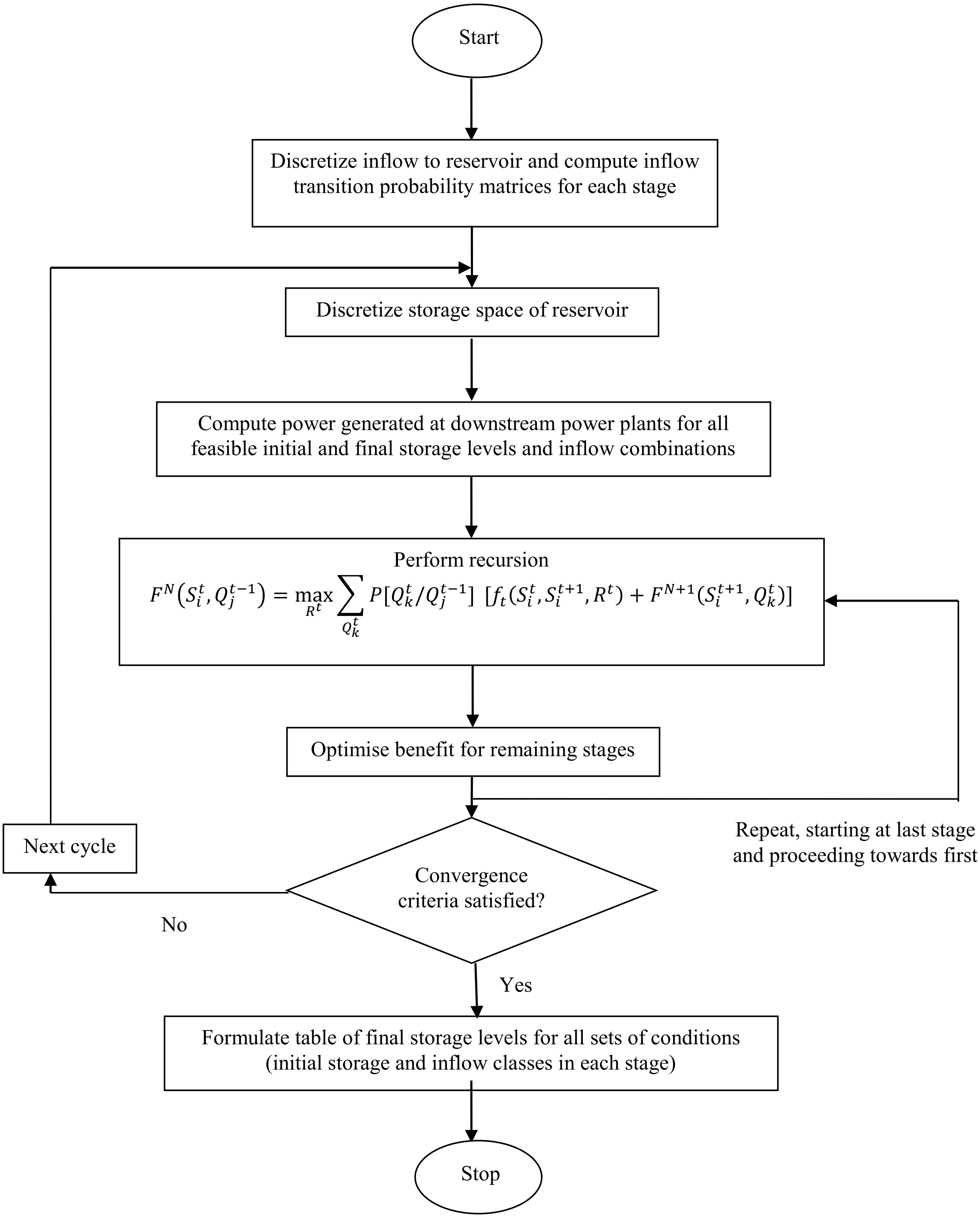


Figure 8.1 Flow diagram for the SDP model (Nadalal and Borgadi, 2007).

8.2 Stochastic inflow characteristics

Lake Victoria is a large lake with annual net basin supply time series characterized by long term persistence and long term periodicities. Overall it is noticeable, even by visual analysis that periods occur when on the whole, annual net basin supply values are above the long term average and others are below it. In Chapter 5, the presence of abrupt shifts in the mean of contiguous time series of annual net basin supply time series of irregular length was confirmed and documented. However the occurrence of departures or shifts from the mean is unpredictable. Various studies have demonstrated that natural lake level response strives to reach a stable equilibrium value during sustained episodes of 10 – 20 years of more or less constant rainfall or net basin supply (Salas *et al.*, 1982; Sene and Plinston, 1994).

Consequently, the annual record of computed net basin supply time series for Lake Victoria for the period 1899 – 2008 were utilised as the basic data for stochastic inflow analysis. The continuous inflows in each year for Lake Victoria were discretized by dividing the entire flow range into three class intervals and assigning a characteristic flow value for each class interval. The choice of inflow classes is influenced by considerations reported in the literature for similar lake-reservoirs such as the High Aswan Dam on the Nile where a framework of indexing the inflows and linking them to qualitative forecasts with categorizations such as "Very High", to "Very Low" was implemented (Abdelkader *et al.*, 1994). The current version of CSUDP restricts the analysis of inflow classes to a maximum of only five classes (Abdelkader *et al.*, 1994). In this case study the "Low", "Medium" and "High" categories have been adopted. It is acknowledged that the adopted discretization is coarse but this is due to the computational burden of the SDP algorithm and limitations imposed by the limited array sizes in CSUDP.

The choice of number of representative values for each state variable is usually made in such a manner as to assure a solution in a moderate amount of time. In this way, the selected three representative values of seasonal net inflow for the state variable are considered adequate since a difference of 1 or 2 million cubic metres is marginal when it is considered that the active storage in Lake Victoria is 215.55 billion cubic metres. The inflow class arrangement for the adopted scheme is illustrated in Figure 8.2.

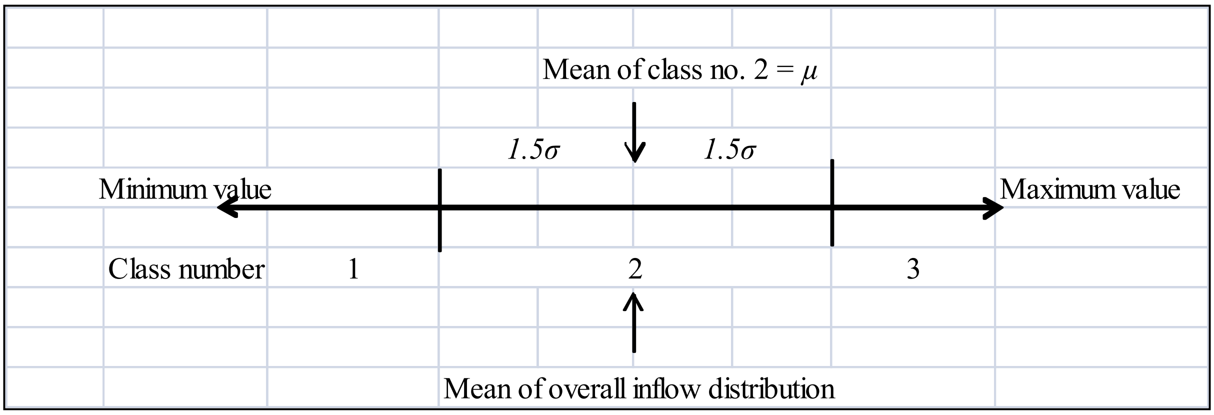


Figure 8.2 Discretisation of seasonal Lake Victoria net basin supply.

The mean of the second inflow class (μ), is positioned to coincide with the mean of the theoretical net basin supply distribution for the annual time series. The class width of this class is set to be three standard deviations (3σ). The interval of the lowest inflow class is taken to be from the minimum value to the lower limit of Class 2. Similarly, the interval of the highest class is taken to be from the upper limit of Class 2 to the maximum value. The representative inflow for Classes 1 and 3 were taken to be the mean of the net basin supply time series in that interval. This method of discretisation of inflows is similar to one first proposed by Ratnayake and Harboe (1992).

With this data, a set of 3 x 3 transition probability matrices for these inflow states were computed from year to the next by counting the frequency of occurrence of the current annual inflow being in class interval *k* given that the previous annual inflow was in class interval *j*. The conditional probability transition matrix for Lake Victoria is presented in Table 8.2.

Table 8.2 Conditional probability transition matrix for Lake Victoria annual inflows

Class No.		1	2	3
	Characteristic inflow value	4075.44	27125.33	52351.85
1	4075.44	0.44	0.41	0.15
2	27125.33	0.25	0.33	0.42
3	52351.85	0.24	0.46	0.30

8.3 Coding and application of the Stochastic CSUDP model

Functions **State,** describing the reservoir mass balance or system state transformations relations and **Object,** which evaluates the hydropower production curves or objective function, were prepared and linked to the main program in CSUDP which applies the stochastic dynamic programming recursion relation (Equation 8.1). The two functions are similar to the ones coded for the IDP model application and the description of the details of the coding are not repeated in this chapter. A third function denoted as **Readin** in CSUDP was also prepared and made available to read in the maximum turbine capacities for the power plants along the Victoria Nile.

Additional data was supplied to the software via an interactive menu driven interface. The maximum and minimum permissible storage limits were entered as 1136.3 m and 1133.0 m respectively. Upper and lower bounds on release were initially set to 0 $m^3.s^{-1}$ and 2150 $m^3.s^{-1}$ with a provision to allow a spillway release flood magnitude of 4500 $m^3.s^{-1}$ in extreme cases. A maximisation problem was specified, with the backwards solution algorithm. The discretisation interval for the storage space was specified as 0.05 m. The maximum number of iterations was specified as 5 cycles. Finally, the discrete classes of seasonal net inflows to Lake Victoria and their corresponding conditional transition probabilities at each stage of the iteration process (Table 8.2) were entered into the dialogue boxes of the interactive menu.

The CSUDP model was successfully run with the above set of data. The model required approximately 1 day of computing time on an IBM Lenovo ThinkPad (T60p) computer fitted with an Intel Core Duo processor with clock speed of 2.33 GHz and 3GB of RAM. The optimal policies for each season, from the point of view of maximising hydropower production, are shown in Figure 8.3. The policies illustrate optimal storage guide curves that specify the final end of period storage targets that are dependent on the observed initial reservoir elevation and previous period's annual inflow.

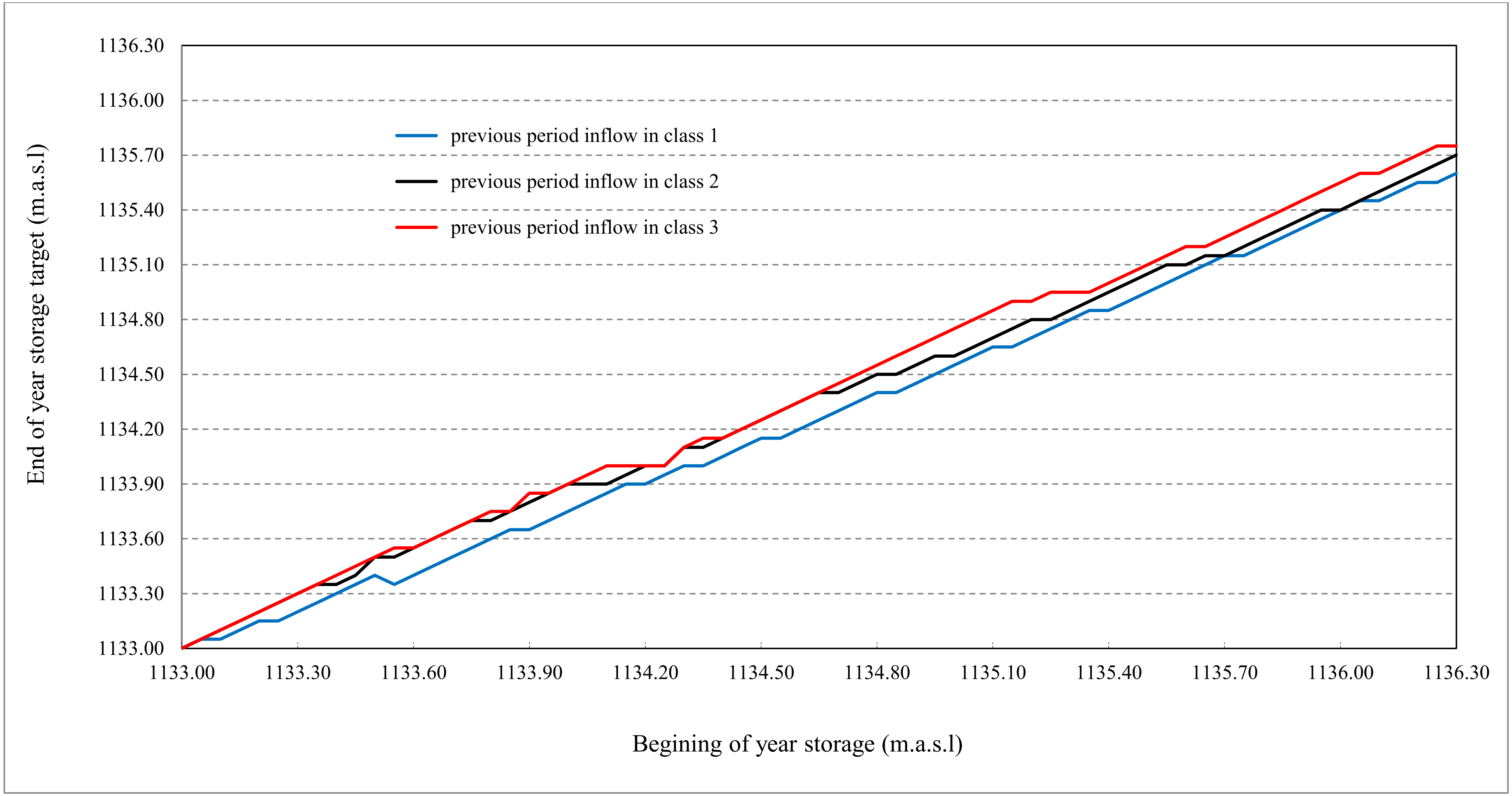


Figure 8.3 Lake Victoria storage guide curves.

The specified guide curves enable the decision maker to operate the Lake as a reservoir within a narrow band of end of year target storage curves conditioned on discrete storage levels and discrete characteristic previous period inflows. In addition, more detailed tabular values are provided to back-up the graphical rules (Table 8.3).

Table 8.3 Lake Victoria storage guide curves

Beginning of year storage (m.a.s.l)	Prescribed end of year storage target (m.a.s.l) given that previous period inflow is in class 1	Prescribed end of year storage target (m.a.s.l) given that previous period inflow is in class 2	Prescribed end of year storage target (m.a.s.l) given that previous period inflow is in class 3
1133.00	1133.00	1133.00	1133.00
1133.05	1133.05	1133.05	1133.05
1133.10	1133.05	1133.10	1133.10
1133.15	1133.10	1133.15	1133.15
1133.20	1133.15	1133.20	1133.20
1133.25	1133.15	1133.25	1133.25
1133.30	1133.20	1133.30	1133.30
1133.35	1133.25	1133.35	1133.35
1133.40	1133.30	1133.35	1133.40
1133.45	1133.35	1133.40	1133.45
1133.50	1133.40	1133.50	1133.50
1133.55	1133.35	1133.50	1133.55
1133.60	1133.40	1133.55	1133.55
1133.65	1133.45	1133.60	1133.60
1133.70	1133.50	1133.65	1133.65
1133.75	1133.55	1133.70	1133.70
1133.80	1133.60	1133.70	1133.75
1133.85	1133.65	1133.75	1133.75
1133.90	1133.65	1133.80	1133.85
1133.95	1133.70	1133.85	1133.85
1134.00	1133.75	1133.90	1133.90
1134.05	1133.80	1133.90	1133.95
1134.10	1133.85	1133.90	1134.00
1134.15	1133.90	1133.95	1134.00
1134.20	1133.90	1134.00	1134.00
1134.25	1133.95	1134.00	1134.00
1134.30	1134.00	1134.10	1134.10
1134.35	1134.00	1134.10	1134.15
1134.40	1134.05	1134.15	1134.15
1134.45	1134.10	1134.20	1134.20
1134.50	1134.15	1134.25	1134.25
1134.55	1134.15	1134.30	1134.30

Beginning of year storage (m.a.s.l)	Prescribed end of year storage target (m.a.s.l) given that previous period inflow is in class 1	Prescribed end of year storage target (m.a.s.l) given that previous period inflow is in class 2	Prescribed end of year storage target (m.a.s.l) given that previous period inflow is in class 3
1134.60	1134.20	1134.35	1134.35
1134.65	1134.25	1134.40	1134.40
1134.70	1134.30	1134.40	1134.45
1134.75	1134.35	1134.45	1134.50
1134.80	1134.40	1134.50	1134.55
1134.85	1134.40	1134.50	1134.60
1134.90	1134.45	1134.55	1134.65
1134.95	1134.50	1134.60	1134.70
1135.00	1134.55	1134.60	1134.75
1135.05	1134.6	1134.65	1134.80
1135.10	1134.65	1134.70	1134.85
1135.15	1134.65	1134.75	1134.90
1135.20	1134.70	1134.80	1134.90
1135.25	1134.75	1134.80	1134.95
1135.30	1134.80	1134.85	1134.95
1135.35	1134.85	1134.90	1134.95
1135.40	1134.85	1134.95	1135.00
1135.45	1134.90	1135.00	1135.05
1135.50	1134.95	1135.05	1135.10
1135.55	1135.00	1135.10	1135.15
1135.60	1135.05	1135.10	1135.20
1135.65	1135.10	1135.15	1135.20
1135.70	1135.15	1135.15	1135.25
1135.75	1135.15	1135.20	1135.30
1135.80	1135.20	1135.25	1135.35
1135.85	1135.25	1135.30	1135.40
1135.90	1135.30	1135.35	1135.45
1135.95	1135.35	1135.40	1135.50
1136.00	1135.40	1135.40	1135.55
1136.05	1135.45	1135.45	1135.60
1136.10	1135.45	1135.50	1135.60
1136.15	1135.50	1135.55	1135.65
1136.20	1135.55	1135.60	1135.70
1136.25	1135.55	1135.65	1135.75
1136.30	1135.60	1135.70	1135.75

8.4 Concluding remarks

The results illustrated in Figure 8.3 are promising and merit more detailed exploration within a multi-reservoir framework. Only one reservoir was considered, when in fact there are three large lakes within the basin. Since the stochastic application of the SDP algorithm is often limited to one or two lakes in series due to the excessive computational burden, the single reservoir modelling approach must of necessity be replaced by an iterative, one at a time decomposition approach (Nandalal and Sakthivadivel, 2002; Nadalal and Borgardi, 2007). Following this approach, the sequential optimisation method has been initiated with the optimisation of Lake Victoria. The resulting operation policy can be used to simulate its operation over the historical time period with data. The simulation would then provide the values of inflows required to search for the optimal Lake Kyoga operational policies. A similar approach would be applied to Lake Albert subject to the condition that the optimal operating procedures for Lake Kyoga are followed. However, given the known limitations associated with DP, the approach might not lead to identification of the global optimum for the 3 Lakes.

Given, that the results yielded from the optimisation of Lake Victoria were satisfactory, it is necessary to find creative ways of combining the results obtained from application of the SDP approach with lessons learned from application of the IDP method in the previous chapter so as to propose system wide operating rules. This approach is favoured over the one at a time decomposition approach, as a practical means to alleviate the dimensionality of the problem. The issue is discussed in the next chapter as part of the formulation of study conclusions.

9. DISCUSSION AND CONCLUSIONS

The approach to the problem of finding alternative operating policies for the Equatorial Lake basin case study was to conceptualize the hydrological system of Lake Victoria, Kyoga and Albert as a system of three interconnected reservoirs in series, where decisions must be made each month or year about the quantities of water to be released for hydro-electric power generation while satisfying system constraints. The search for a solution to this long-term reservoir operation problem has involved the application of a customised Decision Support System (DSS) for the Equatorial Lake basin.

The components of a DSS suitable for managing long term operation of the system of multiple lake-reservoirs and large dams along the White Nile in Uganda, were identified after an extensive literature review to be as follows: power plant functions, a simulation model of the Upper Nile Equatorial Lake Basin, a Stochastic Analysis Modelling and Simulation (SAMS) computer software package for analysing hydrologic time series and the Colorado State University Dynamic Programming (CSUDP) model for solution of the optimisation problem.

The search for feasible reservoir operating rules in the study followed an exploratory strategy, involving the application of traditional dynamic programming optimization tools. The objective of the analysis was to derive the best achievable long-term operational strategy for the system to maximize hydro power production while satisfying constraints related to water levels and flow magnitudes. Since the long-term multi-reservoir operation problem is essentially a stochastic problem where future net inflows to the reservoirs are not known, the evaluation approach involved experimentation with implicit and explicit stochastic optimization. In reservoir operation, implicit optimization implies complete fore-knowledge of inflows whereas under stochastic optimization, the probability distribution of inflows is taken into account. The major findings of the research are presented below.

9.1 Data sets utilized to generate operating policies

Long term records of lake levels and outflows in the Equatorial lake basin are more readily available than other hydrologic variables such as rainfall, evaporation and tributary inflows. Hence, the data utilized to solve the multi-reservoir operation problem was compiled by constructing a concurrent record of lake levels and outflows for the reference period 1899 –

2008 for Lakes Victoria, Kyoga and Albert. The methodology for compiling the reference data set of lake levels and outflows presented in Chapter 4, demonstrated that application of a variety of techniques is required to derive a long term reference data set given the inherent discontinuities in the historical record. The techniques included derivation and update of rating curves at key monitoring stations, regression to estimate missing segments of data and concatenation of various segments of data from diverse sources such as published estimates of water budget studies in the basin.

The reference data set of Lake Victoria, Kyoga and Albert levels and outflows was subsequently utilised to derive monthly series of net basin supply or net inflows, assuming natural and unregulated flow conditions through application of the simulation model of the Upper Nile Equatorial Lake Basin.

The derivation and utilisation of the reference set of net basin supply time series confers an element of creativity and originality to this thesis in several ways. It brings the best available updated concurrent record of net basin supplies for each lake to bear on an old problem of searching for a mechanism to regulate Lakes Victoria, Kyoga and Albert. The results from the exercise of detection and identification of the time of occurrence of abrupt shifts in the annual net basin supply time series presented in Chapter 5, revealed unique timing of the shifts in each lake and a unique pattern of variation in each lake. This led to the contention that hydrological regimes from the point of view of annual net basin supply are not consistently similar in Lake Victoria, Kyoga and Albert sub-basins the during the period 1899 – 2008.

Further analysis of the annual and monthly net basin supply time series documented in Chapter 6 confirmed that the data conform to a stochastic seasonal process with a degree of persistence or memory from year to year and strong seasonality with an almost perfect correlation between net monthly inflows within a given year. This subject of the underlying statistical properties of the historical net basin supply time series has not been previously explored to the extent investigated in this thesis. As such, the findings have enhanced our understanding of how to generate synthetic net basin supplies for utilisation with the framework for identification of alternative reservoir operating rules.

9.2 Implicit stochastic optimisation

Attempts at implicit stochastic optimization reported in Chapter 7, envisaged the utilization of the historically observed and synthetically generated net-basin supply time series to the lakes as inputs to a deterministic dynamic programming algorithm, so as to generate a schedule of optimum storages and releases. Unfortunately, evaluation of the approach revealed that the excessive computation time required is practically prohibitive when implemented over a monthly time step for the period 1899 – 2008. This setback rendered the definition of monthly reservoir operating rules for this case study unattainable. The dimensionality of the problem was subsequently reduced to obtain a tractable solution by reducing the time step of analysis from monthly to annual for the operating horizon 1899 – 2008. In this case, an optimum set of beginning of year storage targets and associated releases were successfully defined for the historically observed net-inflows under two sets of different constraints to lake levels and releases. The two constraints sets were designed as follows:

(i) Permitting variation of lake levels and outflows to a narrow range defined the minimum and maximum magnitudes of lake levels and outflows recorded in the historical data. The storage and release schedules prescribed using these release constraints are referred to as regulation Option 1 under Chapter 7.

(ii) Avoidance of deviation from the historically observed range of lake levels for Lake Victoria and Lake Kyoga by permitting a wider range of releases and allowing Lake Albert to have a wider range of storage level variation by utilizing it as a balancing reservoir in the system (Sutcliffe *et al.*, 1957). The storage and release schedules prescribed using these release constraints are referred to as regulation Option 2 under Chapter 7.

The resulting schedule of beginning of year storage targets and releases for the historical net basin supply time series for each lake is tabulated in Appendix C. It represents two different long-term annual operating policies for Lakes Victoria, Kyoga and Albert that would have been followed if the annual inflows had been known beforehand at the beginning of the year 1899, assuming that all the power plants were in existence at the time. Each run of results presented in Appendix C required approximately 21 days of computing time on an IBM Lenovo ThinkPad

(T60p) computer fitted with an Intel Core Duo processor with clock speed of 2.33 GHz and 3GB of RAM.

A huge amount of computing effort and time would be required by the IDP algorithm to process the 1000 traces of synthetically generated net-basin time series for the Equatorial Lakes presented under Chapter 6. The output would be an optimum schedule of storage targets and releases for each inflow scenario. It had been envisaged that further analysis of such operating rule schedules by application of artificial neural network techniques or other inference techniques would have yielded generalized annual operating rule that would be refined through extensive simulation. Unfortunately the huge computational effort and resources necessary to optimize for the 1000 equally likely inflow sequences proved to be beyond the scope of the study.

Although the definition of generalized operating rules for all possible inflow scenarios has not been achieved, general inferences on how to regulate the Equatorial Lakes can be made based on the impact of prescribed rules on lake levels during the period 1899-2008. The findings illustrated under Chapter 7 suggest that these inferences can be based on the occurrence of a typical low level hydrological regime in Lake Victoria, which was observed from 1899 – 1960 and the relatively wetter period with higher levels that followed after 1961.

With respect to Lake Victoria, the target Lake Victoria levels that yield maximum power generation are shown to be those that generally mimic the Agreed Curve but are about 0.5 m to 1.0 m higher during the entire period 1899 -2008. The prescribed storage targets are more or less the same for the two sets of release constraints. The two regulatory options differ only in the magnitude of prescribed releases for the net inflows.

In the case of Lake Kyoga, the target optimum levels prescribed by regulation in accordance to Option 1 or 2 are approximately the same from the year 1900 up to 1952 where they are slightly lower than the natural lake levels. It has been inferred that Lake Kyoga should be maintained at a constant elevation of 1032.12 m.a.s.l during occurrences of extremely high Lake Victoria levels such as after the year 1962 in the case of Option 1 and at 1030.31 after 1967 in the case of Option 2. For comparison purposes with other studies, it is striking to note that some of the historical plans reviewed by Kite (1984) included trials that suggested that

Lake Kyoga be regulated to maintain a constant elevation of 1031.62 m.a.s.l or 1035.23 m.a.s.l at all times without being successful.

With regard to Lake Albert, it has been inferred that in order to maximize power generation from the planned hydropower plants along the Victoria and Kyoga Nile, Lake Albert should be maintained at a constant elevation of about 621 m.a.s.l at all times in the case of Option 1 and at the minimum constraint elevation of 618.76 m.a.s.l in the case of Option 2.

The pattern of annual maximum hydropower generation over the period 1899 – 2008 that would have resulted if all hydropower plants were online has been illustrated in Figure 7.14 of Chapter 7. It is approximately the same under Options 1 and 2. The simulation shows that annual hydropower generation in Options 1 and 2 is extremely variable prior to 1961 when lake levels were much lower in Lake Victoria and more stabilised thereafter when lake levels rose. It was clearly demonstrated that maintaining high lake levels in Lake Victoria clearly leads to enhancement of hydropower generation. Under regulated lake conditions, power generation can be enhanced in the short term by as much as 64% in a given year when compared against operation using naturalized lake levels or unregulated conditions. However, over the whole planning period considered (1899 – 2008), the average gain in power produced under regulated lake conditions was 13%. These findings demonstrated that the alternative operational rules offer superior performance in terms of hydropower generation particularly during periods of sustained low net basin inflows but markedly alter the water level variation of Lakes Kyoga and Albert.

9.3 Explicit stochastic optimisation

Operation policies at an annual time step for Lake Victoria which comprise of end-of-year storage targets for every possible start-of-year reservoir storage and inflow state have been successfully defined with single reservoir stochastic dynamic programming techniques. The policies are illustrated under Table 8.3 as optimal storage guide curves that specify final end of period storage targets that are dependent on observed initial reservoir elevation and previous period's inflow.

9.4 Heuristic definition of system wide operating rules

The results yielded from the deterministic multiple reservoir analysis (Chapter 7) and the single reservoir Lake Victoria SDP optimisation (Chapter 8) provide a framework for adoption a heuristic approach that exploits knowledge of the suggested approximate form of the system wide operational policy. Efficient descriptions of the optimal release rules can be inferred from combining the results obtained from application of the SDP approach with lessons learned from application of the IDP method.

Such heuristically defined rules indicate that the storage guide curves (Table 8.3) can be implemented with Lake Kyoga levels maintained at a constant elevation of 1032.12 m.a.s.l while Lake Albert is maintained at a constant elevation of 621 m.a.s.l.

9.5 Originality and new knowledge generated from the study

This dissertation makes attempts at originality in as far as bringing new evidence to bear on the challenges posed by attempts to regulate the Equatorial Lakes. It followed, in some parts, a testing-out approach seeking to identify alternative operation rules through application of established dynamic programming algorithms. The techniques utilized made use of a wide range of analytical methodologies. The new knowledge generated is highlighted below.

(i) The reference set of net basin supply time series utilized to derive alternative operational rules is original to this case study. It is the best available concurrent record of historical net basin supplies for each lake. These data were the basis for spectral and statistical analysis which identified unique patters of variation in correlograms and time series plots. Confirmation of the occurrence and timing of abrupt shifts in the annual net basin supply time series of Lakes Victoria, Kyoga and Albert is novel to this study and has never been extensively investigated elsewhere before. The contention that hydrological regimes from the point of view of annual net basin supply are not consistently similar in Lake Victoria, Kyoga and Albert sub-basins during the period 1899 – 2008 has added a new dimension to our understanding of the hydrology of the Nile.

(ii) The assembly and application of the various components of the DSS tools to search for alternative operation rules is believed to be a novel and improved approach compared to earlier studies such as Kite (1984) where trials were conducted by simulation rather than prescriptive optimization. The multi-reservoir analysis results presented in Chapter 7 are considered to be innovative outputs towards regulation of the Equatorial Lakes. This is in contrast to recent studies where the focus has been limited in scope to defining rules for a single reservoir i.e. Lake Victoria and where the resultant rules prescribe constant or increasing release magnitudes with increasing water levels within a broad band of storage zones (Mott MacDonald, 1998; Wardlaw *et al.*, 2005; Centre for Hydrology and Ecology, 2008).

(iii) Application of the IDP algorithm to the optimisation problem revealed the excessive computation time required to derive generalised operating rules for the study. This shed light on the limitations of traditional dynamic programming techniques for this particular case study. Given the limitations applying discrete DP methods, approximate heuristic rules are suggested (Section 9.4). This new knowledge will be beneficial towards focussing future research in this area.

(iv) An optimum set of beginning of year storage targets and associated releases were successfully defined for the historically observed net-inflows of the Equatorial Lakes, under two sets of different constraints to lake levels and releases. These represent two alternative operating rules for the operation of planned dams along the Victoria and Kyoga Nile. The general inferences that have been generated on how to regulate the Equatorial Lakes based on the impact of prescribed rules on lake levels during the period 1899-2008 is novel to this study.

(v) Application of the prescribed operating rules for the period 1899 – 2008 has demonstrated that hydropower generation can be significantly enhanced. Operation policies at an annual time step for Lake Victoria which comprise of storage targets for every possible reservoir storage and inflow state have also been successfully defined. An option presents itself to regulate Lake Victoria in accordance to the rules stipulated under Table 8.3 and maintenance of Lake Kyoga levels at constant elevation of 1032.12 m.a.s.l, while Lake Albert is maintained at a constant elevation of 621 m.a.s.l. Although the rules are beneficial for enhancement of lake navigation and power production, it is likely that they would also adversely affect Lake Kyoga and Albert leading to long periods where lake levels are maintained at a constant level. This is likely to be detrimental ecosystems around these two lakes. This new revelation is critical for the consideration of reservoir managers in this region.

9.6 Concluding remarks in relation to research questions and objectives

The underlying goal of the study was to develop and apply a Decision Support System (DSS) so as to define alternative long-term operation rules for the Equatorial Lake reservoir system. This was based on the premise that current operating policies based on releases in accordance to unregulated lake levels and outflows had proven to be insensitive to the demands for increased energy generation. The conclusions from the study are:

(i) The appropriate components of a DSS suitable for managing long-term operation of the system of multiple lake-reservoirs and large dams along the White Nile in Uganda, are essentially a combination of interlinked models and algorithms. These include river and lake simulation models based on previous research in the Equatorial Lake Region (WMO, 1977; Nemec and Kite 1979; Mott MacDonald, 1998). The simulation models are complemented by analytical hydrological time series software to process the reference hydrologic data (Hubert, 2000; Sveinsson, 2007). Current system data and power plant functions are incorporated from existing short-term reservoir operation models (Georgakakos and Yao 2003; WREM Inc. and Norplan (U), 2004). Output from the simulation models and power plant functions is utilized by prescriptive optimisation models (Labadie, 2003) to identify efficient operating rules. The rules could be refined using other techniques such as regression or neural network analysis.

(ii) The components of the DSS have been assembled, customised and applied to the case study to investigate regulation of the lake reservoirs. Demonstration of application of the DDS tool to the case study requires the consideration of a series of practical decisions. Among these are the compilation of long-term lake levels and outflows, underlying nature of the net inflows to the lake reservoirs and computing effort involved in application of the dynamic programming algorithms. Paucity of hydrological data in this region dictated preference be given to the utilization of long term series of observed lake levels and outflows over other hydrological variables such as tributary inflows and net rainfall. The presence of abrupt shifts in the annual net basin supply time series of each lake and lack of significant cross correlation at lag one in the monthly net basin time series is critical. It dictated the application of a uni-variate shifting mean model to generate synthetic net basin supply time series in the implicit stochastic optimisation approach. The extensive computing effort associated with fine discretization of the storage and release variables during derivation of operating rules with the multiple reservoir IDP algorithm is potentially prohibitive. It was shown that it is more feasible to define deterministic operating rules at an annual rather than monthly time step for the period 1899 – 2008.

(iii) The DSS tool has been successfully utilized to identify two alternative operating rules that maximise hydropower production and satisfy system constraints based on the observed net basin inflows to the lakes for the period 1899 to 2008. The operational policy derived for each lake reservoir is a set of rules specifying the trajectory of beginning of year storage and releases for the known net inflows. Application of the tool to the system configuration of planned dams, facilitates investigation of the effect of alternative regulation scenarios through the alteration of constraints to storage and release magnitudes. The regulation scenarios were formulated by application of the tool based on a set of two different system constraints. The results obtained from attempts to apply the implicit stochastic optimisation approach are not sufficient to define generalized annual operating rules based on all possible occurrences of net inflow. However, general inferences on how to regulate the Equatorial Lakes can be made based on the impact of prescribed rules on lake levels during the period 1899-2008.

(iv) The comparison of results indicates that performance of the system for the two alternative regulatory options in terms of hydropower generation is marginally different. Their average annual generation over the period 1899 to 2008 would have been 1287 MW. On the other hand if the Equatorial Lakes had been unregulated the average annual hydropower production would have been 1127 MW. The two regulatory options enhance energy generation by 13% over the long term operating horizon 1899-2008 when compared against the agreed curve. Regulation of the Equatorial Lakes has the potential to enhance power generation by up to 64% in a given year. Overall, the benefits of enhanced energy generation are markedly higher during periods of sustained low levels e.g. prior to 1961. Therefore the agreed curve mode of operation and maintenance of natural lake levels and outflow is not an attractive operation policy particularly during periods of sustained drought if the objective is to maximise hydropower generation.

(v) Regulation of the Equatorial Lakes for purposes of maximising hydropower production can be attained without exceeding the historically observed range of lake levels and outflows as shown under Option 1. Regulation of the Equatorial Lakes is also feasible by utilizing Lake Albert as a balancing reservoir as shown under Option 2 where a wider range of releases is also permitted. The two regulation options have an identical impact Lake Victoria levels. They tend to mimic the natural variation of Lake Victoria levels but at consistently higher magnitudes. However, the two regulatory options can markedly alter Lake Kyoga and Albert levels. The natural variation of lake levels in Lake Kyoga can be wiped out over the occurrence of lengthy time periods of prevailing high levels in Lake Victoria since these policies dictate that Lake Kyoga levels be maintained at specified constant elevations during such episodes. Similarly both policies radically dictate that Lake Albert be maintained at specified constant elevations at all times. These scenarios are likely to be associated with a range of negative ecological and socio-economic consequences. Improved operating rules for enhancing hydropower generation of large dams along the Victoria and Kyoga Nile have been identified but their application has demonstrated that they would significantly modify the hydrological regimes of Lake Kyoga and Albert.

(vi) The method of application of the multi-reservoir IDP algorithm yielded practical operating rules that satisfy system constraints. Rules specified by the SDP algorithm to Lake Victoria can be implemented in a system wide network by maintaining Lake Kyoga and Lake Albert at constant elevations. This option provides a practical approach of defining approximate and rules given the dimensionality of the case study problem. The applicability of the suggested rules should be subjected to a comprehensive environmental impact assessment to quantify the effects of maintaining constant lake levels on shore line ecology.

9.7 Recommendations

This study has provided a new framework and set of improved tools for the long-term management of Lakes Victoria, Kyoga and Albert. An important finding from the study is the limitation of DP as a practical optimization method due to the "curse of dimensionality". The research findings suggest a heuristic method of regulating the lakes for purposes of enhancing hydropower generation but their application significantly modifies the hydrological regimes of Lake Kyoga and Albert. It is therefore recommended that the results be subjected to further research along the following thematic areas:

(i) Investigation of the applicability of other approaches better suited to handle the 'curse of dimensionality' including variations of linear programming and evolutionary techniques such as the Genetic Algorithm and the Shuffled Complex Evolution algorithm (Duan *et al.*, 1992). The Shuffled Complex Evolution algorithm has been applied solve real time dam optimization in the Orange – Fish – Sundays river basin in South Africa (Pedersen *et al.*, 2007).

(ii) The use of larger computational resources such as parallel computing techniques to effectively optimize the problem.

(iii) Refinement and improvement of algorithmic aspects of the multi-reservoir IDP algorithm to decrease computational effort. This can be done by modifying the code in such a manner as to identify and eliminate infeasible storage states beforehand from further analysis. In this way, operating rules for each of the synthetic sequences of net basin supply can be defined and neural network tools can be applied in order to complete the specification of generalized operating rules

(iv) Identification and quantification of the environmental impacts of the suggested operating rules

(v) Determination of the trade-offs between energy generation and negative environmental and socio-economic impacts

(vi) A larger study should be undertaken by an appropriate River Nile basin management organisation to explore operational rules within a much wider scope of management objectives to seek a compromise solution that involves quantification of trade-offs. Such as study should involve several stakeholder consultations and the analysis should be subjected to multi-criteria methodologies.

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11. APPENDIX A: RESERVOIR DATA

Lake Victoria		Lake Kyoga		Lake Albert	
Elevation (m)	**Storage (BCM)**	**Elevation (m)**	**Storage (BCM)**	**Elevation (m)**	**Storage (BCM)**
1132.0	2834.755	1027.0	0.576	618.0	142.001
1132.1	2841.293	1027.1	0.644	618.1	142.495
1132.2	2847.830	1027.2	0.711	618.2	142.989
1132.3	2854.384	1027.3	0.779	618.3	143.487
1132.4	2860.937	1027.4	0.874	618.4	143.985
1132.5	2867.505	1027.5	0.914	618.5	144.489
1132.6	2874.074	1027.6	0.982	618.6	144.992
1132.7	2880.658	1027.7	1.05	618.7	145.501
1132.8	2887.242	1027.8	1.118	618.8	146.01
1132.9	2893.842	1027.9	1.185	618.9	146.525
1133.0	2900.442	1028.0	1.253	619.0	147.04
1133.1	2907.057	1028.1	1.347	619.1	147.561
1133.2	2913.672	1028.2	1.442	619.2	148.081
1133.3	2920.302	1028.3	1.55	619.3	148.608
1133.4	2926.933	1028.4	1.657	619.4	149.134
1133.5	2933.579	1028.5	1.78	619.5	149.666
1133.6	2940.225	1028.6	1.903	619.6	150.198
1133.7	2946.886	1028.0	2.044	619.7	150.736
1133.8	2953.548	1028.8	2.185	619.8	151.274
1133.9	2960.225	1028.9	2.343	619.9	151.818
1134.0	2966.902	1029.0	2.502	620.0	152.361
1134.1	2973.594	1029.1	2.679	620.1	152.911
1134.2	2980.286	1029.2	2.856	620.2	153.461
1134.3	2986.994	1029.3	3.051	620.3	154.017
1134.4	2993.702	1029.4	3.246	620.4	154.572
1134.5	3000.425	1029.5	3.459	620.5	155.133
1134.6	3007.149	1029.6	3.671	620.6	155.694
1134.7	3013.888	1029.7	3.902	620.7	156.261
1134.8	3020.535	1029.8	4.133	620.8	156.828
1134.9	3027.381	1029.9	4.381	620.9	157.401
1135.0	3034.135	1030.0	4.63	621.0	157.973
1135.1	3040.905	1030.1	4.863	621.1	158.549
1135.2	3047.675	1030.2	5.162	621.2	159.126
1135.3	3054.460	1030.3	5.444	621.3	159.707
1135.4	3061.245	1030.4	5.727	621.4	160.287
1135.5	3068.047	1030.5	6.024	621.5	160.871
1135.6	3074.848	1030.6	6.321	621.6	161.455
1135.7	3081.665	1030.7	6.633	621.7	162.042
1135.8	3088.481	1030.8	6.944	621.8	162.629

Lake Victoria		Lake Kyoga		Lake Albert	
Elevation (m)	**Storage (BCM)**	**Elevation (m)**	**Storage (BCM)**	**Elevation (m)**	**Storage (BCM)**
1135.9	3095.313	1030.9	7.269	621.9	163.219
1136.0	3102.145	1031.0	7.595	622.0	163.809
1136.1	3108.990	1031.1	7.934	622.1	164.401
1136.2	3115.838	1031.2	8.273	622.2	164.994
1136.3	3122.691	1031.3	8.624	622.3	165.589
1136.4	3129.546	1031.4	8.976	622.4	166.184
1136.5	3136.412	1031.5	9.34	622.5	166.782
1136.6	3143.277	1031.6	9.703	622.6	167.38
1136.7	3150.153	1031.7	10.07	622.7	167.98
1136.8	3157.029	1031.8	10.45	622.8	168.58
1136.9	3163.915	1031.9	10.83	622.9	169.182
1137.0	3170.800	1032.0	11.22	623.0	169.784
		1032.1	11.61	623.1	170.388
		1032.2	12.01	623.2	170.992
		1032.3	12.41	623.3	171.599
		1032.4	12.81	623.4	172.205
		1032.5	13.23	623.5	172.813
		1032.6	13.64	623.6	173.421
		1032.7	14.06	623.7	174.03
		1032.8	14.48	623.8	174.64
		1032.9	14.91	623.9	175.251
		1033.0	15.34	624.0	175.862
		1033.1	15.77	624.1	176.477
		1033.2	16.21	624.2	177.091
		1033.3	16.65	624.3	177.706
		1033.4	17.1	624.4	178.321
		1033.5	17.55	624.5	178.936
		1033.6	18	624.6	179.55
		1033.7	18.45	624.7	180.165
		1033.8	18.91	624.8	180.78
		1033.9	19.38	624.9	181.394
		1034.0	19.84	625.0	182.009
		1034.1	20.32	625.1	182.44
		1034.2	20.79	625.2	182.871
		1034.3	21.27	625.3	183.302
		1034.4	21.75	625.4	183.733
		1034.5	22.23	625.5	184.161
		1034.6	22.72	625.6	184.596
		1034.7	23.21	625.7	185.027
		1034.8	23.71	625.8	185.458
		1034.9	24.21	625.9	185.889
		1035.0	24.71		

Lake Victoria		**Lake Kyoga**		**Lake Albert**	
Elevation (m)	**Storage (BCM)**	**Elevation (m)**	**Storage (BCM)**	**Elevation (m)**	**Storage (BCM)**
		1035.1	25.23		
		1035.2	25.75		
		1035.3	26.27		
		1035.4	26.7		
		1035.5	27.32		
		1035.6	27.84		
		1035.7	28.36		
		1035.8	28.88		
		1035.9	29.4		
		1036.0	29.92		

12. APPENDIX B: POWER PLANT DATA

Table B.1 Combined Power Function for Nalubaale & Kiira

SN	**Discharge (m^3/s)**	**Lake Victoria Levels (m.a.s.l)**								
		1133	**1133.5**	**1134**	**1134.5**	**1135**	**1135.5**	**1136**	**1136.5**	**1137**
1	25	2.37	2.44	2.5	2.57	2.64	2.7	2.75	2.8	2.85
2	37.5	6.15	6.35	6.53	6.7	6.86	7.02	7.17	7.3	7.43
3	50	8.56	8.77	8.99	9.2	9.41	9.64	9.86	10.06	10.25
4	66.1	11.25	11.58	11.91	12.24	12.55	12.85	13.16	13.43	13.68
5	82.2	13.99	14.4	14.81	15.21	15.59	15.97	16.35	16.69	17
6	98.31	16.81	17.24	17.66	18.09	18.52	18.96	19.39	19.8	20.18
7	114.41	19.52	20.04	20.58	21.12	21.65	22.16	22.68	23.15	23.61
8	130.51	22.26	22.86	23.51	24.15	24.78	25.38	25.98	26.53	27.05
9	146.61	25.05	25.7	26.44	27.19	27.9	28.59	29.28	29.89	30.45
10	162.71	27.79	28.5	29.3	30.1	30.88	31.63	32.38	33.06	33.71
11	178.81	30.52	31.31	32.17	33.03	33.87	34.68	35.49	36.24	36.97
12	194.92	33.28	34.14	35.09	36.06	37	37.9	38.8	39.62	40.4
13	211.02	36.03	36.96	38.01	39.09	40.12	41.1	42.1	42.98	43.82
14	227.12	38.78	39.77	40.92	42.09	43.2	44.27	45.35	46.31	47.23
15	243.22	41.5	42.59	43.77	44.98	46.17	47.29	48.42	49.47	50.5
16	259.32	44.25	45.41	46.67	47.96	49.22	50.42	51.61	52.76	53.88
17	275.42	47.02	48.24	49.59	50.99	52.34	53.63	54.92	56.15	57.34
18	291.53	49.72	51.04	52.49	55.46	57.14	58.85	60.36	61.65	62.9
19	307.63	54.69	56.4	58	60.03	61.55	62.6	63.88	65.03	66.35
20	323.73	59	60.58	62.17	63.58	64.69	65.83	67.18	68.41	69.77
21	339.83	61.74	63.38	65.09	66.6	67.81	69.03	70.48	71.76	73.14
22	355.93	64.5	66.22	68	69.61	70.87	72.1	73.59	74.88	76.36
23	372.03	67.22	69	70.84	72.48	73.81	75.1	76.69	78.12	79.7
24	388.14	69.94	71.8	73.71	75.46	76.89	78.32	79.99	81.49	83.14
25	404.24	72.67	74.62	76.62	78.48	80.01	81.53	83.29	84.85	86.55
26	420.34	75.41	77.43	79.52	81.5	83.11	84.72	86.56	88.13	89.89
27	436.44	78.14	80.22	82.4	84.44	86.13	87.74	89.62	91.29	93.16
28	452.54	80.84	83.01	85.25	87.33	89.1	90.82	92.8	94.64	96.61
29	468.64	83.58	85.83	88.14	90.34	92.21	94.03	96.1	98	101.8
30	484.75	86.33	88.63	91.04	93.35	95.31	99.22	101.49	103.64	105.57
31	500.85	89.83	92.88	95.61	98.13	100.86	102.99	104.94	107.03	109.01
32	516.95	94.08	97.22	100.11	102.73	104.56	106.13	108.17	110.29	112.3
33	533.05	97.68	100.42	103.15	105.65	107.61	109.26	111.37	113.54	115.51
34	549.15	100.31	103.13	105.94	108.55	110.64	112.34	114.42	116.56	118.6
35	565.25	102.93	105.83	108.72	111.4	113.53	115.25	117.42	119.72	121.94
36	581.36	105.52	108.49	111.44	114.17	116.44	118.3	120.64	123	125.26
37	597.46	108.11	111.18	114.21	117.08	119.49	121.44	123.86	126.25	128.58
38	613.56	110.71	113.88	117	120	122.52	124.57	127.06	129.42	131.76
39	629.66	113.33	116.55	119.79	122.9	125.55	127.67	130.03	132.5	134.98

SN	**Discharge (m^3/s)**	**Lake Victoria Levels (m.a.s.l)**								
		1133	**1133.5**	**1134**	**1134.5**	**1135**	**1135.5**	**1136**	**1136.5**	**1137**
40	645.76	115.9	119.23	122.53	125.72	128.48	130.65	133.13	135.74	138.35
41	661.86	118.47	121.91	125.27	128.55	131.47	133.77	136.34	139	143.15
42	677.97	121.1	124.6	128.06	131.5	134.56	136.94	141.17	143.77	146.42
43	694.07	123.68	127.26	130.83	134.43	137.61	141.68	144.41	147.05	149.74
44	710.17	126.54	130.81	134.77	138.41	142.25	145.24	147.59	150.31	153.13
45	726.27	129.97	133.95	137.93	141.69	145.27	148.33	150.79	153.63	156.47
46	742.37	132.5	136.55	140.72	144.55	148.23	151.41	153.97	156.83	159.65
47	758.47	135.05	139.2	143.42	147.38	151.16	154.41	156.9	159.82	162.95
48	774.58	137.57	141.78	146.11	150.16	153.94	157.27	159.96	163.06	166.23
49	790.68	140.1	144.38	148.77	152.88	156.8	160.3	163.15	166.31	169.49
50	806.78	142.62	147.01	151.46	155.71	159.77	163.37	166.33	169.54	172.68
51	822.88	145.16	149.62	154.17	158.56	162.7	166.43	169.43	172.58	175.8
52	838.98	147.71	152.22	156.87	161.4	165.62	169.37	172.39	175.69	179.13
53	855.08	150.22	154.82	159.53	164.17	168.43	172.27	175.5	178.96	182.39
54	871.19	152.68	157.37	162.13	166.86	171.28	175.3	178.67	182.13	185.59
55	887.29	155.17	159.87	164.73	169.64	174.17	178.32	181.79	185.22	189.07
56	903.39	157.57	162.36	167.33	172.41	177.05	181.78	185.76	189.21	192.28
57	919.49	159.95	164.8	170.15	175.36	180.41	185.05	188.84	192.43	195.52
58	935.59	162.3	167.33	172.71	178.16	183.27	188.04	191.94	195.62	198.63
59	951.69	164.57	169.79	175.25	180.87	186.08	190.94	195.09	198.61	201.75
60	967.8	166.94	172.18	177.74	183.52	188.84	193.73	197.96	201.72	205.02
61	983.9	169.28	174.58	180.24	186.15	191.48	196.45	200.85	204.92	208.39
62	1000	171.59	177.01	182.78	188.66	194.23	199.36	203.91	208.06	211.73
63	1020.69	174.52	180.1	186.01	192.01	197.83	203.08	207.83	212.01	215.69
64	1041.38	177.53	183.2	189.21	195.41	201.39	206.7	211.63	215.8	219.81
65	1062.07	180.43	186.29	192.42	198.73	204.92	210.22	215.34	219.87	223.95
66	1082.76	183.38	189.42	195.63	202.03	208.35	213.96	219.29	223.85	228.32
67	1103.45	186.34	192.54	198.8	205.41	211.98	217.68	223.19	227.87	232.47
68	1124.14	189.19	195.59	201.85	208.67	215.57	221.22	226.79	231.84	236.58
69	1144.83	192	198.59	204.85	211.75	218.88	224.65	230.64	235.73	240.44
70	1165.52	193.31	201.48	207.86	214.85	222.13	228.21	234.33	239.44	244.49
71	1186.21		204.37	210.81	217.89	225.43	231.61	237.81	243.39	248.59
72	1206.9		207.16	213.72	220.85	228.64	234.92	241.54	247.29	251.5
73	1227.59		209.9	216.62	223.82	231.54	238.58	245.26	251.16	256.54
74	1248.28		212.66	219.57	227.05	234.83	242.05	248.84	254.83	260.54
75	1268.97		215.32	222.41	230.22	238.11	245.46	252.39	258.64	264.49
76	1289.66		217.92	225.07	233.35	241.49	248.97	256.12	262.54	268.39
77	1310.35		220.48	228.05	236.34	244.76	252.49	259.82	266.33	272.1
78	1331.03		223.02	231.02	239.24	247.81	256	263.16	269.84	275.99
79	1351.72		225.53	233.88	242.15	250.95	259.29	266.69	273.61	279.72
80	1372.41		224.23	236.59	245.02	254.06	262.46	270.17	277.24	283.39
81	1393.1			239.34	247.84	257.04	265.74	273.54	280.79	287.1

SN	Discharge (m^3/s)	Lake Victoria Levels (m.a.s.l)								
		1133	1133.5	1134	1134.5	1135	1135.5	1136	1136.5	1137
82	1413.79			242	250.65	260.08	268.96	276.82	284.31	290.91
83	1434.48			244.65	253.49	263.11	272.02	280.26	287.89	294.64
84	1455.17			247.34	256.36	266.07	275.15	283.6	291.36	298.37
85	1475.86			249.91	259.21	268.93	278.31	286.9	294.71	301.91
86	1496.55			252.48	262.02	271.87	281.4	290.22	298.12	305.6
87	1517.24			254.5	264.77	274.74	284.34	293.52	301.61	309.21
88	1537.93			255.52	267.55	277.57	287.41	296.87	304.95	312.7
89	1558.62				270.3	280.36	290.39	300.15	308.24	316.19
90	1579.31				272.92	283.17	293.29	303.34	311.62	319.83
91	1600				275.43	285.84	296.07	306.42	314.91	323.24
92	1642.11				280.28	291.26	301.77	312.7	321.4	330.16
93	1684.21				284.97	296.58	307.3	318.7	327.92	337.1
94	1726.32					301.79	312.62	324.56	334.32	343.71
95	1768.42					306.77	317.88	330.25	340.64	350.15
96	1810.53					311.61	323.02	335.69	346.76	356.2
97	1852.63					316.24	328.02	340.77	352.31	362.18
98	1894.74					320.36	332.84	345.47	357.4	368.06
99	1936.84					324.05	337.06	350.04	361.79	373.39
100	1978.95						340.71	354.53	365.8	377.35
101	2021.05						344.08	358.04	369.71	381.27
102	2063.16						346.79	360.83	373.31	384.7
103	2105.26						348.91	363.13	376.58	386.86
104	2147.37						350.55	365.29	378.96	
105	2189.47						352.03	367.07		

Table B.2 Other Run-of-the river power plants

Bujagali	
Q (m^3/s)	P (MW)
1111 m	
50	10.16
100	20.2
150	30.12
200	39.93
250	49.64
300	59.25
350	68.77
400	78.2
450	87.54
500	96.8
530	102.31
560	107.8
590	113.25
620	118.68
650	124.08
680	129.45
710	134.8
740	140.11
770	145.41
800	150.67
830	155.91
860	161.12
890	166.31
920	171.47
950	176.61
980	181.73
1010	186.82
1040	191.89
1070	196.93
1100	201.96
1130	206.96
1160	211.93
1190	216.88
1220	221.82
1250	226.74
1280	231.63
1310	236.51
1340	241.36
1370	246.19

Karuma	
Q (m^3/s)	P (MW)
27 m	
100	22.52
115	25.89
130	29.27
145	32.65
160	36.02
175	39.4
190	42.78
205	46.15
220	49.53
235	52.91
250	56.29
265	59.66
280	63.04
295	66.42
310	69.8
325	73.17
340	76.55
355	79.93
370	83.3
385	86.68
400	90.06
415	93.44
430	96.81
445	100.19
460	103.57
475	106.94
490	110.32
505	113.7
520	117.08
535	120.45
550	123.83
565	127.21
580	130.58
595	133.96
610	137.34
625	140.72
640	144.09
655	147.47
670	150.85

Ayago	
Q (m^3/s)	P (MW)
60 m	
100	50.04
108.75	54.42
117.5	58.8
126.25	63.18
135	67.56
143.75	71.94
152.5	76.32
161.25	80.69
170	85.07
178.75	89.45
187.5	93.82
196.25	98.2
205	102.58
213.75	106.96
222.5	111.34
231.25	115.72
240	120.09
248.75	124.47
257.5	128.85
266.25	133.22
275	137.6
283.75	141.98
292.5	146.35
301.25	150.73
310	155.11
318.75	159.49
327.5	163.87
336.25	168.25
345	172.62
353.75	177
362.5	181.38
371.25	185.75
380	190.13
388.75	194.51
397.5	198.89
406.25	203.26
415	207.64
423.75	212.02
432.5	216.39

Bujagali	
Q (m^3/s)	P (MW)
1111 m	
1400	251

Karuma	
Q (m^3/s)	P (MW)
27 m	
685	154.22
700	157.6
715	160.97
730	164.35
745	167.73
760	171.1
775	174.48
790	177.86
799.51	180

Ayago	
Q (m^3/s)	P (MW)
60 m	
441.25	220.78
450	225.15
458.75	229.52
467.5	233.91
476.25	238.28
485	242.66
493.75	247.04
502.5	251.42
511.25	255.79
520	260.17
528.75	264.55
537.5	268.92
546.25	273.3
555	277.68
563.75	282.05
572.5	286.44
581.25	290.81
590	295.19
598.75	299.57
607.5	303.95

13. APPENDIX C: RESERVOIR OPERATING RULES FOR THE PERIOD 1899 - 2008

Table C.1 Option 1 – Analysis

Year	Lake Victoria			Lake Kyoga			Lake Albert		
	Initial storage (m.a.s.l)	Release (MCM)	Inflow (MCM)	Initial storage (m.a.s.l)	Release (MCM)	Inflow (MCM)	Initial storage (m.a.s.l)	Release (MCM)	Inflow (MCM)
1899	1133.39	8239	-12975	1032.11	11883	4532	621.02	11156	7294
1900	1133.13	8645	5999	1031.07	8890	896	621.02	13676.3	4758
1901	1133.09	13565	13565	1031.26	14019	-1241	621.01	17049.9	3002
1902	1133.09	19735	27674	1030.75	19003	-479	621.01	24230.2	5313
1903	1133.21	22416	57632	1030.83	19210	-4747	621.02	18545.3	-780
1904	1133.74	11740	23083	1030.32	8833	1333	621.00	17547.8	8743
1905	1133.91	17068	23077	1031.61	19218	965	621.01	28095.1	8848
1906	1134.00	20705	46162	1031.28	19232	-2228	621.00	19068.6	-49
1907	1134.38	14537	4475	1031.06	19277	2937	621.02	30249.9	10915
1908	1134.23	11160	18539	1030.49	8839	952	621.01	13333.1	4465
1909	1134.34	17213	3807	1031.48	19276	1243	621.01	27180.5	7905
1910	1134.14	18131	12108	1031.25	19253	73	621.01	29552.1	10328
1911	1134.05	17609	-7085	1030.94	19231	1395	621.01	28631.8	9343
1912	1133.68	12035	21364	1030.87	8870	-2674	621.00	14485.3	5644
1913	1133.82	23490	29500	1031.02	19216	-4407	621.01	25983.7	6854
1914	1133.91	23456	24791	1030.98	19250	-4433	621.02	24846.3	5481
1915	1133.93	24660	28666	1030.91	19472	-4319	621.00	26958	8379
1916	1133.99	27763	46510	1031.17	8842	-8641	621.16	11023.6	1346
1917	1134.27	11492	62672	1033.7	21026	2974	621.01	15021.5	-5976
1918	1135.03	10954	-15354	1032.17	24940	13628	621.02	52259.1	27233
1919	1134.64	16324	3534	1032.08	19620	-2123	621.00	35017.4	15426
1920	1134.45	12139	12812	1030.53	8839	-329	621.01	15675.3	6894
1921	1134.46	19240	-8249	1031.43	19491	-798	621.02	26967.4	7448
1922	1134.05	20529	5832	1031.13	19497	-1405	621.01	21390.9	1836
1923	1133.83	23372	42754	1031.02	19216	-4054	621.00	16731.2	-2485
1924	1134.12	11561	5537	1031.05	8835	-1405	621.00	12297.1	3462
1925	1134.03	22611	27296	1031.43	19268	-2505	621.00	24406.6	5196
1926	1134.10	26459	57320	1031.66	19226	-8496	621.01	14790.9	-4406
1927	1134.56	18280	-523	1031.31	19256	-219	621.02	25438.5	6211
1928	1134.28	11319	17355	1030.96	8843	-1870	621.02	13312.9	4412
1929	1134.37	20019	9957	1031.14	19523	-801	621.01	24201.5	4621
1930	1134.22	27245	46715	1031.05	19583	-6049	621.00	18286.2	-1182
1931	1134.51	24070	31474	1031.51	19569	-3694	621.02	21002.4	1347

Year	Lake Victoria			Lake Kyoga			Lake Albert		
	Initial storage (m.a.s.l)	Release (MCM)	Inflow (MCM)	Initial storage (m.a.s.l)	Release (MCM)	Inflow (MCM)	Initial storage (m.a.s.l)	Release (MCM)	Inflow (MCM)
1932	1134.62	11703	29899	1031.73	8838	-2598	621.01	11602.3	2793
1933	1134.89	17113	11628	1031.8	21187	1055	621.01	28446.8	7231
1934	1134.81	22689	5260	1030.95	25273	1177	621.01	32373	7100
1935	1134.55	22223	18193	1030.5	19832	-1939	621.01	20388.4	4274
1936	1134.49	19201	37312	1030.65	8849	-4339	621.65	11204.2	-1305
1937	1134.76	29902	49554	1032.32	25224	-6755	621.02	25392.4	111
1938	1135.05	26323	12068	1031.79	25253	-2179	621.01	29189.1	3994
1939	1134.84	27391	7241	1031.49	25257	-2743	621.02	33905.1	8562
1940	1134.54	15638	25747	1031.32	8843	-4963	621.00	12160.2	3317
1941	1134.69	29651	38323	1031.82	25256	-4585	621.00	23490.2	-1680
1942	1134.82	21241	21241	1031.77	25256	2092	621.02	19836.4	-5391
1943	1134.82	20298	-11918	1031.24	25284	3712	621.02	35138.7	9826
1944	1134.34	13317	19359	1030.86	8834	-2136	621.02	16080.7	7247
1945	1134.43	27271	8492	1031.54	24885	-3599	621.02	24755.9	-129
1946	1134.15	26342	20989	1031.2	24875	-1222	621.02	23224.9	-1736
1947	1134.07	23929	54783	1031.27	24820	-489	621.00	20417.2	-4317
1948	1134.53	11123	15158	1030.86	8840	649	621.02	14852.5	6012
1949	1134.59	23507	-9373	1031.7	25101	1118	621.02	35760.8	10631
1950	1134.10	26625	15259	1031.57	25109	-2803	621.01	30808.4	5728
1951	1133.93	26069	52847	1031.21	25096	-3809	621.02	22266.8	-2829
1952	1134.33	12073	27522	1030.31	9819	4565	621.02	10878.3	1002
1953	1134.56	26642	1803	1032.27	25339	-783	621.01	33115.1	7747
1954	1134.19	24036	7982	1032.4	25297	-1882	621.00	23053.7	-2157
1955	1133.95	25580	16900	1031.59	25324	36	621.02	26972.6	1677
1956	1133.82	12951	24302	1031.67	9789	-2861	621.02	10818.7	1001
1957	1133.99	24782	27457	1031.75	25345	1289	621.02	27284.7	1882
1958	1134.03	27681	14323	1031.94	25298	-1993	621.01	30094	4882
1959	1133.83	25768	11774	1032.04	25290	-1176	621.02	25788.7	3486
1960	1133.62	13687	22347	1031.86	16825	3524	621.54	10885.4	-9042
1961	1133.75	39376	92271	1031.96	34369	-4381	621.00	31913.4	-2427
1962	1134.54	42255	69238	1032.12	48598	6343	621.01	43223.5	-5403
1963	1134.94	42893	80165	1032.12	46107	3214	621.00	51912.6	5806
1964	1135.49	11601	48431	1032.12	15538	3898	621.00	13360.2	-2178
1965	1136.03	42864	19650	1032.11	49282	6418	621.00	62729.6	13505
1966	1135.69	43903	30967	1032.11	48752	4849	621.01	55724.7	6915
1967	1135.50	43284	37162	1032.11	45674	2429	621.00	52585.8	6912
1968	1135.41	11136	61625	1032.12	16417	5241	621.00	13255.4	-3075
1969	1136.15	44073	31071	1032.11	47122	3049	621.02	52569.9	5419
1970	1135.96	43544	50383	1032.11	46332	2828	621.01	50914.6	4554

Year	Lake Victoria			Lake Kyoga			Lake Albert		
	Initial storage (m.a.s.l)	Release (MCM)	Inflow (MCM)	Initial storage (m.a.s.l)	Release (MCM)	Inflow (MCM)	Initial storage (m.a.s.l)	Release (MCM)	Inflow (MCM)
1971	1136.06	43766	20543	1032.12	47264	3498	621.01	55126.7	7949
1972	1135.72	11435	49727	1032.12	10592	-843	621.02	13483.5	2863
1973	1136.28	44172	18165	1032.12	45236	1024	621.02	49933.2	4726
1974	1135.90	44291	28597	1032.11	45998	1747	621.02	50810.9	4813
1975	1135.67	43551	38099	1032.12	43965	414	621.02	42539.1	-1541
1976	1135.59	11121	19982	1032.12	16488	5367	621.00	20906.8	4476
1977	1135.72	43965	56933	1032.12	42375	-1630	621.01	41446.2	-957
1978	1135.91	43903	68542	1032.11	48030	4166	621.01	49789.1	1817
1979	1136.27	44380	40268	1032.12	45014	2340	621.02	50231.9	7591
1980	1136.21	11046	5567	1032.54	14148	1357	621.43	11537.2	-5013
1981	1136.13	44506	25358	1032.11	50269	5763	621.01	48667.3	-1602
1982	1135.85	44393	58748	1032.11	40159	-4194	621.01	33365.8	-6736
1983	1136.06	46594	30872	1032.12	49851	3218	621.02	47000.3	-2851
1984	1135.83	12554	-7209	1032.11	14986	2432	621.02	10986.1	-4057
1985	1135.54	49590	34640	1032.11	47912	-1678	621.01	37404.7	-10536
1986	1135.32	54225	32543	1032.11	58837	4652	621.01	62782.9	4032
1987	1135.00	52391	34134	1032.12	51797	-633	621.02	46970.2	-4827
1988	1134.73	10947	52242	1032.11	11484	537	621.02	18442	6929
1989	1135.34	43214	28977	1032.11	49101	5927	621.02	48973.3	-99
1990	1135.13	42932	42255	1032.12	41103	-1869	621.02	36665.6	-4437
1991	1135.12	43844	41812	1032.11	46833	3028	621.02	45809.7	-1109
1992	1135.09	12038	14747	1032.12	15071	2993	621.01	18586.3	3487
1993	1135.13	43411	-445	1032.11	47170	3759	621.00	48672.7	1618
1994	1134.48	44257	42912	1032.11	45135	878	621.02	43846.9	-1288
1995	1134.46	34888	27499	1032.11	34559	-329	621.02	64923	30364
1996	1134.35	12246	41093	1032.11	10285	-1961	621.02	31552.4	21267
1997	1134.78	51310	58128	1032.11	48725	-2546	621.02	56526.8	7802
1998	1134.88	52364	49614	1032.12	42272	-10092	621.02	55377.1	13105
1999	1134.84	52550	27025	1032.12	49300	-3290	621.02	59206.1	9849
2000	1134.46	12410	3009	1032.11	9711	-2699	621.01	15885	6117
2001	1134.32	49335	37270	1032.11	52472	3137	621.00	51322.3	-1150
2002	1134.14	48588	41227	1032.11	49881	1293	621.00	53122.3	3327
2003	1134.03	47820	22466	1032.11	51173	3393	621.02	56489.6	5345
2004	1133.65	11232	17893	1032.12	11864	593	621.02	18621.4	6671
2005	1133.75	43580	-241	1032.11	49546	6006	621.01	58958.4	9470
2006	1133.09	42658	49272	1032.12	50535	7877	621.02	60861	10269
2007	1133.19	43323	39354	1032.12	46313	2990	621.01	47921.6	1580
2008	1133.13	11481	28709	1032.12	18087	6567	621.00	23974.3	5973

Table C.2 Option 2 – Analysis

Year	Lake Victoria			Lake Kyoga			Lake Albert		
	Initial storage (m.a.s.l)	Release (MCM)	Inflow (MCM)	Initial storage (m.a.s.l)	Release (MCM)	Inflow (MCM)	Initial storage (m.a.s.l)	Release (MCM)	Inflow (MCM)
1899	1133.39	8239.04	-12975	1030.31	11883.2	4532	618.76	23358.3	7294
1900	1133.13	8644.61	5999	1031.07	8889.56	896	618.77	13647.6	4758
1901	1133.09	13565	13565	1031.26	14019.2	-1241	618.77	17122.9	3002
1902	1133.09	19735.1	27674	1030.75	19003.4	-479	618.75	24214.7	5313
1903	1133.21	22416.4	57632	1030.83	19210.4	-4747	618.77	18481.3	-780
1904	1133.74	11740.4	23083	1030.32	8833.47	1333	618.76	17525.6	8743
1905	1133.91	18404	23077	1031.61	19259.8	965	618.77	28209.6	8848
1906	1133.98	19368.4	46162	1031.64	19259.1	-2228	618.75	19108.4	-49
1907	1134.38	14537	4475	1031.04	19209.4	2937	618.77	30124.4	10915
1908	1134.23	11159.9	18539	1030.49	8839.38	952	618.77	13406.1	4465
1909	1134.34	17213.3	3807	1031.48	19275.5	1243	618.75	27180.5	7905
1910	1134.14	18130.9	12108	1031.25	19252.8	73	618.75	29580.8	10328
1911	1134.05	18941.3	-7085	1030.94	19216.8	1395	618.75	28509	9343
1912	1133.66	12036.8	21364	1031.27	8833.05	-2674	618.76	14477	5644
1913	1133.8	22155.4	29500	1031.42	19527.3	-4407	618.76	26330.5	6854
1914	1133.91	24791	24791	1030.9	19249.6	-4433	618.77	24832.4	5481
1915	1133.91	23324.9	28666	1031.23	19483.3	-4319	618.75	26989.5	8379
1916	1133.99	27762.6	46510	1031.09	8841.98	-8641	618.92	10959	1346
1917	1134.27	11491.6	62672	1033.64	20995.6	2974	618.77	15019.6	-5976
1918	1135.03	10954.1	-15354	1032.11	24700.2	13628	618.77	51933.2	27233
1919	1134.64	16324.2	3534	1032.08	19620.1	-2123	618.77	35147.8	15426
1920	1134.45	12139.4	12812	1030.53	8838.72	-329	618.75	15732.7	6894
1921	1134.46	19239.8	-8249	1031.43	19490.7	-798	618.75	26938.7	7448
1922	1134.05	20529.1	5832	1031.13	19497.5	-1405	618.75	21282.6	1836
1923	1133.83	23371.9	42754	1031.02	19216.2	-4054	618.76	16680.3	-2485
1924	1134.12	11560.6	5537	1031.05	8835.06	-1405	618.77	12347.9	3462
1925	1134.03	22610.5	27296	1031.43	19268	-2505	618.76	24413.2	5196
1926	1134.1	26459.1	57320	1031.66	19225.7	-8496	618.77	14819.7	-4406
1927	1134.56	18279.7	-523	1031.31	19256.2	-219	618.77	25467.2	6211
1928	1134.28	11318.9	17355	1030.96	8843.44	-1870	618.77	13357.2	4412
1929	1134.37	21359.3	9957	1031.14	19543.1	-801	618.75	24062.4	4621
1930	1134.2	25904.3	46715	1031.43	19563.1	-6049	618.77	18431.9	-1182
1931	1134.51	24069.9	31474	1031.51	19569.2	-3694	618.76	20916.2	1347
1932	1134.62	11702.8	29899	1031.73	8837.98	-2598	618.76	11681.8	2793
1933	1134.89	17113.3	11628	1031.8	21187.1	1055	618.75	28316.4	7231
1934	1134.81	22688.9	5260	1030.95	23567.4	1177	618.77	30769.1	7100

Year	Lake Victoria			Lake Kyoga			Lake Albert		
	Initial storage (m.a.s.l)	Release (MCM)	Inflow (MCM)	Initial storage (m.a.s.l)	Release (MCM)	Inflow (MCM)	Initial storage (m.a.s.l)	Release (MCM)	Inflow (MCM)
1935	1134.55	20879.2	18193	1031.04	19820.1	-1939	618.75	20662.2	4274
1936	1134.51	19215.2	37312	1030.77	8832.93	-4339	619.41	10959.7	-1305
1937	1134.78	29876	49554	1032.42	25067.8	-6755	618.75	25178.8	111
1938	1135.07	26303.8	12068	1031.93	25038.4	-2179	618.75	28981.5	3994
1939	1134.86	26076.2	7241	1031.69	25092.8	-2743	618.76	33603.9	8562
1940	1134.58	15669	25747	1031.2	8833.72	-4963	618.77	12252.5	3317
1941	1134.73	29565.8	38323	1031.72	25167.6	-4585	618.75	23385.9	-1680
1942	1134.86	21241	21241	1031.67	25154.9	2092	618.77	19814.8	-5391
1943	1134.86	20358.4	-11918	1031.16	25134.1	3712	618.76	34960.1	9826
1944	1134.38	13309.9	19359	1030.84	8833.85	-2136	618.76	16131.7	7247
1945	1134.47	27284.3	8492	1031.52	24825.2	-3599	618.75	24645.3	-129
1946	1134.19	26342	20989	1031.2	24874.8	-1222	618.76	23189.6	-1736
1947	1134.11	23918.7	54783	1031.27	24875.1	-489	618.75	20558.1	-4317
1948	1134.57	11108.2	15158	1030.84	8834.6	649	618.75	14795.8	6012
1949	1134.63	23534.2	-9373	1031.68	25053.4	1118	618.76	35633.5	10631
1950	1134.14	26631.2	15259	1031.57	25114.9	-2803	618.77	30842.9	5728
1951	1133.97	26056.5	52847	1031.21	25083.5	-3809	618.77	22356.2	-2829
1952	1134.37	12061.3	27522	1030.31	14402.2	4565	618.75	15353.3	1002
1953	1134.6	26654.7	1803	1031.03	25294.5	-783	618.76	33092.3	7747
1954	1134.23	25381.5	7982	1031.2	25296.3	-1882	618.75	23088.5	-2157
1955	1133.97	24244.3	16900	1030.65	25284.8	36	618.76	27012.6	1677
1956	1133.86	12947	24302	1030.31	10086	-2861	618.75	11036.1	1001
1957	1134.03	24779.6	27457	1030.31	26040.8	1289	618.76	27871.9	1882
1958	1134.07	29023.4	14323	1030.32	26328.7	-1993	618.77	31312.5	4882
1959	1133.85	25771.3	11774	1030.56	25297	-1176	618.75	25930.1	3486
1960	1133.64	13687	22347	1030.32	17155.1	3524	619.3	10864.2	-9042
1961	1133.77	40708.1	92271	1030.34	36155.4	-4381	618.77	31764.7	-2427
1962	1134.54	42254.8	69238	1030.4	47754.4	6343	619.15	42247.4	-5403
1963	1134.94	42892.6	80165	1030.68	44947.4	3214	619.17	49702	5806
1964	1135.49	11600.5	48431	1031.04	16752	3898	619.37	17693	-2178
1965	1136.03	42864	19650	1030.65	50174.7	6418	618.77	63781.4	13505
1966	1135.69	43903.3	30967	1030.35	48864.1	4849	618.75	55779.1	6915
1967	1135.5	43284.5	37162	1030.31	45685.7	2429	618.75	52496	6912
1968	1135.41	11135.9	61625	1030.32	16404.6	5241	618.77	13431.4	-3075
1969	1136.15	44073.2	31071	1030.31	47122.2	3049	618.75	52541.2	5419
1970	1135.96	43543.5	50383	1030.31	46343.8	2828	618.75	50897.8	4554
1971	1136.06	43765.9	20543	1030.32	47263.9	3498	618.75	55162	7949
1972	1135.72	11434.7	49727	1030.32	10591.7	-843	618.76	13403.8	2863
1973	1136.28	44172.3	18165	1030.32	45224.1	1024	618.77	50051.8	4726

Year	Lake Victoria			Lake Kyoga			Lake Albert		
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1974	1135.9	44290.5	28597	1030.31	46009.8	1747	618.75	50772	4813
1975	1135.67	43551.2	38099	1030.32	43965.2	414	618.76	42475	-1541
1976	1135.59	11121.2	19982	1030.32	16488.2	5367	618.75	20964.2	4476
1977	1135.72	43964.8	56933	1030.32	42362.6	-1630	618.75	41405.6	-957
1978	1135.91	43903.3	68542	1030.31	48041.5	4166	618.75	49807.7	1817
1979	1136.27	44379.8	40268	1030.32	44624.2	2340	618.76	50825.3	7591
1980	1136.21	11045.9	5567	1031.00	14526.3	1357	619.03	10852.3	-5013
1981	1136.13	44506.3	25358	1030.31	50269.3	5763	618.77	48718.2	-1602
1982	1135.85	44393	58748	1030.31	40171.2	-4194	618.76	33486.1	-6736
1983	1136.06	45227	30872	1030.32	48472.8	3218	618.75	45520	-2851
1984	1135.85	12560.4	-7209	1030.31	14992.4	2432	618.77	11037.1	-4057
1985	1135.56	49593.3	34640	1030.31	47915.3	-1678	618.75	37277.6	-10536
1986	1135.34	55581.2	32543	1030.31	60205.4	4652	618.77	64288.3	4032
1987	1135.00	52390.5	34134	1030.32	51785.3	-633	618.76	46907.4	-4827
1988	1134.73	10947.3	52242	1030.31	11484.3	537	618.77	18413.3	6929
1989	1135.34	43213.8	28977	1030.31	49113	5927	618.77	49115.8	-99
1990	1135.13	42931.9	42255	1030.32	41090.7	-1869	618.75	36551.9	-4437
1991	1135.12	43844.2	41812	1030.31	46844.4	3028	618.77	45786.3	-1109
1992	1135.09	12037.9	14747	1030.32	15058.6	2993	618.76	18596.5	3487
1993	1135.13	43410.6	-445	1030.31	47169.6	3759	618.75	48736.8	1618
1994	1134.48	44256.9	42912	1030.31	45134.9	878	618.76	43846.9	-1288
1995	1134.46	34888	27499	1030.31	34559	-329	618.76	64973.9	30364
1996	1134.35	12246.4	41093	1030.31	10285.4	-1961	618.75	31552.4	21267
1997	1134.78	51310.5	58128	1030.31	48736.7	-2546	618.75	56538.7	7802
1998	1134.88	52364.1	49614	1030.32	42272.1	-10092	618.75	55275.4	13105
1999	1134.84	52549.9	27025	1030.32	49287.7	-3290	618.77	59187.6	9849
2000	1134.46	12409.6	3009	1030.31	9710.6	-2699	618.76	15827.6	6117
2001	1134.32	49335.3	37270	1030.31	52472.3	3137	618.76	51271.4	-1150
2002	1134.14	48588.5	41227	1030.31	49881.5	1293	618.77	53310.2	3327
2003	1134.03	47820	22466	1030.31	51185.3	3393	618.75	56428.5	5345
2004	1133.65	11231.5	17893	1030.32	11852.3	593	618.77	18625	6671
2005	1133.75	43579.6	-241	1030.31	49557.8	6006	618.75	58977	9470
2006	1133.09	42657.5	49272	1030.32	50534.5	7877	618.76	60752.6	10269
2007	1133.19	43322.9	39354	1030.32	46312.9	2990	618.77	47943.8	1580
2008	1133.13	11480.8	28709	1030.32	18075.5	6567	618.76	24048.5	5973