Master's thesis

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OPTIMAL USE OF HYDRO RESOURCES IN THE VICTORIA NILE BASIN

Master's thesis in HYDROPOWER DEVELOPMENT
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Abstract

Uganda’s energy demand has been on a steady increase of about eight percent over the past decade and is expected to increase even more in the future. Several micro, small and large hydropower plants have been constructed and more are expected in the future as the country aims at having enough installed capacity to meet future energy demand. Uganda’s energy sector is hydropower dominated with a total installed capacity of 1182 MW as of May 2019. Over 80 percent of Uganda’s hydropower is generated by large hydropower plants which are all located along the upper Victoria Nile river, there by forming a cascade of four power plants consisting of Nalubaale, Kiira, Bujagali and Isimba HPP(s).

As more power plants are constructed along the Victoria Nile river to increase generation capacity, this study was carried out with an objective of optimizing the production from the Upper Victoria Nile river cascade, with a focus on production maximization. The optimization process was carried out using nMAG simulation model as a decision support tool and human judgement. A model of the cascade was set up in nMAG simulation model and different flow scenarios were studied. An operation strategy was established that increased the total production from Nalubaale and Kiira HPP by 6.2 percent on average over the observed period of 10 years. This operation strategy involved operating Nalubaale HPP as a base load power plant at a constant generation of 25.5 MW and Kiira HPP as both base load and peaking power plant for generation of the rest of the power dispatched to the two power plants.

The impact of climate change on future production from the cascade was assessed for the period 2020 to 2059 and indicated an increase in runoff. The increase in runoff lead to increased production from the cascade with Bujagali and Isimba HPP(s) being able to operate at maximum installed capacity for most of the time.

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1 Introduction

Uganda’s energy demand has been on a steady increase of about eight percent over the past decade and is expected to increase even more in the future as the government works towards lowering the electricity price, increasing electricity accessibility and industrializing the economy (vision 2040). Several micro, small and large hydropower plants have been constructed and more are expected in the future as the country aims at having enough installed capacity to meet future energy demand. Uganda’s energy sector is hydropower dominated with a total installed capacity of 1182 MW as of May 2019. Over 80 percent of Uganda’s hydropower is generated by large hydropower plants which are all located along the upper Victoria Nile river, forming a cascade of four power plants consisting of Nalubaale, Kiira, Bujagali and Isimba HPP(s).

The Victoria Nile offers a high potential for more hydropower development and this potential can be exploited by either constructing more power plants or improving the operation of existing power plants to increase river flow utilization. While construction of new power plants has been implemented, little consideration has been given to improving river flow utilization by the existing plants.

This study will be carried out with an objective of optimizing the production from the Upper Victoria Nile river cascade, with a focus on production maximization. Out of the four power plants making up the cascade, this study will mainly be focused on Nalubaale HPP and Kiira HPP. The optimization process will be carried out using nMAG simulation model as a decision support tool and human judgement. An nMAG model of the cascade will be set up, calibrated and validated using observed production data, and then used to simulate various operation strategies made up of different flow combinations with the aim of obtaining more energy production than observed while utilizing the same volume of water as observed. An operation strategy that meets these targets will be proposed for operation of the power plants in future.

The effects of climate change on future river Nile discharge will be assessed and simulations with projected future flows carried out to establish the impact of climate change on energy production from the cascade.

2 Theory

2.1 Lake Victoria and River Nile

2.1.1 Lake Victoria

Lake Victoria is the largest lake in Africa located along the equator in the eastern part of Africa. It's also the second largest fresh water lake in the world with a surface area of 68,870 km^2, catchment area of 180,950 km^2, water storage of 2760 km^3, average water depth of 40 m and a maximum depth of 79 m. The lake receives most of its inflow from natural rainfall accounting for 82% of total inflow with an annual rainfall average of 1700 mm in the lake zone and 1200 mm in the rest of its catchment area (WRMD, 2005). Lake Victoria experiences a high degree of evaporation with an annual average of 1900 mm which accounts for about 85% of outflow from the lake (CWE, 2014). The lake has approximately 25 major rivers flowing into it from its basin and only one outflow point at Jinja in Uganda which is also the source of River Nile. Lake Victoria is shared by Kenya, Tanzania and Uganda with its basin extending to include Burundi and Rwanda.

2.1.2 Lake Victoria outflow regulation

The natural water flow from Lake Victoria into river Nile is estimated using a mathematical equation representing the lake water level and discharge relationship also referred to as the agreed curve (WRMD, 2005). Approximately three kms downstream of river Nile is Nalubaale dam which creates a reservoir stretching back to the starting point of the river. Nalubaale dam serves two power plants i.e. Nalubaale HPP and Kiira HPP whose combined water releases represents the actual out flow from Lake Victoria (CWE, 2014). These two power plants are run of the river type with a combined reservoir having a capacity approximately 4.4 million cubic meters mainly used for peaking purposes. This small reservoir capacity has little impact on the natural flow from the lake and hence the releases from the two power plants should theoretically be approximated to be equal to the natural outflow from the lake. However, due to the unparallel timing between periods of high-power demand and high-water flows and vice versa, there is some regulation of the natural outflow from Lake Victoria. This regulation is controlled in such a way that the observed annual release from the two power plants does not exceed the annual release had the natural outflow been followed. This restriction is set and monitored by Uganda's Water Resource Management Department (WRMD) which is responsible for issuing water release permits to the operator of the two power plants. These permits are in the form of a daily maximum water release by the two power plants and normally issued for a period of 3 months. The opereator however has the freedom to control the daily release below or above this value to meet the varying daily power demand, but the total value released at the end of the issue period is expected not to exceed the equivalent value permitted by WRMD.

During very dry years when the natural outflow from Lake Victoria is very low compared to the required release by Nalubaale HPP and Kiira HPP to meet the national power demand, WRMD has the mandate to allow the operator to draw more water from Lake Victoria for power production. However, how much extra water can be drawn from Lake Victoria is also set by WRMD with reference to the Net Basin Supply of the lake. The extra water that is drawn from the lake during dry years is compensated for during wet years when lake out flow is higher than the required release for power production. This phenomenon was observed between 2007 to 2011 when the total annual turbine release from Nalubaale HPP and Kiira HPP was higher than the annual lake outflow as per the agreed curve and between 2012 to 2017 when the total annual turbine release was lower than the annual lake outflow as per the agreed curve. This is illustrated in Figure 2.1.

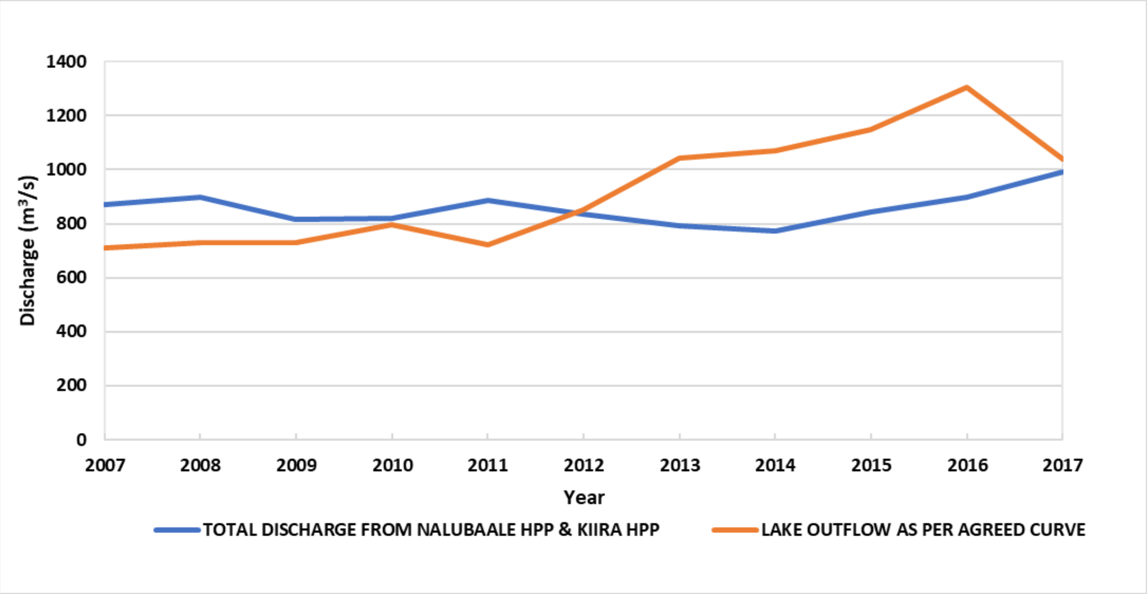


Figure 2.1 Annual average discharge

2.1.3 River Nile.

River Nile is lake Victoria’s only out flow starting from the north mouth of Lake Victoria. The river flows throw Uganda, South Sudan, Sudan, Ethiopia and Egypt before joining the Mediterranean Sea as shown in Figure 2.2. River Nile has two main tributaries one starting at Lake Victoria in Uganda and referred to as the White Nile and the other starting at Lake Tana in Ethiopian referred to as the Blue Nile. The part of the White Nile that flows through Uganda is further divided into three parts; the Upper Victoria Nile flowing between Lake Victoria and Lake Kyoga, the Lower Victoria Nile flowing between Lake Kyoga and Lake Albert and the Albert Nile flowing from Lake Albert to South Sudan Figure 2.3. This study will be limited to the Upper Victoria Nile.

Figure 2.2 River Nile flow through Africa (Hel-hama, 2013)

Figure 2.3 River Nile flow through Uganda (Ezeu, 2006)

Lake Victoria and Victoria Nile basin Climate

Lake Victoria and river Nile basin areas experience mainly tropical savanna climate consisting of two rainy and two dry seasons. The rainy seasons occurring between March to May and September to November while the dry seasons occur between December to February and June to august.

2.2 Hydro power and the Victoria Nile basin

Victoria Nile river is Uganda's largest river and the country's largest hydro power resource. All the four large hydro power plants currently operating in Uganda as of May 2019 are located along this river. On top of the already existing Nalubaale, Kiira and Bujagali HPPs, EPDC (2010) identified seven other potential large hydro power plants along the Victoria Nile River as represented in Figure 2.4. Out of the identified projects, Isimba and Kalagala HPP are located along the upper Victoria nile while Karuma, oriang, ayago, kiba and Murchison hydro are all located along the lower Victoria Nile. Isimba HPP and Karuma were later implemented with the former having been completed in April 2019 and the later still under construction. This study is limited to power plants along the upper Victoria Nile whose characteristics are summarized in Table 1.

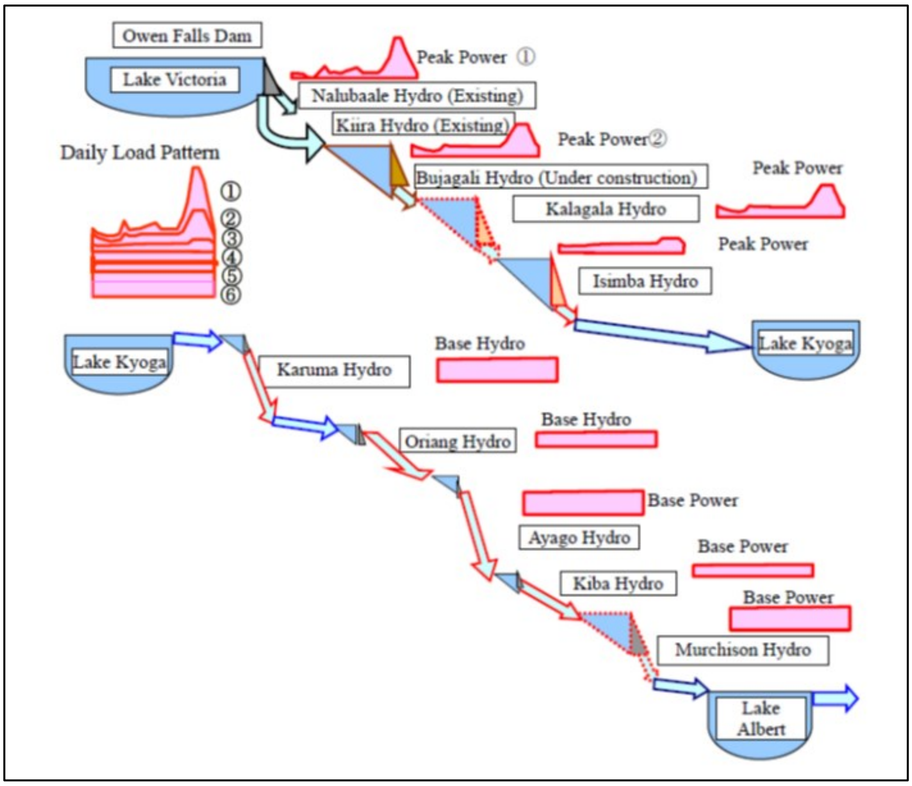
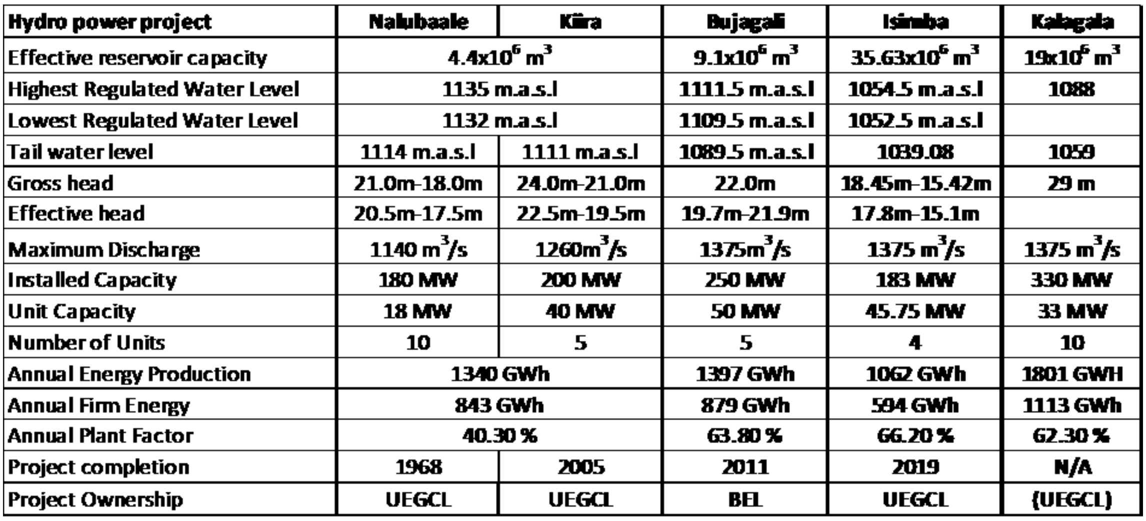


Figure 2.4 Potential Hydropower Projects along the Victoria Nile

Table 1 Characteristics of hydropower power plants on the Victoria Nile



Hydro power project	**Nalubaale**	**Kiira**	**Bujagali**	**Isimba**	**Kalagala**
Effective reservoir capacity	4.4×10^6 m^3		9.1×10^6 m^3	35.63×10^6 m^3	19×10^6 m^3
Highest Regulated Water Level	1135 m.a.s.l		1111.5 m.a.s.l	1054.5 m.a.s.l	1088
Lowest Regulated Water Level	1132 m.a.s.l		1109.5 m.a.s.l	1052.5 m.a.s.l	
Tail water level	1114 m.a.s.l	1111 m.a.s.l	1089.5 m.a.s.l	1039.08	1059
Gross head	21.0m-18.0m	24.0m-21.0m	22.0m	18.45m-15.42m	29 m
Effective head	20.5m-17.5m	22.5m-19.5m	19.7m-21.9m	17.8m-15.1m	
Maximum Discharge	1140 m^3/s	1260m^3/s	1375m^3/s	1375 m^3/s	1375 m^3/s
Installed Capacity	180 MW	200 MW	250 MW	183 MW	330 MW
Unit Capacity	18 MW	40 MW	50 MW	45.75 MW	33 MW
Number of Units	10	5	5	4	10
Annual Energy Production	1340 GWh		1397 GWh	1062 GWh	1801 GWH
Annual Firm Energy	843 GWh		879 GWh	594 GWh	1113 GWh
Annual Plant Factor	40.30 %		63.80 %	66.20 %	62.30 %
Project completion	1968	2005	2011	2019	N/A
Project Ownership	UEGCL	UEGCL	BEL	UEGCL	(UEGCL)

Approximately 3 km from Lake Victoria is Nalubaale HPP and Kiira HPP, approximately 16 km downstream of these two dams is Bujagali HPP and approximately 54 km downstream of Bujagali HPP is Isimba HPP, from which the Victoria Nile river continues to lake Kyoga. Power production data for Nalubaale HPP, Kiira HPP and Bujagali HPP was obtained for use in this study while no data was obtained regarding Isimba as it was commissioned in April 2019 and Kalagala is non-existing. This study will be limited to Nalubaale, Kiira and Bujagali HPP(s) under the past period while Isimba HPP will be introduced under the future period.

2.3 Upper Victoria Nile cascade

2.3.1 Operation of Nalubaale and Kiira HPPs

Nalubaale HPP and Kiira HPP have a parallel layout and share the same reservoir with the same regulation levels. Lake Victoria is theoretically assumed to be the reservoir for Nalubaale HPP and Kiira HPP, but from the operation side these two power plants have two reservoirs, Lake Victoria (with an infinite storage capacity) and the three km river stretch between Nalubaale dam and Lake Victoria (with a 4,400,000 cubic meter capacity) which will hereafter be referred to as Nalubaale reservoir. Lake Victoria serves as the main storage for the two power plants while nalubaale reservoir is used for regulating the upstream water levels during operation. Nalubaale reservoir's highest regulated level is 1135 m.a.s.l, a value higher than the long-term average Lake Victoria level (1948-2018) of 1134.6 m.a.s.l. The assumption of Lake Victoria being the sole reservoir for Nalubaale HPP and Kiira HPP assumes that Nalubaale reservoir can fill up to the same level as Lake Victoria, an assumption that is mainly limited by the mostly negative water balance between the lake outflow into Nalubaale reservoir and Nalubaale reservoir's power production water release.

2.3.2 Operation of the Victoria Nile Cascade

Nalubaale HPP is operated as a base load plant, Kiira HPP as peaking Plant and Bujagali HPP as both base load and Peaking plant. Uganda's daily energy demand consists of two peaking periods and follows the same hourly peaking pattern as shown in Figure 2.5.

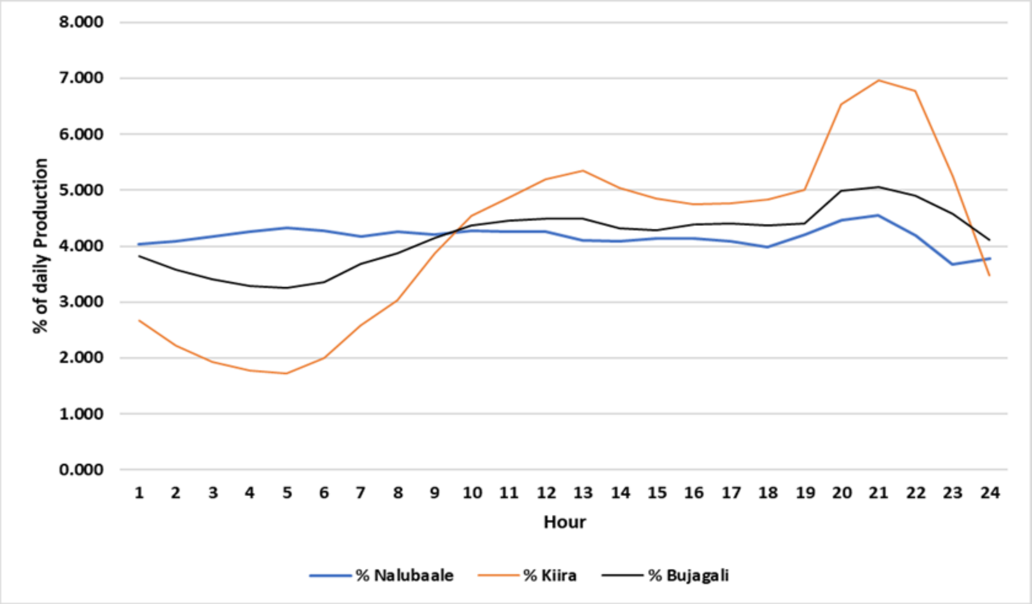


Figure 2.5 Hourly Peaking Pattern of the power plants

2.4 Uganda's Power Sector

Uganda's power sector is currently governed by the 1999 electricity act which led to the establishment of the Electricity Regulatory Authority (ERA), and breakdown of the then Uganda Electricity Board (UEB) which was responsible for generation, transmission and distribution of power into three companies i.e. Uganda Electricity Generating Company Limited (UEGCL), Uganda Electricity Transmission Company Limited (UETCL) and Uganda Electricity Distribution Company Limited (UEDCL) (EPDC, 2010). ERA, UEGCL, UETCL, and UEDCL are all under the jurisdiction of the Ministry of Energy and Mineral Development (MEMD) which among other roles is responsible for formulating power sector policies.

ERA is responsible for the regulation of generation, transmission, distribution, sale, export and import of electrical energy in Uganda. It's also mandated to issue, set conditions and ensure compliance to licenses for electricity generation, transmission, distribution, sale, and import on top of establishing an electricity tariff structure (EPDC, 2010).

UEGCL is a state-owned power utility that is responsible for asset management and development of hydro power stations and other renewable energy projects. Apart from Nalubaale HPP and Kiira HPP whose management it took over from UEB, UEGCL has also developed Isimba HPP which was completed in April 2019, Karuma, Muzizi and Nyagak HPPs which are still under construction (EPDC, 2010).

UETCL is a state-owned power utility and the only purchaser of all generated electricity under Uganda's single buyer model and the only electricity importer and exporter. UETCL owns and operates the country's transmission network and power grid (EPDC, 2010).

UEDCL is a state-owned power distribution utility responsible for asset management of the distribution network. Among other roles, UEDCL is also responsible for administering the lease and assignment agreement for the operation and maintenance of the distribution network that is carried out by a private company, UMEME (EPDC, 2010).

2.5 Power demand and supply.

2.5.1 Power Demand

Uganda’s power demand sector is classified into 6 groups depending on the customer status as domestic, commercial, medium-industrial, large-industrial, extra-large industrial and street lighting as shown in Figure 2.7. Over the past decade, Uganda’s electricity demand has been on the rise as shown in Figure 2.6 with an average increase of 8.3% per year. This value was calculated from the energy sales data from ERA between 2008 to 2018 and corresponds with the average demand growth rate of 8.2% reported by EPDC (2010). The energy sales data used here represents the final energy sold to the final consumers by the distribution companies after all losses have been deducted.

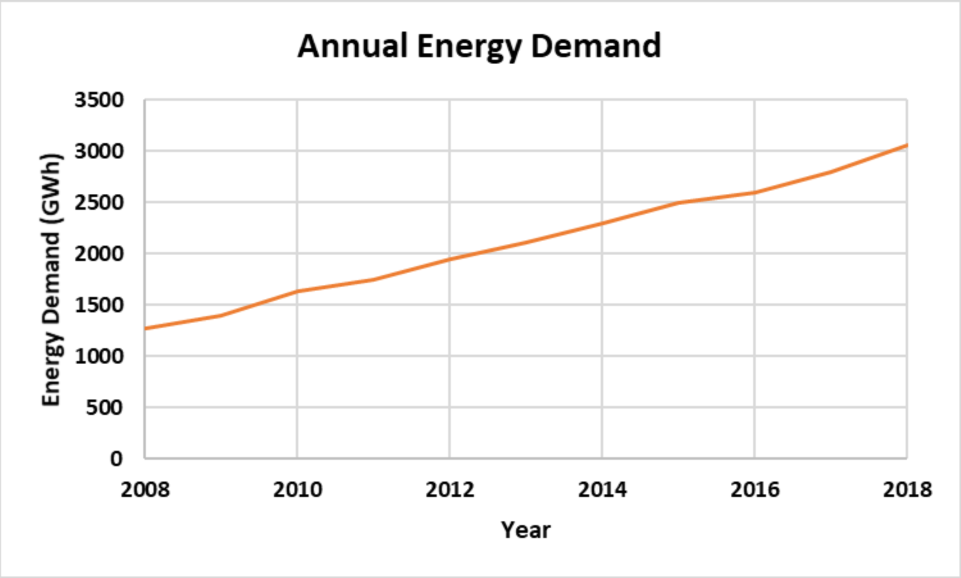


Figure 2.6 Annual energy demand

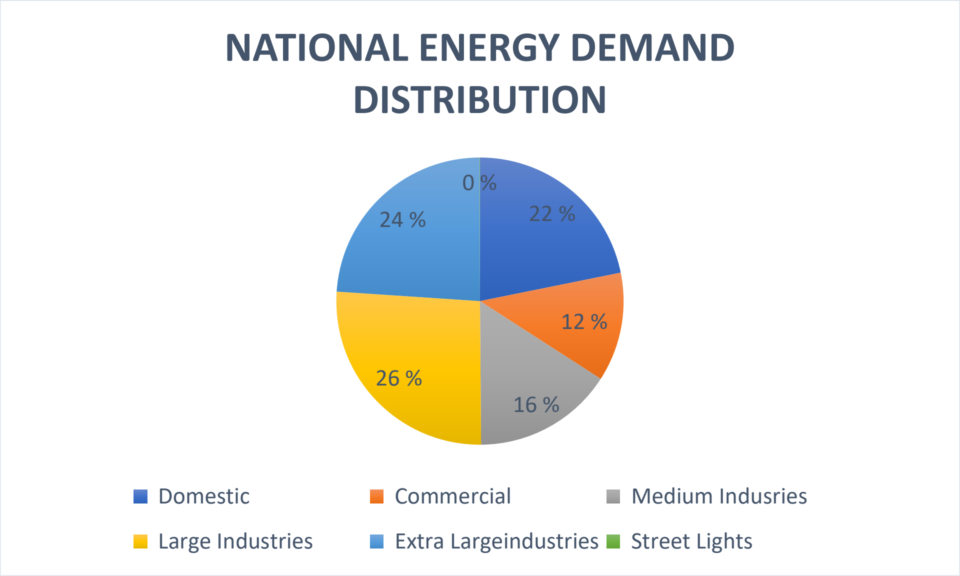


Figure 2.7 National energy demand distribution

2.5.2 Power supply

Uganda's power supply currently relies on 6 forms of generating technology which are; hydro power, thermal, cogeneration, solar, diesel and biomass. As of May 2019, Uganda's total installed capacity had reached 1182.2 MW, including the 183 MW from Isimba HPP that was commissioned in April 2019. Installed capacity of 1182.2 MW is distributed among the different technologies as shown in Figure 2.8.

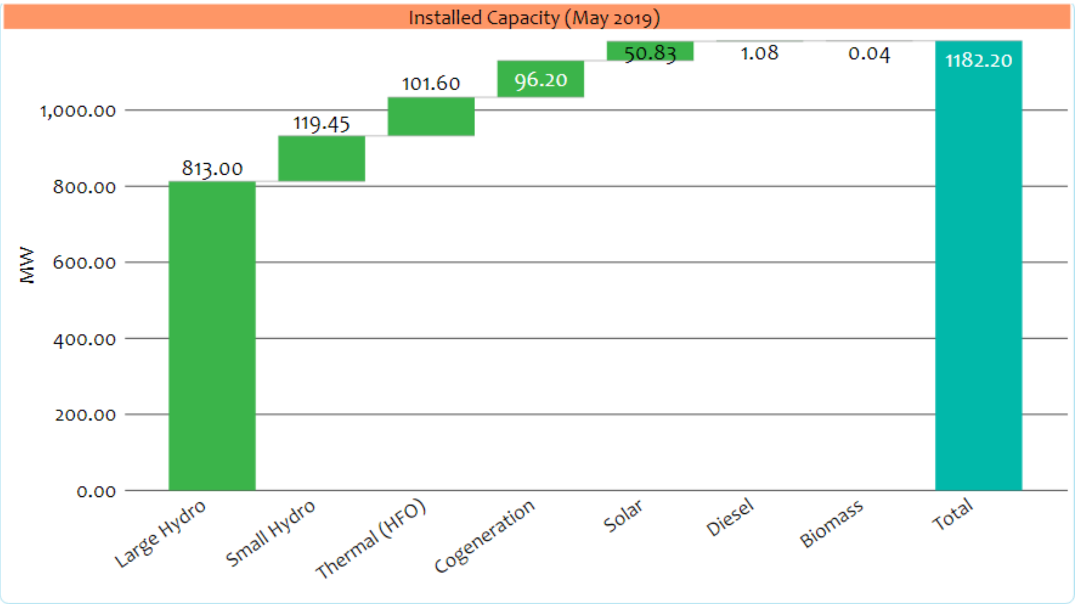


Figure 2.8 Installed capacity of the different technologies (ERA, 2018)

By the end of 2018, Uganda had a total of 37 electricity generating plants and by May 2019 this number had increased to 40, four being large hydro, 19 small hydro, three thermal, five cogeneration, six solar, one diesel and two biomass. Most of these plants generate for national grid supply while others like the biomass, diesel and some small hydro generate for own use and hence their generation is not accounted for on the national tally.

Over the past decade, many generating plants have be constructed which has led to an increase in Uganda's energy generation from 1827 GWh in 2009 to 4084 GWh in 2018 as represented in Figure 2.9.

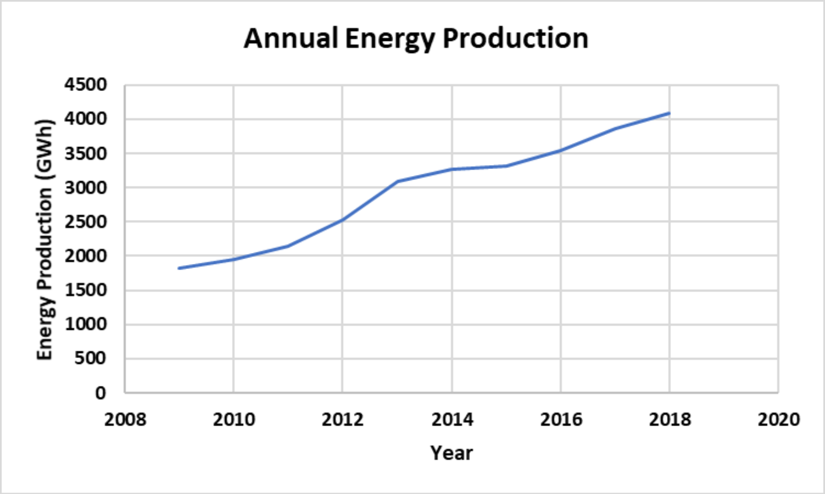


Figure 2.9 Annual energy production

Uganda’s energy generation is dominated by large hydro power plants whose combined generation accounted for 78 percent of the total national generation in 2018 (ERA, 2018). With the commissioning of Isimba HPP in April 2019 and completion of the 600 MW Karuma HPP that is currently under construction, this percentage will increase to over 85 percent. This shows how great the contribution of hydro power is and will be in future to Uganda’s power sector.

2.5.3 Power Tariffs

Power tariffs in Uganda are regulated by ERA and are classified as generation, distribution and bulk supply tariffs. Generation tariff is the rate at which UETCL purchases power from the different generating companies, bulk supply tariff is the rate at which UETCL sells power to the different distributing companies and distribution tariff is the rate at which the distribution companies sell power to the final consumers. These tariffs are reviewed and approved by ERA every quarter a year and a price set which stays constant for the next quarter. Different tariffs are paid by UETCL to the different generating companies depending on the cost of generation and different prices are charged by the distribution companies to the different classes of final consumers.

2.6 Hydropower optimization

Optimization of hydropower production refers to the process of utilizing the hydropower resources within a given energy system in the most effective way to meet a required energy production. This processes together with the consideration of all relevant constrains within the energy system is also referred to as hydro power scheduling (Doorman, 2009).

2.6.1 Energy market

Two sets of energy market exist currently, i.e. regulated and deregulated market. A regulated market is characterized by constant energy prices and a target of minimizing generation costs given an expected demand, while as a deregulated market is characterized by varying energy prices and a target of maximizing profits from generation given a price forecast (Doorman, 2009).

2.6.2 Hydro power optimization challenges

When optimizing hydro power resources, there are several challenges that are normally faced and yet must be considered during the optimization process. Some of these challenges include; number and size of reservoirs and power plants, shared ownership of reservoirs and power plants along a single river system, physical nature of the reservoirs and power plants, constrains especially regarding regulation of flow, time horizon and time step, data requirements for the models used, and uncertainty especially from the energy demand and hydrology (Doorman, 2009).

2.7 Optimization models

The term optimization is commonly used in literature with reference to mathematical programming, but it also includes human judgement, use of either simulation and/or optimization models and use of other decision support tools (Wurbs, 1993). These tools and models mainly involve linear programming and dynamic programming in their analysis although others like mixed integer programming and stochastic dynamic programming are also used (Doorman, 2009).

Optimization is a complex process that requires the use of models for decision support during planning and operation of a given energy system. Since each energy system is unique, different models may have to be used or the same model may have to be used in a different way to be able to meet the requirements of an energy system. Models can either be deterministic or stochastic depending on modelling principle, optimization or simulation depending on modelling approach (Doorman, 2009).

A deterministic model works on the principle that all conditions both at the start and end are known while a stochastic model considers future uncertainty and hence decisions are based on stochastic events (Doorman, 2009). Optimization models are formulated to automatically calculate the best solution to a power system operation with reference to a given criteria (Doorman, 2009) while simulation models are formulated to predict and/or analyse a system's behavior under a given set of conditions (Wurbs, 1993).

For large hydro power systems, a single modelling approach can't be used and hence both the optimization and simulation methods should be used to find an optimum solution (Doorman, 2009). EOPS (EFI's One-area Power market Simulator) and EMPS (EFI's Multi-area Power market Simulator) are both given by Doorman (2009) as examples of models employing both the optimization and simulation methods. In both models, the strategy part utilizes the optimization approach to find an optimal strategy whose consequences are there after calculated using a simulation approach. Wurbs (1993) also states that most models employ both the optimization and simulation modelling approaches and that all optimization models are also in position to simulate the system under consideration.

A hydropower system can either be a storage system or run of the river system with other classifications like pumped storage being subordinates of the first two systems but employing different technologies. Storage system is typically a large system that uses a dam to store water in a reservoir which can be regulated depending on the energy demand and with a storage capacity of weeks, months or years independent of hydrological inflow. A run of the river system on the other hand typically has little or no storage and depends on the hydrological flow through the river system and where storage is included, it has a capacity of only a few hours and normally used for peaking purposes. For storage hydro power systems, optimization is used to refer to reservoir operation optimization most of the time (Wurbs, 1993), while as for run of the river systems, optimization refers to power plant operation optimization.

2.8 Hydro power scheduling hierarchy

A hydropower system may consist of several reservoirs and powerplants which may make the optimization process more complex and requiring more computational time. To overcome this, the decision problem is usually divided into long term, medium term and short-term stages (Warland, Henden, & Mo, 2016).

Long term modelling has a planning horizon of more than one year which depends on hydro system characteristics. With the long planning horizon, simplifications and approximations are normally made to make computational times acceptable and because of this, the long-term scheduling can't provide boundary conditions for short term models (Warland, Henden, & Mo, 2016). This modelling involves the use of stochastic optimization and simulation models.

Medium term scheduling provides boundary conditions for the short-term scheduling thereby acting as a link between the long term and short-term scheduling. It has a time horizon ranging from a few months to one year and involves the use of multi-deterministic optimization or stochastic models (Warland, Henden, & Mo, 2016).

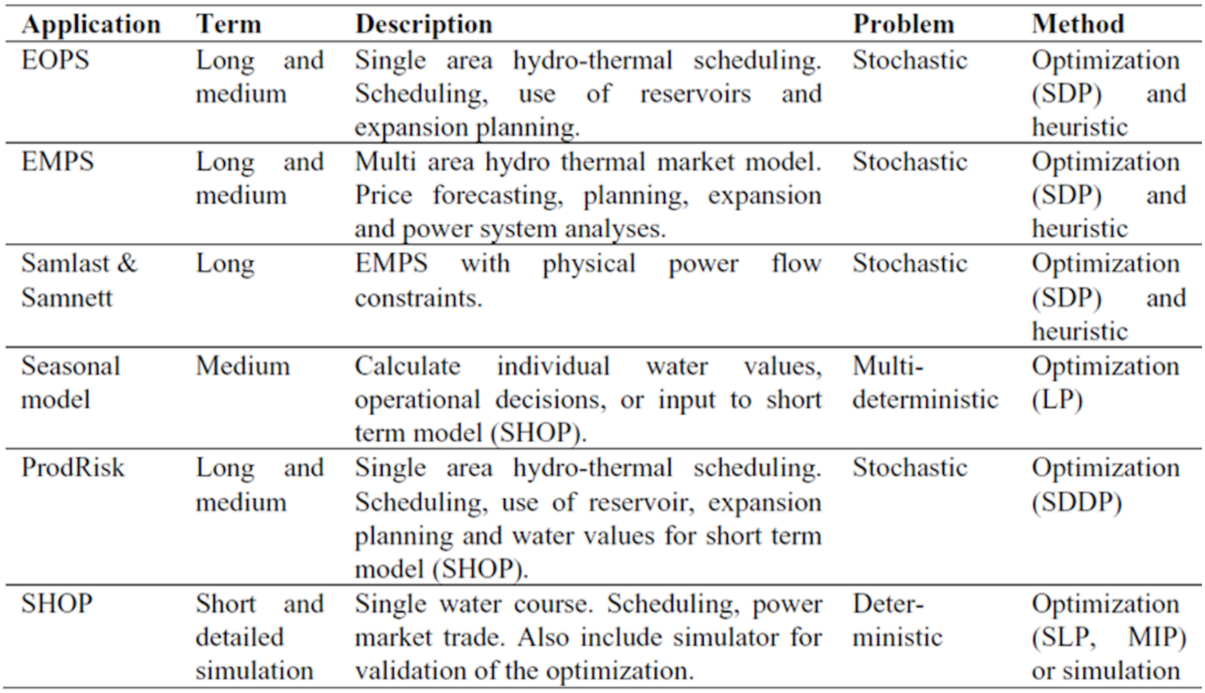
Short term scheduling has a time horizon of a few days to two weeks and uses a deterministic model and linear programming (Warland, Henden, & Mo, 2016).

The time horizon to be used for an energy system depends mainly on the capacity of the reservoirs wit in the system and the energy market conditions. A system comprising of large reservoirs with storage capacities of more than one year will require all the three scheduling stages while systems comprising of small reservoirs typical of run of the river power plants will require only the short-term optimization. Considering the small size of reservoirs along the Victoria Nile, only short time optimization will be considered in this study.

2.9 Examples of models used in optimizing energy systems

Various optimization and simulation models have been developed around the world for various purposes with in the energy system. These purposes include optimization and simulation of reservoir systems, power plant operation systems and electricity market systems. Examples of reservoir system simulation and optimization models are well detailed by Wurbs (1993) while those on electricity market system are reviewed by Felix Teufel (2013). For this study, focus will be placed on optimization and simulation models developed in Norway. Most of the models used for energy systems optimization and simulation in Norway have been developed by SINTEF and an overview of some of these models is presented in Table 2.

Table 2 Optimization models developed by SINTEF (Warland, Henden, & Mo, 2016)



Application	Term	Description	Problem	Method
EOPS	Long and medium	Single area hydro-thermal scheduling. Scheduling, use of reservoirs and expansion planning.	Stochastic	Optimization (SDP) and heuristic
EMPS	Long and medium	Multi area hydro thermal market model. Price forecasting, planning, expansion and power system analyses.	Stochastic	Optimization (SDP) and heuristic
Samlast & Samnett	Long	EMPS with physical power flow constraints.	Stochastic	Optimization (SDP) and heuristic
Seasonal model	Medium	Calculate individual water values, operational decisions, or input to short term model (SHOP).	Multi-deterministic	Optimization (LP)
ProdRisk	Long and medium	Single area hydro-thermal scheduling. Scheduling, use of reservoir, expansion planning and water values for short term model (SHOP).	Stochastic	Optimization (SDDP)
SHOP	Short and detailed simulation	Single water course. Scheduling, power market trade. Also include simulator for validation of the optimization.	Deter-ministic	Optimization (SLP, MIP) or simulation

From Table 2, SHOP which works on a short-term time horizon would be the best to use for optimizing the power plants along the upper Victoria Nile river whose reservoirs have a small storage capacity.

All the above models are mainly used in a deregulated energy market where the energy price keeps varying over time and where water in the reservoirs has different water values depending on the reservoir level. There is therefore a need to develop a strategy on how to utilize the water in the reservoirs in response to both power demand and energy price, this is the reason why the decision process in these models is made up of two parts i.e. a strategy part and a simulation part (Doorman, 2009). The strategy part uses an optimization model to calculate the water values and the simulation part is where detailed simulations carried out from which the reservoir rule curve drawdown method is used to compute the optimal production (Doorman, 2009). For a regulated power market like Uganda where power prices are do not vary significantly and are independent of the reservoir levels, only the simulation part combined with detailed information about the system characteristics is required for optimizing a system like the Victoria Nile power plants.

A program system nMAG was developed at the Norwegian University of science and Technology for simulating the reservoir operation and power production in a hydropower system (Killingtveit, 2004). Compared to the other models in Table 2, nMAG can be likened to their simulation part where the strategies from optimization can be simulated in detail and there after the optimal production is calculated. nMAG is an open source software and requires less learning time from its user since it does not cover the energy market and power price section in detail. This study was based on the nMAG model for both the optimization and simulation of the upper Victoria Nile cascade.

2.10 nMAG model

In the nMAG model, the different components of a power production system are described as modules with links between then that represent how water flows from one model to the next (Killingtveit, 2004). The water flow from one model to another can either be turbine release, bypass release or spill.

The descriptions below regarding the nMAG modules are made with reference to Killingtveit (2004).

2.10.1 Reservoir

Reservoirs are used for water storage and provide a possibility for regulating how water is used for production. In nMAG, a reservoir and its operation are described by its characteristics which include reservoir capacity, regulated levels, relationship between capacity and water levels, water release from the reservoir evaporation and routing to next module.

2.10.2 Power plant

A power plant is the main power generating unit in a production system and is described by its characteristic which include maximum capacity, energy equivalent, nominal head, intake level, tailwater level, head loss coefficient of hydraulic system, total efficiency of turbine, generator and transformer, routing to next module and peaking schedule. For a power plant with more than one unit, a combined total efficiency should be specified.

Inter-basin transfer

An inter-basin transfer can be used between modules when there is need to transfer water with a transfer of limited capacity.

2.10.3 Control points

A control point is used as a check point at a location within the water course where a restriction has been set or where discharge needs to be measured but no other module can be used.

2.10.4 Energy market

Depending on the provided information, nMAG computes the value of the power produced after taking into consideration the operational costs involved in generating the power. The information used to describe this module includes firm power level, firm power distribution, firm power price and a preference function for surplus power and rationing.

2.10.5 Restrictions

Hydropower always has an impact on the water flow in the river system where its developed which normally affects other users of the river system. To create a sustainable use between hydropower and other users, restrictions which also take priority over power production are normally placed on the production system and these are described in nMAG as minimum flow, bypass release, minimum and maximum permitted reservoir levels.

2.10.6 Operation strategy

The operation strategy in nMAG refers to how the reservoir is managed meaning that this strategy also dictates how other modules operate since they depend on the water releases from the reservoir. Three strategies can be used in nMAG which are reservoir release specification, reservoir guide curve and automatic reservoir balancing.

When a production system has only one reservoir, it’s possible to run nMAG under another mode, the ENMAG mode which has two other operational strategies i.e. reservoir rule curves and unconditional firm power.

2.10.7 Hydrological data

Hydrological data is the basis of all simulations and is in put inform of runoff series with monthly, weekly or daily time steps. Different runoff series can be input and scaled down to each module by nMAG depending on the weighted factors given and mean annual runoff. The time step resolution used for hydrological data will also be the same for production simulation and results generation by the model.

2.11 Effect of climate change on future Lake Victoria outflows

The future climate of Lake Victoria is expected to be characterized by increased temperature, precipitation, evaporation and the resulting water balance from this is expected to lead to an increase in the lake water levels, a situation that will result into increase runoff from the lake through the Victoria Nile river (Emmanuel, 2016). These findings are consistent with findings by (Conway, 2017) which also predict an increase in the future Nile river flows. This study will be based on findings by Emmanuel which represent Lake Victoria outflow into River Nile which is also the point of interest for this study.

Studies on climate change impacts are mainly based on data outputs from global climate models which are driven by the state of greenhouse gases in the atmosphere resulting from human activity. Emmanuel (2016) used five Global Climate Model (GCM) outputs from the multi-model dataset representing the Coupled Model Intercomparison Project phase 3 (CMIP3) of the Intergovernmental Panel on Climate Change (IPCC) and considered the A1B emission scenario for his study. Emission scenario A1B is part of the four storylines representing how future global development will impact global surface warming thereby causing climate change as categorized by IPCC's Special Report on Emission Scenarios.

After generating the future climate scenarios, (Emmanuel, 2016) modelled the historical Lake Victoria outflows as per the agreed curve and simulated future outflows for the period 2010 to 2099 as shown in Figure 2.10.

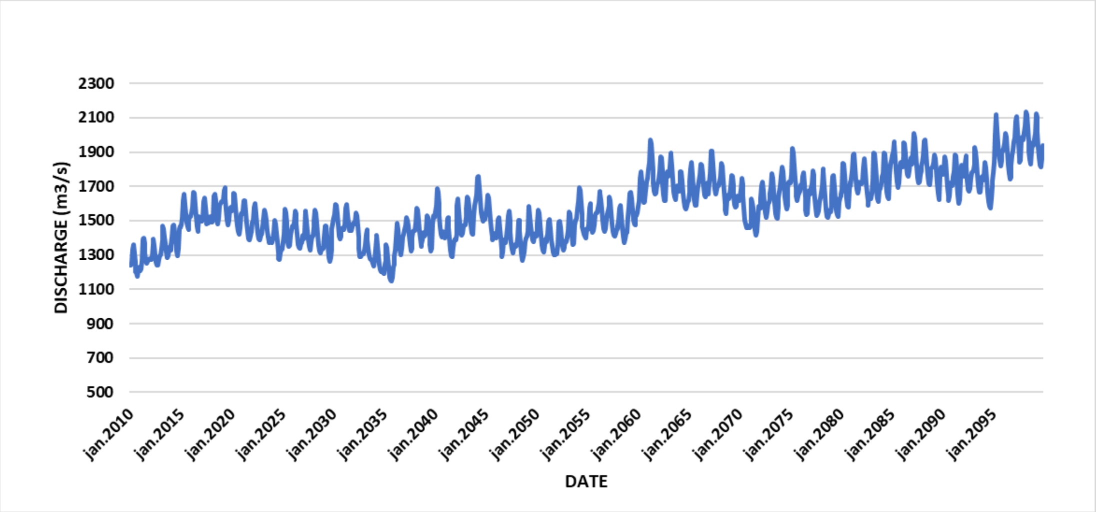


Figure 2.10 Projected future Lake Victoria outflows

3 Materials and methods

3.1 Data acquisition

Observed Power generation data and power plant characteristics for Nalubaale and Kiira HPP(s) was provided by UEGCL. The observed power generation data was provided from 2007 to 2014, and 2016 to 2018 (2015 missing) with an hourly time resolution. This data consisted of total plant power generation, turbine releases (through flow), spilled flow, reservoir and tailwater levels. For Bujagali HPP, this data was provided by Bujagali Energy Limited (BEL) from 2014 to 2018 with an hourly time resolution. The 2018 dataset for Nalubaale and Kiira HPP(s), 2014 and 2018 dataset for Bujagali HPP were incomplete and hence were not considered in this study.

Uganda's national load demand and supply data was provided by UETCL for 2013 to 2018. Datasets for all years provided were incomplete and were complemented by data retrieved for ERA's website when and as required.

Lake Victoria outflow series as per the agreed curve were provided by the Directorate of Water Resource Management-Uganda (DWRM). With the regulation of Lake Victoria outflow at Nalubaale and Kiira HPP(s) and the consideration of this study focusing on already existing power plants, discharge values from Nalubaale and Kiira HPP(s) were used as the hydrological series in preference to the outflow series from the agreed curve.

Projected future Lake Victoria outflow series were provided by Emmanuel (2016) for the period of 2010 to 2099. This data was used as input for simulating future generation from the Victoria Nile cascade.

3.2 Optimization process

Optimization was carried out with a purpose of obtaining an operation strategy that gives the most optimal power production from the Victoria Nile cascade based on the historical production data. For a power system like the Victoria Nile cascade which has very small reservoirs and almost constant energy prices, optimization was carried out using nMAG simulation model as a decision support tool and human judgement.

Based on the cascade layout, total production is mainly influenced by how Nalubaale HPP and Kiira HPP are operated with the water release from these two plants directly affecting the production from Bujagali HPP. The optimization process was focus on the current operation strategy of Nalubaale HPP and Kiira HPP and aimed at finding a better way they could have been operated in the Past Period (2007 to 2017) and the effect on Bujagali HPP.

The process involved altering the historical water flow combinations between Nalubaale HPP and Kiira HPP which always prioritized production through Nalubaale HPP as a base load plant and Kiira HPP for peaking purposes. Nalubaale and Kiira HPP share the same reservoir, are both owned by UEGCL and operated by the same company, thereby making it practically possible to alter the flows through these power plants.

The following steps were followed in optimization process

- Setting up the nMAG model for the Victoria Nile cascade
- Calibrating and validating the model using historical data
- Carrying out simulations with different flow scenarios
- Comparing results from the simulations with the historical production data
- Proposing a strategy for optimal use of the Victoria Nile Cascade.

After studying the past period, the effects of climate change on production from the Victoria Nile cascade in the future period (2020-2059) were investigated. In the future period, the optimal strategy from the past period will be used together with the projected future runoff series to simulate the future generation from the Victoria Nile cascade.

3.3 Model setup

3.3.1 Reservoir setup

The Victoria Nile consists of power plants in both parallel and in series. The parallel power plants (Nalubaale HPP and Kiira HPP) share the same reservoir, something that could not be modelled directly in nMAG. nMAG provides an option where a priority power plant can be chosen which runs on release from the reservoir and a bypass flow specified for the second plant. The variation of the bypass flow in nMAG is however limited to a few values that can’t cover an entire hydrological year of 365 days implying that the flow is assumed constant between different periods of the year. This option would therefore not be used since the flow to Kiira which is be the second power plant in this case varies daily and from year to year. These two were therefore setup independently each having a reservoir identical to Nalubaale reservoir as illustrated in Figure 3.1. Lake Victoria was omitted in this setup because it only influences the flow into Nalubaale reservoir and not the regulated water levels.

The releases from these two power plants were then directed to Bujagali reservoir thereby forming the Victoria Nile Cascade under the past period.

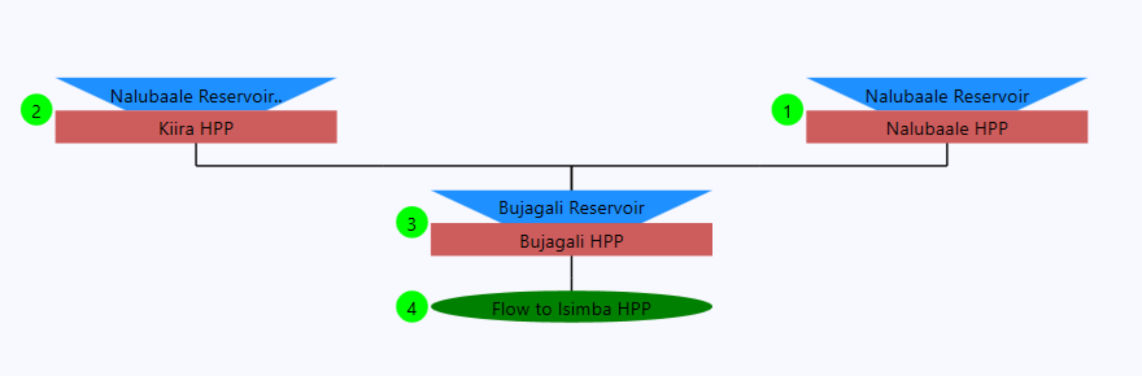


Figure 3.1 Model setup for the past period

3.3.2 Power Plant setup

All power plants have more than one unit, discharge and efficiency of these individual units were transformed into total plant discharge and total plant efficiency for all units so that they could suit the format used by nMAG which considers the entire power plant as a single unit.

3.3.3 Energy Market

The total firm power expected from all the power plants in the cascade was set as the firm power level in nMAG with a constant distribution. The summer season was assumed to cover the entire year since Uganda does not experience winter conditions and temperature variations do not significantly affect the power demand. Uganda's power prices do not vary significantly, hence no preference function was set in the model.

3.3.4 Operation Strategy

The automatic reservoir balancing strategy in nMAG that tries to keep the reservoir level as high as possible while meeting the required demand was used.

3.3.5 Hydrological data

Owing to the regulation of Lake Victoria outflow by Nalubaale reservoir, the hydrological data as observed from the releases of both Nalubaale HPP and Kiira HPP were used in the Past Period simulations since it is the actual representation of the flow through the Victoria Nile River as opposed to the hydrological data obtained from the agreed curve. Having setup Nalubaale HPP and Kiira HPP with separate reservoirs, the hydrological data was split into two series, one for each reservoir with a daily time step as shown in Figure 3.2.

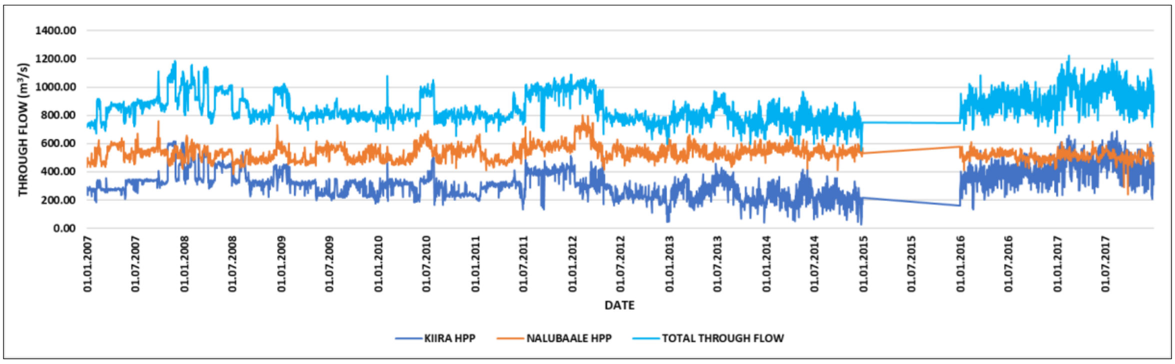


Figure 3.2 Daily average through flow

3.4 Model calibration and validation

3.4.1 Model Calibration

After setting up the model as described in the previous section, the model was calibrated so that it would simulate the observed production as close as possible. The calibration of Nalubaale and Kiira HPP(s) was based on 2007 and 2008 observed production data and through flow of each power plant while that of Bujagali was Based on 2015 observed production data and through flow. Different calibration periods were used because observed data was available for different periods. One year of data was used for Bujagali HPP calibration because the available data was for only three years, hence leaving out the other two years for validation.

During the calibration process, some adjustments were made to the observed physical conditions because of two main reasons;

- Some physical conditions would not be implemented in the model
- Some observed operation conditions varied on a daily and annual basis

The calibration process was carried out with the aim of simulating the observed production as close as possible based on the observed through flow. Several simulations were carried out with adjustments being made using the trial and error method until satisfactory simulations of the observed production were attained. The adjustments included changes to the design discharge, highest regulated reservoir level and tailwater level.

Hydropower plants are designed for a fixed maximum power output that is normally attained at the design maximum discharge and head. However, variations in reservoir levels during operation lead to variations in the attained head and hence requiring varying discharges to meet a given power output. Depending on the downstream water flow conditions, variations in discharge will normally lead to variations in the tailwater level. These variations are typical of the operation of the powerplants along the Victoria Nile Cascade and are represented in Figure 3.3, Figure 3.4, Figure 3.5 and Figure 3.6.

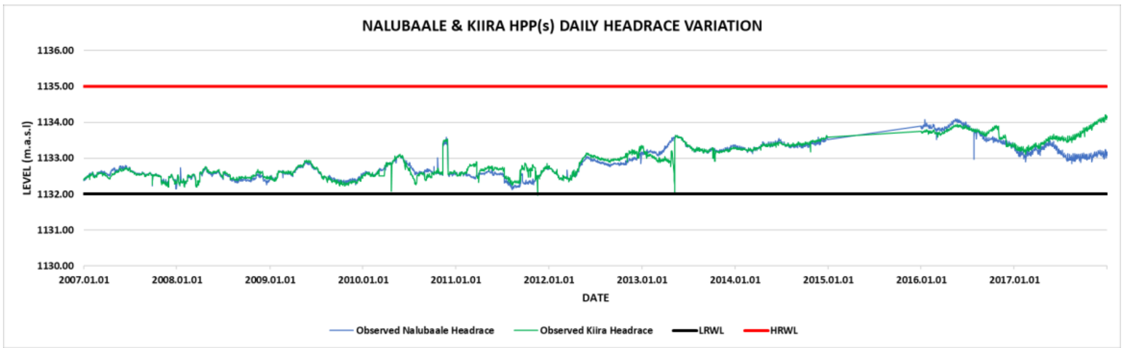


Figure 3.3 Nalubaale HPP and Kiira HPP headrace variation

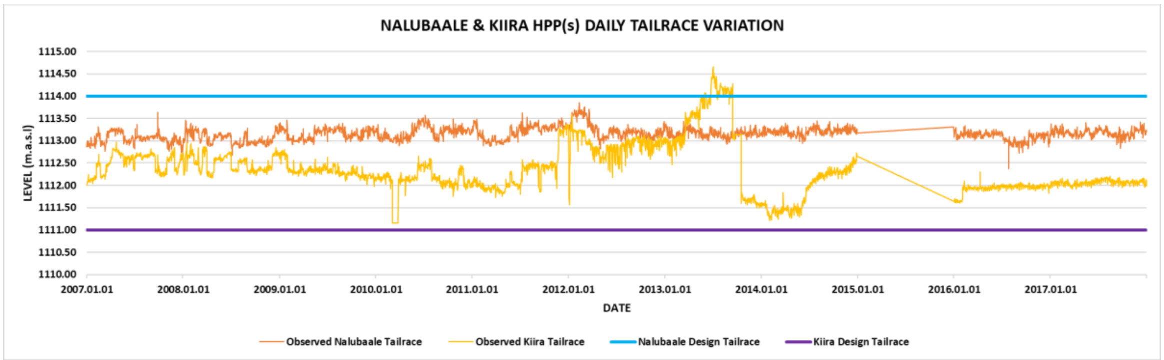


Figure 3.4 Nalubaale HPP and Kiira HPP tailrace variation

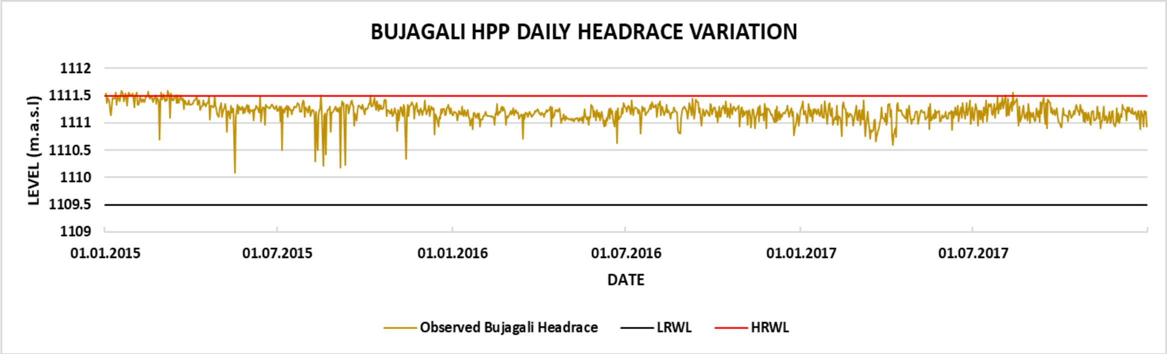


Figure 3.5 Bujagali HPP headrace variation

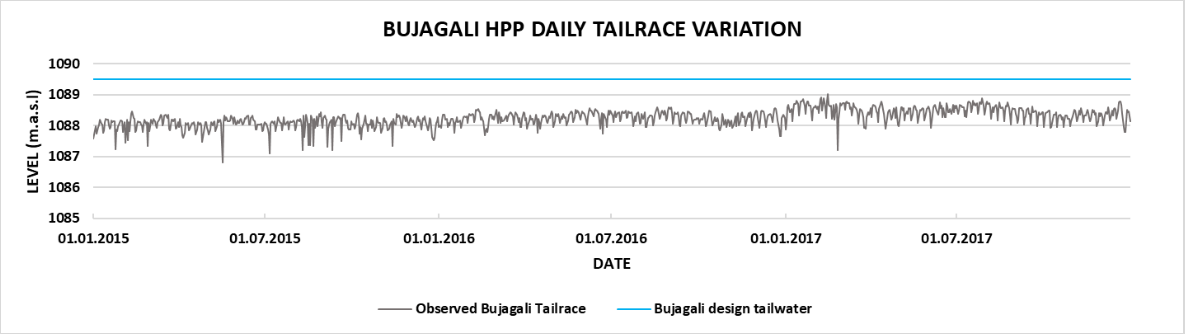


Figure 3.6 Bujagali HPP tailrace variation

3.4.2 Model validation

After model calibration, validation was carried out against observed data to find out if the model would be able to simulate the observed power production given the observed through flow as the input. The setup for Nalubaale and Kiira HPP(s) was validated based on observed data from 2009 to 2017 with exception of 2015 whose data was missing. Bujagali HPP was validated based on 2016 and 2017 data.

3.5 Flow scenarios

Five flow scenarios which involve increasing and decreasing flow through Nalubaale and Kiira HPP(s) were simulated, while maintaining the same combined total through flow of both power plants as observed. Three more scenarios in which Nalubaale HPP was operated at a constant discharge were also simulated, maintaining the same combined total through flow of both power plants as observed.

- Interchanged Through flow

Observed through flow of Nalubaale HPP was changed to Kiira HPP and that of Kiira HPP changed to Nalubaale HPP.

- Kiira Less 50%

Observed through flow of Kiira HPP was reduced by 50% and the other 50% added to Nalubaale HPP through flow, hence reducing through flow of Kiira HPP while increasing through flow of Nalubaale HPP.

- Kiira Plus 50%

Observed through flow of Kiira HPP was increased by 50%, with the extra 50% being deducted off the through flow of Nalubale HPP hence increasing the through flow of Kiira HPP while reducing through flow of Nalubaale HPP.

- Kiira Priority

The total observed through flow of both power plants combined was directed to Kiira HPP which was left to use all the water until its maximum capacity was reached and any extra flow beyond maximum capacity directed to Nalubaale HPP.

- Nalubaale Priority

The total observed through flow of both power plants combined was directed to Nalubaale HPP which was left to use all the water until its maximum capacity was reached and any extra flow beyond maximum capacity directed to Kiira HPP.

- Kiira priority & bypass 105

Nalubaale HPP was operated at a constant flow of 105 m^3/s and the rest of the water directed to Kiira HPP. In case the extra water after subtracting the 105 m^3/s was more than the maximum capacity of Kiira HPP, the rest was directed to Nalubaale HPP.

- Kiira Priority & bypass 210

Nalubaale HPP was operated at a constant flow of 210 m^3/s and the rest of the water directed to Kiira HPP. In case the extra water after subtracting the 210 m^3/s was more than the maximum capacity of Kiira HPP, the rest was directed to Nalubaale HPP.

- Kiira Priority & bypass 143

Nalubaale HPP was operated at a minimum flow of 143 m^3/s and the rest of the water directed to Kiira HPP. In case the extra water after subtracting the 143 m^3/s was more than the maximum capacity of Kiira HPP, the rest was directed to Nalubaale HPP.

4 Results and Discussion

4.1 Model calibration

After carrying out several adjustments to the maximum discharge, headrace water level and tail water level, one set of parameters was obtained that was used as input for the model. This model setup is here after referred to as MODEL-1 and the parameters used are shown in Table 3

Table 3 MODEL-1 calibration parameters

Hydro Power Plant (HPP)	**Nalubaale**	**Kiira**	**Bujagali**	**Isimba**
Callibration Period	**2007-2008**		**2015**	
Validation Period	**2009-2017**		**2016-2017**	
Effective reservoir capacity (m^3)	$2.93x10^6$		$9.1x10^6$	$35.63x10^6$
Highest Regulated Water Level (m.a.s.l)	1134		1111.5	1054.5
Lowest Regulated Water Level (m.a.s.l)	1132		1109.5	1052.5
Tail water level (m.a.s.l)	1113.5	1111.8	1088.15	1039.08
Nominal head (m)	19.833	21.533	22.683	14.753
Energy Equivalent (kwh/m^3)	0.049	0.053	0.053	0.037
Maximum Discharge (m^3/s)	840	1075	1250	1375
Maximum Capacity (MW)	144	200	250	183
Head loss coefficient (s^2/m^5)	4.30E-07	2.60E-07	1.90E-07	1.60E-07

The highest regulated water level in the model was set to 1134 m.a.s.l because it's the maximum level that was attained in the observed period as shown in Figure 3.3 with the assumption of a linear relationship between reservoir volume and water level, this level was equivalent to 2.93 million cubic meters of storage volume. The rest of the parameters were adjusted manually within the observed ranges until when a satisfactory simulation of the observed production was obtained.

The installed capacity of Nalubaale HPP was lowered from its design value of 180 MW to 144 MW in the model corresponding to eight power plant units instead of 10. This was because Nalubaale HPP was never operated at maximum capacity throughout the observed period. The annual maximum observed power values throughout the observed period of 2007 to 2017 ranged from 135 MW to 151 MW with an average of 145.5 MW which is almost equal to the installed capacity for eight power plant units.

4.1.1 Power – Discharge (P-Q) Curves

During the calibration process, the resulting P-Q curves were checked to ensure that the capacity of each power plant was not under or overestimated in the model. A comparison of the observed and simulated P-Q curves of the power plants is shown in Figure 4.1.

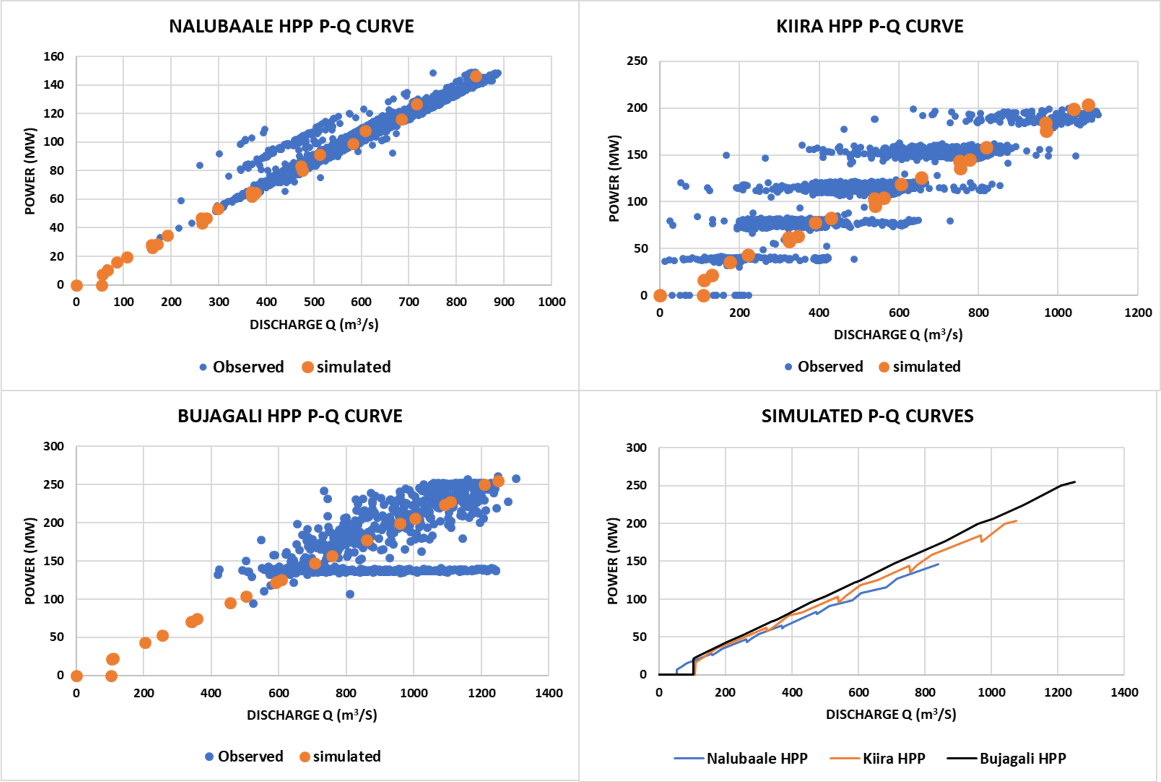


Figure 4.1 P-Q Curves for the power plants

4.1.2 Nalubaale HPP

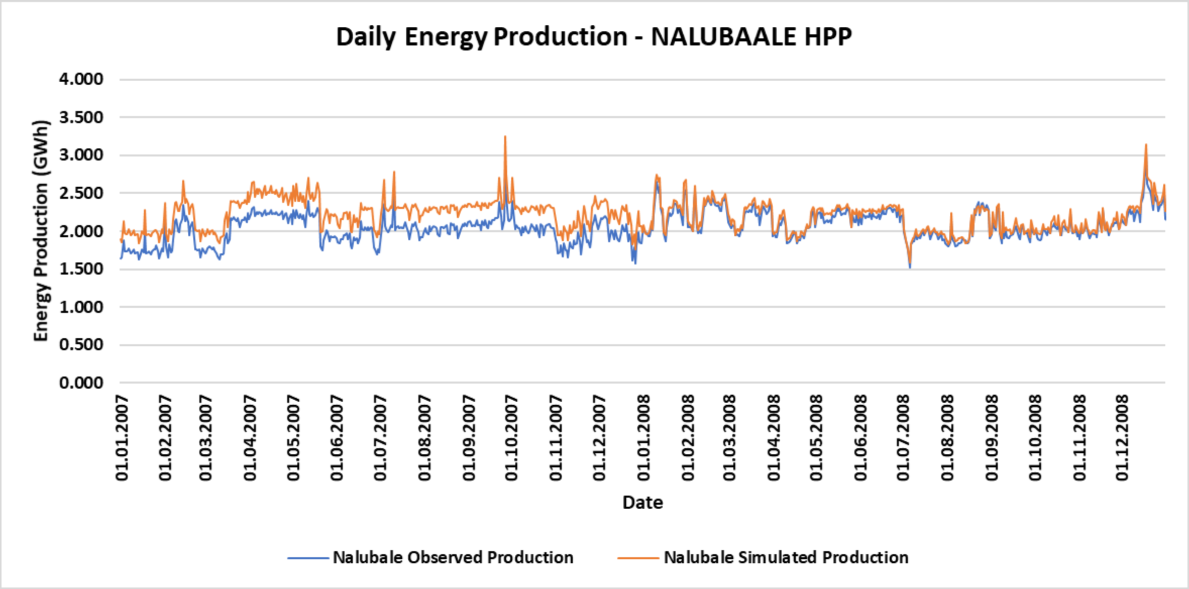


Figure 4.2 Nalubaale HPP calibration

From Figure 4.2, the simulated production follows the observed production quite well except in 2007 where the model over estimates the production. The observed and simulated values were checked for goodness of fit and yielded an R^2 value of 0.75 which was considered low. This low value was a result of the model over estimating production in 2007. When the goodness of fit was checked based on only 2008 data, an R^2 value of 0.96 was obtained which was considered very good. All other simulations carried out yielded the same pattern with the model over estimating production in 2007 which implied that there could have been a problem with the observed data in 2007.

Nalubaale HPP P-Q curves were generated for each year of observed data and they all had a patter typical of the observed Nalubaale HPP P-Q curve in Figure 4.1 With such a pattern, it was easy to add a linear trendline and establish a linear relationship between P and Q for each year. These P-Q relationships were used to recalculate the power based on the same discharge values and then plotted together as shown in Figure 4.3.

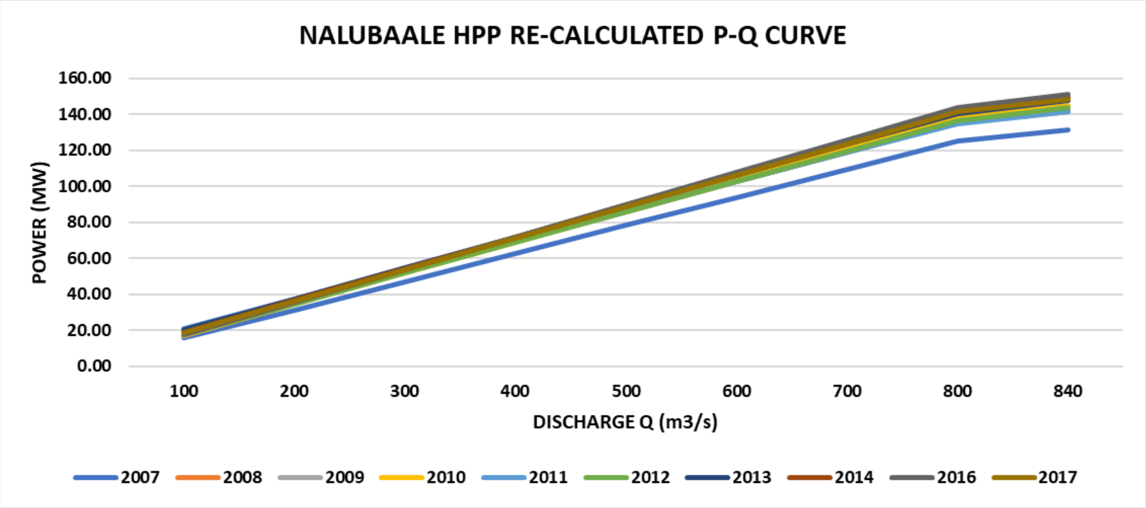


Figure 4.3 Re-calculated P-Q curve for Nalubaale HPP

From Figure 4.3, the P-Q relationship for 2007 yielded very low power values compared to all other years, a reason that could explain the difference observed between observed and simulated production in Figure 4.2 The low observed power values in 2007 are believed to be a result of the power plant operation procedure in that year. Basing on this finding, the 2007 simulated results from the model were considered a good representation of the would have been observed production had the same operation procedure used for other years been applied in 2007. The model calibration was therefore considered to be good enough despite the low R^2 value of 0.75.

4.1.3 Kiira HPP

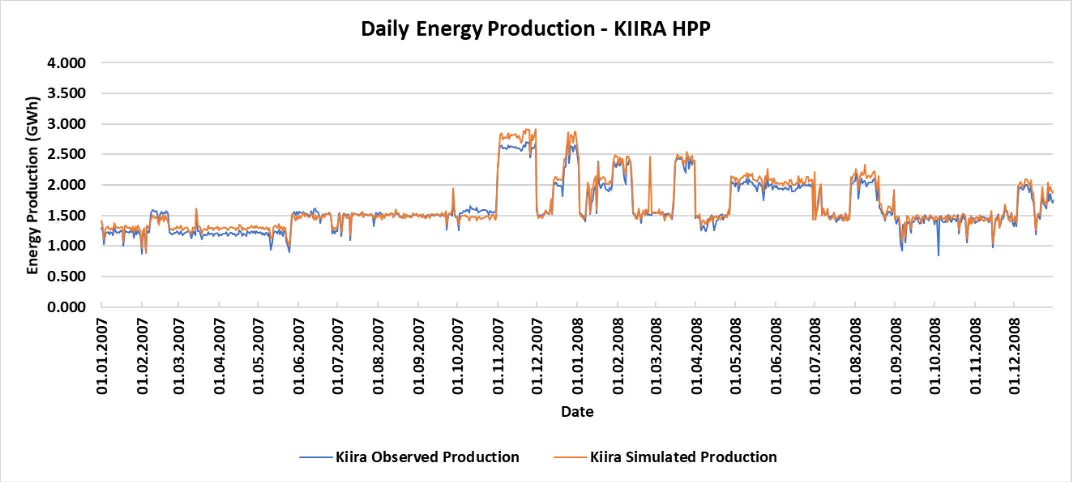


Figure 4.4 Kiira HPP calibration

From Figure 4.4, the simulated production follows the observed production quite well with a goodness of fit check yielding an R^2 value of 0.96 which is very good.

4.1.4 Bujagali HPP

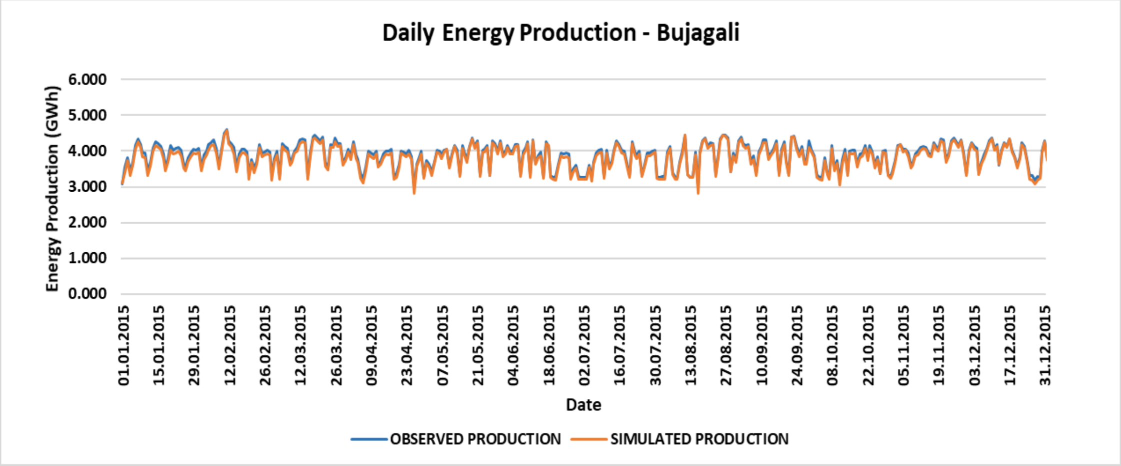


Figure 4.5 Bujagali HPP calibration

From Figure 4.5, the simulated production follows the observed production very well with a goodness of fit check yielding an R^2 value of 0.99 which is very good.

4.2 Model Validation

From the calibration of all the three power plants, a very good correlation was achieved between observed and simulated energy production. The calibrated models were then validated to see how well the models would perform given other data series.

4.2.1 Nalubaale HPP

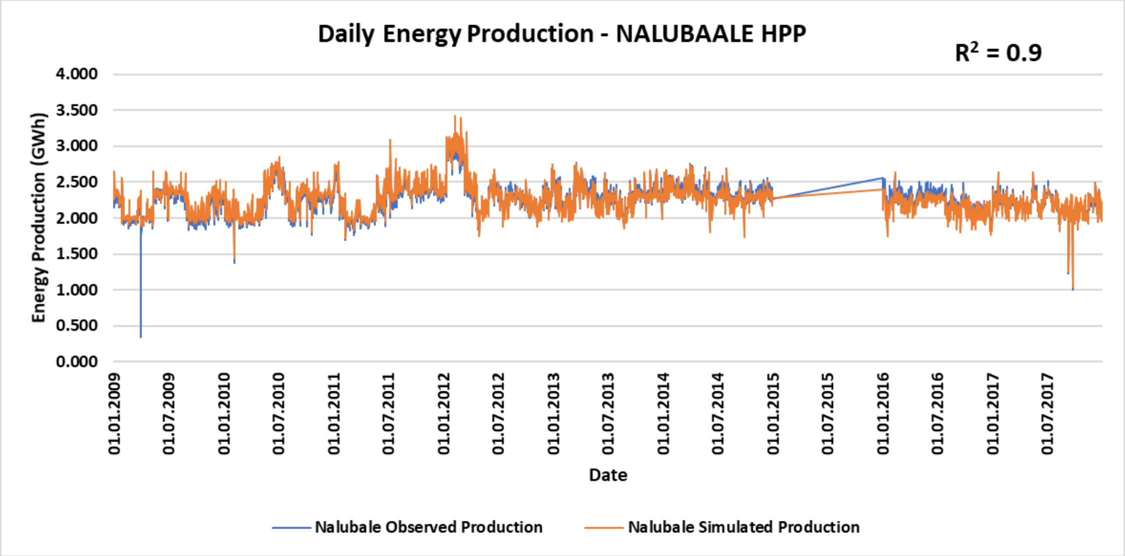


Figure 4.6 Nalubaale HPP validation

The model was able to simulate the observed production very well as shown in Figure 4.6 based on the parameters used for calibration.

4.2.2 Kiira HPP

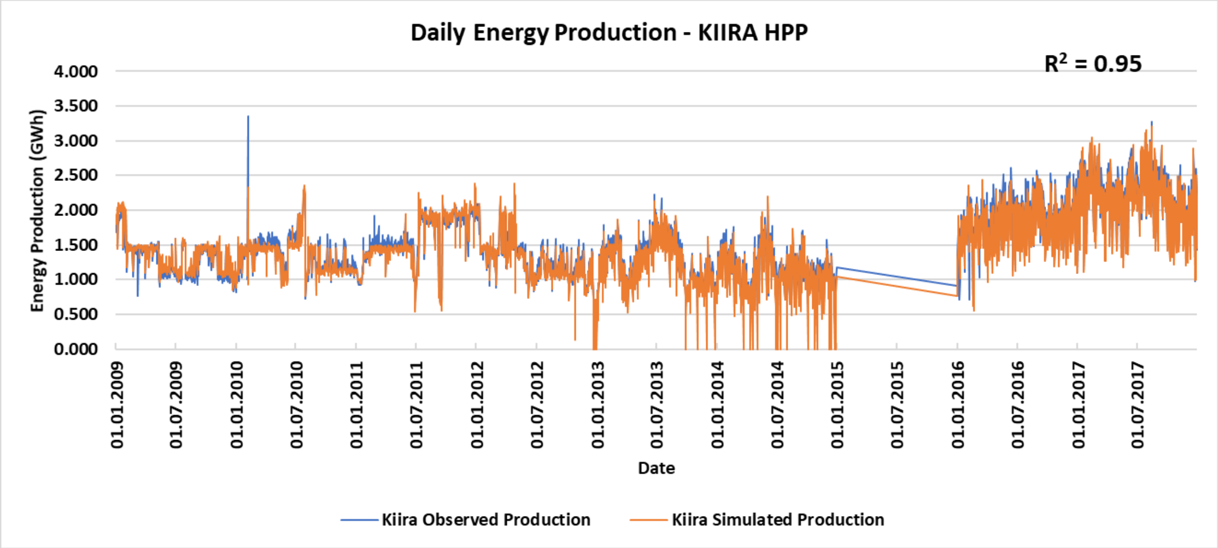


Figure 4.7 Kiira HPP validation

The model was able to simulate the observed production very well as shown in Figure 4.7 based on the parameters used for calibration.

From Figure 4.6 and Figure 4.7 MODEL-1 slightly over estimated the production from start of 2009 to mid of 2012 and after that it slightly under estimated it. This was due to the significant increase in the operational headrace levels of both Nalubaale and Kiira HPP(s) as indicated in Figure 3.3 that resulted into an increased generating head and hence increase in observed production.

From Figure 4.7 simulated production of Kiira HPP resulted into no production on many days between 01.01.2013 and 01.01.2015 which was not the case with the observed production as shown in Figure 4.8

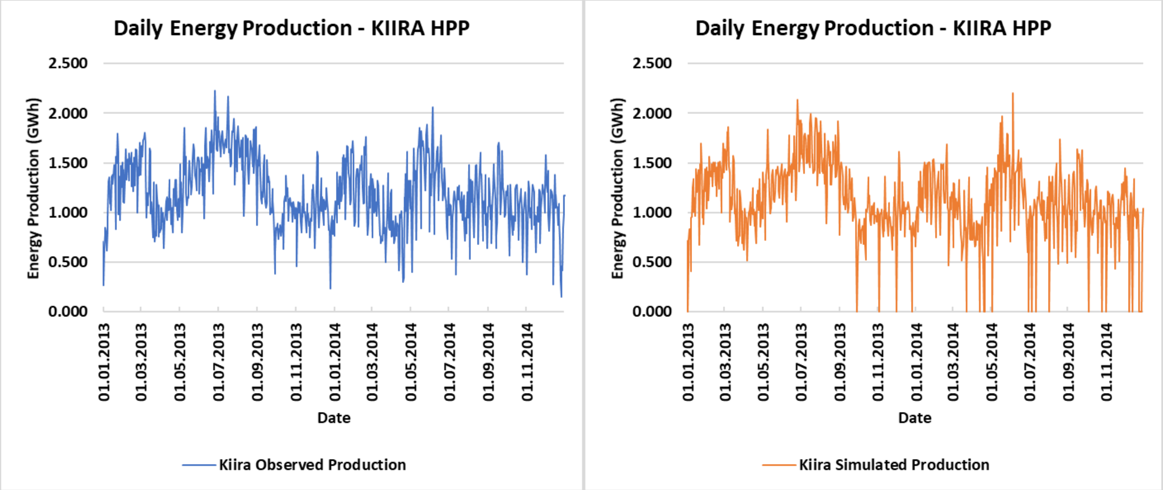


Figure 4.8 Observed and simulated Kiira HPP production

This was a result of the conversion of the observed data from hourly to daily timesteps as required for use in the nMAG model. Being a peaking power plant, Kiira can have hours when it is operating and hours when it is shut down all in the same day. When hourly power (MW) values from such a day are converted into a daily average, a lower power

(MW) value will be obtained, but the resulting daily energy production (GWh) will still be the same. However, when hourly turbine discharges from such a day are converted into a daily average, a lower discharge value maybe obtained which may correspond to point of zero efficiency from the efficiency curve and hence nMAG model will not generate power (MW) from that discharge, leading to zero production (GWh) on that day.

4.2.3 Bujagali HPP

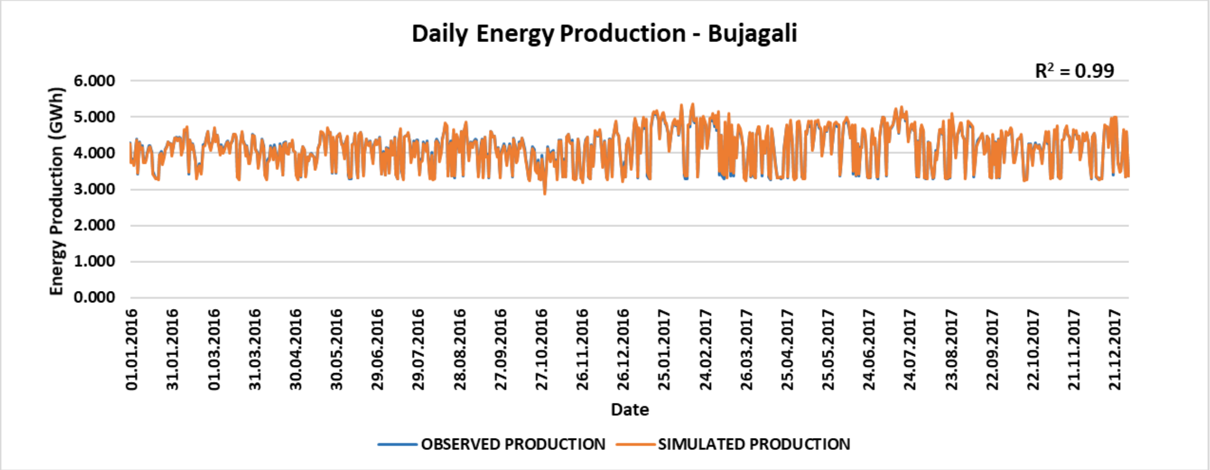


Figure 4.9 Bujagali HPP validation

The model was able to simulate the observed production very well as shown in Figure 4.9 based on the parameters used for calibration.

4.2.4 Comparison of the cascade simulation results

From the calibration and validation results of the three power plants, simulations from Bujagali HPP gave very good results as compared to simulations from Kiira and Nalubaale HPP. This result was attributed to two main reasons;

- Bujagali HPP had a short-observed data series of only three years which made it easier to calibrate the model compared to Kiira and Nalubaale HPP(s) that had a 10 year observed data series.
- From Figure 3.5 and Figure 3.6 the operational headrace level and tailrace level for Bujagali HPP did not vary significantly on a year to year basis as compared to those for Kiira and Nalubale HPP(s) which varied significantly within a single year period and over the entire observed period as shown in Figure 3.3 and Figure 3.4. The high variations observed from Kiira and Nalubaale HPP(s) greatly undermined the calibration process resulting into lower R^2 values as compared to Bujagali HPP.

To obtain better calibration results for Nalubaale HPP and Kiira HPP than those in MODEL-1, there was need to reduce the length of the data series used from 10 years (2007 to 2017) to a shorter duration of three years or less as used for Bujagali HPP in MODEL-1. Another model here after referred to as MODEL-2 was then set up. Unlike MODEL-1 which used the same reservoir and power plant parameters for the entire observed period of 2007-2017 as shown in Table 3. MODEL-2 was a combination of five setups with different reservoir and power plant parameters which were adjusted with the aim of reducing the gap between observed and simulated energy production for Nalubaale and Kiira HPP as presented in Table 4 and Table 5

Table 4 MODEL-2 calibration parameters for Nalubaale HPP

Hydro Power Plant (HPP)	**Nalubaale**				
callibration and Validation Period	**2007**	**2008-2009**	**2010-2012**	**2013-2016**	**2017**
Effective reservoir capacity (m^3)	1.47x10^6	1.47x107	2.93x10^6	2.93x107	2.93x108
Highest Regulated Water Level (m.a.s.l)	1133	1133	1134	1134	1134
Lowest Regulated Water Level (m.a.s.l)	1132	1132	1132	1132	1132
Tail water level (m.a.s.l)	1114	1113.15	1113.5	1113.5	1113.5
Nominal head (m)	18.667	19.517	19.833	19.833	19.833
Energy Equivalent (kwh/m^3)	0.049	0.049	0.049	0.049	0.049
Maximum Discharge (m^3/s)	920	840	840	830	830
Maximum Capacity (MW)	144	144	144	144	144
Head loss coefficient (s^2/m^5)	3.50E-07	4.30E-07	4.30E-07	4.40E-07	4.40E-07

Table 5 MODEL-2 calibration parameters for Kiira HPP

Hydro Power Plant (HPP)	**Kiira**				
callibration and Validation Period	**2007**	**2008-2009**	**2010-2012**	**2013-2016**	**2017**
Effective reservoir capacity (m^3)	1.47x10^6	1.47x107	2.93x106	2.93x107	2.93x108
Highest Regulated Water Level (m.a.s.l)	1133	1133	1134	1134	1134
Lowest Regulated Water Level (m.a.s.l)	1132	1132	1132	1132	1132
Tail water level (m.a.s.l)	1111.55	1111.55	1111.8	1111.13	1112
Nominal head (m)	21.117	21.117	21.533	22.203	21.333
Energy Equivalent (kwh/m^3)	0.053	0.053	0.053	0.053	0.053
Maximum Discharge (m^3/s)	1075	1075	1075	1010	1050
Maximum Capacity (MW)	200	200	200	200	200
Head loss coefficient (s^2/m^5)	2.60E-07	2.60E-07	2.60E-07	2.90E-07	2.70E-07

The results from calibration and verification of MODEL-2 are represented in Figure 4.10 and Figure 4.11.

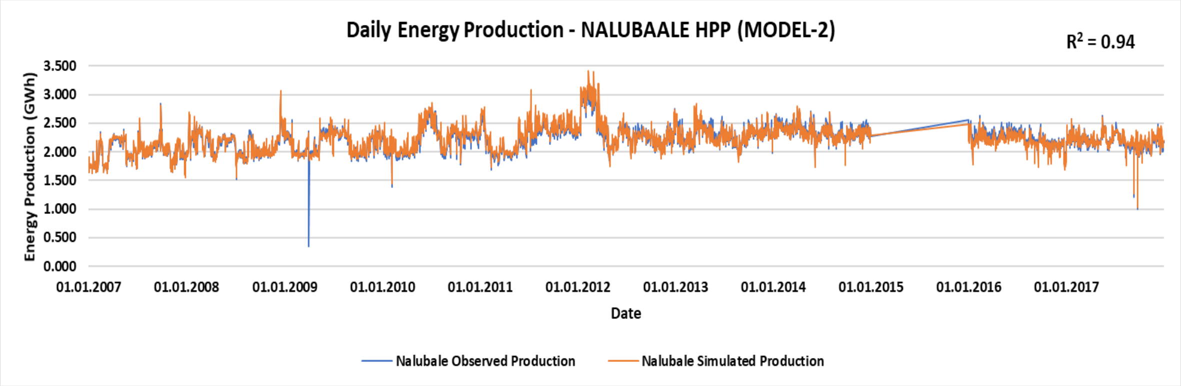


Figure 4.10 MODEL-2 calibration for Nalubaale HPP

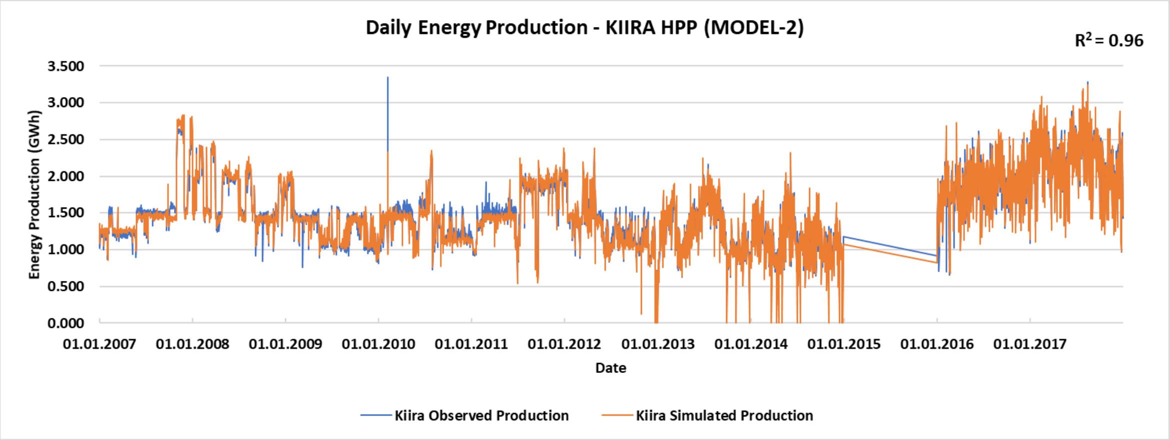


Figure 4.11 MODEL-2 calibration for Kiira HPP

MODEL-2 setup resulted into better simulation results especially for Nalubaale HPP including 2007 which was over estimated by MODEL-1. Better simulation results for 2007 were obtained by lowering the efficiency of Nalubaale HPP in that year as compared to that used for the rest of the years (2008-2017). The efficiency used for 2008-2017 in MODEL-2 was like that used in MODEL-1. Detailed setup information for both model setups can be found in Appendix 1

4.3 Flow scenario simulations

4.3.1 Model simulation

With a purpose of optimizing the total production from both Nalubaale and Kiira HPP(s), the total annual production results of both power plants will be presented in this section.

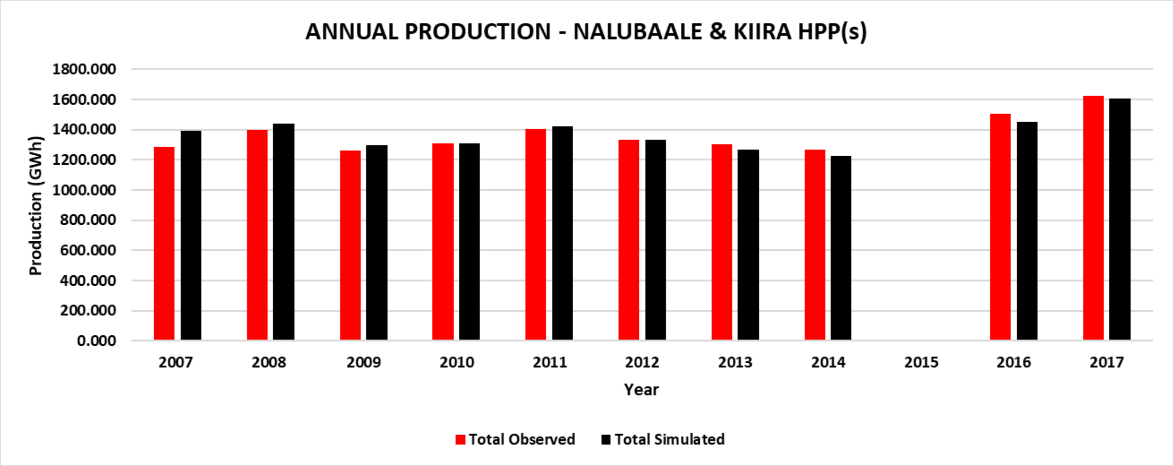


Figure 4.12 MODEL-1 Annual observed and simulated production

On an annual basis as shown in Figure 4.12, MODEL-1 over estimated the observed annual production in 2007, slightly over estimated it between 2008-2011 and slightly under estimated it between 2013 and 2017. The under estimation was more significant in 2016 when the headrace water level of the power plants was observed to be highest as shown in Figure 3.3

MODEL-2 on the other-hand simulated the observed production very well as shown in Figure 4.13

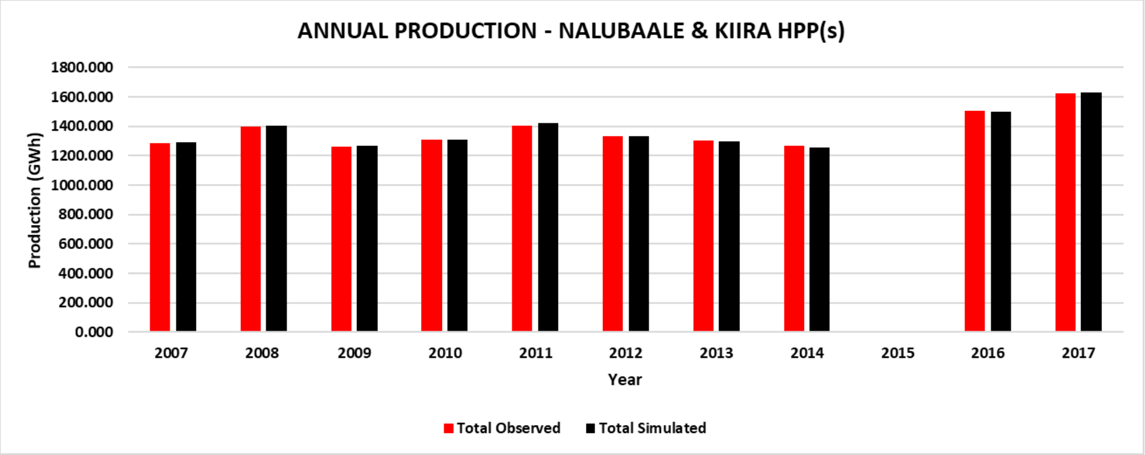


Figure 4.13 MODEL-2 Annual observed and simulated production

4.3.2 Flow scenario simulations

In this section, results from MODEL-1 will be used and discussed since it represents the entire observed period, while results for MODEL-2 will be used only when there is need to add more detail to results from MODEL-1.

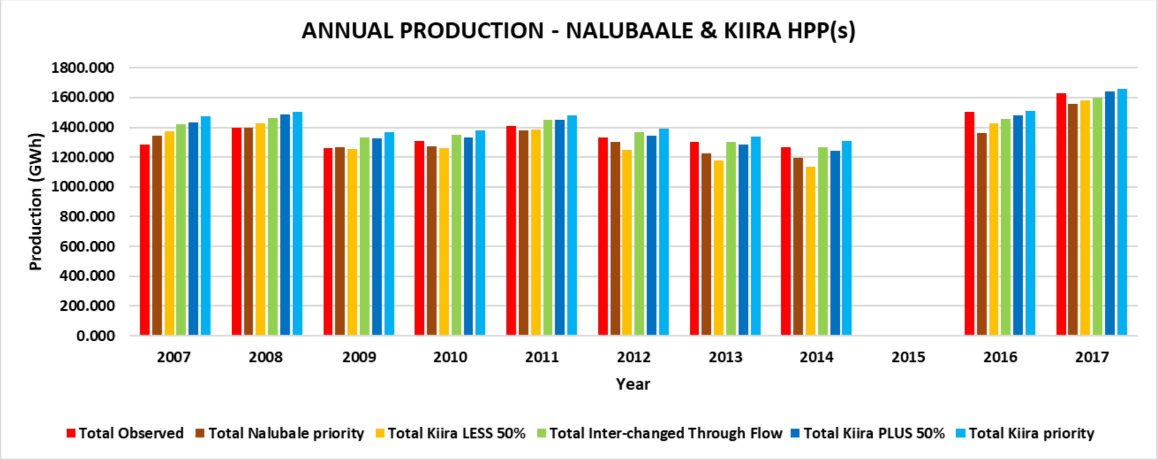


Figure 4.14 MODEL-1 Annual simulated production

From Figure 4.14 all the flow scenarios that led to a decrease in water flow to Kiira HPP resulted into lower generation compared to those that led to an increase in water flow to it. The increased production from Kiira HPP was attributed to it having and operating at a higher head most of the time compared to Nalubaale HPP. Kiira Priority flow scenario resulted into the highest annual production in all years compared to other flow scenarios and the observed annual production. The annual difference between the observed production and Kiira Priority production is shown in Figure 4.15.

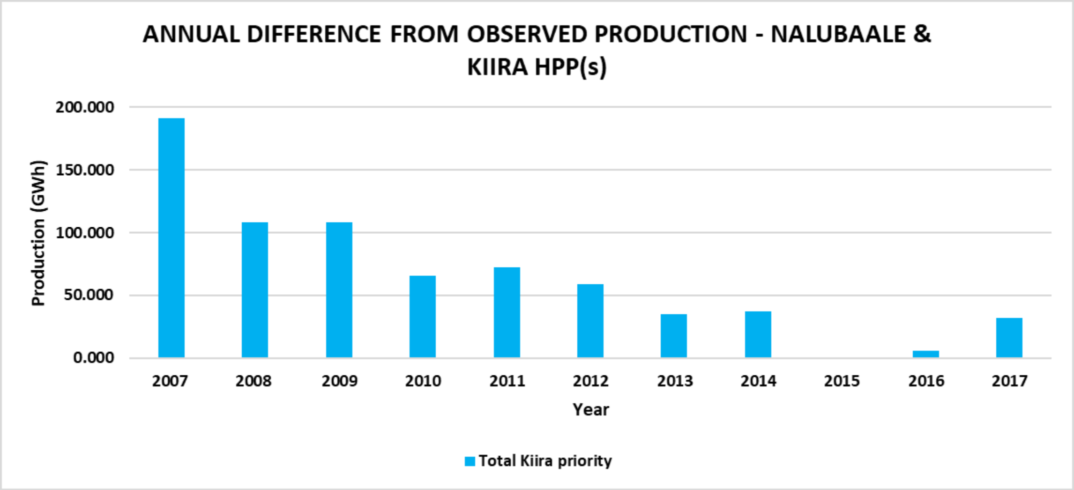


Figure 4.15 MODEL-1 Annual difference from observed production

The annual difference was very low in 2016 due to the under estimation of production by MODEL-1 as explained before. The kiira Priority flow scenario was considered the best scenarios and was studied further.

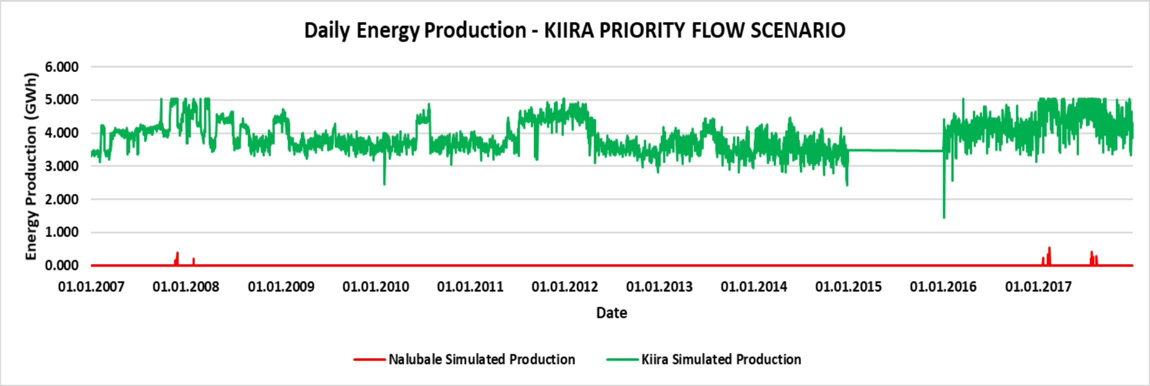


Figure 4.16 Daily energy production-kiira priority

Despite resulting into the highest energy production, power generation following the Kiira Priority flow scenario resulted into minimal utilization or complete shutdown of Nalubaale HPP for most of the time when inflow was less than maximum capacity of Kiira HPP as shown in Figure 4.16. Such a strategy that leaves Nalubaale HPP out of operation most of the time was considered not feasible, hence a need to make some adjustments so that both power plants always remained operational.

4.3.3 Operational strategy of Nalubaale and Kiira HPP

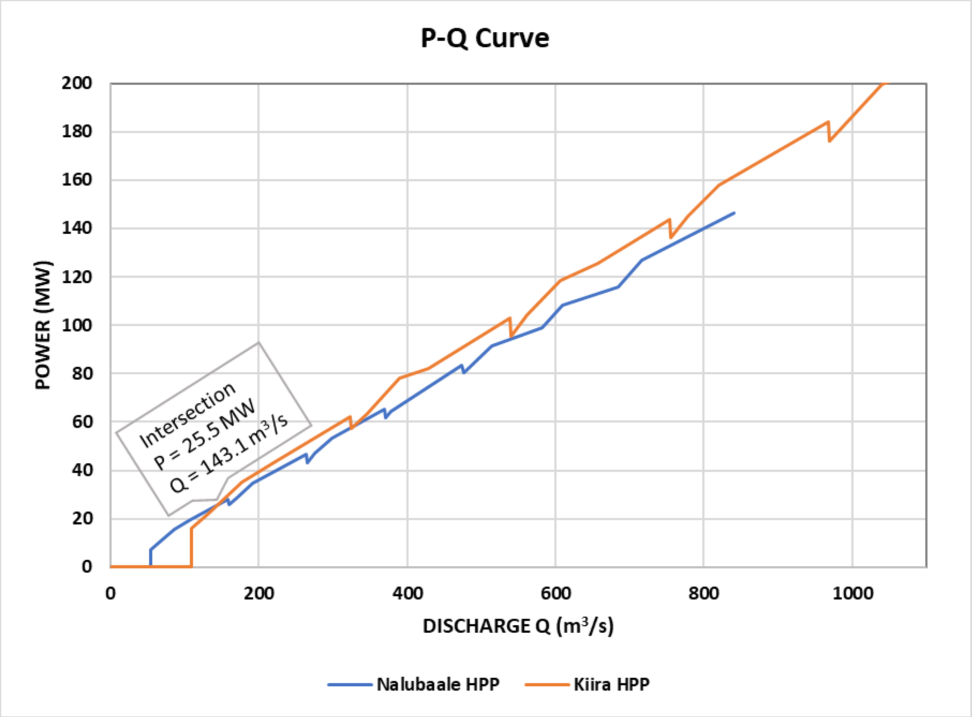


Figure 4.17 MODEL-1 Simulated P-Q curves

From Figure 4.17, Nalubaale HPP generated more power than Kiira HPP from discharge values lower than 143 m^3/s. This value was higher than the modelled discharge of 105 m^3/s for one unit of Nalubaale HPP and less than 210 m^3/s corresponding to two units. Simulations were carried out to investigate the effect of operating Nalubaale HPP at a constant discharge of 105 m^3/s, 143 m^3/s and 210 m^3/s corresponding to 18 MW, 25.5 MW and 36 MW respectively while the rest of the discharge was directed to Kiira HPP and the results in Figure 4.18 were obtained.

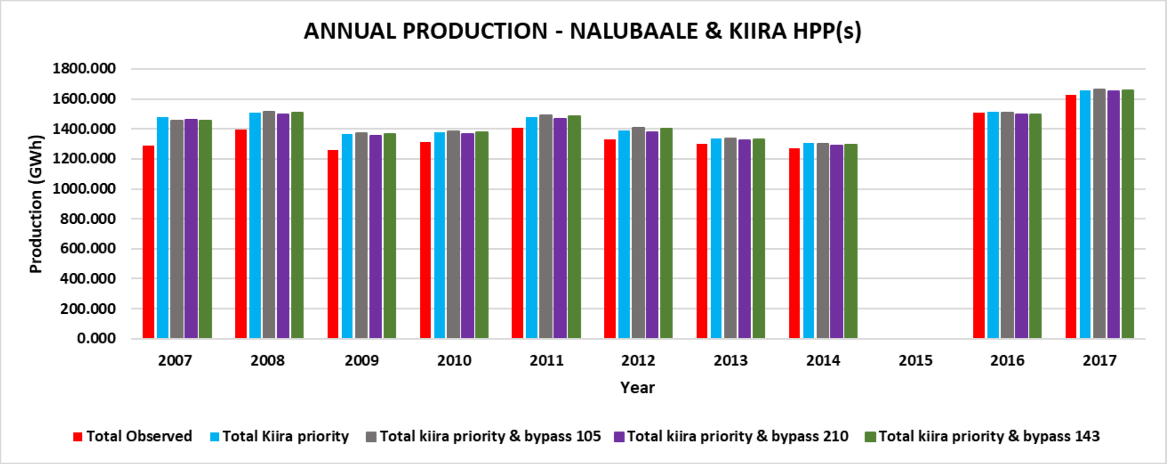


Figure 4.18 MODEL-1 Annual Production

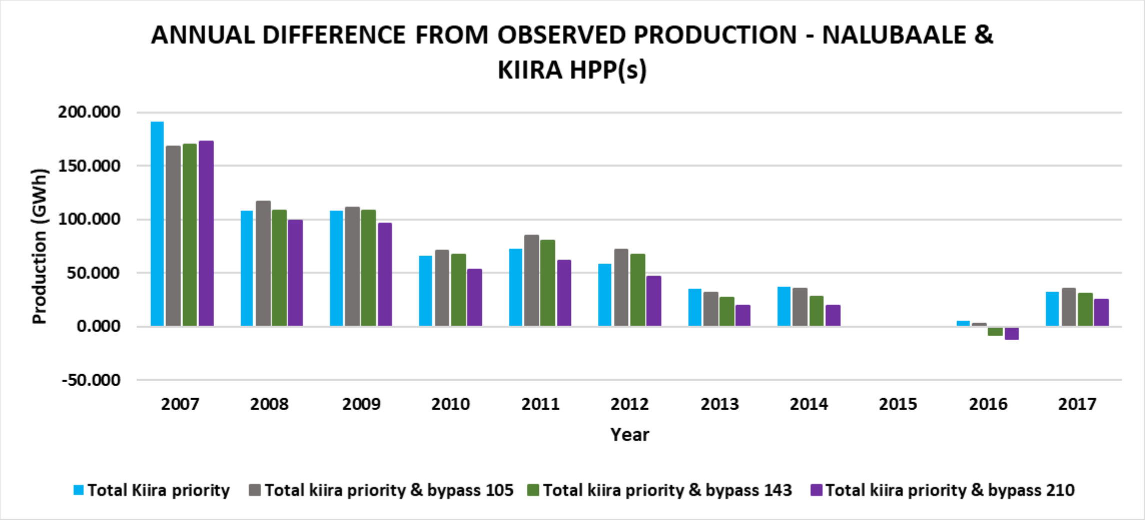


Figure 4.19 MODEL-1 Annual difference from Observed

From Figure 4.19, operating Kiira as the main plant and Nalubaale at a constant discharge of 105, 143 or 210 m^3/s resulted into more production than observed except in 2016. A similar production pattern exists in all years except 2007. In these years, production that followed the Kiira Priority & bypass 105 and Kiira Priority & bypass 143 strategies gave more production than the other two because they took advantage of the P-Q curve relationship from Figure 4.17 by combining the production from Nalubaale HPP best production point (up to 143m3/s) and the rest of the production by Kiira HPP. However, Kiira Priority strategy gave the most production from 2013 to 2016, an occurrence that could not be explained.

In 2016, operating Nalubaale at 143 m^3/s and 210 m^3/s resulted into less production than observed, however, this was a result of MODEL-1 not being able to capture the increase in headrace water level in that year. Results from MODEL-2 were used to give more detail to this part.

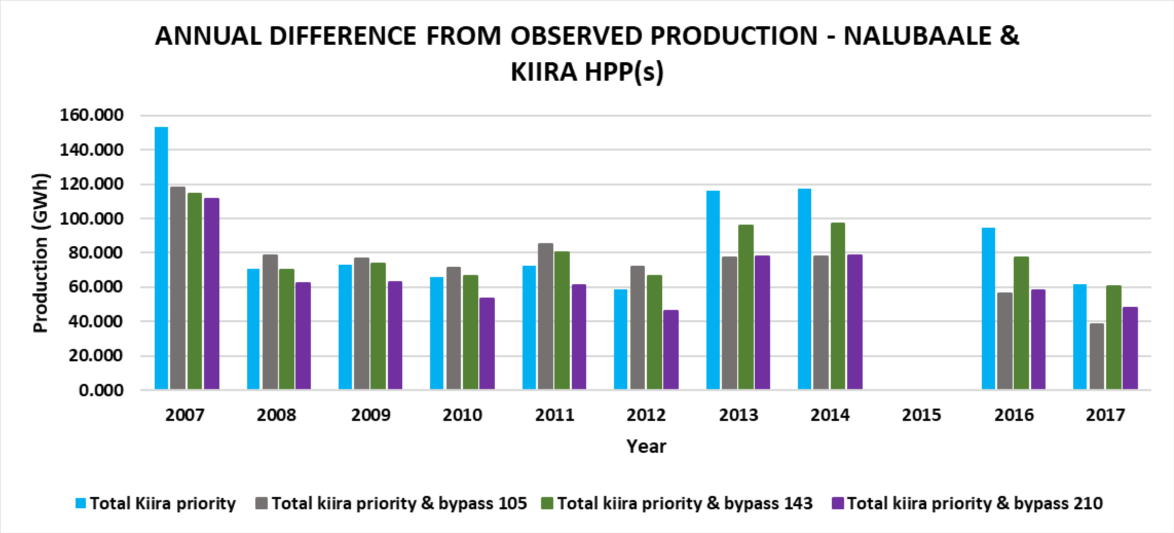


Figure 4.20 MODEL-2 Annual Difference from observed

From Figure 4.20, all flow combinations result into more power production including 2016. This was because MODEL-2 was calibrated on a shorter time series hence giving better simulation results than MODEL-1. From 2013 to 2016, production by Kiira priority increased greatly above other strategies because of the significant increase in head of Kiira HPP resulting from the combination of both increases headrace water level and lowering of tailwater level as shown in Figure 3.3.

4.3.4 Optimal operational strategy for Nalubaale and Kiira HPP(s)

From Figure 4.19 the kiira priority & bypass 105 operation strategy gave the highest production in most of the years and was closely followed by kiira priority & bypass 143 strategy. From Figure 4.20 the same pattern was observed until 2012. After 2012, kiira priority & bypass 143 gives more production than kiira priority & bypass 105. Results from MODEL-2 were more precise, having been calibrated with more detail than MODEL-1 and hence kiira priority & bypass 143 was considered the most optimal operational strategy that ensured that both power plants are always operational. The increase in production that could have been realized had this strategy been used for operation of the power plants in the past period is represented in Figure 4.21

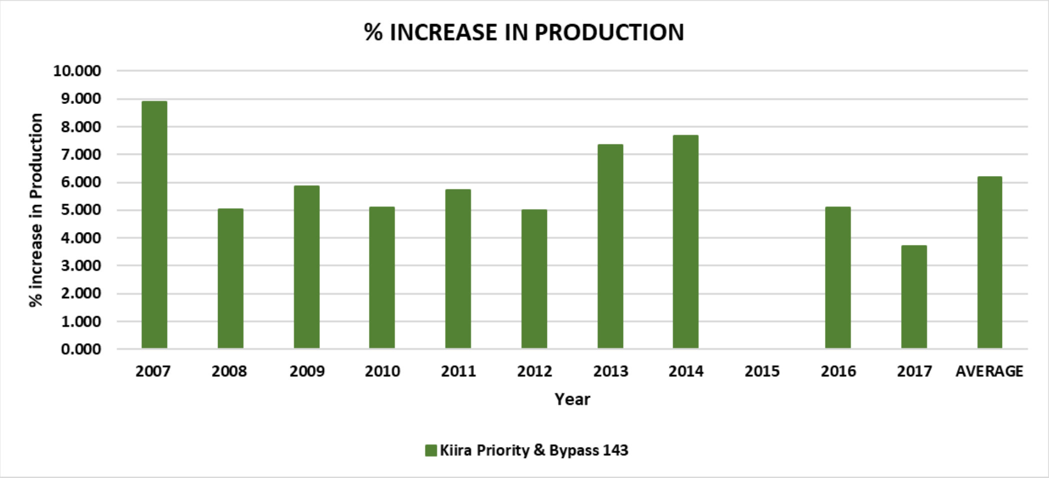


Figure 4.21 Percentage increase in production from proposed strategy

4.3.5 Comparison between Past Period and Proposed operation strategy

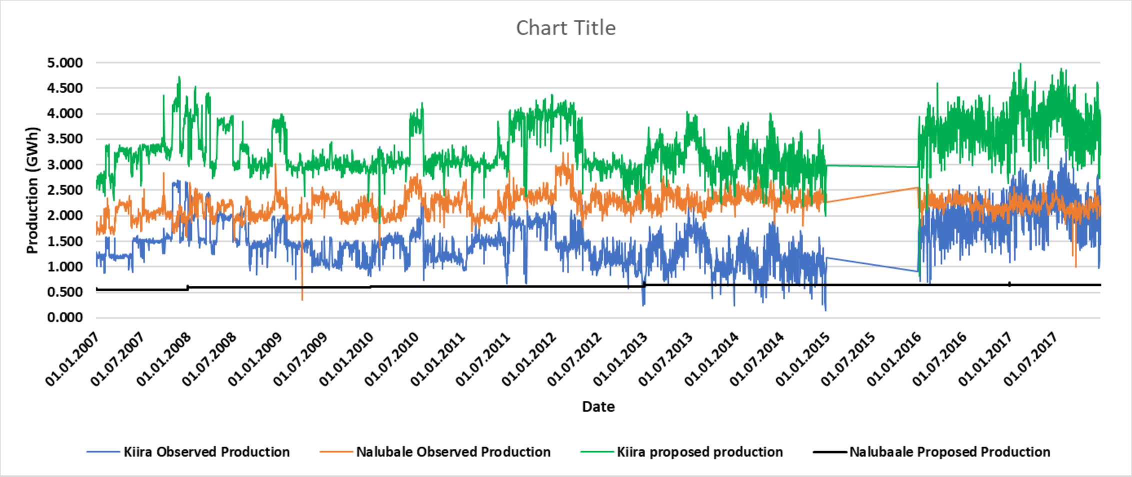


Figure 4.22 Comparison between past period strategy and proposed strategy

As shown in Figure 4.22 and Figure 2.5, the past period operation strategy uses Nalubaale HPP as a base load power plant with varying daily energy production and Kiira HPP as a peaking plant. The proposed strategy also followed the same operation with Nalubaale as a base load power plant, but with a lower and fixed base load energy production. Kiira was used as the priority power plant and was operated as both a base load and peaking plant.

4.3.6 Effect of flow scenarios on Bujagali HPP

Bujagali HPP utilizes the out flow from Nalubaale and Kiira HPP as inflow into its reservoir, hence a change in operation of the two HPPs directly affects the inflow and operation of Bujagali HPP. All the flow scenarios discussed before for Nalubaale and Kiira HPP(s) utilized the same total flow as observed, therefore no change was made to the total inflow into Bujagali's reservoir. Without a change to the total inflow and the limitation of nMAG not being able to simulate at hourly timestep, no study could be carried out regarding optimization of Bujagali HPP.

Nalubaale and Kiira HPP(s) operate in parallel and share the same reservoir, a factor that has played a great role in enabling them to operate without spilling even during outages periods. Bujagali HPP on the other hand is only limited to its reservoir capacity, beyond which excess inflow must be spilled. From the observed data of Bujagali HPP for 2015, 2016 and 2017, spill accounted for 2.1, 3.7 and 4.9 % respectively of the total outflow and mainly occured during outage periods. Had it been possible to store or utilize the spill for production, it could have led to a 3.4, 3.6 and 5.8 % annual increase in production respectively as shown in Figure 4.23.

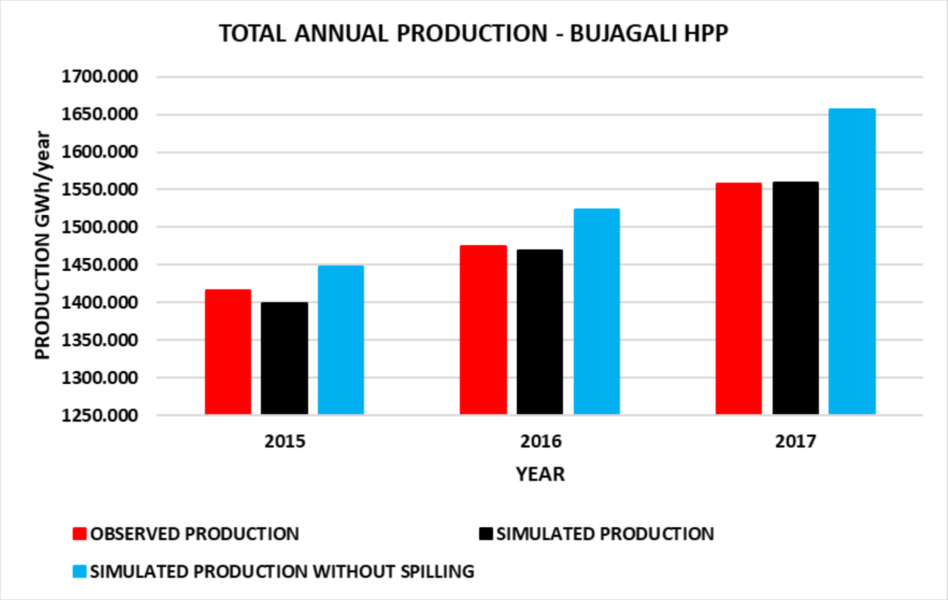


Figure 4.23 Bujagali HPP annual production

4.4 Future Period

In this section, the impact of climate change on hydropower production from the upper Victoria Nile will be studied. New power plants will be added to the cascade and the total production under future flow conditions will be simulated and results discussed.

4.4.1 New power plants

(EPDC, 2010) identified Isimba HPP and Kalagala HPP as potential power plants along the upper Victoria nile as shown in Figure 2.4, but according to future energy demand and supply balance prognosis for 2040 by UETCL (2018), only Isimba HPP was considered for future development hence Kalagala HPP was not considered in this study. Isimba HPP was designed for a 40-year lifespan and this period was taken as the future planning period. The future period used was 2020 to 2059 and all other power plants in the cascade were assumed to be operational through that period as well.

4.4.2 Future hydrological data

Projected future runoff series by Emmanuel (2016) shown in Figure 2.10 were obtained and used in this study. These runoff series were generated on a monthly timestep and hence nMAG was run on a monthly time step for the future period. Unlike the past period where actual releases from Nalubaale and Kiira HPP(s) were known, the release in the future were not known and hence assumed to strictly follow the projected agreed curve flows.

4.4.3 Future model setup

The calibrated MODEL-1 setup used in the past period was used in the future period as well with the addition of Isimba HPP. Without any observed data to be used for calibration of Isimba HPP in the model, design values shown in Table 3 were used. MODEL-1 was chosen over MODEL-2 for future period simulations because it represents the entire observed period with the same parameters, which were assumed to apply in the future period as well. Kiira priority & bypass 143 operation strategy proposed under the past period was applied. The model for the future period was set up in nMAG as illustrated in Figure 4.24.

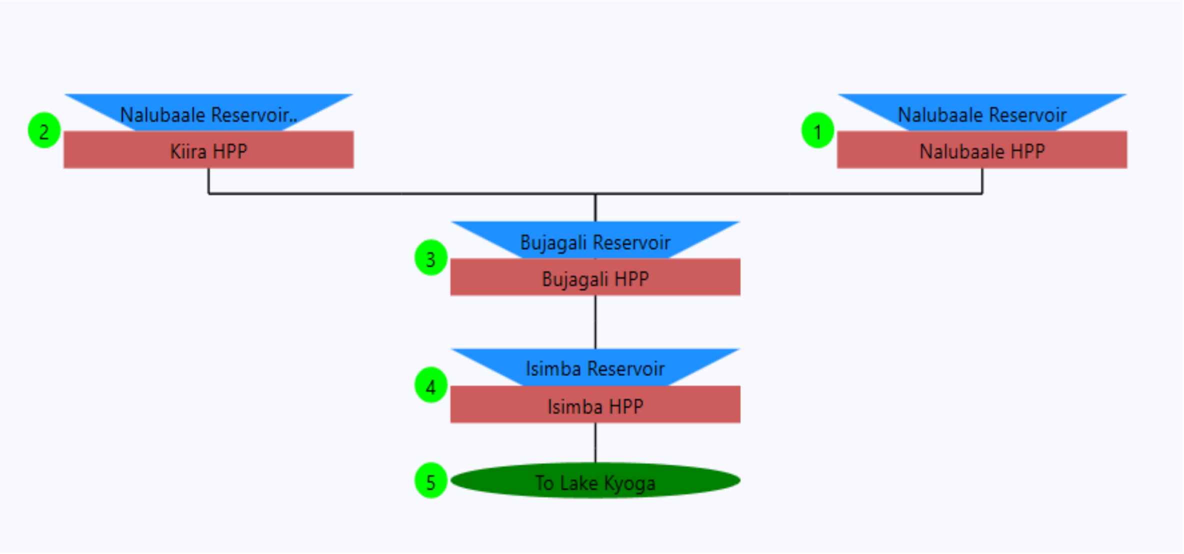


Figure 4.24 Future Period nMAG model setup

4.4.4 Simulation results

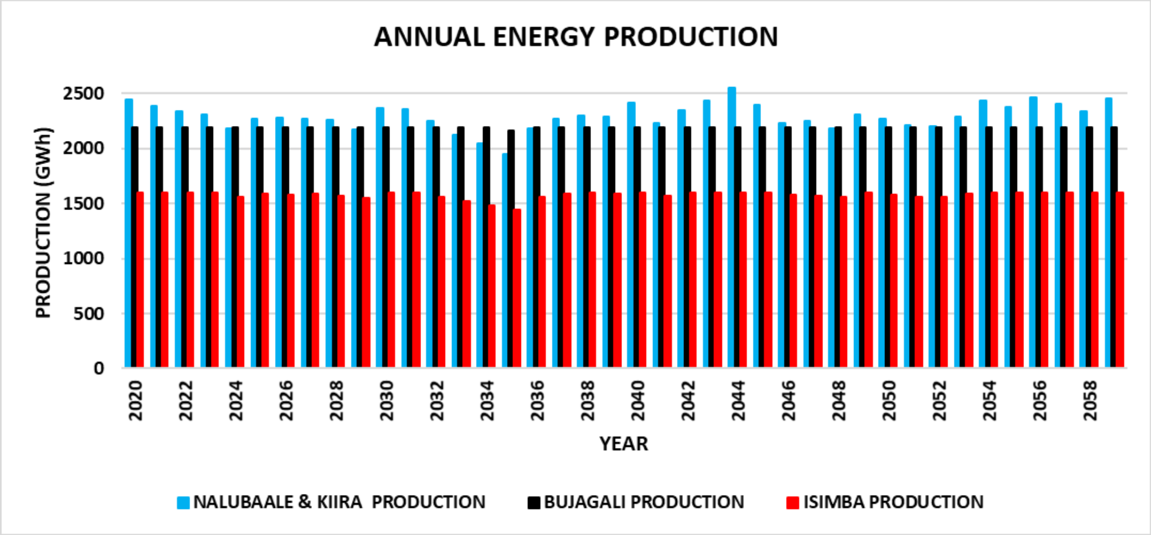


Figure 4.25 Projected Future annual production

From Figure 4.25, there was little variation in production from Bujagali and Isimba HPP over the entire period with the plants operating mostly at maximum capacity. Between 2031 and 2037, there was a drop in Isimba HPP's production, which was a result of drop in the projected river Nile flow below its Qmax as shown in Figure 4.26. Total Production from Nalubaale and Kiira HPP(s) varied significantly from year to year following the same pattern as the projected river Nile flow in Figure 4.26 because the combined total maximum discharge for these two power plants was much higher than the river flow.

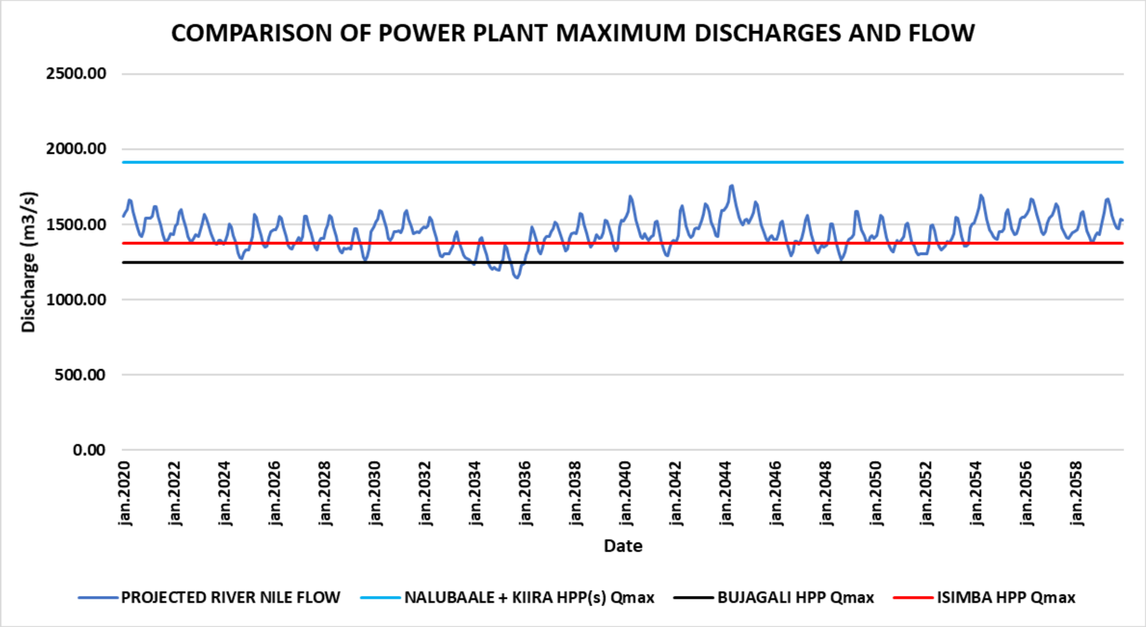


Figure 4.26 comparison of power plant maximum discharges

From Figure 4.26, Qmax of Isimba and Bujagali HPP was less than the river flow for most of the years implying that there would be a lot of spill in the future as shown in Figure

4.27 Nalubaale and Kiira HPP had a high combined capacity hence utilizing all the inflow without spilling.

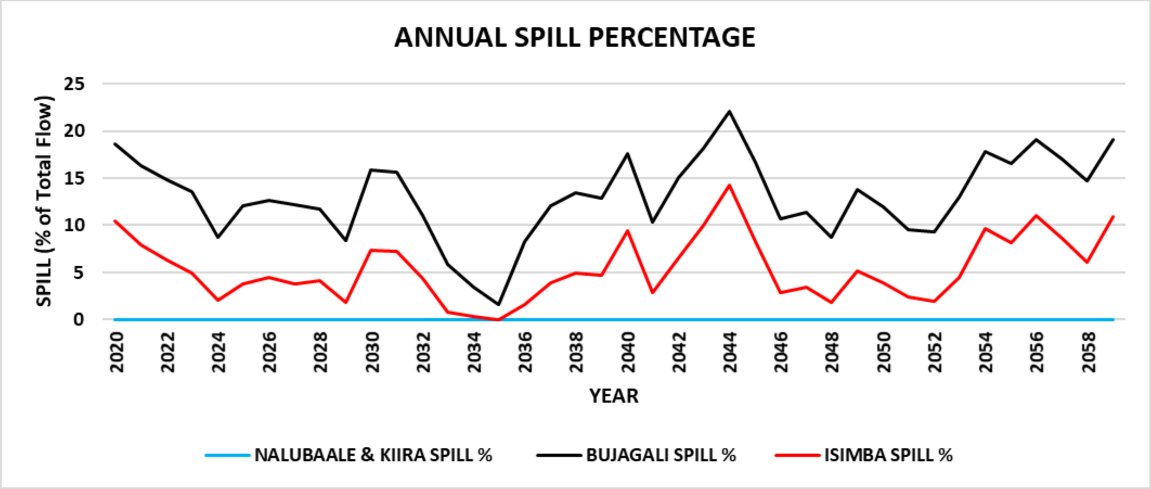


Figure 4.27 Projected future spill

5 Conclusion and Proposals for future work

This study was carried out with an objective of optimizing the hydropower resources along the Upper Victoria Nile River. Focus was placed on Nalubaale and Kiira HPP(s) and their optimization was carried out using nMAG simulation model and application of human judgement. Optimization was carried out with an objective of production maximization. An operation strategy was established that produced 6.2 % more production on average than observed in the past period while utilizing the same amount of discharge as observed. The strategy involved operating Nalubaale HPP at a fixed flow of 143 m^3/s that generated a base load of 25.5 MW and Kiira HPP for generation of the rest of the load dispatched to the two power plants until its maximum capacity. Analysis of future climate change impact on the cascade indicated an increase in production resulting from the projected increase in River Nile runoff. This increase in runoff also lead to an increase in future spilled volume.

Simulations in nMAG were carried out with daily timestep and hence hourly peaking would not be implemented in the model. All power plants along the upper Victoria Nile cascade have small reservoirs that are used for peaking and hence peaking would have been a key factor in the optimization process. Carrying out optimization of the cascade using a model that can simulate at hourly time steps is another approach that can be investigated in future studies.

Optimization in this study was focused on energy production maximization with the assumption that there was enough demand to utilize all the generated energy. This assumption does not apply in a real power market, something that can be investigated in future studies where optimization can be carried out basing on both energy demand and supply.

Nalubaale and Kiira HPP(s) share the same reservoir which is a combination both Lake Victoria and the section of River Nile between Lake Victoria and Nalubaale Dam. Setting up a hydrological model for this reservoir and investigating its influence on headrace water level and operation of both power plants can be a good future study. Such a model can also be used to investigate the influence of back water effects from the reservoir on the agreed curve measurements which depend on Lake Victoria water surface level.

6 references

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Appendices

Appendix 1: Task Description

Appendix 2: nMAG Data Sets

Appendix 3: Referenced Kiira HPP Efficiency Curve

Appendix 4: Referenced Bujagali HPP Efficiency Curve

Appendix 5: Isimba HPP Total Efficiency Curve

Appendix 1: TASK DESCRIPTION

M.Sc. THESIS IN HYDRAULIC ENGINEERING

Candidate: Mr Charles Mwase

Title: Optimal use of hydro resources in the Victoria-Nile Basin

1. Background

SN Power is a partner in the Hydropower Development scholarship program. SN Power is part owner of the Bujagali Hydropower Plant in the Victoria Nile in Uganda. At present there are three hydropower plants in operation in the Victoria Nile river system: Nalubaale, Kiira and Bujagali. And two more are expecting to come online in 2019-2020: Isimba and Karuma. Nalubaale, Kiira, Isimba and Karuma is owned and operated by UEGCL.

The main objective of this Master thesis is to analyse the optimal use of hydro resources in the Victoria Nile basin in Uganda.

2. Work description

The thesis shall cover, though not necessarily be limited to the main tasks listed below.

The candidate must collect available documents such as reports, relevant studies and maps. Based on the available documentation the following shall be carried out:

1 Literature review covering
    a. Energy production and consumption in Uganda and the role of the hydropower production in the Upper Blue Nile cascade
    b. Optimization of hydropower production in an energy supply system and to an energy market
    c. Overview on Optimization tools, their use, need of data, their advantages and limitation
2 Data collection necessary for simulations
3 If possible a field trip to the site to get an impression of the region and relevant investigation areas and to get missing data for the simulations
4 Define criteria's for the optimization and select suitable tool for optimization in this cascade and the defined purpose. Vansimtap, ProdRisk and NMag shall be considered.
5 Set up the model in the selected tool for the cascade. The model shall include all relevant constraints of the present market conditions to get a reliable result. This includes the hydro power system, additional production, demand and supply and import and export.
6 Run simulations with the long-term model and compare the results with historical data from the existing power plants. Analyze and explain the deviations.
7 Run the simulations in the short-term model to meet the demand on an hourly basis.
8 Compare results from the models and propose a tool and strategy for the optimal use of the Victoria-Nile hydropower system.
9 Check the robustness of the system against future climate change
10 Proposals for future work
11 Presentation

3. Supervision

Professor Oddbjørn Bruland will be the main supervisor at NTNU. Professor Knut Alfredsen will be co-supervisor from NTNU together with resources from SINTEF Energy, Sweco and SN Power.

Discussion with and input from other research or engineering staff at NTNU or other institutions are recommended. Significant inputs from others shall be referenced in a convenient manner.

The research and engineering work carried out by the candidate in connection with this thesis shall remain within an educational context. The candidate and the supervisors are free to introduce assumptions and limitations which may be considered unrealistic or inappropriate in a contract research or a professional/commercial context.

4 Report format and submission

The report should be written with a text editing software. Figures, tables and photos shall be of high quality. The report format shall be in the style of scientific reports and must contain a summary, a table of content, and a list of references.

The report shall be submitted electronically in B5-format .pdf-file in Blackboard, and three paper copies should be handed in to the institute. Supplementary working files such as spreadsheets, numerical models/model setups, program scripts, figures and pictures shall be uploaded to Blackboard. The summary shall not exceed 450 words. The Master's thesis should be submitted within 15th of June 2019.

The candidate shall present the work towards the end of the master period. The presentation shall be given with the use of MS PowerPoint or similar presentation tools. The data and format for the MSc. seminar will be announced during the semester.

Trondheim, 13. january 2019

____

Oddbjørn Bruland
Professor
Department of Civil and Environmental Engineering

NTNU

Appendix 2: nMAG DATA SET FILES USED

MODEL-1 DATA SET (PAST PERIOD)

```
365,                     * Number of timesteps in one year
6,                      * Total no of Modules (*MA, *KR, *OF og *KO)
3,                      * No of reservoirs
3,                      * No of power plants
0,                      * No of transfer modules
1,                      * No of control points
25,                      * Max. permitted no of entries in a Table
*MO                       * Mode
0,                      * 1=ENMAG mode, 0=nMAG mode
***
*CO
NTNU, SN Power, UEGCL
MWASE CHARLES
***
*MA                       ************ RESERVOIRS ************
1,                      * Modul nr. 1  -  Nalubaale
Nalubaale
1132.0,
1134.0,
2.93,
3,3,3,
2,                      * Modul nr. 2  -  kiira
kiira
1132.0,
1134.0,
2.93,
3,3,3,
3,                      * Modul nr. 3  -  Bujagali
Bujagali
1109.5,
1111.5,
9.1,
4,4,4,
***
*KR                       ************ POWER PLANTS ************
1,                      * Modul nr. 1  -  Nalubaale HPP
Nalubaale HPP
3,3,3,
840.0,
0.04905,
200,
19.833,
1129.0,
1113.5,
4.3e-007,
25,
0.000,0.000,
6.400,0.000,
6.500,0.700,
7.800,0.800,
10.200,0.950,
12.800,0.930,
18.900,0.910,
19.000,0.840,
```

```
20.300,0.870,
22.800,0.930,
31.400,0.910,
31.600,0.840,
32.700,0.880,
35.600,0.920,
43.900,0.910,
44.100,0.860,
45.000,0.880,
56.400,0.910,
56.700,0.870,
61.100,0.920,
69.300,0.880,
72.500,0.920,
81.500,0.880,
85.300,0.920,
100.000,0.910,
2,                  * Modul nr. 2  -  Kiira HPP
Kiira HPP
3,3,3,
1075.0,
0.052974,
200,
21.533,
1129.0,
1111.8,
2.6e-007,
24,
0.000,0.000,
10.100,0.000,
10.200,0.700,
12.200,0.790,
16.400,0.950,
20.600,0.930,
30.100,0.910,
30.200,0.840,
32.200,0.870,
36.300,0.950,
39.900,0.910,
50.100,0.910,
50.200,0.840,
52.300,0.880,
56.400,0.930,
61.100,0.910,
70.100,0.910,
70.200,0.860,
72.400,0.890,
76.300,0.920,
90.100,0.910,
90.200,0.870,
96.700,0.920,
100.000,0.910,
3,                  * Modul nr. 3  -  Bujagali HPP
Bujagali HPP
4,4,4,
1250.0,
0.053,
```

```
200,
22.683,
1106.5,
1088.15,
1.9e-007,
23,
0.000,0.000,
8.300,0.000,
8.400,0.930,
8.800,0.930,
16.400,0.950,
20.400,0.930,
27.300,0.930,
27.400,0.930,
28.700,0.930,
36.500,0.940,
40.300,0.930,
47.300,0.930,
47.400,0.930,
48.700,0.930,
56.600,0.940,
60.700,0.930,
68.900,0.930,
76.800,0.940,
80.400,0.930,
87.400,0.930,
88.700,0.930,
96.700,0.940,
100.000,0.930,
***
*OF                  ************ TRANSFER MODULES ************
***
*KO                  ************ CONTROL POINTS ************
4,                  * Modul nr. 4  -  To Isimba
To Isimba
0,0,0,
***
*KM                  ************ POWER MARKET ************
1722.0,
10.0,
1,365,
4,
0,                  * Antall preferansefunksjoner
***
*RS                  ************ RESTRICTIONS ************
***
*ST                  ************ OPERATIONAL STRATEGY ************
300,
2,                  * Modul nr. 2  -  kiira/Kiira HPP
300,
1,                  * Modul nr. 1  -  Nalubaale/Nalubaale HPP
300,
3,                  * Modul nr. 3  -  Bujagali/Bujagali HPP
***
*HY                  ************ HYDROLOGICAL INPUT DATA ************
2007,2017,
6,
```

```
2,
1,                    * Modul nr. 1  -  Nalubaale/Nalubaale HPP
  16811.0,1.0,0.0,
1,                    * Modul nr. 1  -  Nalubaale/Nalubaale HPP
  16811.0,1.0,0.0,
2,                    * Modul nr. 2  -  kiira/Kiira HPP
  10014.0,0.0,1.0,
4,                    * Modul nr. 4  -  To Isimba
  0.0,1.0,0.0,
3,                    * Modul nr. 3  -  Bujagali/Bujagali HPP
  0.0,1.0,0.0,
3,                    * Modul nr. 3  -  Bujagali/Bujagali HPP
  0.0,1.0,0.0,
1,
nalubale
4,,
1.0,
nalubale.prn
1,
kiira
1,,
1.0,
kiira.prn
***
*JK                    ************ JOB CONTROL ************
Victoria Nile Cascade HPPs
2007,
2017,
1722,
100.0,
0,
1,
365,
1,1,1,1,
3,
1,
2,
3,
0,
None
0,1,5,1Nalthr.txt,
0,2,5,1KIIthr.txt,
0,3,5,1Bujathr.txt,
***
*EX
```

MODEL-1 DATA SET (FUTURE PERIOD)

```
12,                   * Number of timesteps in one year
8,                   * Total no of Modules (*MA, *KR, *OF og *KO)
4,                   * No of reservoirs
4,                   * No of power plants
0,                   * No of transfer modules
1,                   * No of control points
25,                   * Max. permitted no of entries in a Table
*MO                    * Mode
0,                   * 1=ENMAG mode, 0=nMAG mode
***
*CO
NTNU, SN Power, UEGCL
MWASE CHARLES
***
*MA                    ************ RESERVOIRS ************
1,                   * Modul nr. 1  -  Nalubaale
Nalubaale
1132.0,
1134.0,
2.93,
3,3,3,
2,                   * Modul nr. 2  -  kiira
kiira
1132.0,
1134.0,
2.93,
3,1,1,
3,                   * Modul nr. 3  -  Bujagali
Bujagali
1109.5,
1111.5,
9.1,
4,4,4,
4,                   * Modul nr. 4  -  Isimba
Isimba
1052.5,
1054.5,
35.63,
5,5,5,
200,
4,
1052.500,0.000,
1053.000,8.250,
1054.000,26.100,
1054.500,35.630,
***
*KR                    ************ POWER PLANTS ************
1,                   * Modul nr. 1  -  Nalubaale HPP
Nalubaale HPP
3,3,3,
840.0,
0.04905,
200,
19.833,
1129.0,
1113.5,
```

```
4.3e-007,
25,
0.000,0.000,
6.400,0.000,
6.500,0.700,
7.800,0.800,
10.200,0.950,
12.800,0.930,
18.900,0.910,
19.000,0.840,
20.300,0.870,
22.800,0.930,
31.400,0.910,
31.600,0.840,
32.700,0.880,
35.600,0.920,
43.900,0.910,
44.100,0.860,
45.000,0.880,
56.400,0.910,
56.700,0.870,
61.100,0.920,
69.300,0.880,
72.500,0.920,
81.500,0.880,
85.300,0.920,
100.000,0.910,
2,                        * Modul nr. 2  -  Kiira HPP
Kiira HPP
3,1,1,
1100.0,
0.052974,
200,
20.933,
1129.0,
1112.4,
2.5e-007,
24,
0.000,0.000,
10.100,0.000,
10.200,0.700,
12.200,0.790,
16.400,0.950,
20.600,0.930,
30.100,0.910,
30.200,0.840,
32.200,0.870,
36.300,0.950,
39.900,0.910,
50.100,0.910,
50.200,0.840,
52.300,0.880,
56.400,0.930,
61.100,0.910,
70.100,0.910,
70.200,0.860,
72.400,0.890,
```

```
76.300,0.920,
90.100,0.910,
90.200,0.870,
96.700,0.920,
100.000,0.910,
3,                  * Modul nr. 3  -  Bujagali HPP
Bujagali HPP
4,4,4,
1250.0,
0.053,
200,
22.683,
1106.5,
1088.15,
1.9e-007,
23,
0.000,0.000,
8.300,0.000,
8.400,0.930,
8.800,0.930,
16.400,0.950,
20.400,0.930,
27.300,0.930,
27.400,0.930,
28.700,0.930,
36.500,0.940,
40.300,0.930,
47.300,0.930,
47.400,0.930,
48.700,0.930,
56.600,0.940,
60.700,0.930,
68.900,0.930,
76.800,0.940,
80.400,0.930,
87.400,0.930,
88.700,0.930,
96.700,0.940,
100.000,0.930,
4,                  * Modul nr. 4  -  ISIMBA HPP
ISIMBA HPP
5,5,5,
1375.0,
0.0371,
200,
14.753,
1049.0,
1039.08,
1.6e-007,
18,
0.000,0.000,
11.390,0.000,
11.400,0.930,
15.260,0.930,
17.420,0.940,
21.780,0.940,
23.440,0.930,
```

```
25.680,0.930,
33.220,0.930,
40.820,0.940,
45.760,0.930,
54.440,0.940,
64.240,0.940,
68.070,0.930,
75.120,0.940,
84.380,0.940,
91.530,0.930,
100.000,0.930,
***
*OF                  ************ TRANSFER MODULES ************
***
*KO                  ************ CONTROL POINTS ************
5,                  * Modul nr. 5  -  To Lake Kyoga
To Lake Kyoga
0,0,0,
***
*KM                  ************ POWER MARKET ************
2316.0,
10.0,
1,12,
3,
12,
1,8.333,
2,8.333,
3,8.333,
4,8.337,
5,8.333,
6,8.333,
7,8.333,
8,8.333,
9,8.333,
10,8.333,
11,8.333,
12,8.333,
1,                  * Antall preferansefunksjoner
1,
1,12,
9,
-100.000,-10.000,
-100.000,-10.000,
-15.000,-10.000,
0.000,-10.000,
0.000,10.000,
15.000,0.000,
8.500,0.000,
4.500,0.000,
72.000,0.000,
7,2,
***
*RS                  ************ RESTRICTIONS ************
***
*ST                  ************ OPERATIONAL STRATEGY ************
300,
2,                  * Modul nr. 2  -  kiira/Kiira HPP
```

```
300,
1,                      * Modul nr. 1  -  Nalubaale/Nalubaale HPP
300,
3,                      * Modul nr. 3  -  Bujagali/Bujagali HPP
300,
4,                      * Modul nr. 4  -  Isimba/ISIMBA HPP
***
*HY                       ************ HYDROLOGICAL INPUT DATA ************
2020,2059,
8,
1,
1,                      * Modul nr. 1  -  Nalubaale/Nalubaale HPP
  0.0,1.0,
1,                      * Modul nr. 1  -  Nalubaale/Nalubaale HPP
  0.0,1.0,
2,                      * Modul nr. 2  -  kiira/Kiira HPP
  45507.0,1.0,
3,                      * Modul nr. 3  -  Bujagali/Bujagali HPP
  0.0,1.0,
3,                      * Modul nr. 3  -  Bujagali/Bujagali HPP
  0.0,1.0,
5,                      * Modul nr. 5  -  To Lake Kyoga
  0.0,1.0,
4,                      * Modul nr. 4  -  Isimba/ISIMBA HPP
  0.0,1.0,
4,                      * Modul nr. 4  -  Isimba/ISIMBA HPP
  0.0,1.0,
1,
kiira
7,,
1.0,
future.prn
***
*JK                       ************ JOB CONTROL ************
Victoria Nile Cascade HPPs
2020,
2059,
2316,
100.0,
0,
1,
12,
1,1,1,1,
3,
4,
2,
3,
0,
None
0,4,8,isimbaPW.txt,
0,4,4,isimbaLev.txt,
0,4,7,isimbaSPL.txt,
***
*EX
```

MODEL-2 DATA SET 2007

```
365,                   * Number of timesteps in one year
4,                    * Total no of Modules (*MA, *KR, *OF og *KO)
2,                    * No of reservoirs
2,                    * No of power plants
0,                    * No of transfer modules
1,                    * No of control points
25,                    * Max. permitted no of entries in a Table
*MO                     * Mode
0,                    * 1=ENMAG mode, 0=nMAG mode
***
*CO
NTNU, SN Power, UEGCL
MWASE CHARLES
Optimization Of Hydropower Resources In The Victoria Nile Basin
***
*MA                    ************ RESERVOIRS ************
1,                    * Modul nr. 1  -  Nalubaale
Nalubaale
1132.0,
1133.0,
1.47,
4,4,4,
2,                    * Modul nr. 2  -  kiira
kiira
1132.0,
1133.0,
1.47,
4,4,4,
***
*KR                    ************ POWER PLANTS ************
1,                    * Modul nr. 1  -  Nalubaale HPP
Nalubaale HPP
4,4,4,
920.0,
0.04905,
200,
18.667,
1129.0,
1114.0,
3.5e-007,
25,
0.000,0.000,
6.400,0.000,
6.500,0.600,
7.800,0.790,
10.200,0.920,
12.800,0.870,
18.900,0.870,
19.000,0.750,
20.300,0.830,
22.800,0.890,
31.400,0.870,
31.600,0.800,
32.700,0.840,
35.600,0.880,
```

```
43.900,0.870,
44.100,0.820,
45.000,0.840,
56.400,0.870,
56.700,0.830,
61.100,0.880,
69.300,0.840,
72.500,0.880,
81.500,0.840,
85.300,0.880,
100.000,0.870,
2,                  * Modul nr. 2  -  Kiira HPP
Kiira HPP
4,4,4,
1075.0,
0.052974,
200,
21.117,
1129.0,
1111.55,
2.6e-007,
24,
0.000,0.000,
10.100,0.000,
10.200,0.700,
12.200,0.790,
16.400,0.950,
20.600,0.930,
30.100,0.910,
30.200,0.840,
32.200,0.870,
36.300,0.950,
39.900,0.910,
50.100,0.910,
50.200,0.840,
52.300,0.880,
56.400,0.930,
61.100,0.910,
70.100,0.910,
70.200,0.860,
72.400,0.890,
76.300,0.920,
90.100,0.910,
90.200,0.870,
96.700,0.920,
100.000,0.910,
***
*OF                  ************ TRANSFER MODULES ************
***
*KO                  ************ CONTROL POINTS ************
4,                  * Modul nr. 4  -  To Isimba
To Isimba
0,0,0,
***
*KM                  ************ POWER MARKET ************
843.0,
10.0,
```

```
1,365,
4,
0,                    * Antall preferansefunksjoner
***
*RS                    ************ RESTRICTIONS ************
***
*ST                    ************ OPERATIONAL STRATEGY ************
300,
2,                    * Modul nr. 2  -  kiira/Kiira HPP
300,
1,                    * Modul nr. 1  -  Nalubaale/Nalubaale HPP
***
*HY                    ************ HYDROLOGICAL INPUT DATA ************
2007,2017,
4,
2,
1,                    * Modul nr. 1  -  Nalubaale/Nalubaale HPP
  16811.0,1.0,0.0,
1,                    * Modul nr. 1  -  Nalubaale/Nalubaale HPP
  16811.0,1.0,0.0,
2,                    * Modul nr. 2  -  kiira/Kiira HPP
  10014.0,0.0,1.0,
4,                    * Modul nr. 4  -  To Isimba
  0.0,1.0,0.0,
1,
nalubale
4,,
1.0,
nalubale.prn
1,
kiira
1,,
1.0,
kiira.prn
***
*JK                    ************ JOB CONTROL ************
NALUBAALE & KIIRA HPPs
2007,
2007,
843,
100.0,
0,
1,
365,
1,1,1,1,
3,
1,
2,
4,
0,
None
0,1,8,1Nalupw.txt,
0,2,8,1Kiirapw.txt,
0,4,2,1ToBujaTH.txt,
***
*EX
```

MODEL-2 DATA SET 2008-2009

```
365,                     * Number of timesteps in one year
4,                      * Total no of Modules (*MA, *KR, *OF og *KO)
2,                      * No of reservoirs
2,                      * No of power plants
0,                      * No of transfer modules
1,                      * No of control points
25,                      * Max. permitted no of entries in a Table
*MO                       * Mode
0,                      * 1=ENMAG mode, 0=nMAG mode
***
*CO
NTNU, SN Power, UEGCL
MWASE CHARLES
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***
*MA                       ************ RESERVOIRS ************
1,                      * Modul nr. 1  -  Nalubaale
Nalubaale
1132.0,
1133.0,
1.47,
4,4,4,
2,                      * Modul nr. 2  -  kiira
kiira
1132.0,
1133.0,
1.47,
4,4,4,
***
*KR                       ************ POWER PLANTS ************
1,                      * Modul nr. 1  -  Nalubaale HPP
Nalubaale HPP
4,4,4,
840.0,
0.04905,
200,
19.517,
1129.0,
1113.15,
4.3e-007,
25,
0.000,0.000,
6.400,0.000,
6.500,0.700,
7.800,0.800,
10.200,0.950,
12.800,0.930,
18.900,0.910,
19.000,0.840,
20.300,0.870,
22.800,0.930,
31.400,0.910,
31.600,0.840,
32.700,0.880,
35.600,0.920,
```

```
43.900,0.910,
44.100,0.860,
45.000,0.880,
56.400,0.910,
56.700,0.870,
61.100,0.920,
69.300,0.880,
72.500,0.920,
81.500,0.880,
85.300,0.920,
100.000,0.910,
2,                  * Modul nr. 2  -  Kiira HPP
Kiira HPP
4,4,4,
1075.0,
0.052974,
200,
21.117,
1129.0,
1111.55,
2.6e-007,
24,
0.000,0.000,
10.100,0.000,
10.200,0.700,
12.200,0.790,
16.400,0.950,
20.600,0.930,
30.100,0.910,
30.200,0.840,
32.200,0.870,
36.300,0.950,
39.900,0.910,
50.100,0.910,
50.200,0.840,
52.300,0.880,
56.400,0.930,
61.100,0.910,
70.100,0.910,
70.200,0.860,
72.400,0.890,
76.300,0.920,
90.100,0.910,
90.200,0.870,
96.700,0.920,
100.000,0.910,
***
*OF                  ************ TRANSFER MODULES ************
***
*KO                  ************ CONTROL POINTS ************
4,                  * Modul nr. 4  -  To Isimba
To Isimba
0,0,0,
***
*KM                  ************ POWER MARKET ************
843.0,
10.0,
```

```
1,365,
4,
0,                  * Antall preferansefunksjoner
***
*RS                  ************ RESTRICTIONS ************
***
*ST                  ************ OPERATIONAL STRATEGY ************
300,
2,                  * Modul nr. 2  -  kiira/Kiira HPP
300,
1,                  * Modul nr. 1  -  Nalubaale/Nalubaale HPP
***
*HY                  ************ HYDROLOGICAL INPUT DATA ************
2007,2017,
4,
2,
1,                  * Modul nr. 1  -  Nalubaale/Nalubaale HPP
  16811.0,1.0,0.0,
1,                  * Modul nr. 1  -  Nalubaale/Nalubaale HPP
  16811.0,1.0,0.0,
2,                  * Modul nr. 2  -  kiira/Kiira HPP
  10014.0,0.0,1.0,
4,                  * Modul nr. 4  -  To Isimba
  0.0,1.0,0.0,
1,
nalubale
4,,
1.0,
nalubale.prn
1,
kiira
1,,
1.0,
kiira.prn
***
*JK                  ************ JOB CONTROL ************
NALUBAALE & KIIRA HPPs
2008,
2009,
843,
100.0,
0,
1,
365,
1,1,1,1,
3,
1,
2,
4,
0,
None
0,1,8,Nalupw.txt,
0,2,8,Kiirapw.txt,
0,4,2,ToBujaTH.txt,
***
*EX
```

MODEL-2 DATA SET 2010-2012

```
365,                     * Number of timesteps in one year
4,                     * Total no of Modules (*MA, *KR, *OF og *KO)
2,                     * No of reservoirs
2,                     * No of power plants
0,                     * No of transfer modules
1,                     * No of control points
25,                     * Max. permitted no of entries in a Table
*MO                      * Mode
0,                     * 1=ENMAG mode, 0=nMAG mode
***
*CO
NTNU, SN Power, UEGCL
MWASE CHARLES
Optimization Of Hydropower Resources In The Victoria Nile Basin
***
*MA                      ************ RESERVOIRS ************
1,                     * Modul nr. 1  -  Nalubaale
Nalubaale
1132.0,
1134.0,
2.93,
4,4,4,
2,                     * Modul nr. 2  -  kiira
kiira
1132.0,
1134.0,
2.93,
4,4,4,
***
*KR                      ************ POWER PLANTS ************
1,                     * Modul nr. 1  -  Nalubaale HPP
Nalubaale HPP
4,4,4,
840.0,
0.04905,
200,
19.833,
1129.0,
1113.5,
4.3e-007,
25,
0.000,0.000,
6.400,0.000,
6.500,0.700,
7.800,0.800,
10.200,0.950,
12.800,0.930,
18.900,0.910,
19.000,0.840,
20.300,0.870,
22.800,0.930,
31.400,0.910,
31.600,0.840,
32.700,0.880,
35.600,0.920,
43.900,0.910,
```

```
44.100,0.860,
45.000,0.880,
56.400,0.910,
56.700,0.870,
61.100,0.920,
69.300,0.880,
72.500,0.920,
81.500,0.880,
85.300,0.920,
100.000,0.910,
2,                 * Modul nr. 2  -  Kiira HPP
Kiira HPP
4,4,4,
1100.0,
0.052974,
200,
20.933,
1129.0,
1112.4,
2.5e-007,
24,
0.000,0.000,
10.100,0.000,
10.200,0.700,
12.200,0.790,
16.400,0.950,
20.600,0.930,
30.100,0.910,
30.200,0.840,
32.200,0.870,
36.300,0.950,
39.900,0.910,
50.100,0.910,
50.200,0.840,
52.300,0.880,
56.400,0.930,
61.100,0.910,
70.100,0.910,
70.200,0.860,
72.400,0.890,
76.300,0.920,
90.100,0.910,
90.200,0.870,
96.700,0.920,
100.000,0.910,
***
*OF                 ************ TRANSFER MODULES ************
***
*KO                 ************ CONTROL POINTS ************
4,                 * Modul nr. 4  -  To Isimba
To Isimba
0,0,0,
***
*KM                 ************ POWER MARKET ************
843.0,
10.0,
1,365,
```

```
4,
0,                      * Antall preferansefunksjoner
***
*RS                       ************ RESTRICTIONS ************
***
*ST                       ************ OPERATIONAL STRATEGY ************
300,
2,                      * Modul nr. 2  -  kiira/Kiira HPP
300,
1,                      * Modul nr. 1  -  Nalubaale/Nalubaale HPP
***
*HY                       ************ HYDROLOGICAL INPUT DATA ************
2007,2017,
4,
2,
1,                      * Modul nr. 1  -  Nalubaale/Nalubaale HPP
  16811.0,1.0,0.0,
1,                      * Modul nr. 1  -  Nalubaale/Nalubaale HPP
  16811.0,1.0,0.0,
2,                      * Modul nr. 2  -  kiira/Kiira HPP
  10014.0,0.0,1.0,
4,                      * Modul nr. 4  -  To Isimba
  0.0,1.0,0.0,
1,
nalubale
4,,
1.0,
nalubale.prn
1,
kiira
1,,
1.0,
kiira.prn
***
*JK                       ************ JOB CONTROL ************
NALUBAALE & KIIRA HPPs
2010,
2012,
843,
100.0,
0,
1,
365,
1,1,1,1,
3,
1,
2,
4,
0,
None
0,1,4,NaluLEV.txt,
0,2,4,KiiraLEV.txt,
0,4,2,ToBujaTH.txt,
***
*EX
```

MODEL-2 DATA SET 2013-2016

```
365,                 * Number of timesteps in one year
4,                  * Total no of Modules (*MA, *KR, *OF og *KO)
2,                  * No of reservoirs
2,                  * No of power plants
0,                  * No of transfer modules
1,                  * No of control points
25,                  * Max. permitted no of entries in a Table
*MO                   * Mode
0,                  * 1=ENMAG mode, 0=nMAG mode
***
*CO
NTNU, SN Power, UEGCL
MWASE CHARLES
Optimization Of Hydropower Resources In The Victoria Nile Basin
***
*MA                  ************ RESERVOIRS ************
1,                  * Modul nr. 1  -  Nalubaale
Nalubaale
1132.0,
1134.0,
2.93,
4,4,4,
2,                  * Modul nr. 2  -  kiira
kiira
1132.0,
1134.0,
2.93,
4,4,4,
***
*KR                  ************ POWER PLANTS ************
1,                  * Modul nr. 1  -  Nalubaale HPP
Nalubaale HPP
4,4,4,
830.0,
0.04905,
200,
19.833,
1129.0,
1113.5,
4.4e-007,
24,
0.000,0.000,
10.100,0.000,
10.200,0.700,
12.200,0.790,
16.400,0.950,
20.600,0.930,
30.100,0.910,
30.200,0.840,
32.200,0.870,
36.300,0.950,
39.900,0.910,
50.100,0.910,
50.200,0.840,
52.300,0.880,
56.400,0.930,
```

```
61.100,0.910,
70.100,0.910,
70.200,0.860,
72.400,0.890,
76.300,0.920,
90.100,0.910,
90.200,0.870,
96.700,0.920,
100.000,0.910,
2,                  * Modul nr. 2  -  Kiira HPP
Kiira HPP
4,4,4,
1010.0,
0.052974,
200,
22.203,
1129.0,
1111.13,
2.9e-007,
23,
0.000,0.000,
8.300,0.000,
8.400,0.930,
8.800,0.930,
16.400,0.950,
20.400,0.930,
27.300,0.930,
27.400,0.930,
28.700,0.930,
36.500,0.940,
40.300,0.930,
47.300,0.930,
47.400,0.930,
48.700,0.930,
56.600,0.940,
60.700,0.930,
68.900,0.930,
76.800,0.940,
80.400,0.930,
87.400,0.930,
88.700,0.930,
96.700,0.940,
100.000,0.930,
***
*OF                   ************ TRANSFER MODULES ************
***
*KO                   ************ CONTROL POINTS ************
4,                  * Modul nr. 4  -  To Isimba
To Isimba
0,0,0,
***
*KM                   ************ POWER MARKET ************
843.0,
10.0,
1,365,
4,
0,                  * Antall preferansefunksjoner
```

```
***
*RS                    ************ RESTRICTIONS ************
***
*ST                    ************ OPERATIONAL STRATEGY ************
300,
2,                   * Modul nr. 2  -  kiira/Kiira HPP
300,
1,                   * Modul nr. 1  -  Nalubaale/Nalubaale HPP
***
*HY                    ************ HYDROLOGICAL INPUT DATA ************
2007,2017,
4,
2,
1,                   * Modul nr. 1  -  Nalubaale/Nalubaale HPP
  16811.0,1.0,0.0,
1,                   * Modul nr. 1  -  Nalubaale/Nalubaale HPP
  16811.0,1.0,0.0,
2,                   * Modul nr. 2  -  kiira/Kiira HPP
  10014.0,0.0,1.0,
4,                   * Modul nr. 4  -  To Isimba
  0.0,1.0,0.0,
1,
nalubale
4,,
1.0,
nalubale.prn
1,
kiira
1,,
1.0,
kiira.prn
***
*JK                    ************ JOB CONTROL ************
NALUBAALE & KIIRA HPPs
2013,
2016,
843,
100.0,
0,
1,
365,
1,1,1,1,
3,
1,
2,
4,
0,
None
0,1,8,1Nalupw.txt,
0,2,8,1Kiirapw.txt,
0,4,2,1ToBujaTH.txt,
***
*EX
```

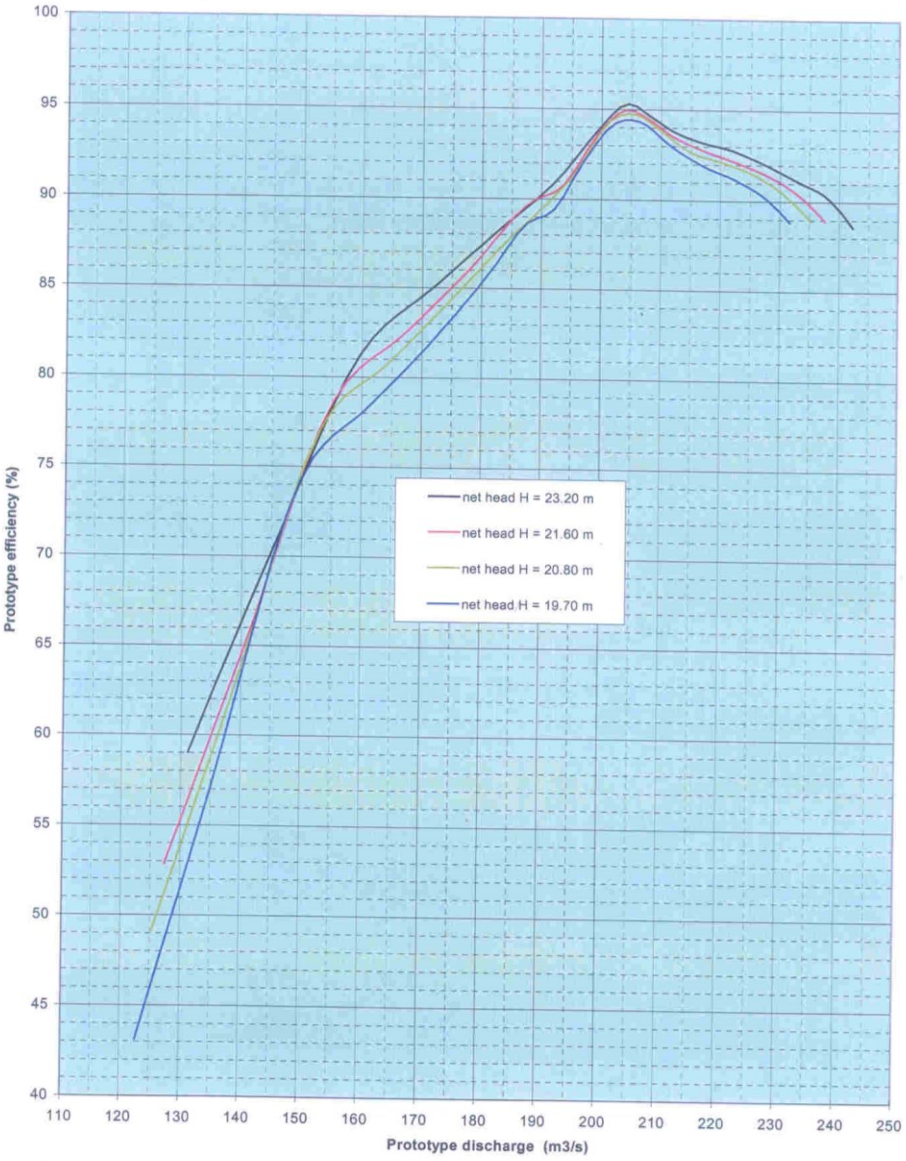
MODEL-2 DATA SET 2017

```
365,                      * Number of timesteps in one year
4,                      * Total no of Modules (*MA, *KR, *OF og *KO)
2,                      * No of reservoirs
2,                      * No of power plants
0,                      * No of transfer modules
1,                      * No of control points
25,                      * Max. permitted no of entries in a Table
*MO                       * Mode
0,                      * 1=ENMAG mode, 0=nMAG mode
***
*CO
NTNU, SN Power, UEGCL
MWASE CHARLES
Optimization Of Hydropower Resources In The Victoria Nile Basin
***
*MA                       ************ RESERVOIRS ************
1,                      * Modul nr. 1  -  Nalubaale
Nalubaale
1132.0,
1134.0,
2.93,
4,4,4,
2,                      * Modul nr. 2  -  kiira
kiira
1132.0,
1134.0,
2.93,
4,4,4,
***
*KR                       ************ POWER PLANTS ************
1,                      * Modul nr. 1  -  Nalubaale HPP
Nalubaale HPP
4,4,4,
830.0,
0.04905,
200,
19.833,
1129.0,
1113.5,
4.4e-007,
24,
0.000,0.000,
10.100,0.000,
10.200,0.700,
12.200,0.790,
16.400,0.950,
20.600,0.930,
30.100,0.910,
30.200,0.840,
32.200,0.870,
36.300,0.950,
39.900,0.910,
50.100,0.910,
50.200,0.840,
52.300,0.880,
56.400,0.930,
```

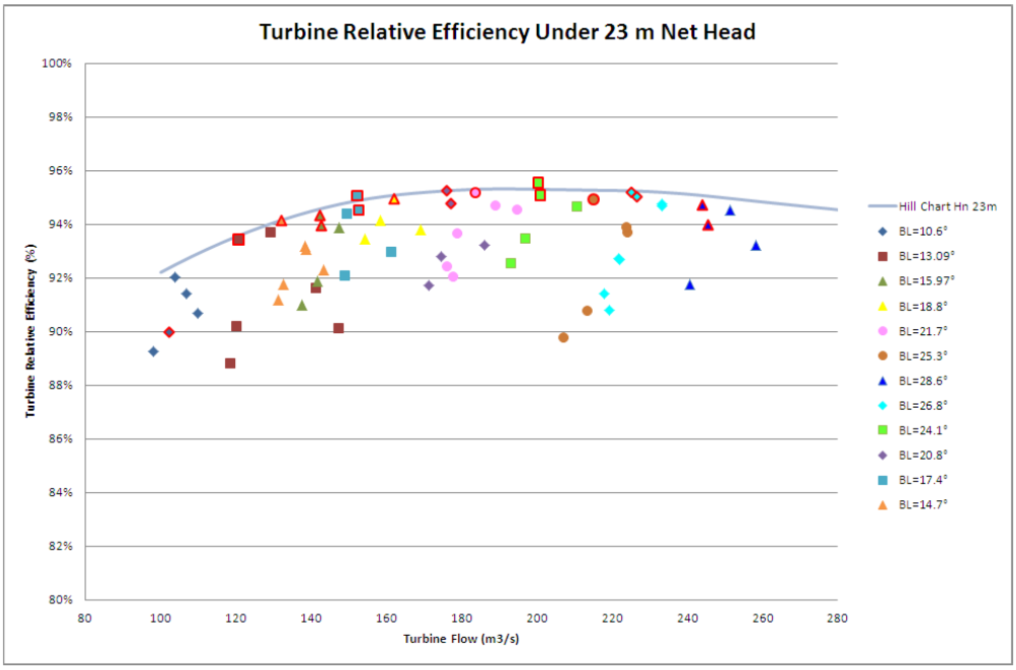
```
61.100,0.910,
70.100,0.910,
70.200,0.860,
72.400,0.890,
76.300,0.920,
90.100,0.910,
90.200,0.870,
96.700,0.920,
100.000,0.910,
2,                  * Modul nr. 2  -  Kiira HPP
Kiira HPP
4,4,4,
1050.0,
0.052974,
200,
21.333,
1129.0,
1112.0,
2.7e-007,
23,
0.000,0.000,
8.300,0.000,
8.400,0.930,
8.800,0.930,
16.400,0.950,
20.400,0.930,
27.300,0.930,
27.400,0.930,
28.700,0.930,
36.500,0.940,
40.300,0.930,
47.300,0.930,
47.400,0.930,
48.700,0.930,
56.600,0.940,
60.700,0.930,
68.900,0.930,
76.800,0.940,
80.400,0.930,
87.400,0.930,
88.700,0.930,
96.700,0.940,
100.000,0.930,
***
*OF                  ************ TRANSFER MODULES ************
***
*KO                  ************ CONTROL POINTS ************
4,                  * Modul nr. 4  -  To Isimba
To Isimba
0,0,0,
***
*KM                  ************ POWER MARKET ************
843.0,
10.0,
1,365,
4,
0,                  * Antall preferansefunksjoner
```

```
***
*RS                       ************ RESTRICTIONS ************
***
*ST                       ************ OPERATIONAL STRATEGY ************
300,
2,                       * Modul nr. 2  -  kiira/Kiira HPP
300,
1,                       * Modul nr. 1  -  Nalubaale/Nalubaale HPP
***
*HY                       ************ HYDROLOGICAL INPUT DATA ************
2007,2017,
4,
2,
1,                       * Modul nr. 1  -  Nalubaale/Nalubaale HPP
  16811.0,1.0,0.0,
1,                       * Modul nr. 1  -  Nalubaale/Nalubaale HPP
  16811.0,1.0,0.0,
2,                       * Modul nr. 2  -  kiira/Kiira HPP
  10014.0,0.0,1.0,
4,                       * Modul nr. 4  -  To Isimba
  0.0,1.0,0.0,
1,
nalubale
4,,
1.0,
nalubale.prn
1,
kiira
1,,
1.0,
kiira.prn
***
*JK                       ************ JOB CONTROL ************
NALUBAALE & KIIRA HPPs
2017,
2017,
843,
100.0,
0,
1,
365,
1,1,1,1,
3,
1,
2,
4,
0,
None
0,1,8,1Nalupw.txt,
0,2,8,1Kiirapw.txt,
0,4,2,1ToBujaTH.txt,
***
*EX
```

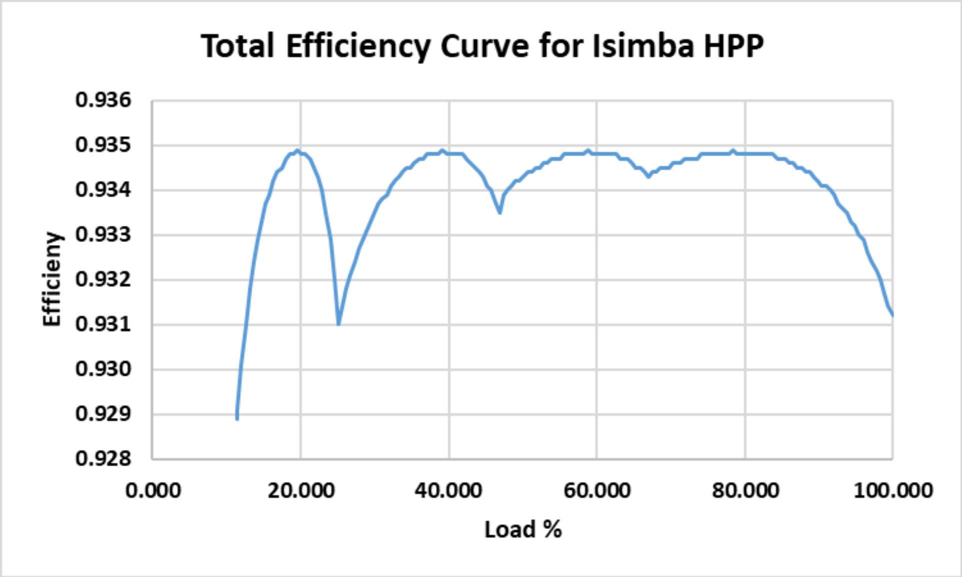
Appendix 3: Referenced Efficiency Curve for Kiira HPP (1 unit)



Appendix 4: Referenced Efficiency Curve for Bujagali HPP (1 Unit)



Appendix 5: Referenced Efficiency Curve for Isimba HPP (1 Unit)



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Science and Technology