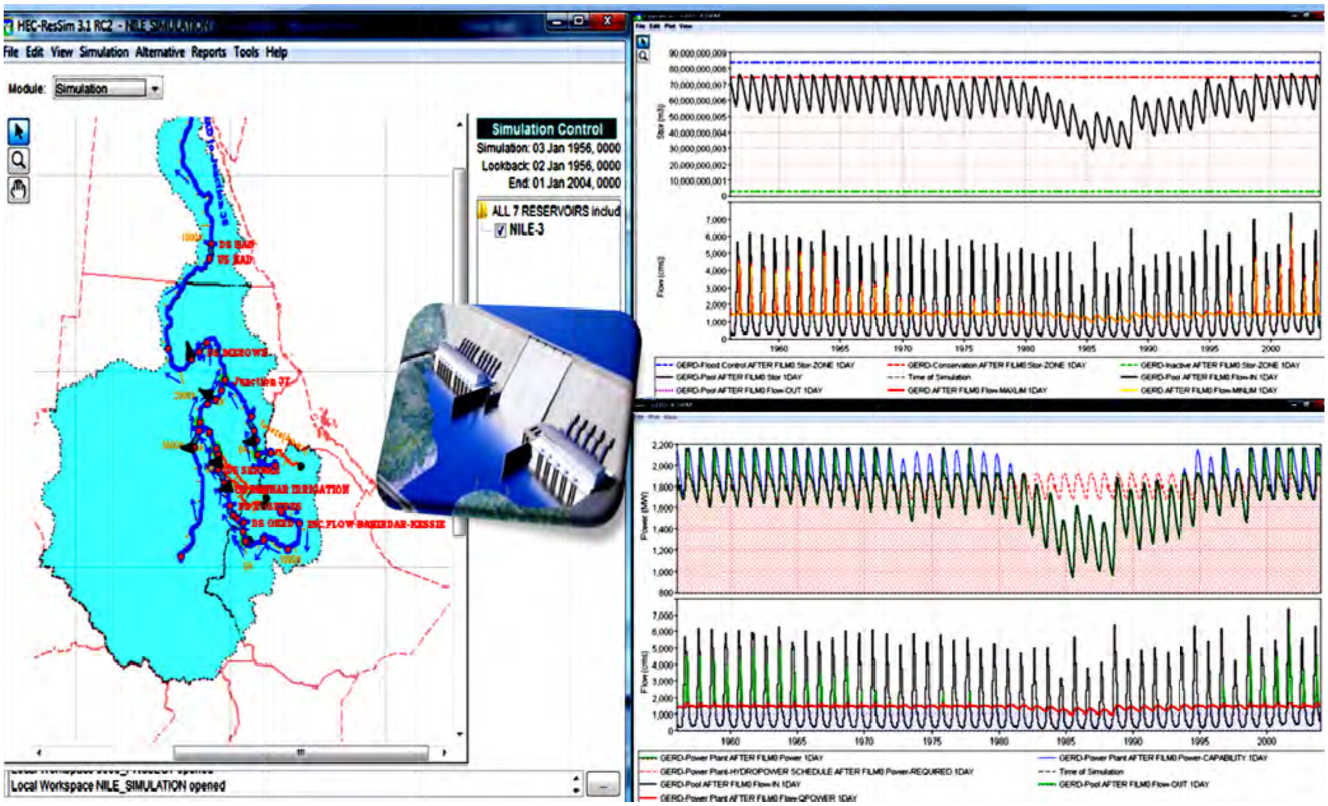
Grand Ethiopian Renaissance Dam Reservoir Operation Simulation using HEC-ResSim and its impact on downstream Hydropower Generation



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By

Zelalem Tesfaye

Addis Ababa University

March, 2014

ADDIS ABABA UNIVERSITY

ADDIS ABABA INSTITIUTE OF TECHNOLOGY (AAiT)

SCHOOL OF GRADUATE STUDIES

Grand Ethiopian Renaissance Dam Reservoir Operation Simulation using HEC-ResSim and its impact on downstream Hydropower Generation

A thesis submitted and presented to the
School of graduate studies of Addis Ababa University
in partial fulfillment of the requirements for
degree of Master of Science
Department of Civil and Environmental Engineering
(Major Hydropower Engineering)

By

Zelalem Tesfaye

Advisor

Dr. Yilma Sileshi

Addis Ababa
March, 2014

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Addis Ababa Institute of Technology

School of Graduate Studies

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Approval by Board of Examiners

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CERTIFICATION

I, the undersigned, certify that I have read and hereby recommended for acceptance by the Addis Ababa University a dissertation entitled: **Grand Ethiopian Renaissance Dam Reservoir Operation Simulation using HEC-ResSim and its impact on downstream Hydropower Generation** in partial fulfillment of the requirements of the degree of Masters of Science in Hydropower Engineering.

Dr. Yilma Sileshi
(Supervisor)

Date

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March, 2014

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Abbreviations

BASWN	Baro-Akobo-Sobat-White Nile
BCM	Billion Cubic Meter(10^9 m^3)
BAS	Baro-Akobo-Sobat
ENTRO	Eastern Nile Technical Regional Office
EEPCO	Ethiopian Electric Power Corporation
ET	Ethiopian
EG	Egypt
EACE	Ethiopian Association of Civil Engineers
FSL	Full supply level
GERDP	Grand Ethiopian Renaissance Dam Project
GWh	Giga-Watt Hour
GAUL	Global Administrative Unit Layers
GUI	Graphical User Interface
HAD	High Aswan Dam
Ha	Hectare
HEC-ResSim	Hydraulic engineering center reservoir simulation
HEC-Dss	Hydraulic engineering center data storage service
ICS	Inter-Connected Systems
IWRM	Integrated Water Resources Management
MIWR	Ministry of water resources
masl	Meter above sea level
MOL	Minimum operating level
MCM	million cubic meters(10^6 m^3)
mm	millimeters
MEE	Ministry of Electricity and Energy
MW	Mega watt(10^6 Watt)
NEC	National Electricity Corporation
SNNPR	Southern Nations, Nationalities and Peoples Regions
SCS	Self-Contained System
SU	Sudan
TSA	Tekeze-Setit Atbara
UNESCO	United Nations Education, Scientific and Cultural Organization
UNECA	United Nations Economic Commission for Africa

ABSTRACT

In this study, HEC-ResSim model was used to simulate operation of existing hydraulic infrastructure, and major irrigation schemes in the Eastern Nile river basin and the new hydraulic infrastructure (GERDP).The main objective of this research is to find out the extents of the impact to which the introduction of new upstream reservoir, GERDP, on downstream users of the Nile waters by using the HEC-ResSim reservoir simulation model. Repeated runs of the HEC-ResSim model were made using different filling and after filling of GERDP scenarios to compare the effect of GERDP under alternative operating policies.

The computational algorithm in HEC-ResSim is divided in to three major components: (1) watershed setup, (2) reservoir network, and (3) simulation for Calibration, Baseline and Alternative (Dry, Wet and Average filling and after filling) phase scenarios. The methodology computes the required releases to limit storage to the capacity available based on the probabilistic properties of future flows, conditional to current stream flow conditions.

The first setup was to simulate gaged flow routing without taking into account effects of development using the flow data of 1956 to 2003 and a good agreement was observed between simulated and gaged data at El-Deim, Khartoum, Dongola, Hassanab and Tamaniat stations. The correlation coefficient R^2 values for those stations were found to be in good agreement and found to be more than 0.925 for each station. Following this, the model was configured to simulate the existing and proposed development intervention.

The baseline development Scenario is considering only existing major water infrastructures (i.e. reservoirs) and major irrigation schemes in Sudan and Egypt for a period of 1956 to 2003. The simulation result showed that an average annual energy of 14,810.83GWh/year is produced by Roseires, Sennar, Merowe and HAD.

The Alternative scenario development which includes during filling and after filling of GERDP, HEC-ResSim simulation, has discovered that long term effects of new upstream reservoir on the operation of downstream reservoirs. After filling of GERDP phase scenario simulation using flow data of 1956 to 2003, the simulation result showed that an average annual energy of 31,363.63GWh/year will be produced by GERD, Roseries, Sennar, Merowe, and HAD (111.76% increase than without GERD), the reduction of average annual energy by 395.41 GWh/year from HAD will be compensated by the energy produced by GERDP and Sudan power plants, which will increase the total energy produced by the whole Eastern Nile system. During the filling phase scenario simulation results showed that an average annual energy of 27,041.96 GWh/year, 25,695.48 GWh/year, and 31,213.61 GWh/year will be produced by the 5 power plants during Average, Dry and Wet filling Scenarios respectively and average annual energy production from GERDP will be 11,314.38, 8,974.19, and 11,925.61GWh/year for the respective sequence of filling years. An average monthly power of 1,625.46MW and average annual energy of 14,238.99GWh/year will be produced during normal operation of GERDP (i.e. after filling from 2019-2066 for 48 years).

Due to upstream regulation (i.e. intervention of GERDP, in the upstream of the Eastern Nile river basin) there will be an increase in average monthly inflow downstream in the driest month of the year and the annual average reservoir pool level increase which result in increase of power head.

Keywords: HEC-ResSim, Reservoir Operation, Simulation scenario, GERDP, Roseries, Sennar, Merowe and HAD.

Dedication

This work is dedicated solely to my beloved

Nekemte Melaku, My Parents and Brother Andualem Tesfaye

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Chapter One

Introduction

1.1 General

Water is a finite resource which is under increasing stress as human population and per capita demands increase through the world (IWMI, 2000). The demand for water for agricultural, industrial, power generation, domestic use and sanitation, waste collection, treatment and disposal uses are rising with the growth in the world economies. Flow in most of the rivers of the world are affected by the random and cyclic seasonal fluctuations, hence reservoir storage play a key role in regulating stream flow fluctuations, to develop reliable water supplies, optimal operation of the reservoirs is crucial (Wurbs and James, 2001).

If the water demand and equitable allocation and distribution is complex computer simulation models are used as analysis tools (Asit, 1976). Several runs of simulation models under various scenarios can be used to come up with optimal strategies for distribution and allocation of water (Wurbs and James, 2001). For a sustainable and equitable water supply from reservoirs on the river system simulation models can provide the support required in water resources system analysis, for management strategies in the reservoirs operation.

Basin-scale analyses are often undertaken using one of the two types of models: one is to simulate water resources behavior in accordance with a predefined set of rules governing water allocations and infrastructure operations, or the other is to optimize and select allocations and infrastructure based on an objective function and accompanying constraints. Often the assessment of system performance can best be addressed with simulation models, whereas, optimization models tend to be more useful when system improvement is the main goal.

Reservoir simulation deals with the mathematical simulation of river network with reservoirs. The simulation models include the mass balance of reservoir inflows, outflows and storage fluctuations. These models provide an economic evaluation of damages due to floods, benefits from irrigation, hydropower generation or other such activities. Simulation models provide a realistic and detailed representation of reservoir operations.

Hydro Electric power is a renewable, economic, non-polluting and an environmental friendly source of energy. The Government of Ethiopia imagines the GERDP Hydroelectric power Project as one of the development projects to meet the country’s rising demand for energy in the GTP. The project will have the capacity to generate 6000MW of electricity. The dam site is located in the Western part of the country in the Benishangul Gumuz Regional state of Blue Nile river basin. The dam is under construction.

In Nile Basin there are so many water storage facilities, like lakes and swampy place and manmade reservoirs are constructed and also some are in progress of construction. High Aswan dam in Egypt, Merowe reservoir in Sudan, and Renaissance Dam in Ethiopia are the main manmade reservoir in upper Blue Nile and lower Nile river parts.

To balance the demands for water to support the production of hydroelectric power, water supply and for agricultural purpose we must preserve the river and reservoir levels, a comprehensive investigation has to be undertaken to evaluate the effectiveness of proposed water rights and to analyze the impacts of introducing new reservoirs by making reservoir operating rules and policies.

One of the most popularly used reservoir system simulation models is the HEC–5 model developed by Hydrologic Engineering Center. HEC–ResSim is the Next Generation (NexGen) model which eventually replaces HEC–5. Hence, the aim of this research is to configure and simulate the present and likely future water resource systems of Nile river basin using HEC-ResSim model.

HEC-ResSim is a planning and real time decision support tool that meets the needs of modelers for single and multi reservoir system management during real time events. The HEC-ResSim software performs hydrologic routing and determines reservoir releases based on a rule curve approach plus user-specified operating rule to meet multipurpose, seasonal, at-site and downstream operational goals, including flood reduction, water supply, hydropower generation, and stream flow requirements. The water supplies demanded for municipal, industrial, and agricultural needs, as well as environmental instream flow requirements, and hydropower generation and flood control have increased over the past decades as a result of population and economic growth.

1.2 Problem Statement

Hydropower plants are usually a key element of multipurpose water resources systems. The major conflict issues in operation of hydropower systems arise when a reservoir that supplies water for different activities must also provide enough discharge and head for energy supply. Monthly variations of energy demand and water demands usually do not follow the same pattern; therefore, supplying one of these demands in a specific period of time might clash with supplying the other demands in the future. The major conflict issues in operation of hydropower reservoirs can be summarized as follows:

- Keeping enough head in reservoirs for power generation with high efficiency is in conflict with
- Supplying water demands, especially in dry seasons
- Keeping flood control storage
- Water and energy demands do not follow the same pattern; therefore, optimal scheduling of water release from the reservoir for these purposes might vary.

The developments of reservoirs have significant effect on the flow of the rivers on which they are situated. For the case of the Nile River basin where the reservoirs are located downstream there is the possibility of inadequate flows in the downstream portion of the basin and other hydrological problems such as increased evaporation leading to rapid dry up of some of the streams generating serious consequences.

There is also the problem of location of reservoirs to ensure adequate water throughout the year to meet demands. There is the need to ascertain the impact of these major reservoirs on the system of Nile River basin with regards to the downstream communities and the general flow condition of the rivers.

This can assist in the construction and planning of these reservoirs in order to minimize the effect on the downstream users. There is also the need to find out how these reservoirs in the upstream portion of the basin affect the dams located in Sudan and Egypt which are the downstream countries of the Nile River.

1.3 Objective of the study

1.3.1 General objectives

The purpose of this study is to model dams and reservoirs operation in the Eastern Nile river basin to simulate reservoir operation for Hydropower Generation.

1.3.2 Specific objectives

The specific objectives of the study are

- To develop Eastern Nile River and Reservoir simulation model using Hec-ResSim
- To undertake reservoirs operation simulation for maximum power generation from GERD
- To compare the effect of different filling scenarios of GERD
- To compare and evaluate the effects of GERD reservoir operating alternative scenarios on downstream reservoirs pool level, flow and power production.

1.4 Scope of Work

The thesis work will cover the White Nile from Melaka, Blue Nile from Lake Tana and Atbara from Wad El-Hilew on the three sub basins of the Eastern Nile River Basin considering seven Reservoirs and six irrigation diversions, with the GERD and HAD being the biggest reservoirs. The study will cover reservoirs which are located on the three sub basins in the Basin. That means other small water infrastructures which are located on the system will not be considered in this study. This may produce some discrepancies in the results.

The thesis will involve the following;

- Identification of the various reservoirs and their locations in the Basin
- Diversion of water for Irrigation use
- Calibration of the HEC-ResSim model
- Creation of scenario models and evaluation of the results

The primary inputs to the model include assumed future hydrologic inflows, demands, and reservoir conditions. Due to the uncertain nature of these projected inputs, the outputs are naturally subject to a greater degree of uncertainty and any application of a model must recognize these limitations.

Models are conceptual representations of the real world. In the Eastern Nile HEC ResSim model there exist limitations in its ability to accurately simulate actual conditions. The resolution of hydrologic inflows and demands can always be improved upon, and updated descriptions of the physical characteristics of the basin can be readily incorporated. During the model development period, the majority of data was obtained from ENTRO and relied on their previous efforts of compiling multiple data sources. As the application of the model expands to stakeholders, additional data and information about the basin is likely to be available through new perspective. The developer of this model encourages ongoing improvement to it by multiple parties, and hope that it provides a foundation from which to build upon.

1.5 Structure of the Thesis

This thesis consists of seven chapters including the *introduction* as Chapter 1 (this Chapter). The conclusions, recommendation obtained from the study and future works are presented in Chapter 6. The other three chapters (Chapter 2 to Chapter 5) can be summarized as follows.

Chapter two is the *literature review* and explains about integrated water resources in the Nile River Basin and general reservoir properties construction and its importance.

The third chapter is a *description of the study area* and describes about the main characteristics of the Nile river basin including the location, rainfall characteristics, land use, topography and drainage sub basins. The chapter also discusses about the location, physical and operational characteristics of the existing hydropower plants and reservoirs.

The fourth chapter is the *methodology* and describes methods and materials taken to achieve the objectives of the thesis. The chapter focuses on hydrological, operational and physical data collection and analysis, i.e. the steps taken to achieve the objectives of the thesis.

The chapter that follows this presents the *summary of results and discussion* of the thesis and *reference and the appendix* will follow chapter six.

Chapter Two

Literature review

2.1. Reservoir System Analysis

A significant amount of attempt on developing and applying reservoir system operation models has been documented in the published literatures during the past decades. Much additional work has been accomplished without being reported in the published literature. Yeh (1985) provides a comprehensive state-of-the-art review of reservoir operation models with a strong emphasis on optimization methods. Wurbs et al. (1985) provide an annotated bibliography which cites several hundred references on reservoir systems analysis models. The USACE Hydrologic Engineering Center (1991) presents a complete analysis of reservoir system modeling and analysis approaches. Wurbs (1993) also reviews reservoir system simulation and optimization models. Traditionally, reservoir operation is based on trial and error procedures, embracing rule curves and subjective judgments by the operator. This provides general operation strategies for reservoir releases according to the current reservoir level, hydrological conditions, water demands and the time of the year. Figure 2.1 shows the different elements for the multipurpose reservoir systems [Ostrowski, 2009].

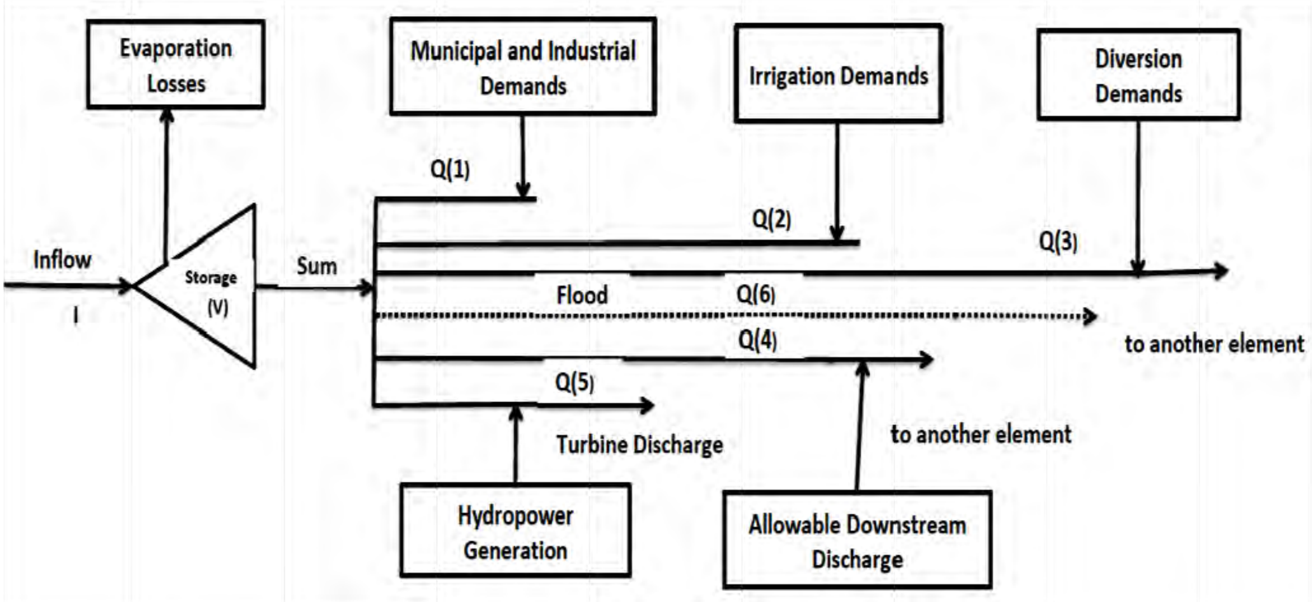


Figure 2.1 Different elements of Multi-purpose reservoir system [Ostrowski, 2009].

Efficiently managing reservoir operations has been a significant issue for decades. Working to discover the maximum potential and firm reliability from water resources is a not easy and dynamic process encompassing several disciplines. Typically previous research has been focused in arid regions of the world, such as the Western United States. Yet increasing water demands calls for skillfully managed watersheds to attain the greatest benefit to the world. The field of water resource management has been influenced by researchers of many backgrounds. Engineering, economic, statistical, and optimization disciplines have been involved in exploring the influences and effects of watershed management.

Apart from the field, a balance between water allocations is nearly always essential since reservoirs have multiple competing uses and benefits. A priority structure between the different uses of the water is typically well established. The influence of such allotments, however, can vary considerably depending on the regional requirements and basin characteristics. For instance, flood control and water supply typically are non-compromised uses. On the other hand, the weight of energy production, irrigation, and recreation are more readily arguable between policy makers and experts.

The operation of most multiple reservoir systems in North America reflects the reality that there are sometimes conflicting and sometimes complementary multiple purposes served by the water stored in and released from reservoirs (Daniel P. Louck and Oskar T. Sigvaldaso, 1982). These purposes can include:

a) *Water Supp1y* for municipal (drinking water etc.), industrial (water for production, for cooling etc.) and agricultural (for irrigation) needs from lakes and streams.

b) *Water Quality enhancement* by releasing water of higher quality upstream to dilute and transport downstream wastes.

c) *Flood Control* through the provision of available storage capacity during periods when floods are possible and maximum use of downstream channel capacities during periods of high runoff to reduce the possibility of flood damage. Flood flow retention in order to prevent inundation.

d) *Hydropower Production* by operating reservoirs so as to minimize loss of energy and meet energy and power requirements(i.e. maximizing power production)

e) *Navigation* by insuring enough depth of water in navigation channels and sufficient water supply for lockages.

f) *Recreation*, whose benefits, while sometimes difficult to quantify in monetary terms, are however often present if suitable pool levels and limits on level variations are maintained.

g) *Fish and Wildlife improvement* through the maintenance of desirable pool levels or flows during significant periods in the year for greater fish and wildlife production, fishing and hunting benefits.

h) *Flow augmentation*, in particular during low flow periods, to guarantee in the downstream river section:

   - ➢ The required minimum flow,
   - ➢ Sufficient water quality (considering the unavoidable waste water releases into the river)

Kim (1999) described safe yield as the amount of energy that is 100% reliable and its importance in consideration of reservoir operation. It is stated by Kim (1999) that, the seasonal supply of water causes annual fluctuations in the reservoir volume and associated variations in power and energy potential. It determines whether or not the plant can be operated over long periods of time, that is only during a few hours of peak load periods, or base-loaded for longer periods. Flexibility within the operational rules, while taking advantage of high reservoir levels was important in optimizing energy for hydro power generation.

Assuming that it is possible to define ideal storage levels and downstream releases and/or diversions for every day, week or month throughout the year (i.e. assuming there exists a set of storage and release values that best satisfies all water users), reservoir operating procedures are needed and used to guide operators when it is not possible to satisfy these ideal conditions. Reservoir operating policies used in North America usually include a definition of ideal conditions (with regard to storage levels, or releases, or both) and some guidelines for operation when these ideal conditions cannot be maintained, i.e. for non-ideal conditions (Daniel P. Louck and Oskar T. Sigvaldaso, 1982).

Ideal storage volumes or levels in individual reservoirs are typically defined by "rule curves." When situations are not ideal, operating policies or "rules of system operation" define what should be done for various combinations of system states and hydrologic situations. Together, rule curves and rules of system operation define desired storage volumes or levels, reservoir releases, and diversion quantities. Ideal storage volumes or levels usually fluctuate throughout the year, but do not differ from year to year. Similarly, releases or diversions are also expressed as functions of the time of year as well as the storage condition of upstream. These functions or rule curves apply to reservoirs that are in a stationary state (in a probabilistic sense) and that are being operated under the same policy from one year to the next. The purpose of operating policies is to distribute any necessary deviations from ideal conditions in a way that satisfies mandated rules or regulations and/or that minimizes the total perceived discomfort or hardship to all water users in the scheme.

There is a variety of operating policies in use at the present time. These operating policies vary from those that only define each reservoir's model pool level, or target level (and provide no information or guidance on what to do if maintaining those levels becomes unfeasible or impossible), to those that define very accurately how much water to withdraw or release at every control structure for all possible combinations of hydrologic and reservoir storage conditions. The principal types of operating policies presently in use will be reviewed below.

2.2Simulation of Reservoir System Operations

Reservoir storage is necessary to regulate highly variable water flows for more constant uses such as municipal and industrial water supply, irrigation, hydroelectric power generation, and navigation.

Typically, the water drawn from a reservoir is used at a much slower (and constant) rate than the rate and consistency of the water flowing into the reservoir (Figure 2.2). Reservoir modeling has typically been employed to help size reservoir storage capacities, establishing operating policies, evaluating operating plans, administering water allocations, developing management strategies, and real-time operations.

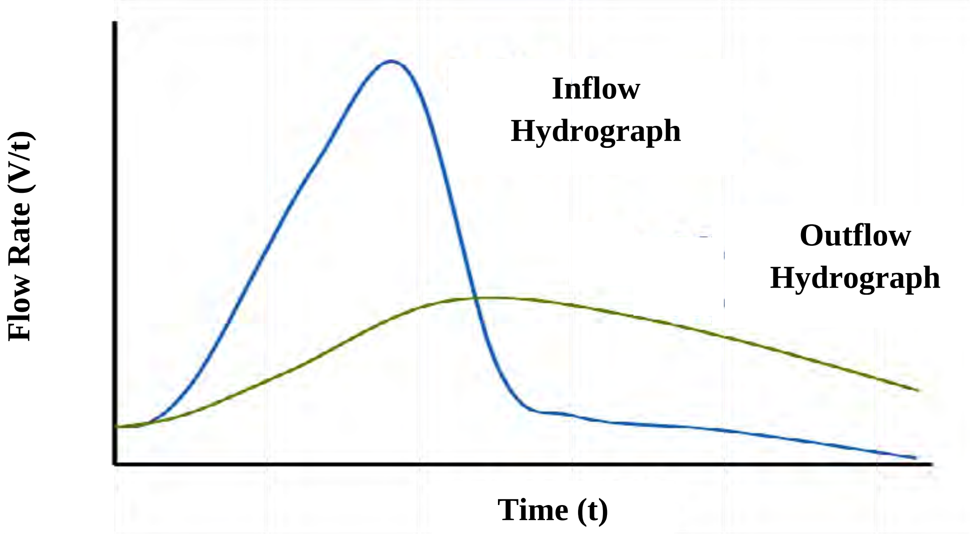


Figure 2.2 - Inflow and Outflow Hydrograph

The basic requirement for adequate representation of a reservoir is employment of the continuity equation, or conservation of volume over a period of time. This is a function that interacts dynamically with the current state of the reservoir. The foundational equation for conservation of volume is:

$$I - O = \Delta S \qquad (2.1)$$

Where: I is the inflow into the system which includes runoff and rainfall

O is the outflow from the system which includes evaporation, abstraction, transmission losses and spillage

ΔS is the change in storage over the period under consideration and is given by:

$$\Delta S = S(t) - S(t-1) \qquad (2.2)$$

Where: S (t) is storage level at time t

S (t-1) is storage level at time t-1.

The term “Reservoir System Operations” refers to the practice of maintaining and managing a reservoir for multiple purposes, under dynamic conditions. The word “system” is used because of the complexity inherent in the operations of a typical reservoir or network of reservoirs. The state of the reservoir system is constantly in flux, requiring dynamic methods of simulation to evaluate and model them. The term “Reservoir System Operations Model” refers to a computer program used for simulating and optimizing changes in storage, water deliveries, and flood control for one or multiple reservoirs.

Often times, the objective of the reservoir operation is to balance the control of flood storage and maintain reliable water supply. Operational procedures are different for flood events than what are employed under water scarce conditions and therefore, the model must be adapted for these changing conditions. To better manage potential changes to reservoir operations given uncertainties or changes in circumstances, it is helpful to develop a calibrated simulation model of the reservoir. Some key topics related to reservoir system operations modeling are presented in this paper.

2.2.1 Single pool operations

The main purpose of a reservoir is to control a determined amount of water during some period of time. The amounts that are controlled depend on the properties of the reservoir system, which include components such as the dam, spillway, inflow, and outlet works. Figure 2.3 depicts a simple example of a basic reservoir system. Inflow to a reservoir is typically uncontrolled if the reservoir is on the river. Some dams are built off-stream and water is delivered to the reservoir in a controlled manner. Usually, the controls on inflows to the reservoir are a function of the water level in the reservoir.

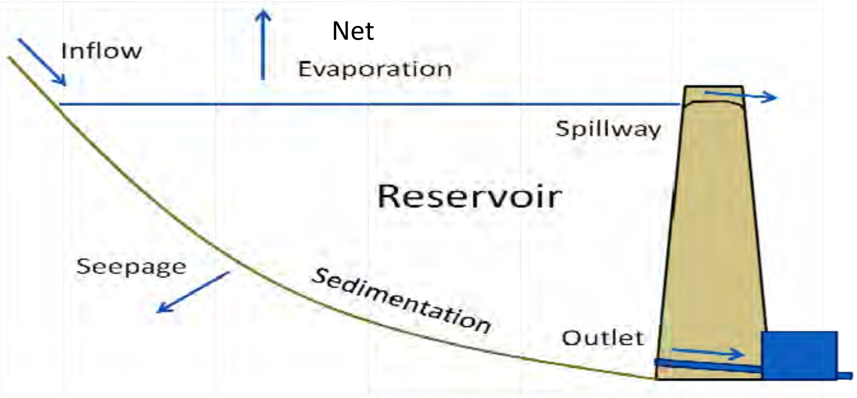


Figure 2.3 - Simple Reservoir Diagram

As the reservoir begins to approach an upper limit, the flow into the reservoir is turned off if the inflows are able to be controlled. For reservoirs that are located on a stream, the inflows cannot be controlled so the reservoir must operate a flood control system that usually includes an outlet works and an uncontrolled spillway. When the outlet works are not able to discharge enough water to lower the reservoir level, then the water will rise above the spillway and water will discharge over the spillway at a flow rate that is dependent on the height of water above the spillway. Often times the reservoir system operations need to be simulated in a computer model. Typically, a reservoir model must include the major parts of the reservoir system in order to evaluate the reservoir system operations. The fundamental aspect of reservoir modeling is the routing of water.

2.2.2 Operation of multiple pools

Reservoirs are operated based on policies that involve multiple pools that are defined to be used for different purposes. An example of a typical multi-pool reservoir is shown in Figure 2.4, where the reservoir is divided into surcharge, flood control, conservation, and dead pool zones. Often times, the conservation pool is referred to as the multi-use zone because water needs to be conserved in this pool for multiple and often conflicting uses.

The flood control zone is to remain empty except during the times following a flood event upstream of the reservoir. Flood control zones often include a surcharge zone, which is the uncontrolled storage volume above a spillway elevation. Usually, it is not in the interest of reservoir operators to spill water over the spillway because it is uncontrolled and poses a risk to the channel downstream. The flood zone is typically drained in a controlled manner through use of an outlet works with an operated gate or valve.

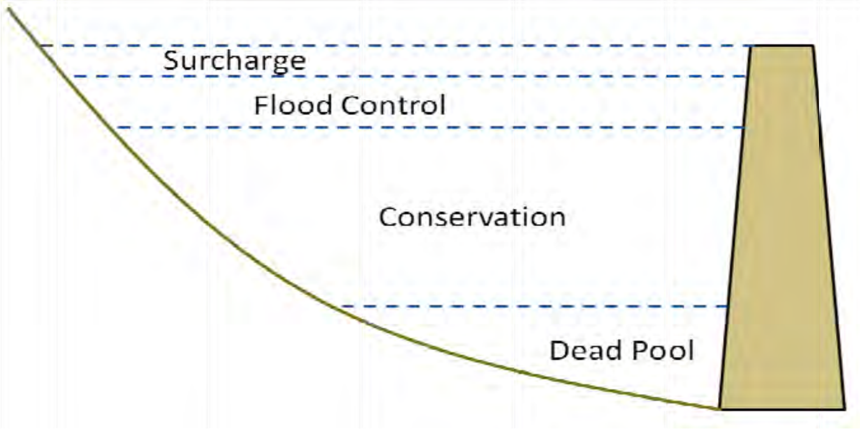


Figure 2.4 - Reservoir Pools

The conservation pool is used to store water temporarily for downstream uses such as power generation, navigation, irrigation, municipal and industrial water supply, and in-stream flows for habitat. Often times the top of the conservation pool varies seasonally as shown in the simple example in Figure 2.5. Typically, the top of the conservation pool rises during the part of year that additional storage is needed to supply water for beneficial use later on. A rise in the conservation pool poses greater risk on the operations of the reservoir because it requires that the flood pool zone is decreased, which gives the reservoir less opportunity to evacuate flood flows before the reservoir level enters the surcharge stage.

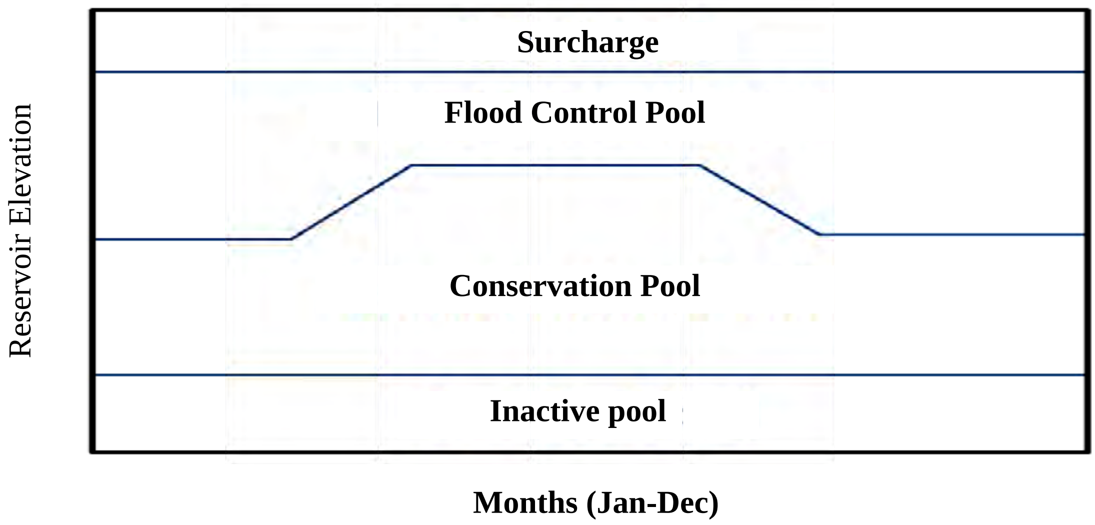


Figure 2.5 - Seasonal Variations in Conservation Pool

Often times, the top of the conservation pool acts as a guide, target, or rule curve for operators. The reservoir is operated in order to try and keep the reservoir level as close as possible to the top of the conservation pool. Obviously, it is critical that the seasonally varying conservation pool limit is first optimized using appropriate methods prior to actual use in the field.

2.3 General problems in reservoir operation

According to the increasing water demand and to the increasing amount of waste water, the reservoir functions for water supply and flow augmentation have become increasingly significant. It is characterized by a typical seasonal variation with a remarkable demand peak in dry and hot summer periods when the natural water yield is generally low.

During such periods, the users try to satisfy their increased demand from the reservoirs. Therefore, the responsible water authorities are interested in storing as much water as possible during periods of high flow, in particular during flood periods. This leads to the following primary setback in reservoir operation:

- ➢ The desire to reduce the flood control volume of the reservoir in favor of increased water storage for low flow periods (problem of reservoir space allocation).

The other general problem is:

- ➢ To find an optimum or at least reasonable strategy for the allotment of reservoir water among the different water uses to be supplied (allocation of reservoir releases).

2.4 Operating policies

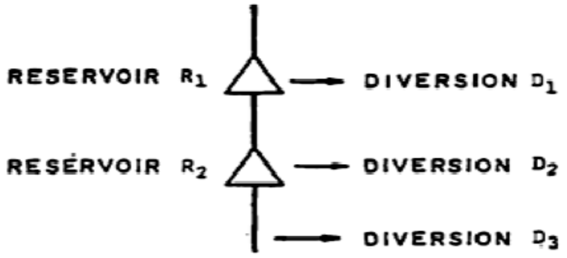
Prior to reviewing various types of operating policies for the operation of multiple reservoirs designed to provide multiple purposes, some discussion of single purpose multiple reservoir operation may be useful.

Consider the single-purpose water supply reservoir providing a dependable source of water. For such systems various operating policies expressed in terms of release rates have been planned to minimize water loss. These policies vary depending on whether the reservoirs are in parallel or in series, as illustrated by Figure 2.6.

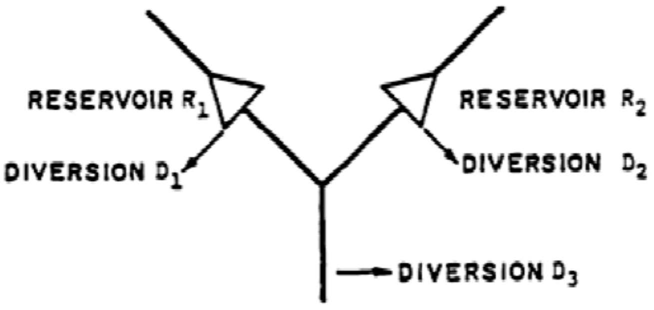
For sing1e purpose water supply reservoirs, the following simple operating rules have general1y been adopted:

2.4.1. Reservoirs in Series – When evaluating the operations of multiple reservoirs in series, special considerations need to be made. The decision of which reservoir to release water from will affect overall operations of the system. Typically, it is best practice to minimize spills from the upstream reservoirs so that capacity in the downstream reservoirs is preserved and will be able to hold uncontrolled spills from the upper reservoirs and thus protect the downstream river channel. It is also helpful to maximize conservation pool water in the upper reservoirs so that the most users will benefit at any given time.

For such systems the downstream reservoirs are depleted before using upstream reservoir water to meet downstream demands. In Figure 2.6 a, this would mean that the upstream reservoir (R_1) would not be drawn down to meet diversions D_2 and D_3 until the downstream reservoir (R_2) was empty. This procedure guarantees maximum use of available storage and that no unnecessary lower reservoir spilling will take place.



(a) RESERVOIRS IN SERIES



(b) RESERVOIRS IN PARALLEL

Figure 2.6 Types of multi Reservoir configurations (Daniel P. Louck and Oskar T. Sigvaldaso, 1982)

2.4.2. Reservoirs in Parallel - The objective for reservoirs in parallel should be to balance storage depletions between the two (Reservoir R_1 and Reservoir R_2 in figure 2.6b). Two procedures are usually used. One involves discharging water first from reservoirs with relatively larger drainage areas (or potential inflows) per unit storage volume capacity. In Figure 2.2b, the drainage area to storage volume capacity ratios for the two parallel reservoirs is compared. The reservoir with the larger ratio is used to supply diversion D_3 before the other reservoir is drawn down. This procedure is applicable only when the runoff per unit area is essentially similar in each reservoir's watershed. Discharging water first from the reservoir having the biggest drainage area to storage volume capacity ratio will usually result in a rational conservation of water. Another, and more precise, procedure involves drawing in tandem from each reservoir in a way that equalizes the likelihood of reservoir filling for each reservoir. This requires monitoring storage volumes and estimating future inflows. Such a policy reduces expected water loss.

For multiple-purpose reservoirs, or for single-purpose reservoirs involving recreation or hydropower, operating policies and related rule curves usually define the desired storage volumes and discharges at any time of the year as a function of existing storage volumes, the time of the year, demand for water or hydropower, and possibly the anticipated inflows. Such operating policies may include one or more of four general components.

2.5 Target Storage Levels or Volumes

These operating rules are limited to a prescription of the desired storage volumes or levels in each reservoir. Reservoir operators are expected to uphold these levels as closely as possible while generally trying to satisfy various water needs downstream. If the reservoir storage levels are above the target or desired levels, the release rates are increased. On the other hand, if the levels are below target levels, the release rates are decreased. These release rates may or may not be specified but will depend in part on any maximum or minimum flow requirements and on the expected inflow.

Figure 2.7 shows a representative rule curve. The desired storage Levels may be based on a compromise among recreational, fish and wild-1ife, flood control, hydropower and water supply requirements. They are most often based on historical operating practice and experience occasionally supplemented by the outcomes of simulation studies. Having only these target volumes or levels for each reservoir, the reservoir operator has significant flexibility in day-to-day operation with respect to the suitable trade-off among storage volumes and discharge deviations from ideal circumstances, and on deciding from which reservoirs to withdraw water in order to meet downstream flow demands. Operating policies that are defined only by rule curves indicating ideal storage levels or volumes need experienced operators that have developed good judgment on how to minimize, over time and space, necessary storage volume and discharge variations.

2.6. Multiple Zoning

Operation rules are often defined to include not only storage target levels, but also various storage allotment zones. For example, the following five zones might be considered:

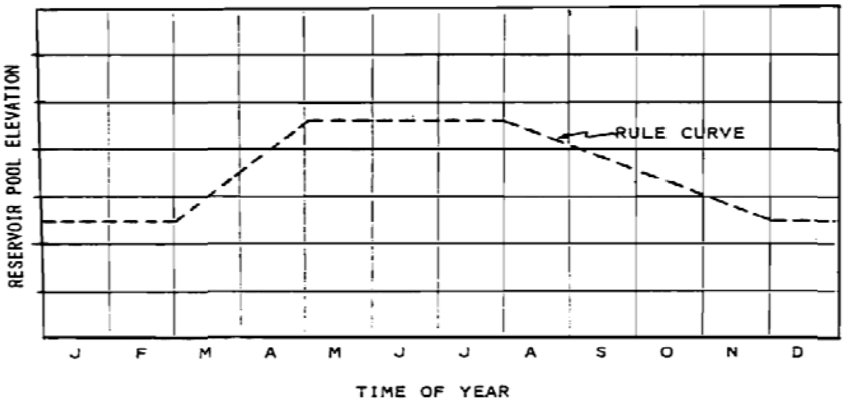


Fig 2.7 rule curve defining ideal storage pool level (Daniel P. Louck and Oskar T. Sigvaldaso, 1982)

(a) **Conservation Zone** - the zone of storage from which different water-based needs are fulfilled. Water levels within this zone are generally satisfactory for recreational and environmental needs. The ideal storage volume or level is generally located within this zone.

(b) **Flood Control Zone –** it is a zone for storing large inflows during periods of unusually high runoff. When storage volumes are within this zone, downstream flows are increased provisionally to pass excess water out of the reservoir as quickly as possible.

(c) Spill or Surcharge Zone - the storage above the flood control zone associated with actual flood damage. Reservoir releases are usually at or near their maximum when the storage volume is within this zone.

(d) Buffer Zone - a reservoir beneath the conservation zone entered only in abnormally dry periods. When storage volumes are within this zone, downstream flows are decreased temporarily to satisfy essential needs only.

(e) Inactive Zone - the "dead" storage beneath the buffer zone which would, if possible, be entered only under extremely dry conditions. Reservoir withdrawals may or may not be possible, and if so, the withdrawals are an absolute minimum. Dead storage in excess of that below the sill of the water outlet structure may be required during some or all of the year to meet legal or institutional constraints.

Figures 2.8 and 2.9 illustrate such zones, which may vary throughout the year. The flood control zone is above curve B. If the storage level is in the flood control zone, the rule may provide for the maximum possible release if the storage level is above curve A, and the maximum release possible without causing flood damage when the storage level is between curve A and curve B. Reservoirs would be kept at or below curve B whenever possible for flood control purposes. Clearly if the need for flood control storage capacity varies throughout the year, the volume of flood control storage capacity should also vary, as is illustrated in Figure 2.9.

Similarly, reservoir zones may dictate curtailing or reducing the allocation to lower priority uses when the storage volume falls below a specified level. Curve C of Figure 2.9 shows that storage level below which allocations to only critical or high priority uses would be maintained. Even further restrictions would be required if the storage level or volume were to fall below curve D in Figure 2.9.Figure 2.10 illustrates the combination of zones and rule curve levels that may define the operating policy of each reservoir in a multiple reservoir system.

These reservoir operating policies permit some flexibility in multiple reservoir operation. To assist operators of multiple-reservoir systems, similar curves defining different release zones have been derived for groups of reservoirs. These multiple reservoir-system rules, together with the individual reservoir rules, propose additional guidance to those responsible for multiple-reservoir operation.

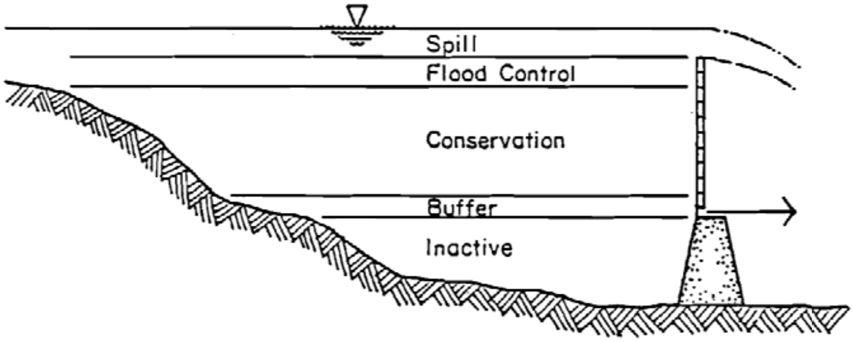


Figure 2.8 types of zones for individual reservoirs (Daniel P. Louck and Oskar T. Sigvaldaso, 1982)

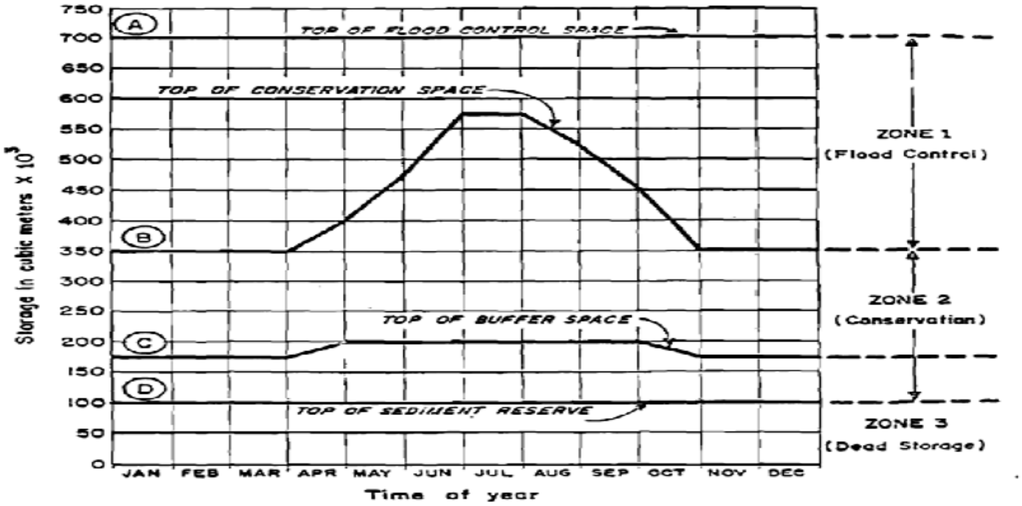


Figure 2.9 example of seasonally varying storage boundaries for a multipurpose reservoir (Daniel P. Louck and Oskar T. Sigvaldaso, 1982)

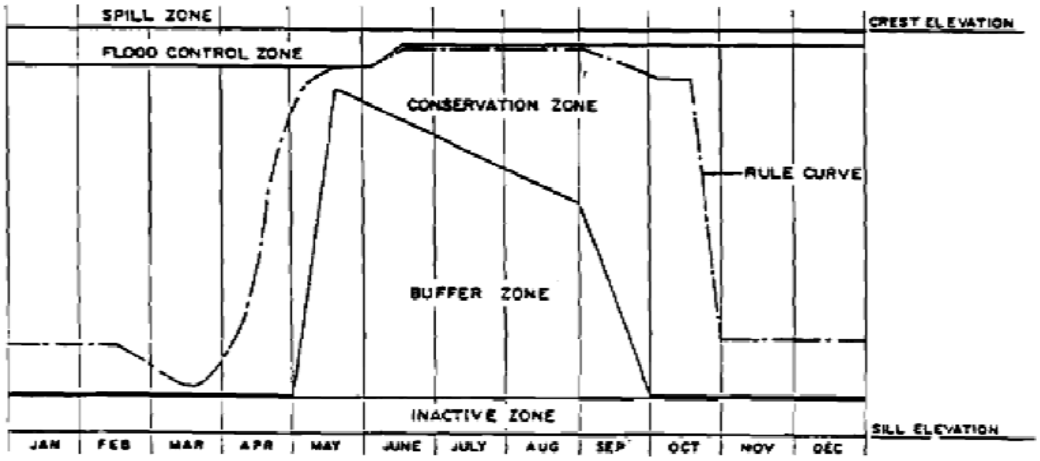
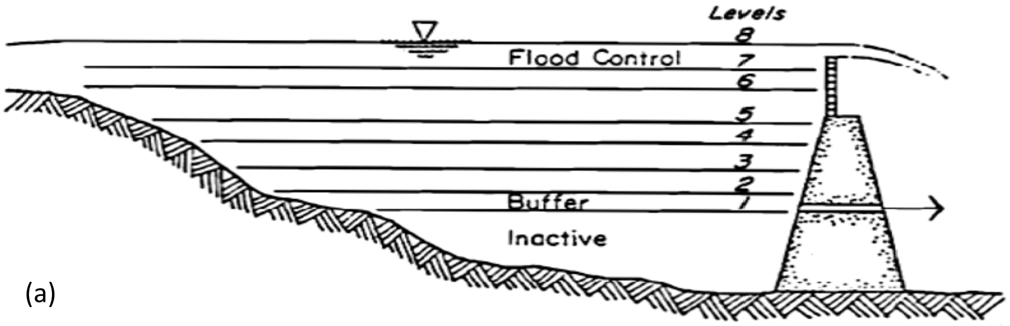


Figure 2.10 Zones and rule curve for a typical reservoir (Daniel P. Louck and Oskar T. Sigvaldaso, 1982)

A further aid in multiple-reservoir operation is provided by identifying multiple subzones within the conservation zone. Figure 2.11 illustrates such multiple subzones or levels. The volume within these levels can vary in magnitude, at a given time and over time. Their main purpose is for multi-reservoir storage-level balancing.

Using the zoning concept for reservoir operation, all reservoir storage volumes should be maintained in the same zone or subzone to the maximum level possible. There are three basic concepts for such balancing of reservoir storage volumes. The first concept is based on keeping all reservoirs at their same zonal position, i.e. at a level where the percentage filling of the zone is equal for all reservoirs. This is sometimes referred to as the "equal function" policy. The second concept is based on a reservoir ranking or priority concept. The entire zone of the lowest ranking reservoir is utilized fully before starting on the next lowest ranking reservoir, and so on. The third concept is based on a "storage lag" policy. Withdrawals from the zones of some reservoirs are begun before withdrawals are begun from the same zones of other reservoirs. After a certain volume has been released from the initial group of reservoirs, releases are made from all reservoirs, maintaining the percentage difference of available zone volume. This policy is often used to provide a readily available reserve of water in case corrections in inter reservoir balancing are needed after an unexpected or extreme hydrologic event.



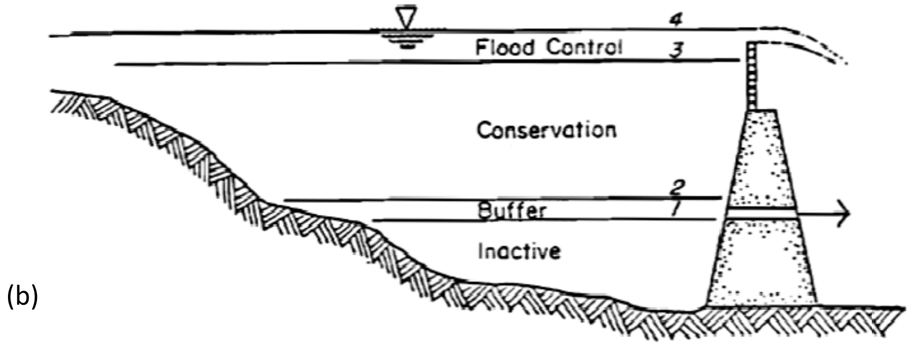


Figure 2.11 Reservoir storage zones showing conservation zone with and without multiple sub zones (Daniel P. Louck and Oskar T. Sigvaldaso, 1982)

Operating policies that are defined by storage zones and related release rates and balancing procedures are much more prescriptive than policies defined only by reservoir rule curves. With only rule curves, the operators have considerable freedom and must use much more judgment in the operation of multiple reservoir systems. Operational planning studies are leaning toward reducing this latitude by defining more prescriptive policies that will raise the possibility that a system will be operated as optimally as possible.

2.7 Flow Ranging

This component of an operating policy provides a more prescriptive relationship between reservoir levels and channel flows. The reservoir release and/or diversion depend on which subzone or zone the storage volume is in. Instead of a possibly large reduction in the discharge from a reservoir when its storage volume falls from the conservation zone to the buffer zone, a sequence of smaller reductions can be specified, as the storage volume falls into progressively lower subzones or levels.

2.8 Conditional Rule Curves

In some cases conditional rules have been defined for multiple reservoir systems. These policies define reservoir releases not only as a function of the existing storage volumes and time of year, but also as a function of the expected natural inflows into the reservoirs for some predefined time period in the future. Such policies can be described as functions, in tabular form, or as a diagram. While approximate methods for determining these conditional rules exist, Beard, L.R (1976), research continues towards finding improved methods for defining conditional operating policies for multiple-reservoir systems.

In addition to the general components of operating policies and their modifications as illustrated above, there is also the use of computer programs developed to be run each time a new release decision is to be made, as a support to those responsible for multiple-reservoir operation [Sigvaldason, O.T., R.Ellis and R.B.Allen(1975), Yeh. W.W-G., et al. (1975)]. Input data for these programs usually include flow forecasts, the current state of the reservoir system, the system operating policies, and appropriate objective functions for reservoir operation. The program output includes computed releases at each reservoir site or control structure that will best satisfy the prescribed operating objectives. When revised estimates of future inflows, storage volumes, and possibly economic environmental or ecological parameters are obtained, the program is rerun to obtain new estimates of appropriate reservoir releases, and their respective impacts. This process can be repeated at regular intervals (daily or weekly or even hourly during flood events).

2.9 Operating policy analysis

Over the past several decades, increasing attention has been given to the use of mathematical (simulation and optimization) models for deriving operating policies of multi-reservoir systems. In some cases, with only small improvements in system operation (for example, only 1 or 2 percent increase in hydropower production), millions of dollars of additional annual economic benefits can be appreciated. This approval has been coupled with a considerable research attempt during the years, and has led to ongoing developments in the conceptual thoughts and the mathematical formulations for a variety of models. As a result, there are now available a variety of techniques for analyzing the operation of multi-reservoir systems used to satisfy collective water-based needs of river basins. The improvement of mathematical models for deriving optimal policies for scheduling releases for multi-reservoir systems has been much more difficult compared to that for single-reservoir systems. Much of the early developmental work was aimed at translating the release from a single reservoir into equivalent economic benefits. Optimization or simulation models were then used to develop time-based patterns of releases so that the total of the benefits over time was maximized. Many of these early developments were performed with either linear programming (LP) or dynamic programming (DP) optimization procedures.

These early single-reservoir operating models, however, proved to be both time consuming and expensive. In some cases, several hours of computer time were required to get an optimal solution, even when analyzing only a single reservoir. In analyzing two or more interconnected reservoirs, the problem, while simply modeled, often proved to be nearly unsolvable from a computational perspective. It is still not possible to find an explicit multiple reservoir operating policy that specifies the release that should be made from each reservoir as a function of;

a) The current storage volumes in all reservoirs,

b) The time period, and

c) The actual or expected natural inflows when these inflows are uncertain. Recent developments, however, have indicated significant premise in using optimization models for developing rule curves for system with several reservoirs, or for indicating the releases to be made from each reservoir on a real-time bases. When considering more than two or three reservoirs, it has been necessary to adopt a different modeling approach than that used for single-reservoir systems. Most of the work to date has focused on the use of simulation models, but limited use has also been made of optimization models for estimating policies which can then be more precisely evaluated using simulation. Since simulation models do not define the optimum policy or procedure to be used directly, it is necessary to use a trial-and-error procedure to look for an optimal or nearly optimal solution. To achieve this, it may be necessary to carry out a large number of simulation runs – which can of course be computationally expensive.

Simulation models, on the other hand, have certain other advantages. They usually permit more detailed representation of different parts of the system (such as detailed responses of individual reservoirs and channels or the effects of certain time-varying phenomena). They also a1low added flexibility in deriving responses which cannot always be readily defined in economic terms (Agricultural/irrigation, Hydropower, recreational benefits, conservation of fish and wild life, etc.). Finally, they provide an effective focus for dialogue with system operators (the ideas inherent in simulation modeling can usually be understood rare easily than the ideas in optimization modeling).

Simulations track the movement of water through a system while optimization programs search for an optimal operating policy to achieve a specific objective (Loucks et al, 1981; Simonovic, 1992; Wurbs, 1993; Labadie, 2004; Gourbesville, 2008).

To present a brief state-of-the-art overview of diverse modeling strategies which are being used to define policies and procedures for scheduling releases from multi-reservoir systems, the models have been divided into three general groups:

- Optimization models for single reservoirs;
- Optimization models for mu1ti reservoir Systems;
- Simulation models.

2.9.1. Optimization Models for Single Reservoir

In a broad sense, optimization includes human judgment, use of simulation and/or optimization models, and use of other decision support tools. However, the term optimization is often used synonymously with mathematical programming to refer to a mathematical formulation in which a standard algorithm is used to compute a set of decision variable values that minimize or maximize an objective function subject to constraints. Optimization models automatically search for an optimum set of decision variable values (Wurbs and James, 2001).

The early concepts for defining reservoir releases were based on adaptations of inventory theory. The initial connection was developed by (Little, 1955), who used a DP approach to develop an operating policy for minimizing power production costs in a mixed hydroelectric-thermal system. (Manne, 1960) showed that LP could also be adapted to inventory problems, later on; he showed how this method could be used for deriving reservoir release policies in which the supply is uncertain. He represented time as a series of individual time intervals and then considered the release in each period to be a function of storage at the beginning of the period and of average inflow rate during the period (Manne, 1962). (Thomas and Watermeyer, 1961) used a slightly different approach, but again used LP to solve the same problem. They assumed that inflows had known probability distributions, but were independent or serially correlated random events (Watermeyer. P. and H.A. Thomas J r., 1962). Others adopted the Thomas and Watemeyer approach in principle and carried out more detailed investigations [(Dietrich, G. N. and O.P. Loucks, 1967), (Gablinger, M. and D.P. Loucks, 1970), and (Loucks, D.P., 1970)].

In parallel with developing the use of LP models for defining optimal release policies, other techniques were being followed. In 1962, Bather developed an approach based on the use of DP. (Falkson, 1961) also developed an approach which is based on the combined use of LP and DP and is referred to as the "policy iteration” approach. In 1963, Buras used DP for scheduling releases from a combined reservoir-aquifer System.

All the models described above can be classified as being “explicit stochastic models," i.e., they use probability distributions of inflow directly in deriving optimal release policies (Roefs, 1970). Despite the different techniques which were developed, many of the models proved to be very expensive from a computational perspective. In their 1970 paper, for example, (Gablinger and Loucks ,1970) showed that a single reservoir operating problem in the northeastern U.S., if solved using LP, required about 2,000 equations, 15,000 variables, and 2 hours of computer time (on a 360/65 computer [announced in 1960’s by IBM]). Even though the same solution would be obtained more efficiently with the use of DP, such a model would require more programming effort. (Loucks and Fa1kson, 1970) compared the use of stochastic LP, DP, and policy iteration methods. They concluded that the use of LP to determine sequential operating policies for 1arge mu1ti-period problems was the most expensive computationally and that, for all practical purposes, its use was limited to analyzing only single-reservoir systems in which the number of possible distinct storage volumes, inflows and time intervals was comparatively small. Although the other two methods were also computationally expensive, they appeared to show more promise in applications to multi-reservoir systems.

2.9.2. Optimization Models for Multi-Reservoir systems

Since the early development of single-reservoir optimization models, considerable work has been carried out in extending some of the modeling strategies to multi-reservoir systems. As anticipated, the amount of development based on using the explicit stochastic approach has been limited. In 1968, Roefs demonstrated that this strategy led to increasing computational effort as the number of reservoirs increased. One known application using this method on a mu1ti reservoir system was performed by (Schweig and Cole, 1968). They applied DP to a two reservoir system and found that computational costs were high, even when using only very simplified stream flow representations. Similar results were found by (Gablinger, 1971) and (Houck and Cohon ,1978).

2.9.3. Multi Reservoir Simulation Models

Simulation is a modeling technique that is used to predict the behavior of the system under a given set of conditions, representing all the characteristics of the system largely by a mathematical or algebraic description (cited in Yeh, 1985).

Simulation models continue to be used widely for analyzing water resources systems. This is especially true for systems with many reservoirs as well as for those which have non quantifiable benefits. While there are literally thousands of simulation models being used in practice by water management agencies to support reservoir system planning and/or operation decisions.

For providing useful framework in terms of testing specific possibilities for tandem or parallel reservoir operation simulation modeling was used. Here selected simulations software and joint operations for reservoirs in series or parallel in all levels will be discussed. Some of the models are HEC-3, SIMYLD-II, Oswego system, Acres mu1ti reservoir model, HEC-5, SUPER, HEC-ResSim, RiverWare, MODSIM, HEC PRM and WRAP.

Among these models, the USACE Southwestern Division Reservoir System Simulation Model (*SUPER*), USACE Hydrologic Engineering Center (*HEC*) Reservoir System Simulation (ResSim), River and Reservoir Operations (*RiverWare*), Generalized River Basin Network Flow Model (*MODSIM*) modeling systems, the Hydrologic Engineering Center (*HEC*) Prescriptive Reservoir Model (*PRM*) and Water Rights Analysis Package (*WRAP*) are representative of state-of-the-art reservoir/river system modeling capabilities in general and are particularly pertinent to practical applications by water resources planning and management agencies in Texas and elsewhere (Wurbs 2005a). A detailed review of the literature of simulating reservoir system operations is provided. Out of these models the recent models are of special interest.

HEC-3 Modeling System

The first of these is the HEC-3 model developed by the U.S. Corps of Engineers. The purpose of this model is to simulate the response of water resource systems designed to simultaneously satisfy a variety of water-based requirements. This model is sufficiently flexible to comprise any arbitrary configuration of reservoirs and channels. The algorithm searches through the system in the upstream to downstream direction, determining each system requirement in turn and the amount of that requirement to be satisfied by each reservoir. Since individual project responses are not identified until the entire system is searched, it is usually necessary to make three sequential searches through the entire system in each time interval in order to attain the desired reservoir balancing. The model then proceeds to the next time interval (monthly time intervals are typical) and the procedure is repeated. After proceeding through a11 time intervals, which may take account of several years of hydrology, simulated responses are appropriate1y summarized.

One particular development in HEC-3 is of special interest. While the idea of maintaining time-based rule curves to represent ideal operating levels for each of the various reservoirs was retained, this was supplemented with the idea of reservoir zoning (see Figure 2.11 a). Each reservoir would have a number of zones (typically about 6), with each zone representing a specific level range. The algorithm was then structured so as to bring all the reservoirs to the same zonal position if the optimal (or rule curve) level could not be attained. This idea permitted considerable flexibility in representing a variety of different operating policies. These included both reservoir ranking as well as policies based on ensuring that deviations from optimal operating levels were distributed in some reasonable way.

The HEC-3 model has been used widely in practice. This is due not only to both the general and flexible nature of the HEC-3 program, but also to the fact that the model is well documented and well supported. Representative applications include the Corps studies of the Willamette River system in Oregon and the series of operational studies on the Arkansas-White-Red system in the southern United States [(Beard, 1975), (Frederich and Beard, 1972)]. For the Arkansas-White-Red system, one of the more recent representations consisted of 18 reservoirs, 15 service locations and 8 hydroelectric power plants. Water-based needs include hydropower, navigation, recreation and flood control. The model was used to derive optimal operating policies by simulating various strategies for a 21-year hydro1ogic sequence.

SIMYLD-II Modeling System

A second model which is also of special interest is the SIMYLD-II model which was developed in the research portion of the Texas Water Study. This model is a multi reservoir simulation model. I n each time interval, however, an optimization sub model, using the out-of-kilter algorithm, is used to define the optimal operating strategy. The objective of the sub model is to minimize system costs (primarily pumping costs) in each time interval. Policies of operation are represented by varying the limit constraints of each arc which represent either reservoir releases or storage values.

Oswego Modeling System

A third model is the multi-reservoir model developed for the Oswego system by the New York State Department of Environmental Conservation (Tedrow, 1970). This particular model is of concern because it extended some of the fundamental ideas of multi-reservoir zoning inherent in the U.S. Corps HEC-3 model. The number of zones was reduced to four. These were referred to as the flood control, conservation, buffer and inactive zones (see Figure 2.11 b).

The flood control zone was used as short-term storage for alleviating downstream flood damage during periods of excessive inflow. Likewise, during periods of abnormally low inflow, the buffer zone could be used for releasing minimal flows to assure essential downstream needs only. The conservation zone represented the zone of normal operation, with the ideal operating level being implicitly positioned at the top of this zone. The inactive zone, situated under the buffer zone, defined the range of levels which are usually not available for regulation purposes. The algorithm for the Oswego simulation model was based on maintaining all reservoirs at the same zonal position, if ideal operating levels could not be achieved (similar in concept to the HEC-3 model). Downstream flows were adjusted in accordance with the zonal position of the upstream reservoirs. However, since the model was designed particularly for the Oswego system, it cannot readily be adapted to other multi-reservoir systems.

Acres Mu1ti Reservoir Modeling System

The fourth model is the Acres mu1ti reservoir model, which was initially developed for exploring alternative strategies for operating the Trent River Basin in Ontario, Canada (Sigvaldason, 1975 and1976). The algorithm for this model was an adaptation and extension of the basic ideas contained in all three models explained above. It included the combined rule curve-zoning representation which was inherent in both the HEC-3 and Oswego models. However, this representation was extended by including an additional “spill zone” and by having the rule curve positioned anywhere in the conservation zone (and not necessarily only at the top of this zone).

Additional flexibility was achieved by representing flows in the various channels by a series of flow ranges. This permitted not only a balancing of the relative levels in the individual reservoirs, according to equal function, priority ranking or storage lag policies, but also a general balancing of reservoir levels with channel flows.

As with the SIMYLD-II model, the Acres model used the out-of-kilter optimization routine as a sub model for achieving optimal responses during individual time intervals. However, instead of minimizing system cost, which the SIMYLD model did, the objective function in the Acres model was designed to reflect the chief operator's optimal decision and monitoring process for a particular operating policy. For any given hydrologic condition, it was perceived that the operator would minimize a combined sum of penalized deviations from ideal operating conditions for the system as a whole. Each of the deviations, which were either violations from reservoir rule curves or channel flows outside "normal ranges," was penalized with representative "penalty coefficients.” By assigning appropriate values to the various penalty coefficients, it was then possible to reproduce the system response which the operator would achieve for the prescribed operating policy and given hydrologic conditions.

The Acres model, which was structured for any arbitrary configuration of reservoirs and interconnecting channels, has been used as an aid in defining reservoir operating policies for eight separate river basins. It has also been modified slightly and is now being used as a day to day operating tool for defining reservoir releases in the Trent River System in Ontario (Sigvaldason, Ellis and Allen, 1975)

HEC-5 Modeling System

The fifth, and perhaps the most commonly used of a11 reservoir simulation models in North America, is the HEC-5 computer program titled Simulation of Flood Control and Conservation Systems. This program, like HEC-3, was developed by the U.S. Army Corps of Engineers Hydrologic Engineering Center at Davis, California (Eichert, 1979) .As the title suggests, the model simulates the operation of any spatial configuration of multiple reservoirs with in a river basin, and can be used for studying proposed operating policies for both conservation and flood control purposes.

HEC-5 operation for flood control is based on the release of waters from the seasonal flood storage capacity of each gated reservoir as quickly as possible without exceeding certain predefined maximum flows that would cause flood damage at various downstream sites. Where the choice of which discharge rates should be made from which reservoirs, the decision is based on a pre specified ba1ancing rule, similar to those used to balance conservation storage volumes in multiple reservoirs. Stream flow routing effects are considered, as they together with the discharge rates determine the spatial and temporal distributions of f1ows downstream from various reservoirs.

The HEC-5 conservation operation attempts to meet all downstream demands without wasting water. The program time steps can be as short as one hour for flood control, or as long as one month for conservation operation. During flood periods these time sequences can be combined to consider flood and conservation operation simultaneously.

While the model is primarily for hydrologic simulation it can also be used to evaluate economic effects of flood control and hydropower. Through simulation of alternative operating policies, rule curves can be improved and the sizing and location of potential reservoirs can be studied. HEC-5 provides a means of accurately simulating and refining the results of any optimization model developed and used for the preliminary definition of multiple reservoir operation policies. The model is well documented and maintained for anyone's use by HEC. During 1979 over 500 executions of HEC-5 were recorded per month on the HEC-maintained HEC-5 program and over 70 source decks were distributed.

Multiple reservoir simulation models used to assess the impact of various operating policies are useful only if the multitude of data derived from all simulations can be compared and evaluated. Obviously the means and variances, and even the time distribution, of various site specific variables such as reservoir storage volumes and releases, and their associated benefits or losses, can be computed and used for policy evaluation.

SWD SUPER Modeling System

The SUPER model was developed by the Southwestern Division (SWD) of the U.S. Army Corps of Engineers (USACE) and has been applied by the SWD office in Dallas and the Forth Worth, Tulsa, and Little Rock District offices of the SWD. SUPER is a system of computer programs designed to simulate the daily sequential regulation of a multipurpose system of reservoirs and the corresponding hydrologic and economic impacts (Hula 1981). A simulation reflects a specified regulation plan, economic parameters, and long sequences of daily flows and net reservoir evaporation rates.

Multiple simulations are performed to compare alternative variations in regulation plans. Simulation results include stage or discharge hydrographs for each reservoir and river control points, which may also be integrated with economic benefits functions.

Hydrologic results may be expressed as monthly and annual frequency relationships for maximum and minimum reservoir storage and stream flow, storage and flow duration relationships, and diversion and in stream flow shortages. Economic results may include flood damages, recreation benefits, power value, cost of purchased power, dredging costs, and navigation costs (Wurbs 2005a).

HEC-ResSim Modeling System

The ResSim modeling system (USACE, 2007) was developed by the USACE Hydrologic Engineering Center as the successor to the HEC-5 Simulation of Flood Control and Conservation Systems model. The object-oriented ResSim is composed of a Graphical User Interface (GUI), a computational program to simulate reservoir operation, data storage and management capabilities, and graphics and reporting facilities. ResSim has three sets of modules for providing access to specific types of data within a watershed. These models are Watershed Setup, Reservoir Network, and Simulation.

Each module has specific purposes and an associated set of functions accessible through menus, toolbars, and schematic elements. The computational time interval is 15 minutes to a day. The routing methods of stream flow are coefficient routing, Muskingum, Muskingum-Cunge, modified Plus routing, and a routing methodology from the USACE stream flow Synthesis and Reservoir Regulation (SSARR) model. The simulation progresses from upstream to downstream. Single or multiple reservoirs are modeled, with each reservoir having multi-purposes pools and multiple outlet structures. Operations are controlled by specified goals and constrained governing releases. The case study river/reservoir system was modeled with both HEC-ResSim and the expanded WRAP-SIM simulation model for comparison and testing of modeling capabilities.

RIVERWARE Modeling System

The objected-oriented RiverWare modeling system (Zagona et. al. 2001) was developed by the Center for Advanced Decision Support for Water and Environmental Systems at the University of Colorado, sponsored by the U.S. Bureau of Reclamation and the Tennessee Valley Authority. The computation time interval is an hour to a year.

Options are provided for pure and rule-based simulation and optimization. The pure simulation solves a uniquely and completely specified problem. Each object should have enough information but not more information than is required. Each object has a number of dispatch methods that map the input/output configuration specified by the user to the correct solution algorithm. The rule-based simulation does not require information associated with the objects to obtain a solution. The additional information required is generated by prioritized policy statements (rules) that are specified by the user and interpreted by the rule processor. The optimization uses a linear programming (LP) solver, which is combined with preemptive goal programming. The optimization constraint editor and expression language in RiverWare are designed to allow the model user to provide required input information without necessarily having to be proficient in linear programming.

HEC-PRM Modeling System

The Hydrologic Engineering Center (HEC) Prescriptive Reservoir Model (PRM) was originally developed in conjunction with studies of reservoir systems in the Missouri and Columbia River Basins (USACE HEC February 1991, October 1991, 1992, 1993).

However, the generalized model can be applied to any reservoir system. HEC-PRM is a network flow programming model designed for prescriptive oriented applications. Improved network flow computational algorithms have been developed in conjunction with the model.

HEC-PRM is used in combination with the HEC-DSS (Data Storage System) which provides input data preparation and output analysis capabilities. Studies to date have used a monthly time interval with historical period-of-record, or a critical sub-period thereof, hydrology.

Reservoir system operation is driven by user-inputted convex cost based piecewise linear penalty functions (dollars versus storage or flow) associated with various purposes including hydroelectric power, recreation, water supply, navigation, and flood control. The model minimizes a cost based objective function. Noneconomic components can also be included in the basically economic HEC-PRM objective function. User-specified lower and upper bounds on flows and storages are reflected in the constraint equations. Unlike MODSIM, the HECPRM performs the computations simultaneously for all the time intervals. Thus, the HEC-PRM results show a set of reservoir storages and releases which would minimize cost (as defined by the user-inputted penalty functions) for the given inflow sequences assuming all future flows are known as release decisions are made during each period.

MODSIM Modeling System

MODSIM was developed at Colorado State University (Labadie et al. 2000). The computational time interval is a month, week, or day. The objected-oriented simulation model is based on network flow programming and user-specified priorities. The objective function consists of the summation over all links in the network of the flow in each link multiplied by a priority or cost coefficient. The user assigns relative priorities for meeting diversion, instream flow, hydroelectric power, and storage targets, as well as lower and upper bounds on flows and storages. The program is divided into two functions; a graphical user interface allows the model user to build the river/reservoir system topology, and river/reservoir system as a network of nodes connected by links.

The nodes represent river gages, diversion dams, and tributary confluences, sites where return flows enter the river, consumptive diversion, instream flow requirement, reservoir, hydropower plants, and appurtenant structures. The links represent artificial, general flow, natural flow, storage ownership, and accrual. Tables 2.1 and 2.2 summarize reservoir system models and analysis methods

Table 2.1 Structure of some of the Alternative Modeling Systems

Model	**Organizing Computation Structure**
SUPER	Ad hoc simulation computations progressing from upstream to downstream
ResSim	Object-oriented ad hoc simulation progressing from upstream to downstream
RiverWare	Object-oriented, options for pure and rule-based simulation and optimization
MODSIM	Objected-oriented based on network flow programming & user-specified priorities
WRAP	Ad hoc simulation progressing in order of user-defined priorities

Source: Wurbs (2005b)

Table 2.2 Characteristics of the Alternative Modeling Systems

Model	**Language**	**Method**	**Time Step**	**GUI**	**Graphics**	**Cost**
SUPER	Fortran	ad hoc	Day	No	No	Free
ResSim	Java	ad hoc	15 min to day	Yes	Yes	Free
RiverWare	C++	ad hoc/LP	Hour to year	Yes	Yes	Proprietary
MODSIM	C,C++	LP	Month, week, day	Yes	Yes	Free
WRAP	Fortran	ad hoc	Month, day, any sub-monthly	Yes	No	No

Source: Wurbs (2005b)

2.10. Hydroelectric Energy Development in Ethiopia

2.10.1. Historical overview

The first electric generator was introduced by emperor Menelik II in 1898 to light his palace in the capital city, Addis Ababa. Few years after the WWII, in1948, the electric sector became a state-run institution named “Shewa Electric Power”, with an authorization to generate, distribute and sell electricity (Worede, 2011). Its service was of course, confined to the town of Addis Ababa and its surroundings of the then Shewa province. Later on the firm undergoes a series of structural changes and reorganizations during different political regimes. In 1956, Shewa Electric Power was substituted by the Ethiopian Electric Light and Power Authority (EELPA). After this period, electric service extended to provincial and other smaller towns in the country at a slow rate with incomplete spatial coverage (Solomon 1998). Shortly after the fall of the military regime in 1991, EELPA was restructured and reorganized in 1997 and named Ethiopian Electric Power Corporation (EEPCo). This public firm is in charge for producing, transmitting, distributing and selling electricity all over the country (Solomon 1998, UNESCO, 2004).

2.10.2. Hydroelectric generation

Hydropower is not a new source of electricity in the history of Ethiopia’s energy sector. Its beginning goes back over seventy years. The first hydroelectric dam in production was Aba-Samuel hydropower plant some 30 km south west of Addis Ababa, commissioned in 1939 with a generating capacity of 6.6MW (Solomon 1998, UNESCO 2004). Then about 70km south of Addis Ababa on the Awash River, the Koka hydroelectric plant started service in 1960 with an installed capacity of 43MW. Later on several other power plants were commissioned at different locations around the country (table 2.3).

In general, the beginning and expansion of electricity in Ethiopia as part of transformation had a center-periphery characteristic starting at the Menilik II palace, the capital city Addis Ababa, the towns around the capital city, i.e., the then Shewa province and then to other major towns of the country. The other important point is the central role of hydropower in the process of modern electric supply in Ethiopia. It began serving around the same period with many other hydropower dams in the western countries. The issue, however, is this sector didn't show a marked development even if it has a long history of giving modern services in Ethiopia.

Table 2.3 Existing Hydropower Plants and Installed Capacity

S.No.	Stations	Capacity (MW)	In-service Date
1	Koka	43.20	1960
2	Awash II	32.00	1966
3	Awash III	32.00	1971
4	Finchaa	134.00	1973/2003
5	Melka Wakena	153.00	1988
6	Tis Abay I	11.40	1964
7	Tis Abay II	73.00	2001
8	Gilegel Gibe I	184.00	2004
9	Tekeze	300.00	2009
10	Gilgel Gibe II	420.00	2010
11	Beles	460.00	2010

Source: Extracted from EEPCO's "Facts in brief" 2009/10.

2.10.3. Projects identified for Power development in Ethiopia

2.10.3.1. The Hydropower Potential of Ethiopia

Ethiopia has a huge hydropower potential, which is estimated to be about 15,000 - 30,000 MW. So far very little percentage (less than 2%) of the vast potential has been exploited. In order to develop this vast potential of power several projects have been initiated to generate more and more hydroelectric power.

Some 300 hydropower plant sites in the whole eight river basins of the country with a total technical power potential of 158,700 Gwh/year have been identified. Out of these potential sites, 102 are large scale (more than 60 MW) and the rest are small (less than 40 MW) and medium scale (40-60 MW) hydropower plant sites summarized in Table 2.4.

2.10.3.1.1. Large Scale Hydropower Projects

The favorable sites for Large Scale Hydropower Development Scheme within river basins of Ethiopia are 102 in number and are reasonably distributed throughout the width and breadth of the country. As the development of these schemes requires huge investment, they are not in the priority list by the government. Nevertheless, projects like Gilgel Gibe III (1800 MW) and GERD (6000MW) hydropower projects are presently under construction, and they are assumed, when commissioned, would alleviate the current critical power shortage to a certain degree to meet the GTP.

2.10.3.1.2. Medium Scale Hydropower Projects

The promising and candidate sites for the development of Medium Scale Hydropower Development are 25 in number. From these potential sites three in Tekeze, three in Gojeb and one in the Blue Nile Basin had been selected for studies.

2.10.3.1.3. Small Scale Hydropower Projects

The potential for small Scale Hydropower development are immense and amount to 173 in number. The development of these potentials needs also to be given special attention and encouraged along with the Medium Scale Hydropower Schemes especially in the rural areas of the country. Ways and means should, therefore, be required and facilitated in harnessing small hydropower resources in Ethiopia even if it is not encompassed within the top priority lists. These are areas where private participation should be fully supported and encouraged in developing these untouched resources without any limitations.

Table 2.4 Hydropower Potential of Ethiopia

Name of River Basin	**Number of Potential Sites**					
	Small Scale <40 MW	**Medium Scale 40-60 MW**	**Large Scale > 60 MW**	**Total**	**Technical Hydropower Potential (GWh/year)**	**Percentage Share of the Total %**
Abbay	74	11	44	129	78,800	49.7
Rift Valley Lakes	7	-	1	8	800	0.5
Awash	33	2	-	35	4,500	2.8
Omo – Gibe	4	-	16	20	35,000	22.1
Genale – Dawa	18	4	9	31	9,300	5.9
Wabi Shebelle	9	4	3	16	5,400	3.4
Baro Akabo	17	3	21	41	18,900	11.9
Tekeze– Angereb	11	1	8	20	6,000	3.8
Total	**173**	**25**	**102**	**300**	**158,700**	**100**

Source: EACE, 1998

2.10.4. Committed generation projects and Supply-Demand balance

Once the planned Power plant projects are completed, the projected 'demand-supply 'balance is expected to be as shown in the following two tables, one with own demand and the other with export demand of Sudan and Djibouti as pointed out in the respective feasibility studies of interconnection.

Table 2.5 Projected Supply and Demand Balance-Own Demand

	Short Term (To 2009)		**Medium Term** (To 2011)		**Medium Term** (To 2013)		**Medium Term** (To 2016)	
	Energy (GW.h)	**Power** (Mw)	**Energy** (GW.h)	**Power** (Mw)	**Energy** (GW.h)	**Power** (Mw)	**Energy** (GW.h)	**Power** (Mw)
Forecast Demand								
Target scenario	5,708	1,360	7,856	1,920	10,309	2,456	15,309	3,039
Moderate scenario	5,041	1,201	6,603	1,573	8,245	1,964	11,398	2,715
Existing and Committed supply capability	6,600	1,794	7,301	1,894	7,301	1,894	7,301	1,894
Projected needs								
Target scenario	Nil	Nil	555	26	3,008	562	8,008	1,145

NEW Plant Required

Table 2.6 Projected Supply and Demand Balance-With Export Demand of Sudan & Djibouti

	Short Term (To 2009)		**Medium Term** (To 2011)		**Medium Term** (To 2013)		**Medium Term** (To 2016)	
	Energy (GW.h)	**Power** (Mw)	**Energy** (GW.h)	**Power** (Mw)	**Energy** (GW.h)	**Power** (Mw)	**Energy** (GW.h)	**Power** (Mw)
Forecast Demand								
Target scenario	6,509	1,610	9,958	2,220	12,442	2,756	17,411	3,039
Moderate scenario	5,842	1,445	8,706	1,873	10,348	2,264	13,500	3,015
Existing and Committed supply capability	6,600	1,794	7,301	1,894	7,301	1,894	7,301	1,894
Projected needs								
Target scenario	Nil	Nil	2,657	326	5,141	862	10,110	1,145

NEW Plant Required

Source: EEPCo, Ethiopian Power System Expansion Master Plan Update (EPSEMPU).

2.11 Hydropower Production from the HAD

The power station of the HAD comprises 12 generating units each having a capacity of 175MW. Each generating unit is equipped with a Francis turbine (Moussa et al., 2001).The first unit was put into operation on 15 October 1967, HAD hydropower plant began generating power at that time with an output of 71 GWh in 1967, and gradually increased production to about 3,700 GWh in 1972 against a total power generation in Egypt of 7,400 GWh, i.e. about 50% of total power generated at that time. Production by the HAD hydropower plant is now about 8000 GWh/year (Abu-Zeid and El-Shibini, 1997).

Respectively, the power generated from the turbines is transmitted through transmission overhead lines to the load centers on voltage Levels 500, 132 kv (MEE, 2005). The turbines are designed to operate within 50 to 74 meters net hydraulic head, implying that power generation below 160 meters wears out the turbines and therefore not desirable (Georgakakos et al., 1997).

The water discharge gradually raise from1,504.63 m^3/s to 2,546.30 m^3/s (130 MCM/day to 220 MCM/day) from April until August and then declines from 1,388.89 m^3/s to1,504.63 m^3/s (120 MCM/day - 130 MCM/day) in November. The minimum flow period is November to March. The minimum discharge reaches about 1,250 m^3/sec (108 MCM/day). The central load dispatching centre schedules generation for successive 10 day periods based on projections of water flow received from the Ministry of Water Resources and Irrigation. Daily modifications are introduced according to actual conditions (Mobasher, 2010).

2.12 Toshka Spillway

According to rules of operating the HAD reservoir, the flood control capacity must be emptied down to level 175 m. before the arrival of the following flood; this will result in releasing high discharges that may reach 4,050-4,630 m^3/s (350-400 MCM/day). In this case, further degradation is anticipated. This may affect the river bed downstream the control structures existing on the river, the canal intakes and water pumping stations etc. To avoid this it was decided to link Lake Nasser at (khor Toshka) to (Toshka depression) in the western desert by an artificial canal to act as additional spillway (Mahmud et al., 2006).

Toshka spillway has played a significant part in flood control and management, during years 1998-2002, the flood classification in these years was "high floods". The total discharges passed through Toshka Spillway during this period were 41 BCM (Mahmud et al., 2006).

The project was executed during 1978-1982. It is located 250 km upstream of the Aswan High Dam on the left side of the Nile. The project includes of Khor Toshka, Toshka canal and Toshka depression.

2.12.1. Toshka Spillway Outflow

In the case that the water level is higher than 178 meters, the excess water is diverted into Toshka depression through the free spillway of Toshka. The discharge is computed using a weir equation form (Fahmy, 2001):

$$Q = \beta * (H-H_{ot})\, g * 30.40 * 10^{-3} \qquad (2.2)$$

Where:

β is 19.0

g is 1.6667.

H is the average water level.

Hot is the crest level of the diversion (=178 meters).

Using the measured data of the water level upstream of HAD and the discharge of the Toshka channel for flood of year (1998/1999), another linear regression analysis equation is obtained by (Abdel-Moteleb and Saad, 2001). The equation is as follows:

$$Q = 519.84 H - 93{,}028 \quad (2.3)$$

Where:

Q is the discharge in m3/s.

H is the water level upstream of HAD in meters.

The calibration for the spillway indicates that the maximum discharge of the channel will be about 137 MCM/day (1,586 m3/s) at a water level of 182 m, instead of 250 MCM/day (1,894 m3/s) which was the designed discharge (Abdel-Moteleb and Saad, 2001).

2.13 Nile Water use

The majority of water balance studies of the Nile River have analyzed flows at Aswan. However, flow records over the past two decades have verified the importance of the different rainfall regimes over the catchments of the Blue Nile and White Nile Rivers. Flows in the White Nile River between 1962 and 1985 have increased by 32 %, or 8 BCM, above the 1912‑1961 mean. This occurred as flows in the Blue Nile River decreased by 9 BCM in the period 1965‑1986, or 16 % below their 1912-1964 mean. Although it could be inferred that the two rainfall regimes are negatively correlated, past records show that the relationship between annual inflow to Lake Victoria and recorded flows in the Blue Nile River at Khartoum is random (MacDonald and Partners, 1988). A main feature of the Nile flow series, apart from the high flow period at the end of the last century, is the sudden fall in discharge since the mid-1960s. This fall is more pronounced and persistent than any preceding low-flow period. An analysis of the long-term records of water levels measured with the Roda Island “Nilometer” indicates that during the past two centuries the variability of the annual flood far exceeded that of other periods since records began.

If we divide this yield into water units each amounting to 12 BCM the annual yield at Aswan would be composed of 7 units. The flows of the various tributaries at selected points in their equivalent units at Aswan are as shown in the following:

Bahr el Jebel downstream Lake Mobutu	2 units
Bahr el Jebel downstream the Sudd	1 unit
Sobat River	1 unit

White Nile	2 units
Blue Nile River	4 units
Atbara River	1 unit
Main Nile at Aswan High Dam	7 units

Source: Drawn based on data available at www.grdc.sr.unh.edu/

The Lake Nasser and Nubia reservoir is so huge that it permits storage of several years of average flow of the Nile (Evans, 1996.), completely eliminating the natural cycle of annual flooding in Egypt. To a large extent, Egypt has been unscathed by droughts owing to large over year storage in Lake Nasser. However, other factors have contributed to reducing the impact of drought. One of these is the exceptionally high water level in Lake Victoria, which has helped maintain higher flows in the White Nile River. The higher levels result from very heavy rainfall in Kenya and Uganda between 1961 and 1963 and above average rainfall since. The higher flows of the White Nile River have helped to compensate for lower discharges from the Blue Nile River, which have been more adversely affected by the Sahelian drought.

Chapter Three

Description of the Study Area

3.1 Location of Nile River Basin

The Nile River extends for some 6,700 km through much of the Northeastern Africa. The setting is highly variable and ranges from tropical rain forest to desert and from mountainous relief to areas which are below sea level. The Basin extends over many ranges and altitude and contains wide variation in climate. The climate ranges from desert conditions in the north, to tropical climates in the southern regions, and includes alpine extremes in mountain regions.

The main braches of the Nile River, the Atbara, the Blue Nile and the White Nile system form the feature of the Nile Basin. The White Nile source is from the Equatorial Lake Plateau (Burundi, Rwanda, Tanzania, Kenya, D.R. of Congo and Uganda), and the Blue Nile with its sources from the Ethiopian Highlands. The sources are located in humid regions, with an average rainfall of over 1000 mm/year. The arid region starts in Sudan, which can be divided into three rainfall zones: the extreme south of the country part at the present South Sudan where rainfall ranges from 1200 to 1500 mm/ year; the fertile clay-plains where 400 to 800 mm/year of rain falls per annum; and the desert northern third of the country where rainfall averages only 20 mm/year. Further north, in Egypt, precipitation falls to less than 20 mm/year.

The area of the Nile Basin represents 11.15percent of the total area of the African Continent and spreads over 35percent of the total area of ten riparian countries. Table 3-1 shows the share and contribution of the 11 riparian countries to the Nile Basin.

Table 3-1 Nile Basin: areas and rainfall by country.

Country	Country area (km^2)	Country Area within the basin (km^2)	As %of total basin area	As % of country area	Av. annual rainfall in the basin (mm)		
					Min.	Max.	Mean
Burundi	28,062	13,860	0.4%	49.4%	895	1 570	1 110
DR Congo	2,401,941	21,976	0.7%	0.9%	875	1 915	1 245
Egypt	996,960	302,452	9.5%	30.3%	0	120	15
Eritrea	121,722	25,697	0.8%	21.1%	240	665	520
Ethiopia	1,144,035	365,318	11.5%	31.9%	205	2 010	1 125
Kenya	593,116	51,363	1.6%	8.7%	505	1 790	1 260
Rwanda	24,550	20,625	0.6%	84.0%	840	1 935	1 105
South Sudan	635,150	620,626	19.5%	97.7%	0	1 610	600
Sudan	1,864,049	1,396,230	44.0%	74.9%	0	1 610	500
Tanzania	933,566	118,507	3.7%	12.7%	625	1 630	1 015
Uganda	241,248	240,067	7.6%	99.5%	395	2 060	1 140
For Nile basin	**8,984,399**	**3,176,721**	**100.0%**	**35.4%**	**0**	**2 060**	**615**
Source	GAUL(Global Administrative Unit Layers; Projected GCS-WGS-1984-UTM Zone 36N						

3.2 River Nile Watershed

Nile River has three main distinct regions see Figure 3-1, from where it obtains its flow. These are namely: the Equatorial Lake Plateau in the south, the Sudd (Bahr el Ghazal region in the center), and the Ethiopian Highlands in the east). From the confluence of the Atbara River north to the Mediterranean, see Figure 3-1, the Nile receives no effective inflow. The total estimated annual inflow entering Lake Victoria from stream flow and rainfall is 118 BCM while the evaporation is estimated to be 94.5 BCM, leaving only 23.5 BCM to flow down the Victoria Lake. In the Sudd the loss calculated as 33.9 BCM, leaving 15 BCM to flow the White Nile. In the High Aswan Dam Reservoir, the losses are calculated to be 10.5 BCM per annum, while the losses within Sudan downstream Malakal is estimated to be about 7.0 BCM per annum(UNESCO Regional Office in Cairo, 2007).

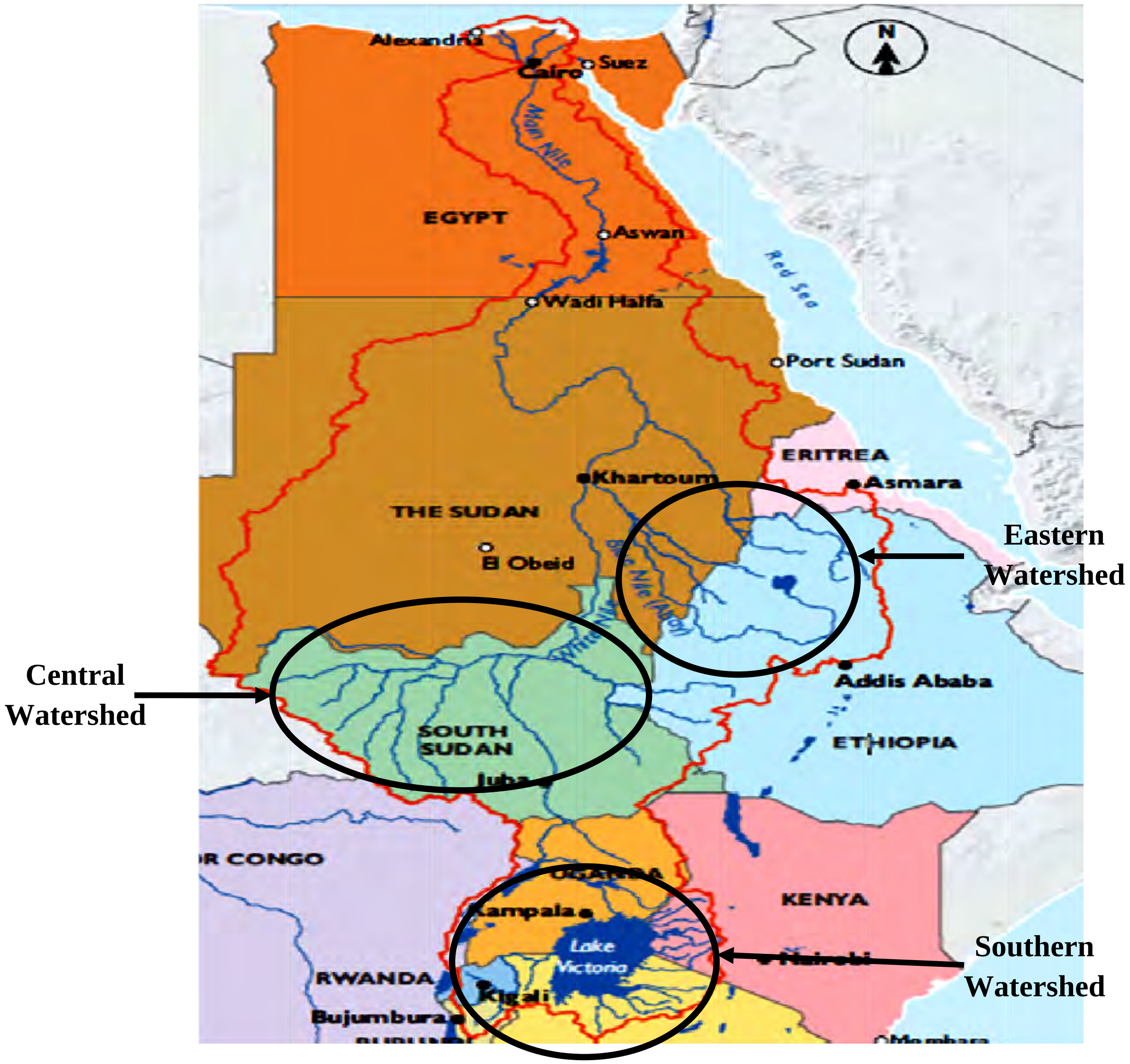


Figure 3-1 the three Watersheds of the Nile River. [Source: UNESCO Regional Office in Cairo, 2007]

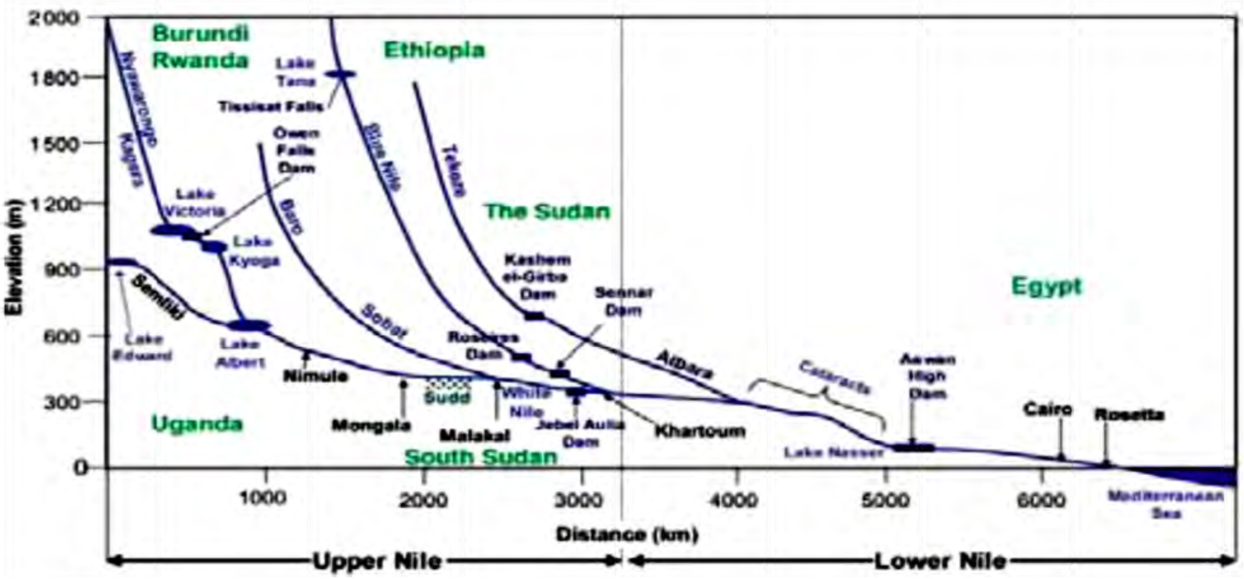


Fig 3-2 Elevation cross-section of the Nile Basin [Source: Adapted from the Nile River Awareness Kit, courtesy Hatfield Consultants Ltd.]

On the hand, the rest comes from the Ethiopian Highlands via the Sobat (13.5 BCM), the Blue Nile (54 BCM) and Atbara River (12 BCM). The White Nile is extremely well regulated with relatively constant contribution to the Nile River because of several lakes and swamps within the Sudd area. Flow from the Ethiopian Highlands is highly concentrated in the period from July to October where 85percent of the Nile River total flow occurs.

The Blue Nile is nearly dry from January through June and Atbara is normally dry during that period as well. (UNESCO Regional Office in Cairo, 2007)

The Atbara River joins the Nile River 300 km downstream of Khartoum and is the last major tributary of the Nile River. It originates in Ethiopia north of Lake Tana and is 800 km long. The Atbara River draws its floodwater from rain on the northern part of the Ethiopian Plateau, but it shrinks to a series of pools in the dry season. The Nile River then reaches Lake Nasser, 270 km from the border between the Sudan and Egypt.

The peak of the flood does not enter Lake Nasser until late July or August, when the average daily inflow from the Nile River rises to 7.7 BCM. Of this, 64 percent is from the Blue Nile River, 21 percent from the Atbara and Sobat Rivers and 15 percent from the White Nile River. The White Nile River provides a steady stream all year, therefore its crucial importance. In early May, the inflow into Lake Nasser drops to a minimum and the total discharge of 0.5 BCM/day comes mainly from the White Nile River. On average, about 85 percent of the water in Lake Nasser comes from the Ethiopian Plateau. The rest is contributed by the East African Plateau and its system of lakes.

3.3 Hydrology of the Nile

The Nile River obtains its flows from two major sources, i.e. the Equatorial lakes basin and the Ethiopian highland plateau.

The rough equivalents of these flows at Aswan are $12x10^9$ m^3/year from Equatorial lakes basin along with southern Sudan and 72x 10^9 m^3/year from the three rivers from the Ethiopian plateau. The total yield from Nile at Aswan is $84x10^9m^3$.

A. the Equatorial lakes basin with a very small contribution in southern Sudan contributes 15.5x 10^9 m^3 annually to the White Nile at Malakal. The Equatorial lakes basin is composed of:

i) Lakes Victoria and Kyoga basin feeding the Victoria Nile

ii) Lakes George and Edward basin together with Semliki river flowing into Lake Albert (Mobutu Sese-Seko) and

iii) Lake Albert basin from which emerges the Albert Nile which ultimately forms the Bahr el Jebel

B .The Ethiopian and Eritrean part of the Nile basin is composed of and their contribution annually as follows:

i) Sobat River Basin:	13 $5xl0^9$ m^3 to the White Nile at Malakal
ii) Blue Nile River basin:	$54.0xl0^9$ m^3 to the Nile at Khartoum
iii) Atbara River basin:	$12.5x10^9$ m^3 to the Nile at Atbara

C .The SUDD basin and the White Nile

D .The Main Nile River (from Khartoum up to the Mediterranean Sea)

3.3.1 Flow contribution of the Equatorial Lakes Basin

a) **Lake Victoria Basin**

This basin has an area of 263,000 km^2 of which 68,000 km^2 is the area of the lake. The elevation of the lake surface is about 1130 m above sea level. Mean annual rainfall of 1500 mm on the lake and 1150 mm on the catchment area surrounding the lake is received. Annual evaporation rate from the lake surface is about 1260 mm. The total net annual yield of water of Lake Victoria is 23.5 BCM.

Flows from the lake are discharged through the Victoria Nile to Lake Kyoga. This stretch of the river has a length of about 80 km. Elevation fall between Lake Victoria and Lake Kyoga is 102m.

b) **Lake Kyoga and Victoria Nile**

Lake Kyoga has an area of 1800 km^2 and is surrounded by a swamp of an area of 4520 km^2.It has an elevation of 1030 m above sea level. In addition, there is a catchment area of 75000 km^2 draining to the Victoria Nile and Lake Kyoga. Rainfall over the lake and its catchment area is about 1290 mm annually.

Regardless of such a high rainfall, an extremely high evapotranspiration (2230 mm/year) over the swamp surrounding the lake consumes much of the inflow resulting in a net water loss of about 1.0 BCM yearly.

Therefore, the average annual discharge from Lake Kyoga which receives 23.5 BCM /annum from Lake Victoria is 22.5 BCM.

The Victoria Nile flowing between Lake Kyoga and Lake Albert/Mobutu has a length of 410 km and fall a total of 412 m in elevation between the two lakes. It discharges an annual flow of 22.5 BCM to Lake Albert at its northern tip in Uganda.

c) **Lake Mobutu Sese Seko (Albert)**

This lake has an area of 5300 km^{2}. In addition to the Victoria Nile which enters the lake at the northern end, the Semliki River discharges its waters at its southern end. The Semliki River carries run-off from its own catchment and flows from lakes George and Edward further south. Lake Mobutu has a catchment area of 17,000 km^{2}.

Lake George and Lake Edward have surface areas of 300 km^{2} and 2200 km^{2} and catchment basin areas of 8,000 km^{2} and 12,000 km^{2} respectively.

The Semliki River which receives flows from these two lakes and also runoff from its own catchment delivers a total of 4.0 BCM of water to Lake Mobutu annually. Evaporation over Lake Mobutu is estimated at 1200 mm per annum and rainfall is 710mm.

Summarizing, the inflow and outflow of the lake is as follows.

Inflows:

From Victoria Nile	22.5x10^{9} m^{3}/year
From Semliki River	4.0xl0^{9} m^{3}/year
From Lake Mobutu Basin	2.5x10^{9} m^{3}/year
Direct Rainfall	3.6x10^{9} m^{3}/year
Sub-total	**32.6xl0^{9} m^{3}/year**
Evaporation Loss	6.3x10^{9} m^{3}/year
Net outflow from Lake Mobutu	26.3x10^{9} m^{3}/year

Lake Mobutu Sese Seko outflows discharge through the Albert Nile to Bahr el Jebel at Nimule town at the southern border of the Sudan. Taking water losses between Lake Mobutu outlet and Mongalla into account and taking into consideration run-off discharging into the river (Bahr el Jebel), the average annual discharge at Mongalla, which is considered the 'southern end of the Sudd, is about 30 BCM/annum. About half of this flow is lost by seepage, direct evaporation and evapotranspiration in the Sudd and thus the average flow reaching Malakal from Bahr el Jebel and Bahr el Zeraf is 15 BCM per annum.

3.3.2 Flow contribution of the Ethiopian River Basins to the Nile

a) Sobat River:

The Sobat River which is mainly made up of the two rivers of Baro and Pibor coming from the Ethiopian highlands joins the White Nile south of Malakal and contributes an average annual flow of 13.5 BCM.

b) The Blue Nile River:

The Blue Nile River originates from Lake Tana in the Ethiopian highlands. The river at the outlet from the lake has an average annual discharge of about 4 BCM. It is joined by several rivers originating in Ethiopia which discharge into it within Ethiopia. Two of its tributaries which have their catchments largely in Ethiopia, namely Dinder and Rahad, join the Blue Nile in the Sudan.

The Blue Nile joins the White Nile at Khartoum to form the Main Nile and discharges an annual flow of 54 BCM. This flow is estimated to be equivalent to 48 BCM at Aswan.

c) Atbara River:

The Atbara River known as Tekeze in Ethiopia drains the adjacent highlands north of the Blue Nile Basin. It joins the Nile River at Atbara town in the Sudan and discharges an annual flow of 12 BCM into the Nile which is estimated to be equivalent to 11.5 BCM at Aswan.

The Blue Nile and the Atbara rivers which drain the western highlands of Ethiopia and Eritrea get most of their yearly flow in the three months between mid June and mid September. Their flows are consequently torrential, characterized with aggressive floods and with heavy loads of silt. The fertile Nile delta in Egypt has been formed as an outcome of the silt transported down mostly by the Blue Nile and Atbara rivers.

3.3.3 The SUDD Basin and the White Nile

Bahr el Ghazal receives flow of a number of rivers draining western and south western Sudan bordering Zaire and the Central African Republic. The catchment has an area of 526,000 km^2 of which about 40,000 km^2 is swamp. nearly all of the inflow to Bahr el Ghazal from tributary rivers and direct rainfall on the swamp is lost in the swamp with only about half a billion cubic meters of water per annum reaching the White Nile at Malakal.

Considering this net contribution of flow (i.e. 0.5 BCM) from the Bahr el Ghazal basin, the total discharge from the Sudd to the White Nile at Malakal comes to 15.5 BCM /year. Thus the average annual flow of the White Nile at Malakal which is considered as the northern end of the Sudd region is as follows:

Contribution from Bahr el Jebel and Zeraf	$15.00x10^9m^3$/year
Contribution from Bahr el Ghazal	$0.50x\ 10^9m^3$/year
Contribution from Sobat River	$13.50x10^9m^3$/year
Total flow of White Nile at Malakal	**$29.00x10^9m^3$/year**

This figure after deducting losses becomes 24 BCM at Aswan in Egypt.

3.3.4 The Main Nile River:

Starting from Khartoum where the Blue Nile and the White Nile join, the river is named the Main Nile up to its confluence with the Mediterranean Sea. The Main Nile has a length of 3065km.The average annual flow of the Nile estimated at Aswan is 84 BCM.

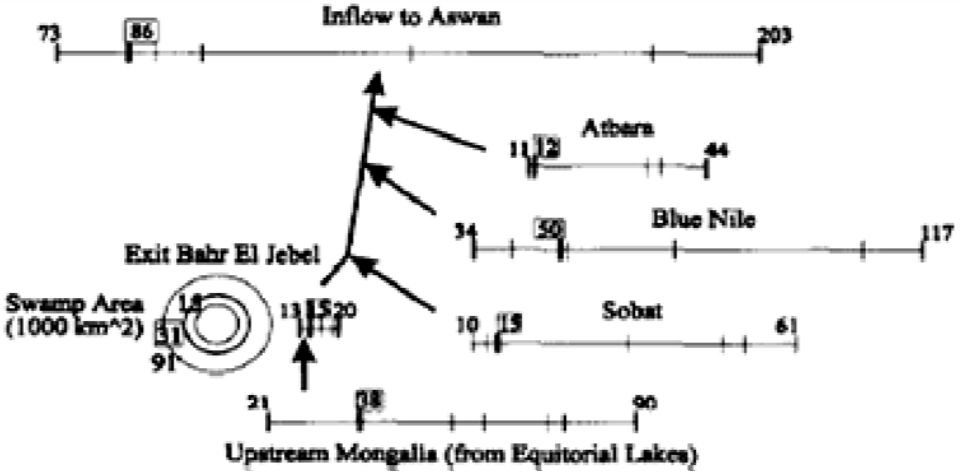


Figure 3.3 Range of discharges for major points along the Nile. (Yates, 1998)

The percentage contribution of the main tributaries of the Nile is as follows [Source: Ibrahim, 1985]:

Blue Nile	59%
Sobat	14%
River Atbara	13%
Bahr el Jebel	14%

In other words 85percent of the flow of the Nile comes from the Ethiopian plateau and only 15 percent comes from the other African riparian countries.

During flood time the percentage contribution of the tributaries is as follows:

Blue Nile	68%
River Atbara	22%
Sobat	5%
Bahr el Jebel	5%

In other words, during flood 95 percent of the water comes from the Ethiopian highlands and only 5 percent comes from East Africa. During the low flow period 60 percent of the water comes from Ethiopia and 40 percent from East Africa. The low contribution of the White Nile to the Main Nile is attributed to the great amount of water which is vanished by evaporation in the swamps while the Ethiopian plateau acts efficiently for draining the water to the Nile.

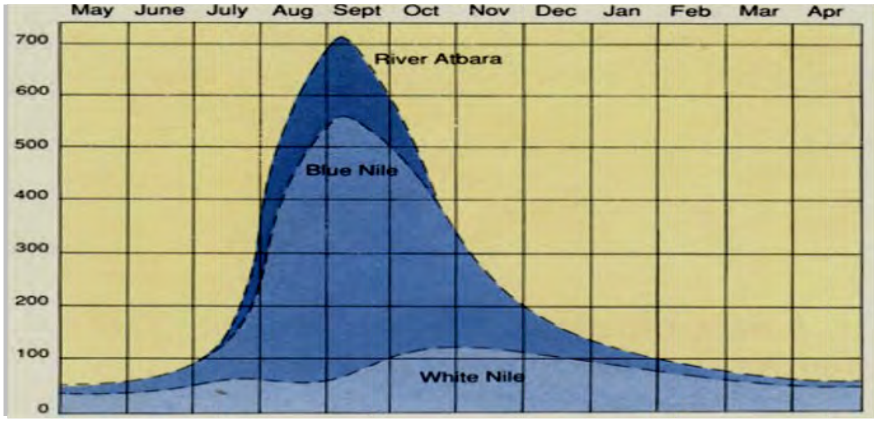


Figure 3.4 The flow rate of the Nile at different times of the year [Source: Arthur, 2004].

3.4 Nile Water use and early Plans

The Nile has provided the basis for agricultural expansion in Egypt for as long as agriculture has been known in that country. Irrigation in Egypt and Sudan started about 5000 years ago all along the banks of the Nile River mostly by flooding areas enclosed by artificial dikes in the form of basin irrigation. This system of irrigation with gradual introduction of water lifting devices during seasons of low flow continued mainly unchanged until the middle of the nineteenth century. As improved areas of irrigation required control of levels of Nile waters, the first man made structure, the Delta Barrage, was completed in 1861 at the head of the Nile delta feeding the main irrigation canals with water at all times from the natural flow of the Nile.

Sudanese irrigation cannot be supplied with adequate water except the floods coming from Ethiopia are retained in the identified huge reservoir of the Blue Nile.

These water saving schemes would need to be part of the overall integrated development of the Nile River Basin in full participation of all the upper riparian countries.

At the end of the nineteenth century, irrigated agriculture was constrained by inadequacy of low natural flow of the river.

The first storage dam on the Nile, the Aswan Dam, was constructed in 1902 with a storage capacity of 1.0 BCM.

As this storage dam proved successful, its height was later increased twice; once in 1912 and later in 1934 enlarging its storage capacity to 5.1 BCM. After the construction of the Aswan Storage Dam, constructions of additional barrages downstream in the delta were carried out to optimize use of the waters released from the Aswan Storage Dam. This significantly improved irrigation in Egypt.

Irrigation in Sudan has a similar evolution and parallel growth with that in Egypt .A major breakthrough came about with the construction of the Sennar Dam in 1925 on the Blue Nile for the irrigation of 1260 km^2 under the Gezira scheme. The Gezira project was later gradually expanded to the current total of 8400km^2.

Further irrigation expansion both in Egypt and in the Sudan was made possible after the construction of the HAD in Egypt in 1964 and Roseires Dam on the Blue Nile and Khashm el Girba Dam on the Atbara, both in the Sudan. These dams were constructed as a result of the Nile Water Agreement of 1959 between Egypt and Sudan which provided the framework for cooperation between the two downstream countries of the Nile basin. On the basis of the average long term natural flow of the Nile at Aswan of 84 BCM per annum, Egypt and Sudan agreed to share the assumed Nile yield at the Aswan Dam which would come to 74 BCM after deducting the estimated 10 BCM loss due to evaporation from the reservoir. Egypt's share was put at 55.5 BCM and that of the Sudan at 18.5 BCM. Under the terms of this agreement the two countries established a Permanent Joint Technical Commission to administer implementation of the agreement and to provide overall technical input in the harmonization of Nile waters development and operation in the two countries.

Presently Egypt is using 62 BCM yearly (including reuse) while Sudan uses about 16 BCM yearly.

According to the Nile Waters Agreement of 1959 the two countries have constructed the dams stipulated in the agreement in order to allow them to utilize their respective shares of the flow.

Hence, Egypt having constructed HAD with a large storage capacity almost double the average long term volume of flow at the site, can grab any flood coming from the upstream countries, mainly from Ethiopia, for its own use downstream.

HAD has also a hydroelectric power generating station with an installed capacity of 2100 MW. Old Aswan (I & II) has a total of 645 MW installed capacity of hydropower.

Egypt at present irrigates a total of 30,000km^2. Cropping intensity is about 190% and overall irrigation efficiency 65percent considering reuse of drainage water.

Sudan has constructed the Roseires dam on the Blue Nile River and the Khashm el Girba dam on the Atbara River in 1966 to store the floods coming from the Ethiopian highlands, for irrigation and production of hydroelectricity. The Roseires Dam has an original reservoir volume of 3.0 BCM and the Khashm el Girba 1.3 BCM both of which have at the present lost a big part of their capacity due to sedimentation. Roseires has a hydroelectric generating station of installed capacity of 250 MW. At present the Sudan has developed a total of 16800 km^2 under irrigation. It has a total of 278 MW of installed capacity for hydropower generation on the Nile tributaries.

Recently Sudan has heightened the Roseries dam by about 10 m. and increases its reservoir capacity to 7.1 BCM. This is to make extension of irrigation in the Sudan promising and to raise its power generation at Roseires.

Utilization of Nile waters in the upstream riparian countries is insignificant. No major construction in irrigation exists both in the Equatorial Nile basin countries and in Ethiopia. With agreement between Uganda and Egypt, a dam, i.e. the Owen Falls Dam, at the outlet of the Nile from Lake Victoria has been constructed to generate hydroelectric power for Uganda and to provide irrigation water for Egypt. The hydroelectric power station has an installed capacity of 150 MW. In Ethiopia a hydropower plant has been constructed with a dam having a reservoir volume of about 600MCM on the Fincha River and Tana Beles with a power generating capacity of 270 MW, which are part of the Blue Nile.

3.5 Current situation

3.5.1 Egypt

Egypt has an area of about 30,000km^2 under irrigation with an average cropping intensity of 190%. It uses up its share of water allocation given to it under the 1959 Nile Waters Agreement with the Sudan. It is now faced with water shortage to go for a major expansion of irrigation.

Egypt constructed the Aswan Dam in 1902 with a reservoir capacity of 1.0 BCM which was later raised to 3.5 BCM in 1912 and then to 5.1 BCM in 1934.HAD was completed in 1971 (filling of the reservoir started in 1964 at the completion of the cofferdam). The reservoir has a capacity of 164 BCM (of which 107 billion is active storage).

because it is now obvious that the Upper Nile riparian countries, that is, the Equatorial Nile basin countries and Ethiopia are interested in participating in the development of the Nile tributaries in their region, it would be fair to examine how best to fully control the Nile as a single hydrological unit and with the highest yield of water from the system.

3.5.2 Sudan

The Sudan has an area of about 40000km^2 under irrigation with a cropping intensity of 67 percent, it does not yet use up its share of 18.5 BCM of water per annum allocated to it by the 1959 Nile Waters Agreement with Egypt. Its current annual water consumption is estimated at 16 BCM (MIWR of Sudan)

The storage dams which it constructed to store water for its own use are;

a) **Sennar Dam**-Built in 1925 on the Blue Nile River with a storage capacity of 0.9 BCM and a hydroelectric power station of 15 MW installation.

b) **Roseires Dam**-Built in 1966 on the Blue Nile River with a storage capacity of 3.0 BCM and a hydroelectric power station of 250 MW installation.

c) **Khashm el Girba Dam -** Built in 1961 on the Atbara River with a storage capacity of 1.3 BCM and a hydroelectric power station of 13 MW installation.

d) **Jebel Aulia Dam -** Built in 1937 on the White Nile just south of Khartoum and having a storage capacity of 3.5 BCM was initially meant to control Nile flows for use in Egypt. After the construction of HAD, its main utility is restricted to providing services as a flood control reservoir for high flows coming from the Sobat River.

Ethio-Sudan border) is hot tropical with a dominant dry spell. Further in the south where altitude is higher (in the Sude watershed) climate is of the sub humid tropical type while to the north, around Khartoum and Rosaries reservoir, climate is hot tropical. Dry and hot tropical type of climate governs in the further northern reaches due to the wide coverage of the Sahara desert.

Rainfall: Rainfall in the sub basin varies seasonally and spatially. Spatial variability is both horizontal (south-north direction) and vertical (along the river course). Horizontal variation ranges from above 1,500 mm in the southern portion of its upper course to about 1,000 mm in the northern portion of its upper course. Likewise, in its lower course mean annual rainfall ranges from 700 mm (south portion at El-Damazin station) to less than 500 mm in its northern portion. Vertical variation ranges from above 1,500 mm (at the western highlands of Ethiopia) to 120 mm at Khartoum at its mouth. In the southern half of the upper course, the length of the wet spell is comparatively longer, lasting for more than five months (April/May to October/November). In most of the northern part of the upper course of the Blue Nile sub basin, the wet period is limited to less than three months and seasonal variability is higher.

Temperature: Temperature and evaporation are well correlated with altitude in the Blue Nile sub basin. At high altitudes (>2,300masl) in the western highland plateau of Ethiopia mean annual temperature is in the range of 17^0C to 19.5^0C. Temperatures rise close to the Ethio-Sudan border where altitude is lowered to less than 1,000 masl, ranging from 24^0C to 26.5^0C. At its mouth, around Khartoum, altitude is below 500 masl and temperature ranges from 28.5^0C to 30.5^0C.

Evaporation: Variation of evaporation follows the same pattern as temperature. In the upper course, evaporation is less due to high altitudes. Mean annual evaporation ranges from about 1,500 mm in the Highlands of the sub basin to more than 6,800 mm around Khartoum. Horizontal variation of evaporation is also significant. In the southern half of the upper course, mean annual evaporation is even below 1,500 mm and in the northern half, in particular at its northern tip, evaporation is above 1,800 mm.

Relative Humidity: Half the sub basin has a mean annual relative humidity of above 55 percent. Some 16 percent of the basin, largely located in its mouth, is dry with mean annual relative humidity of less than 40 percent.

3.6.2 The Baro-Akobo-Sobat-White Nile (BASWN)

The Baro, Gillo and large part of the Akobo watershed areas, located in the south-western highland plateaus of Ethiopia, have a dominantly tropical climate with distinct dry winter. The mean temperature of the coldest month is >18^0C and the mean annual rainfall in the range of 680-1200 mm and the dry months are in winter. Some portion of this area (some 10%) is identified to have tropical monsoon rainy climate with short dry season and some other parts (>5%) are identified to have warm temperate rainy climate with distinct dry season. The Pibor watershed starts in semi arid south eastern area of the Sudan land characterized with dry tropical type of climate. Alike the Sobat area, the WN watershed of the BASWN sub basin is also characterized with arid type of tropical climate.

The entire sub basin has distinct dry and wet seasons. In the summer, warm moist winds cover the whole sub basin, bringing the wet season to the complete upper course of the sub basin from April/May to October/ November. The Baro and Gillo watersheds have comparatively high moisture and longer wet periods. In the downstream reaches of these watersheds, moisture is limited with relatively shorter wet periods, with arid tropical climate dominating towards its mouth around Khartoum.

Rainfall: The sub-basin is in a particularly well-watered region of Ethiopia, but there is significant spatial variation of the mean annual rainfall due to the great range of difference in elevation across the basin. Average annual precipitation is as low as 600 mm in the lowlands (less than 500 masl), while it reaches as high as 3,000 mm over the highlands (over 2,000 masl). High altitude regions in the Baro and Gillo watersheds are characterized with relatively high moisture and longer wet periods. The rainy period is generally from May to October when 85% of the annual precipitation occurs with a single peak in July. Average rainfall is greater than 200 mm in June, July, August and September.

On average, November, December, January and February are dry months. Within Sudan the highest rainfall is found in the southwest and southeast of the Sub-basin where the mean annual rainfall exceeds 1,000 mm per annum. Over much of the Pibor-Sobat Sub basin it varies between 750 and 1,000 mm/year. In the White Nile Sub basin rainfall decreases northwards from 750 to 250 mm near the junction of the White and Blue Niles. Rainfall exhibits both seasonal and year-on-year variability. Variability increases form south to north.

Temperature: The temperature range in the sub basin is from about 27.5^0C below 500 meters elevation on the flood plain to about 17.5^0C at 2,500 meters in the highlands. Temperature is maximum in April and minimum in December. Maximum temperatures in the highlands rarely exceed 25^0C, whereas in the lowlands they generally exceed 36^0C during the hotter months of January to April. In the Pibor watershed it ranges from 24.5^0C to 26.5^0C. In the Sobat and Malakal areas where altitude is below 500 masl, temperature ranges from 26.5^0C, reaching to a range of 30.5^0C at the mouth of the sub basin around Khartoum. In the White Nile valley temperatures are generally $25\text{-}27^0$C along the river but decrease with altitude in the Nuba Mountains and towards the Ethiopian highlands.

Evaporation: Mean annual evaporation within the sub-basin varies from below 1000 mm in the highland plateaus of Ethiopia, to 6815 mm at Khartoum. Evaporation in the upper course of the Baro-Gillo watersheds ranges from 783 mm to 1200 mm. In the low-lying areas (<1000 masl) mean annual evaporation is in the range of 1200 mm to 2000 mm. In the upper course of Pibor and Akobo rivers (low lying areas in the land of Sudan) it ranges from 2000 mm to 3200 mm. At Khartoum, the mouth of White Nile, it ranges from 6500 mm to 7500 mm.

Relative humidity: About 50 percent of the area has a mean annual relative humidity exceeding 55 percent. Nearly 35 percent of the sub basin has a mean annual relative humidity ranging from 40- 55 percent, while less than 20 percent of the sub basin has a relative humidity of less than 40 percent.

3.6.3The Main Nile Sub-basin

Owing to its altitude, this portion of the Nile is known for its arid climate where moisture is almost non-existent. The presence of Nile has enabled to support life along its narrow banks of the downstream of Khartoum and HAD and into the large delta downstream of the Delta barrages. The delta, where life including green area in the system is confined, accounts for less than 5 percent of the area of Egypt. The Main Nile sub basin in both Sudan and Egypt has arid-desert to semi-desert climate, characterized by a long hot rainless summer and short rainy mild winter with scarce rainfall.

Rainfall: More than 65% of the sub-basin has mean annual rainfall of less than 50 mm and only 17 percent of the sub-basin has mean annual rainfall of above 100 mm. Mean annual rainfall at Khartoum is below 200 mm, which reduces to less than 20 mm at Atbara, and to less than 5 mm at Dongola and the HAD. At Cairo it is 25 mm and increases to 200 mm in Alexandria in the coastal line of the Mediterranean Sea. Average runoff over the entire area of the delta in Egypt is estimated at 1BCM, accounting only for 3 percent of the runoff reaching the Delta through the Nile system.

Temperature: Temperature in this sub-basin is very hot, due to the desert climate, with mean annual daily temperature varying from above 30^0C (around Dongola and HAD) to 18^0C in the coastal areas (Alexandria)The maximum air temperature increases generally from north to south. The difference between the maximum temperatures from north to south reaches 15^0C in May and June, and 5^0C in January. The hottest month in the north is during June, while August is the hottest month in the northern coast. The minimum air temperature in the Egyptian part of the sub basin is during January.

Evaporation: Evaporation is considerably high with lake evaporation at HAD estimated at 2.6 meter per year. Potential evapo-transpiration in the sub-basin is estimated at 6.8metres at Khartoum, 7.8 metres at Dongola, 5.8 metres at HAD and 1.8 metres at Alexandria on the coast of the Mediterranean Sea.

Relative Humidity: Nearly 85 percent of the sub-basin is dry with mean annual relative humidity of less than 40 percent. Only 5 percent of the sub-basin has mean annual relative humidity of above 50 percent. The highest relative humidity is over the northern coast of Egypt, being above 70 percent during summer, decreasing inwards to reach 20 percent far to the south with appreciable gradient at the north and weak gradient at the south. Furthermore, a steep relative humidity gradient is evident near the Red Sea coast, which weakens westwards.

3.6.4 The Tekeze-Setit-Atbara (TSA) Sub-basin

The TSA sub-basin has four climatic zones, (i) moist sub humid, largely prevails in high altitude areas (>2,500 masl) of the northern highland massive of Ethiopia; (ii) dry sub humid, in the central part of the upper course of the sub basin, (iii) semi-arid, virtually covering more than 80 percent of the upper course of the sub basin, and (iv) arid, in the low lying areas of the middle and lower courses of the sub basin in Sudan. The wet period in the upper course of this sub basin is restricted to two months extending from June/July to July/August, while the dry period is prevailing in the middle and lower course of the sub basin as a result of the vast Sahara Desert.

Rainfall: The mean annual rainfall in the TSA sub-basin is significantly lower than the Baro-Akobo and Blue Nile sub-basins, and varies from 1,000 mm in the northern highlands of the Tekeze watershed, to 700 mm at Humera station (at the Ethio- Sudan border) in the middle course, to less than 400 mm at el-Girba station in Sudan and to only 20 mm at the Atbara station, at the mouth of the sub basin.

Temperature: Mean annual temperature is a pleasant 18^0C for a large part of the highland plateau, around 25^0C in the western low-lying area of the sub basin, around 25^0C at the border with Sudan, rising to 30^0C in the downstream reach of the sub basin, around the Girba reservoir and in its immediate upstream reach, but exceeds 30^0C in the lower course of the Atbara, the mouth of the sub basin. The minimum monthly temperature ranges between 3^0C and 21^0C and occurs in the December – February period, while maximum mean monthly values occur in March – April and range between 19 ^{0}C and 43^0C.

Evaporation: Mean annual potential evapo-transpiration (PE) follows similar trend as that of temperature, ranging from below 2,000 mm per annum in the highland plateaus of the sub basin, to between 2,000 and 3,000 mm in the valleys of these highland plateaus, and rising to 6,000 mm at Atbara, the mouth of the sub basin.

Relative Humidity: Nearly 80 percent of the sub basin has a mean annual relative humidity of less than 55 percent. It is higher in the 20 percent of the sub basin lying in the highland plateaus of the Semen (North) mountains of Ethiopia.

3.7 Topography

3.7.1 Blue Nile sub-basin

Altitude: The Gelgel Abbay in the right bank of the main stem starts at the Choke Mountains in Gojjam with an altitude of above 3,800 masl. The Beshilo (a direct tributary of the Blue Nile main stem) and the Gummara & Rib Rivers (major tributaries of Lake Tana in the east) start flowing from the Guna peak, in south Gondar, with an altitude of above 4,000 masl. The major tributaries in its left bank start flowing from the central highland plateaus of north Showa with an average altitude of above 2,200 masl. In the south left bank its main tributaries like Guder, Fincha, Angar and Deddessa starts flowing from the western highland plateaus of

Ethiopia with an average altitude of above 2,000 masl. Likewise tributaries in the right bank start flowing from the Gojjam highlands with peaks reaching above 3,000 masl. The Dabus in the left bank and the Rahad & Dindir in the right bank starts flowing in the mid altitude plateaus (about 2,000 masl) of west Wollega and North Gondar respectively. At the Ethio-Sudan border the altitude drops to 600 masl. At Khartoum, its mouth, the altitude drops to 400 masl.

Slope: Given the extent of the lowlands, in proportion with the mountainous relief, most of the sub-basin has a slope of less than 2.5 percent.

Relief: Two main landscape units are observed in Abbay-Blue Nile Sub basin: (1) A mountainous relief that extends in Ethiopia and (2) a flat piedmont starting close to the Ethiopian border and extending out across the Sudanese portion. The Ethiopian Highlands are a gently undulating plateau from 2,000 to 2,500 masl with isolated volcanic remains rising above the plateau to 3,500 masl to 4,200 masl. The Abbay River and its tributaries are deeply engraved into the plateau leaving a series of isolated tablelands separated by deep gorges. In Ethiopia the lowlands are undulating between 600 masl to 1,000 masl with isolated hilly or mountain outliers rising to 2,700 masl. Towards the border with Sudan and extending westwards to the Main Nile the topography is almost flat or slightly undulating, with just the occasional granite jebel rising above the clay plain. The lowland region between the Atbara River and the Blue Nile is occupied by the Butana Plains.

3.7.2 Baro-Akobo-Sobat-White Nile (BASWN) Sub-basin

Altitude: The Ethiopian part of the sub-basin comprises high plateau elevations ranging from 1500 masl to 2000 masl and mountains with peaks exceeding 2,500 masl, the elevation decreases towards the Sudan reaching as low as 250 masl. The upper course of the sub basin (largely the watershed east of the Ethio-Sudan border) ranges from above 3,000 masl (south western highland plateaus of Ethiopia around Bedele and Jimma) to below 500 masl as it fall down to the Gambella low land flood plain. Upstream of the Gambella town, the highland plateau first drops in to an altitude of 1,000 masl where hilly and steeply dissected land topography starts dominating which divides the south-western highland plateaus of Ethiopia with the Gambella low lying flood plain. In the further west direction towards the border elevation drops to below 600 masl and in between the rivers in the watershed entered in to a vast low lying savannah area. Approaching the border between Ethiopia and Sudan the elevation of the watershed drops to below 500 masl, where the rivers in the watershed cross flat seasonally flooded area. At Khartoum, the mouth of the sub basin, altitude drops to below 400 masl.

Slope: More than 88 percent of the sub basin has a slope of less than 5 percent comprising the low-lying area of the Gambella flood plain in Ethiopia, the Machar flood plain, the low lying seasonally flood plains at the mouth of the Gillo, Akobo and Pibor watersheds including the major portion of the Sobat and White Nile watersheds in the further downstream reaches of the sub basin. About 6 percent of the sub basin has a gentle slope of 5 - 10 percent, while less than 2 percent of the area (in the highlands) has a land slope of more than 20 percent.

Land forms: Plain areas with land slope of less than 3 percent covers nearly 60 percent of the sub basin. Dunes (8 percent) and Hills & major Scarps (about 6 percent) are the next major land forms in the sub basin. The flood plains and Piedmont Plains cover 5.2 percent and 4 percent respectively. Mountains and major scarps largely located in the eastern portion of the sub basin covers only 2.4 percent. Other land forms in the sub basin include plateaus, valleys, Deltas, dunes, water bodies and etc.

Relief: In Ethiopia the Baro-Akobo Sub-basin can be divided into two major landscape units of approximately equal size, the western lowlands and the eastern highlands, separated by an escarpment and areas of severely dissected highlands. The Gambella catchments in the Ethiopian portion gently slope to almost flat plains that continue into the Sudan crossing the border. The plains are abruptly terminated in the east by a well defined, north-south escarpment. North of the salient the foot of the escarpment is less precise and forms a belt of lower altitude broken highlands in Beneshangul Gumuz Revenue State. A similar area of broken highland terrain is found in the western part of SNNPR around Mizan Teferi and reaching out to Gurafarda, a highland outlier. Steep slopes clearly mirror the high 5 relief, with the escarpment at the edge of the Ethiopian Highlands, the Imatong Mountains and associated hills and the Nuba Hills standing out. Less clear are the steep slopes of the hills on the Boma Plateau. The main relief features in the south of the Pibor-Sobat Sub basin are a series of steep hills and mountains of basement complex rocks stretching north east wards along the Sudan-Uganda-Kenya border reaching up to 3,187 masl on Mount Kinyeti in the Imatong Mountains.

On the western side of the southern part of White Nile Sub-basin are the Nuba Mountains rising to about 1,500 masl. To the east are wide clay plains with the Machar Marshes in the south. These plains terminate abruptly in the east against the Ethiopian Highlands. Further north the valley widens with low relief on both sides of the river with a very low watershed between the White and Blue Niles.

3.7.3 Main Nile Sub-basin

Altitude: Large proportion of the sub-basin area (69 percent) is confined in an altitude that ranges from 200 masl to 500 masl and it occupies the central area of the sub-basin extending from Khartoum to the Delta in Egypt, equally distributed on both banks of the Nile. About 22 percent of the sub basin has an altitude from 500 masl to 1,000 masl. Almost 1 percent of the sub basin has an altitude less than 20 masl and this area is largely confined in the delta around the mouth of the sub basin. Some 3 percent of the sub basin has an altitude ranging from 20 masl to 100 masl and the remaining 4.5 percent has an altitude between 100 masl and 200 masl. Less than 0.1 percent of the sub basin is above an altitude of 1,000 masl.

Slope: Most of the Main Nile sub-basin (96 percent) has a mild land of slope less than 5 percent. Land slope ranging from 5 - 10 percent covers nearly 3 percent of the sub-basin and the remaining area (less than 1 percent) is identified to have land slope greater than 10 percent.

3.7.4 Tekeze-Setit-Atbara (TSA) sub-basin

Altitude: Altitude in the sub basin ranges from above 3,500masl (4,620 masl at Ras Dashen) to less than 200 masl at Atbara, its mouth (Tekeze Master Plan Project, Vol, VII, May 1998). A third (33 percent) of the sub basin lies below 500 masl, another third (31 percent) from 500 to 1,000 masl, and the remaining third (36 percent) is divided as follows: 12 percent is at an elevation of 1,000 to 1,500 masl, 13 percent from 1,500 to 2,000 masl and the remaining 11 percent lies at an altitude above 2,000 masl.

Slope: Nearly 65 percent of the land in the TSA sub basin has a slope of less than 5 percent, which is largely the middle and lower courses of the sub basin in Sudan. Some 12 percent of the sub basin has land slope ranging from 5 - 10 percent, while 9 percent of the area has land slope ranging from 10- 15 percent. The remaining portion of the sub basin is characterized to have land slope of greater than 15 percent.

Land forms: The TSA sub-basin as a whole is characterized by the dominance of steep land and more than 50 percent of the basin has slope gradient of over 30 percent. The dominant landform in the basin is steep hilly land, with which one third of the basin is covered. Sloping land (gradients 8-30 percent) covers about 14 percent and level land (<8 percent) about 16 percent. The composite landforms, which combine two or more major landforms, cover 18 percent of the basin. Actually flat land (<2 percent gradient) occurs in only 5 percent of the basin.

Relief: Two main landscape units are observed in the TSA sub basin: A mountainous relief that extends in Ethiopia and Eritrea and a flat piedmont starting close to the Ethiopian border and extending across the Sudanese portion.

Mountainous relief: The incised nature of the Tekeze River in the Ethiopian highlands mirrors that of the Abay River. But the Tekeze basin also has isolated volcano necks that contrast sharply with the surrounding undulating relief. Extremely rugged topography exists where the highlands are cut into a number of blocks by deeply incised gorges of the Tekeze River and its tributaries.

Flat piedmont: In proportion with the mountainous relief, most of the sub basin is characterized by slopes lower than 2.5 percent. In the Ethiopian and Sudan Lowlands the topography is almost flat or slightly undulating becoming more undulating to the east.

3.8 Land Cover / Land Use

3.8.1 Blue Nile sub-basin

Woodlands and shrub lands cover some 28 percent and grasslands 25 percent of the sub-basin. Sedentary rain fed cropping covers nearly 26 percent of the area mainly located in the Ethiopian Highlands. In Sudan, semi mechanized farms cover 10 percent but irrigation cultivated land is only 2.6 percent.

3.8.2 Baro-Akobo-Sobat-White Nile (BASWN) Sub-basin

The land cover is dominated by grassland and open woodland and shrub land. Grass land, open shrub lands and open wood land with coverage of 30 percent, 23 percent and 17 percent respectively are the dominant land cover units in the sub basin. The grass land mainly covers the low lying area of the sub basin. In the low lying area of the Gambella seasonally flooded area and around the border is a considerably large savannah. Semi mechanized farms are fourth in terms of area coverage, followed by seasonal swamps and wetlands (most prominently, the permanent Machar wetland) and Montane and Lowland High Forests.

3.8.3 Main Nile sub basin

On nearly on 95 percent of the sub basin, a general desert or semi-desert conditions with little or no vegetation except along the wadis with high water table prevails as it falls below the 100 mm isohyets. Semi desert scrub exists in those areas of the sub basin that falls above the 100 mm isohyets and accounts only 5 percent of the sub basin. The Nile Delta area covers about 10,000 km^2 and extends for 175 kilometers from south to north and 220 kilometers from east to west along its base at the north. Most of the southern part is now cultivated, while a part of the northern delta is being occupied by extensive shallow lakes and marshes and in part consists of low lying salty ground which is under reclamation.

3.8.4 Tekeze Setit Atbara (TSA) sub-basin

Cultivated lands are well distributed over the upstream region of Tekeze Atbara Sub basin. A higher percentage is observed in the north and the high plateau that reaches to Lake Tana. Woodlands are primarily located in the south west part of the lowlands. The northern region is generally characterized by desert or semi desert conditions, with little or no vegetation except along wadis with a high water table. Between the 75mm and about 250 mm isohyets semi desert scrub is the most common vegetation type, while south eastwards, from the 250 mm to the 360 mm isohyet, the vegetation is semi desert grassland. Much of this vegetation is now covered by the Gezira and Managil Irrigation Schemes. Between the 360 mm and 570 mm isohyets on the heavy clays grassland merges into a mellifera thornland. Above 570 mm to the border with Ethiopia there is increasing dominance by a seyal in association with Balanites aegyptiaca. a senegal is retained for gum arabic harvesting whilst A. seyal is used for charcoal production. B. aegyptiaca becomes increasing prevalent because it is fire resistant. The lowlands located in Ethiopia are mainly covered by shrublands, as are the dissected highlands around the upper head of Tekeze River in the south east. Grasses are mainly annuals in Sudan as heavy grazing and low rainfall ensures that there is insufficient dry matter for annual fires. Barelands (rock and bare soil) are scattered in the highlands, with a higher concentration within the gorge of Tekeze River, as well as within the central mountainous ridge. Forests and afro-alpine vegetation represent less than 1 percent of Tekeze Basin.Below the Kashm el Girba dam is the New Halfa irrigation scheme adding up some 190,000 ha. Above the dam are extensive areas of semi mechanized farms.

3.9 Dams and Reservoirs

3.9.1 Existing Dams and Reservoirs:

The Blue Nile system currently has four reservoirs, three man made and one natural, which make up the existing water resources infrastructure. The two reservoirs in the Ethiopian highlands are Lake Tana and Fincha reservoirs, and the other two reservoirs are Rosaries and Sennar, located in the Sudan upstream of the Khartoum station. Outflow from the natural reservoir of Lake Tana is regulated by the Chara-Chara regulation weir. The Roseires reservoir is located some 100 kilometers downstream of the Ethio-Sudan border on the main stem of the Blue Nile, and is largely used for irrigation and hydropower. The Sennar reservoir is used mainly to regulate the inflow from the Roseires reservoir for developing irrigation and hydropower.

Alewero reservoir in the upper course of the Baro watershed in Ethiopia, and the Jebel Aulia reservoir at the mouth of the White Nile in the Sudan are the two dams/reservoirs existing in the BAS sub basin.

Alewero Reservoir: Located in the upper course of the Baro watershed, at Alewero River, in Ethiopia, the reservoir was initially built for irrigation and is currently used for both irrigation and hydropower. Initially planned to command 10,400 hectares of agricultural area, there is no data regarding the current level of irrigated agriculture development from this reservoir. According to available estimates, the mean annual sediment yield is in the range of 35 tones/ km^2 per year, which is equivalent to a mean annual loss of 3 mm depth of soil from the agricultural land in the upper course of the sub basin. At 60percent project efficiency the hydro-module is estimated at 13,106 cubic meters per hectare per year, posing a considerable threat to reservoir life and agricultural production.

Jebel Aulia Reservoir: This reservoir is located at the mouth of the White Nile and was built with a storage capacity of 3.5 BCM. The reservoir is used for both irrigation and hydropower. The Assalaya and Kenana sugar schemes with a total command area of 80,144 ha are the two state owned large scale irrigated farms in the system, along with 300 ha of small scale irrigated farms. Mean annual evaporation from the reservoir is 2.12 BCM on average (No seasonal distribution is available). After nearly 70 years, reservoir sedimentation is not yet a threat for the Jebel Aulia reservoir and it still maintains its original designed storage capacity, largely because the flat land in the lower courses of the Baro river (Gambella low lying plain) and the Pibor tributaries (Akobo, Gillo & Alewero), the entire watershed of the Sobat river and the Machar wet land in the eastern portion of the sub basin and the presence of the Sude in the south portion, are filtering the sediment load from the highlands of the sub basin. At 60percent project efficiency, the hydro module is estimated at 10,125 cubic meters per year with mean annual abstraction of about 820 MCM, including abstractions for small scale projects. The average evaporation loss is 2.12 BCM per year.

The Khasm-el-Girba located downstream of the Angereb-Goang-Tekeze confluence in Sudan is one of the two existing reservoir in the Tekeze-Setite-Atbara system the other being Tekeze dam in Ethiopia. Khasm-el-Girba dam was built in 1966 in the Atbara main stem at initial storage capacity of 1,300 MCM, and intended for irrigation and hydropower purposes. The New Halfa scheme (146,138 ha) and New Halfa sugar scheme (22,569 ha) are the two large scale irrigation projects in the sub-basin both fed from the el-Girba reservoir in Sudan. Current irrigation practice in the upstream reach of the system is almost non-existent.

The only major infrastructure in the main Nile part of Sudan is the Merowe Dam upstream of the Dongola station. More than 95percent of the Egypt water supply comes from the Nile sources. Currently major abstraction in the Nile system is made at four points using the historic barrages.

The High Aswan Dam (HAD) is the major water conservation dam in operation in the Main Nile Sub-Basin. It was constructed to meet the demand for high capacity storage of Nile waters for use downstream in Egypt. There is also the old Aswan Dam, downstream of the HAD, built in 1902 which had been raised twice, the last one being in 1934 and with a final reservoir capacity of 5.1 BCM.

3.9.2 Potential Water Infrastructures identified:

Four major reservoirs in the main stem of the Blue Nile (GERDP, Mandaya, Mabil and Karadobi) are reservoirs envisaged largely for hydropower development. Quite a number of reservoirs in the highland tributaries of the Blue Nile sub basin in its upper course, including the Tana natural reservoir, are envisaged for the development of irrigated agriculture in the system although no reservoir development is envisaged in the lower course of the sub basin. Even though a problem of land degradation, the sub basin has significant potential both for hydropower and irrigated agriculture developments.

Both dams and irrigation projects have been identified in BAS sub basin:

- *Dams and reservoirs*: fourteen dams and reservoirs, five for irrigated agriculture development, one for multipurpose development and eight for hydropower development purposes, have been identified in the upper course of the sub basin by the Integrated Master Plan Studies conducted in 1997 by the Ethiopian Government for the Baro-Akobo basin.
- *Irrigation Projects***:** Six irrigation projects have been planned in the upper course of the sub basin in Ethiopia, with a total gross command area of 631,000 ha, and a net command area of 480,000 ha. In Sudan, the current irrigated area of 346,000 ha is to be expanded to 582,000 ha by 2015 and to 750,000 ha by 2025. All this will raise the current abstraction of Sudan in the Nile system, from 20BCM to 40 BCM.

The upper course of the TSA sub basin has considerable hydropower potential, as rivers are quite steep and some have deep gorges, which make ideal dam sites. Eleven hydropower sites have been identified, eight located in the main stem and three in major tributaries, namely Tserare, Angereb and Goang Sub watersheds. Out of these identified projects three dams, TK-04A, TK-04B and TK-05 (TK-05 is commissioned) are designed for installed capacities of 168 MW, 85 MW and 300 MW respectively. In addition, three large scale irrigation, three projects have been proposed:

(1) Humera, with a gross irrigable area of 50,500 ha and net irrigable area of 42,965 ha;

(2) Angereb, with a gross irrigable area of 13,592ha and net irrigable area of 11,561 ha and

(3) Metema, with a gross irrigable area of 19,276 ha and net irrigable area of 16,385 ha.

Currently only Tekeze in Ethiopia and Girba Dam in Sudan have hydropower plant in the system with installed capacity of 300 MW and 12.5 MW respectively. There is no hydropower plant in the upper course.

3.10 Hydropower and Transmission

3.10.1 Installed capacity:

- The four hydropower plants existing in the Blue Nile system are, the Tiss Abay (I & II), Fincha and Amertinesh hydropower plants in Ethiopia and the Roseires & Sennar hydropower plants in Sudan. The installed capacity of Tiss Abay I&II is 72 MW while the Fincha is 78 MW and Amertinesh is 100MW. The installed capacity of Roseires and Sennar hydropower plants are 280 MW and 15 MW respectively.
- In the upper course of the BAS sub basin, eight large projects (2375 MW), six medium projects (395 MW) and three small projects (55 MW) were identified as viable for the first screening stage.
- Merowe Hydropower plant has an installed capacity of 1250MW .Both the HAD and the old Aswan Dam are used for the generation of hydroelectric power, which is connected to Cairo through the ultra-HV of 500 KV transmission line and the upper Egypt HV 220 & 132KVs. Historic barrages like Isna and Nag Hammadi are also used for production of hydropower energy. The major proportion of the hydropower energy production comes from HAD and the old Aswan Dam, but hydropower generation from the Nile system accounts only 20percent with a total production of 14,425.61 GWH in Egypt.

3.10.2 Proposed Interconnections and/or Transmission Lines:

The high potential for hydropower, in the upper course of the Blue Nile sub basin, is largely derived from its topography.

The upper course alone (Abay in Ethiopia) has more than 70,000GWH/year hydropower potential and only about 1percent has been tapped so far. Both the Tiss Abbay (I&II) and the Fincha hydropower plants are connected to the national grid system of Ethiopia, while the Roseires and Sennar hydropower plants are connected in to the national grid of the Sudan. So far there is no power transmission connection between the two national grids.

In BAS sub basin

(1) Interconnections with the Ethiopian ICS: In the Baro-Akobo master plan studies large and medium scale hydropower plants are to be connected to the existing national grid system;

(2) Interconnection with the Sudan: These have been justified on the basis that there will be periodic surplus of energy by the time the envisaged hydropower plants are commissioned of exchange of surplus energy between the two systems.

Chapter Four

Methodology

4.1. General

This chapter presents various research methods which were used to collect data, the type of data collected, how it was processed or treated. It also explains the development and components of the Computer model, the scenarios that are used to test the model and analyze reservoirs operation under the different water demand scenarios.

Developing a model to analyses future development of water resources yield and demand and related modifications of the infrastructure for the reservoir is strongly related to the available input data. In order to start a simulation certain input data has to be provided.

4.2 Data Collection, Data Processing

Availability of data is an important part to run the model and finding accurate result for the simulations. Most of the result for operation part in model was calculated by previous data range like hydropower's information's and details, spillways releases by elevations variations, precipitations, river sections and so forth.

For data processing the following items are considered.

- Establishing the river networks by using GIS or ArcView software (shape files are used)

- Simulate the reservoir system analysis by the Hec-ResSim hydrologic model software.

- Estimate the maximum hydropower production, reservoir elevation and releases downstream that can be utilized by existing water resources in the future.

Specific activities and approaches include:

1. Gather and analyze data required for reservoir modeling. This data includes:

   - Time-series data (inflow and incremental local flow, observed flow, observed reservoir pool elevations and releases and the associated computed reservoir inflows, etc.).
   - Physical and operational reservoir data including reservoir pool definition (elevation storage- area tables), outlet capacity curves, hydro power plant data (outflow and generation capacities, efficiency, losses, etc), operational zones, minimum and maximum release requirements, etc.

2. Develop a model schematic that identifies the key locations in the watershed. For definition of key locations reservoirs, gage locations, control points, diversion location, and any other locations that are needed and will be used as information for the analysis of results. shape files of the selective part of Eastern Nile River Basin including a rivers and streams shape file, lakes shape file that identifies the reservoir locations, a watershed boundary map file that may include the sub-basin delineations, a stream gage locations map file, and a state boundaries map file .

3. Define the physical and operational data for each major reservoir in the basin. Physical reservoir data includes: reservoir pool storage definition, dam elevation and length, outlets and their release capacities, and power plant data. Defining the operational data includes specifying the operation zones or levels, the rules that constrain the releases for each zone and a release allocation strategy that indicates how the releases will be allotted to the available outlets.

4. Calibration of the model will be done by simulation of the flow using observed flow.

5. Simulation of the reservoirs using different scenarios.

6. Compare and Analysis of simulation results using Microsoft excel to know the impact.

4.3 Simulation assumptions

The simulation made a number of assumptions to simplify the complexity of the actual Operation system and river basin simulations. Some of the basic assumptions must be made:

1. No seepage throughout the reservoir and the body of the dam
2. Seepage and evaporation throughout the reaches are insignificant and assumed to be zero
3. Only free water surface evaporation losses from reservoirs were assumed.

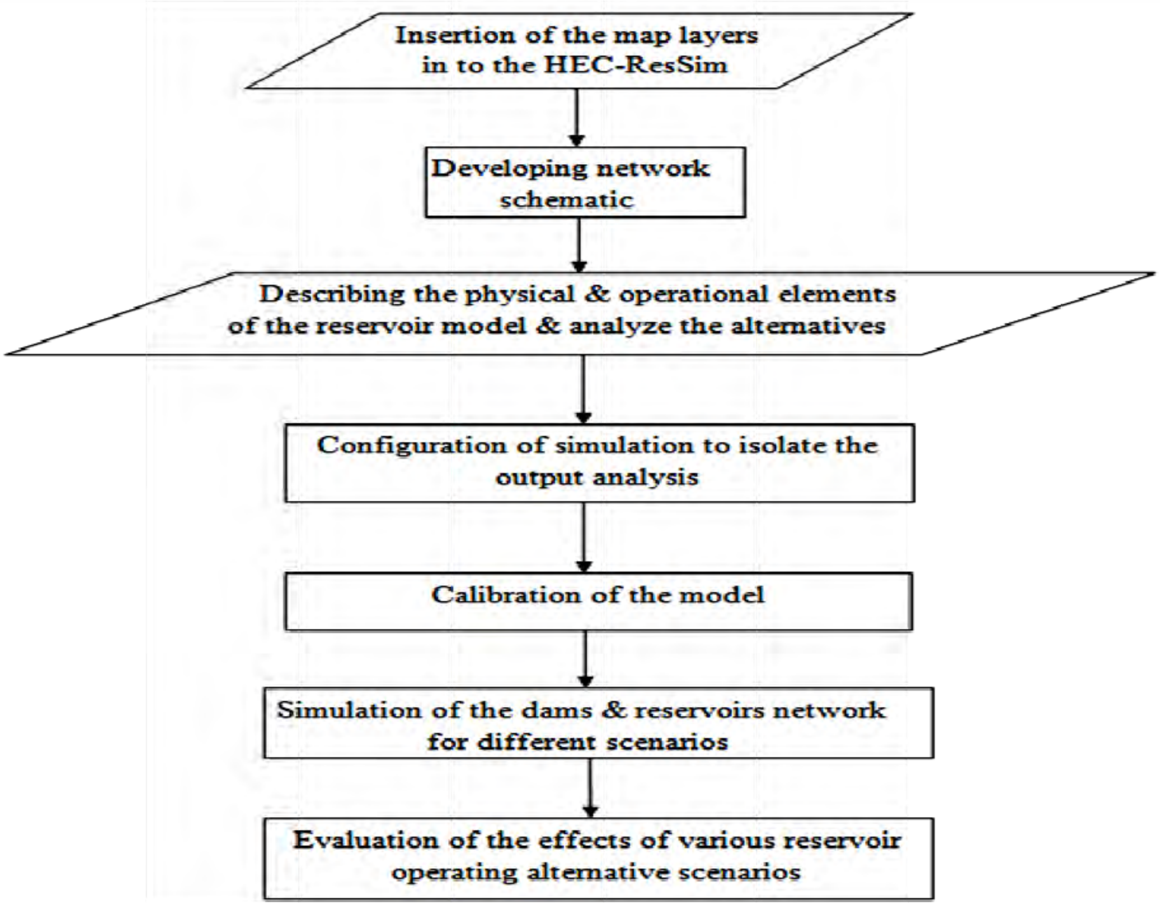
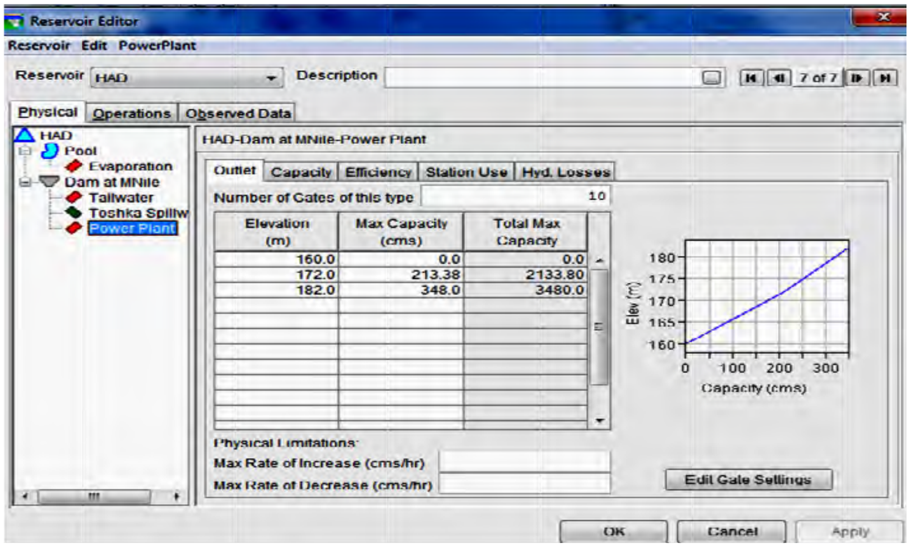


Figure 4.1. Flow chart for reservoir operation simulation

4.4. HEC-ResSim Data

In addition to the time series data, reservoir data had to be entered into the HEC-ResSim model. This information includes reservoir operations, elevation-area-capacity curves and average monthly evaporation rate in mm, controlled and uncontrolled outlets, power plant(outlet, capacity, efficiency, station use and hydraulic losses) and tail water (level vs. discharge).All of this data is entered into the HEC-ResSim Reservoir Editor with screen captures of the data entry screens in HEC-ResSim (Figure 4.2). Currently a tool does not exist for automatically transferring the data from the object class tables in the geo-database to HEC-ResSim. For this project, copy and paste was utilized to transfer the data from EXCEL spreadsheets into the Reservoir Editor. The data used in the project is shown in the Appendix.



Reservoir: HAD

Description:

HAD-Dam at MNile-Power Plant

Number of Gates of this type: 10

Elevation (m)	Max Capacity (cms)	Total Max Capacity
160.0	0.0	0.0
172.0	213.38	2133.80
182.0	348.0	3480.0

Physical Limitations:

Max Rate of Increase (cms/hr):

Max Rate of Decrease (cms/hr):

Figure 4.2 HEC-ResSim Reservoir Editor

4.4.1 Data Management

Managing data in the Nile HEC-ResSim simulation model is accomplished by using efficient and accessible internal data storage in addition to the ability to import data from and export data to external sources. The data that is required to operate a single execution of the model is contained within the model and HEC-DSSVue while all output data can also be optionally stored within the same model file.

HEC-DSS provides an efficient database for storing and retrieving serial data for application and utility programs. It has been incorporated into the current hydrologic and hydraulic modeling programs developed by HEC, as well as programs developed by other organizations. HEC-DSSVue is a Java-based graphical user interface program for graphing, tabulating, editing and manipulating HEC-DSS data. It is supported on Sun Solaris and Microsoft Windows platforms. It may be obtained free of charge for the Windows environment from the HEC web site at: http://www.hec.usace.army.mil.

4.5 Phase Scenario approach

The HEC-ResSim model development consisted of three distinct Scenario phases:

- Phase 1: Calibration
- Phase 2: Baseline Development
- Phase 3: Alternative Scenario Development which includes the filling phase(Dry, Wet and Average) and after GERDP is fully operational(i.e. after filling phase)

A description of the primary objective of each phase is provided below, along with the general methods used to accomplish the objective. Details of the implementation of each phase and the results are provided in subsequent sections. Each phase resulted in a distinct model that achieved the purpose of the particular phase and built the foundation for subsequent models.

4.5.1 Calibration Phase

Calibration of a model to a specific water system is a key step in model use, especially in conceptual lumped models. The calibration process consists of setting model parameters to optimal values manually or automatically based on given criteria (often called the objective function) which describe the fit between observed and modeled results. A framework for model calibration involves three main elements:

(1) Selection of parameters calibrated,

(2) Specification of calibration criteria, and

(3) Choice of optimization algorithms (Madsen et al., 2002).

The objective of the calibration phase was to construct a model of the Eastern Nile River that would verify the accuracy of the assumed model configuration and identify the physical characteristics and processes of the basin that must be considered in modeling the future operations and management of the basin. To complete this task, a thorough understanding was required of both the natural conditions and human influences over a historical period of time.

A variety of inputs were used in the development of the calibration model including historical hydrologic inflows, demand characteristics, stream gage records, and historical topology of the principal components in the basin. In addition, assumptions of historical operations were made when necessary to augment the calibration process.

The command in the scope of the current project was to maximize the use of existing datasets, therefore historical naturalized hydrologic inflow data was primarily obtained from ENTRO. These inflow datasets were incorporated into the HEC-ResSim model and used to simulate historical conditions for the calibration phase.

An ideal calibration process utilizes known or reconstructed data of the system including hydrologic inflows, diversions from the river, historical development of infrastructure that affected the natural system, and various physical historical characteristics of the natural and modified system. This information is used to determine unknown physical properties through mass balance comparisons with historical stream gage data.

To perform a proper calibration, data is required over a common period of history for all aspects that describe the known hydrology. The historical period selected in the calibration phase is 1978 to 1992.This period was selected primarily based on the availability of stream flow data and reconstructed prevailing inflows to the system. Using this historical period, a successful calibration model was developed that adequately simulated the historical conditions of the basin and provided a method to estimate the physical gains and losses in the system.

4.5.1.1 Methods used for calibration test:

a) NASH represents the Nash and Sutcliffe efficiency coefficient.

It is a classical criteria used in hydrology to assess the quality of hydrological models. NASH helps to assess how close to observations the simulated data obtained with calibrated models are. NASH can range from -∞ to 1. An efficiency of 1 corresponds to a perfect match of simulated flow to observed data. An efficiency of 0 indicates that the model assessment is as accurate as the mean monthly value of the observed data (reference and simplistic model). An efficiency lower than 0 occurs when the observed mean monthly data is closer to observed data than the simulated data using the calibrated model. In other words, the closer the model efficiency is to 1, the more accurate the model is.

At a given station, NASH can be defined as:

$$NASH = 1 - \frac{\sum_{i=1}^{n} \left(Q_{obs}(m) - Q_{sim}(m)\right)^2}{\sum_{i=1}^{n} \left(Q_{obs}(m) - Q_{mean\ month}\right)^2} \qquad \text{- - - - - - - - - - - - - - - - (4.1)}$$

Where: m- the considered month,

Q_{obs} -the observed flows for month m,

Q_{sim} -the simulated flows for month m,

$Q_{mean\ month}$ -the mean monthly value on the whole available period of observed data.

In this thesis work the observed and simulated values are the flows at the gaged stations.

b) R^2 is the correlation coefficient

The correlation coefficient, like the NASH, is a measure of the extent to which two measurement variables "vary together." Unlike the NASH, the correlation coefficient is scaled so that its value is independent of the units in which the two measurement variables are expressed.

It is obtained by dividing the covariance of the two variables (observed and simulated data) by the product of their standard deviation. It ranges from +1 to -1. If R^2 is equal to 1, the relation between simulated and observed time-series is a perfect linear relationship. If R^2 is equal to -1, the relation between simulated and observed time-series is perfectly anti-correlated. Finally, if R^2 is equal to 0, both series are uncorrelated. Like for the NASH efficiency, the closer the R^2 is to 1, the more accurate the model is.

c) ΔV is a comparison of water volume

At a given hydrological station, ΔV is defined as:

$$\Delta V = \frac{\left(Q_{year\ sim} - Q_{year\ obs}\right)}{Q_{year\ obs}} \text{ X 100} \qquad \text{- - - - - - - - - - - - - - - (4.2)}$$

Where Q $_{\text{year-sim}}$ the average yearly simulated flows in Mm^3/yr and

Q $_{\text{year-obs}}$ the average yearly observed flows in Mm^3/yr.

ΔV is expressed in %.

The close ΔV is to 0 %, the more accurate the model is. If ΔV is greater than 0 %, the model overestimates observations. If ΔV is lower than 0 %, the model underestimates observations.

From the calibration methods stated above for this thesis work R² correlation is used to compare the agreement of simulated and observed data in the Blue Nile and Main Nile gaging stations. For checking of the other methods (NASH and ΔV) assessment is conducted at Ed-Deim Station.

4.5.2 Baseline phase

The primary goal of the baseline scenario development phase is to generate a model that accurately reflects current conditions and potential future conditions using currently established infrastructure. The baseline model is similar to the calibration model but it incorporates the six existing reservoirs by using the general model framework developed in the first phase, but model inputs and structure are modified to simulate the current condition. The primary inputs to the baseline model include assumed future hydrologic inflows, demands, and reservoir conditions. Due to the uncertain nature of these projected inputs, the outputs are naturally subject to a greater degree of uncertainty and any application of a model must recognize these limitations.

The hydrologic inflows used in the baseline model are historical inflows and therefore identical to the calibration model. Although this provides a sound justification for estimates of future inflows, this method assumes stationarity /homogeneity/ and does not consider hydrologic conditions that have not been historically recorded. In the development of the Nile HEC-ResSim Planning Model, historical hydrologic inflows are used for the baseline model and future planning scenarios; however the model is configured to readily accept alternative hydrologic inputs as they are developed in the future.

The fundamental difference between the calibration model and the baseline model is in the solution method. The calibration model utilizes historical data whenever available to specify reservoir operations. In contrast, the baseline model relies on operating policy to simulate the future operations of the reservoirs. Initial conditions of the reservoirs in the Baseline model were assumed (i.e. all dams and reservoirs are assumed to operate with operational rules based on logic as opposed to using historical data for pool elevations or outflows). No precise data for current reservoir levels were known, therefore all reservoirs were considered at full capacity on the starting time step except HAD. Due to the nature of the current application of this model for the purpose of long-term comparative studies or proposed infrastructure, this assumption was deemed reasonable.

4.5.3 Scenario phase

The third phase of the HEC-ResSim model development was the addition of proposed reservoir to the model. Proposed reservoir (i.e. Grand Ethiopian Renaissance Dam) is incorporated into the model that could be sufficiently characterized by its physical properties including storage, elevation, evaporation, and hydropower generation characteristics.

The primary goal of operating to maximize hydropower generation was assumed for each location. The scenario model was developed in a format that allows the proposed reservoir for different filling cases (Wet, Dry and Average years) and after filling of GERD reservoir.

4.6 General Model Design

4.6.1 Overall network layout

The Nile HEC ResSim simulation Model consists of the principal Nile sub-basins including the Blue Nile, Tekeze-Setit-Atbara, portions of the White Nile from Melakal to Khartoum and the Main Nile. The basin is modeled with the primary inflow tributaries, reaches, reservoirs, demand locations and stream gages.

Hydrologic inflows are included throughout the model based on datasets generated through previous modeling efforts. The locations of these inflows represent a combination of gaged tributary locations, prevailing inflows representing ungaged inflows, and synthetically generated inflows in regions where little historical gaged data exists. Similarly, diversions are aggregated into groups representing cumulative depletions in particular reaches and at generalized locations. The relative location of assumed inflow locations and these aggregate depletion locations may affect the ability of the model to accurately simulate shortages to particular water users. In such cases of unavoidable uncertainty due to spatial resolution, it is important to recognize that the purpose of modeling is not to be predictive, but to allow a relative analysis between alternatives that affect the overall system mass balance.

Infrastructure included in the model reflects the actual infrastructure during the period of simulation. The historical calibration model contains the major infrastructure in operation between 1956 and 2003, the Baseline model contains the infrastructure that is currently operational, and the Scenario Model contains the proposed future infrastructure in addition the current infrastructure that will likely be operational into the modeled future period. Table 4-1 describes which reservoirs were included or active in each of the three phases of model development.

Table 4-1 Infrastructure included in Phased Model development

	Phase 1: Calibration Model	Phase 2: Baseline Model	Phase 3: Scenario Model
Sennar Dam		X	X
Jebel Aulia Dam		X	X
Khashm el Girba Dam		X	X
High Aswan Dam		X	X
Roseries Dam		X	X
Merowe Dam		X	X
GERDP Dam			X
Irrigation Diversions	X	X	X

4.7. HEC-ResSim model description

Large man-made reservoirs are constructed and operated for multiple purposes. Reservoir operators must simultaneously meet requirements for many needs, including flood control, power generation, and recreational use of the reservoir pool, environmental quality downstream of the reservoir, and the safety and structural integrity of the dam itself.

Each of these needs imposes constraints on the storage and release of water from the reservoir, and the needs and constraints often conflict with one another. Setting a schedule of reservoir releases that fulfils the purpose of a reservoir, meets operating constraints, and is physically possible is not a simple task, and engineers have created reservoir simulation models to help develop those release schedules.

HEC-ResSim is one such reservoir simulation model that it has been developed by the Hydrologic Engineering Center of the US Army Corps of Engineers to aid engineers and planners in predicting the behavior of reservoir systems in water management studies and to help reservoir operators plan releases in real time during day-to-day and emergency operations. During last four decades study on water resource system have been developed and it consent of variety of analysis techniques including simulation and optimization algorithms. (Madani H, 2013).

HEC-ResSim consist of three main parts that each of them must consider sequentially obtaining relevant results. The program represents the physical behavior of reservoir systems with a combination of hydraulic computations for flows through control structures and hydrologic routing to represent the lag and attenuation of flows through segments of streams. It represents operating goals and constraints with an original system of rule-based logic that has been specifically developed to represent the decision making process of reservoir operation.

4.7.1. Watershed setup

The purpose of the Watershed Setup module is to provide a common framework for watershed creation and definition among different modeling applications. This module is currently common to other HEC productions like HEC-ResSim, HEC-FIA, HEC-HMS and HEC-RAS.

Eastern Nile Watershed is associated with a geographic region for which multiple models and area coverage's can be configured. The watershed may include all of the major streams, projects (e.g., reservoirs), computation points, time-series locations and hydrologic and hydraulic data points for a specific area. All of these details together, once configured, form a watershed framework of the system (Wakena, 2006).

In this module insertion of the map layers in to the HEC-ResSim model, Schematization & configuration of stream alignment & configurations of the projects were done. Arc-View GIS files (Shape files) of the basin were used as the background layer for the model schematic and for delineation of the stream alignment. Map/shape/ file includes rivers, streams, the existing and the proposed dam sites (projects), hydrological and metrological gage locations and a watershed boundary. These projects and computation points are created by using the appropriate drawing tools from the HEC-ResSim drawing toolbar. Computation points (modeling points) include reservoir inflow and outflow points, operational location and confluences.

4.7.2. Reservoir Network

Next development step after watershed set up is the Reservoir Network. The function of the Reservoir Network Module is to separate the development of the reservoir model from the output analysis. In the Reservoir Network module, one will build the river system schematic, describe the physical and operational elements of the reservoir model, and develop the alternatives to be analyzed. Using configurations that are created in the Watershed Setup Module as a template, the basis of a Reservoir Network has been created. Then the routing reaches have been added and other network elements have been added to complete the connectivity of the network scheme as well. Once the schematic is complete, physical and operational data for each network element are incorporated. Also, alternatives were created that specify the Reservoir Network, operation set(s), initial conditions and assignment of DSS pathnames (time-series mapping) (Wakena, 2006).

The network components that are represented by HEC-ResSim can be of four types: junctions, routing reaches, diversions, and reservoirs. Each element is defined with enough information to be physically realistic without requiring excessive detail that would halt computation time.

By network system developing HEC users are able to combine the reaches, junctions, and reservoirs and prepare interconnected system like Nile River Basin network.

- **Junctions**

The junction elements serve four functions: 1) they link model elements together, 2) they are the means by which flow (headwater or incremental) enters the network, 3) they combine flow, the outflow of a junction is the sum of the inflows to the junction, and 4) when provided with an optional rating curve, they calculate stage using the computed junction outflow.

- **Streams/ Reaches/**

The reaches route water from one junction to another in the network. Routing is performed in HEC-ResSim using one of a handful of hydrologic routing methods. Routing reaches represent the natural streams in the system and the lag and attenuation of flow in a reach is computed by one of a variety of available standard hydrologic routing methods, such as Muskingum, Modified Puls Coefficient, Muskingum-Cunge or, null routing. Losses through seepage can be specified for each routing reach.

- **Reservoirs**

A reservoir is the most complex element of the reservoir network and is composed of a pool and a dam. HEC-ResSim assumes that the pool is level (i.e., it has no routing behavior) and its hydraulic behavior is partly defined by an elevation-storage-area table. The real complexity of HEC ResSim reservoir network begins with the dam (Wakena, 2006).

The pool is described by the reservoir's elevation-storage-area relationship and can optionally include evaporation and seepage losses. The dam represents both an uncontrolled outlet and an outlet group –the top of dam elevation and length specifies the minimum parameters for an uncontrolled spillway and the dam may contain one or more controlled or uncontrolled outlets. The advanced outlet types are power plant and pump, both of which are controlled outlets with additional features to represent their special purposes. The power plant adds the ability to compute energy production to the standard controlled outlet. Reservoir elements also hold the operational data for a reservoir. The operational data represents the goals and constraints that guide the release decision process. The operation data is grouped as a unit called an operation set. A reservoir can have multiple operation sets, but only one operation set per reservoir may be used in an alternative. The operation set is made up of a set of operating zones, each of which contains a prioritized set of rules. Rules describe a minimum or maximum constraint on the reservoir releases.

After Watershed Setup and addition of reservoirs, streams, junctions and computational point’s Reservoir Network development must be operated. Reservoir Network consist of two main parts a physical part and an operational part.

4.8 Data Sources

A wide variety of data sources were accessed and incorporated into the model including EEPCo’s Project report, historical records, previous models, spreadsheets, reports and individual conversations with ENTRO staff. When sources conflicted with each other, decisions were made to identify the most useful and reliable data source for the objective of the HEC-ResSim model.

4.8.1 Hydrologic inflow data sources

The HEC ResSim model uses hydrologic inflows as direct inputs to the model, as opposed to computing inflows using a rainfall-runoff approach. Historical inflows were used for the calibration, baseline and scenario models whenever required. The distinct source was used to develop this historical inflow dataset.

Monthly Blue Nile Dataset: An inflow dataset was acquired at ENTRO that focused on monthly inflows in the Blue Nile and covered variable periods of history. This dataset was developed through scoping studies of the alternative Blue Nile reservoir sites and contained a higher spatial resolution of incremental inflow locations for the period of 1956 to 2003.

4.8.2 Demand data sources

The availability of measured historical depletions is incomplete in some regions of the Nile Basin and non-existent in others. However average monthly demands are available and published in a variety of data sources. This existing dataset provided a comprehensive suite of demand locations throughout the area of interest. All available demands are average monthly values and do not indicate any inter-annual variability. These same demands are used in the calibration, baseline and scenario models.

4.8.3 Reservoir characteristic data sources

Reservoir characteristics can be divided into physical and operational components. Physical characteristics include descriptive aspects such as elevation-volume-surface area curves, operational elevations, evaporation rates, and power generation characteristics. Operational characteristics describe how the reservoirs are used to meet objectives. Five general sources of information were used to identify these reservoir characteristics:

1. EEPCO’s GERDP Study reports Volume-I, Volume -VII, Volume -VIII and Volume - X,

2. A spreadsheet titled “High Aswan system diagram final” was provided by ENTRO that contained both physical and operational characteristics of many of the existing reservoirs and a limited amount of information on some of the proposed reservoirs. This spreadsheet also contained a significant diversity of operational characteristics for existing reservoirs. In particular, monthly target elevations, target releases and elevation discharge relationships were available.

This source was essentially a collection of several management schemes. The logic included in the HEC ResSim model extensively used one or more of these schemes for each reservoir.

3. The Power Toolkit offered by ENTRO provided a variety of physical and operational characteristics for many of the existing and proposed reservoirs in the Eastern Nile Region.

Information contained in a spreadsheet describes the elevation-volume-surface area relationships, reservoir characteristics, dam characteristics, power plant and turbine characteristics, and spillway characteristics. In addition, information includes environmental demands, tail water elevations and a wide variety of descriptions related to the economic and environmental impacts of the reservoirs. It was observed that the Power Toolkit is an extensive repository of many sources of information; however it was also observed that not all the information is complete. The primary use of this data source was to inform where other sources were inadequate, or insufficient, especially describing the proposed reservoirs and the power generation objectives of these future projects.

4. A key report to understanding the operation of the Dams within Sudan was the National Electricity Corporation Long-Term Power System Planning Study for the Reservoirs of Sudan (NEC 2003). This report supported the descriptions provided in the other sources describing the reservoir operations.

5. Personal communications with ENTRO staff provided valuable insight to the multiple objectives of the reservoirs. The availability of information describing the physical and operational characteristics of dam structures varied significantly between dam sites. In compiling the multiple sources of reservoir operation data, it became clear that some reservoirs are well defined and operational rules could be validated from multiple sources, while other sites had limited physical information available. HEC ResSim offers a variety of engineering methods that can be used to simulate characteristics such a power generation and spillways, depending on the reservoir characteristics and information available. Methods were selected and customized for each reservoir depending on the availability of data.

4.9 Model simulation period

The period of overlapping historical hydrologic data is from 1956 to 2003; therefore, this period was used to calibrate the model.

The baseline model and the scenario model are used to model future conditions. The HEC ResSim model was configured to simulate the period from 2020 to 2067, using the same 48 years of historical hydrologic data from 1956 to 2003. In other words, historical inflow data from 1956 to 2003 was used for the 2020 to 2067 time period to simulate with and without GERDP scenarios to evaluate long term effect of GERDP by comparing after filling with the baseline phase. Moreover, Average sequence of years (1970-1978), Wet sequence of years (1993-2001), and Sequence of dry years (1979-1988) scenario models during filling of GERDP from 2011-2019. By shifting the analysis to the future period, it becomes clear that only future operations apply and historical operations cease to apply. Shifting the simulation period as described above prevents model users from making this critical modeling error in the future.

A daily time step was selected for the HEC ResSim model for its current and projected application with the focus of the Nile HEC ResSim simulation Model being long-term strategic planning and management of the GERDP.

4.9.1 Identification of the sequence of Average, Dry, and Wet years

- The normal case to analyze GERDP impounding stage and its downstream impacts, especially on HAD operation, considers an average sequence of years regarding HAD inflows. To select the sequence, the 5-year moving average on HAD time-series is used. The period of 5 years which presents the closest mean value to the average HAD naturalized inflows value on the whole available period has been selected.
- A critical case for GERDP impounding stage and its downstream impacts, especially on HAD operation, considers a sequence of dry years related to HAD inflows. To select this sequence, the 6-year moving average on HAD time-series has been utilized. The minimum value of this 6-year average curve helps in the identification of the sequence of dry years.
- A third and more optimistic case for GERDP impounding stage and its downstream impacts on HAD considers a sequence of wet years regarding HAD inflows. To select this sequence, the 4-year moving average on HAD time-series has been utilized. To identify the sequence of wet years, the maximum value of this 4-year average years has been selected.

4.10 Model schematic and network

The Blue Nile sub-basin is modeled from Lake Tana to the confluence with the White Nile at Khartoum.

The historical and existing modeled network consists of eleven inflow locations, two diversion locations and three reservoir sites.

Figure 4.3 the Blue Nile Sub-Basin (source: ENTRO)

The Tekeze-Setit-Atbara sub-basin is the last significant tributary to the Nile River. This tributary has the highest seasonal variation of the entire basin and had the least amount of data available describing its characteristics. The Atbara River originates just north of Lake Tana. The primary tributary to the Atbara River is the Tekeze/Setit, which forms part of the border between Eritrea and Ethiopia and originates in the high mountains of northern Ethiopia. The principal reservoirs in the sub-basin are the Khashm el Girba Dam just downstream of the confluence of the rivers and the Tekeze Dam on the Tekeze River.

The Tekeze Reservoir was not constructed until after the modeled calibration period, therefore is not included. The primary consumptive use is a direct diversion from the Khashm el Girba Dam.

Figure 4.4 the Tekeze-Setit-Atbara Sub-Basin (source: ENTRO)

The White Nile at Malakal represents the upstream boundary of the modeled region for the White Nile. This gage represents the combined flows from the Sobat and the outflows from the Sudd marshes. The lower extent of this reach is at the confluence with the Blue Nile at Khartoum. The Jebel Aulia Dam is the only dam in this reach along with two diversion locations.

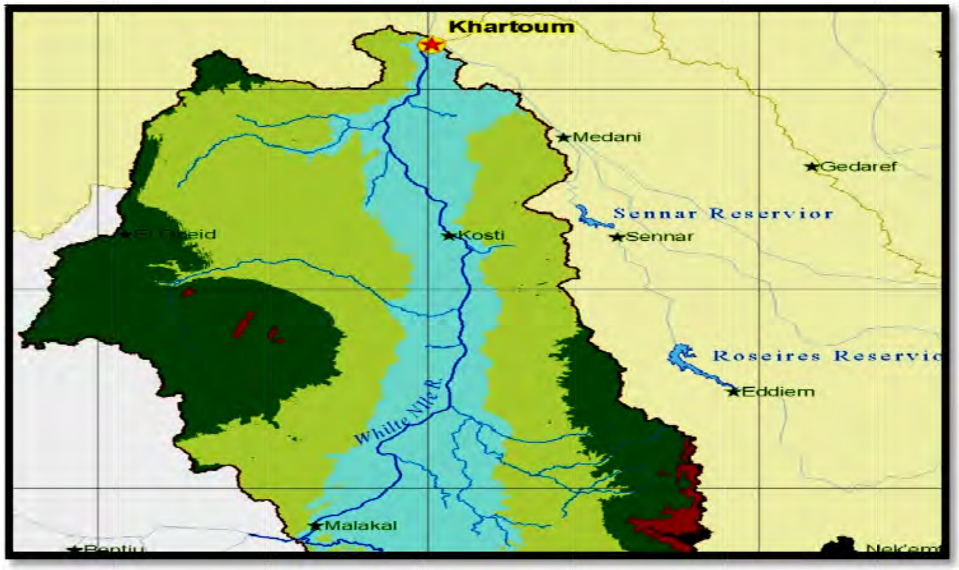


Figure 4.5 the White Nile sub basin between Malakal and Khartoum (source: ENTRO)

The Main Nile is considered to be the reach below the confluence of the White and Blue Nile to the Delta and outflow the Mediterranean Sea. The Atbara joins the Nile in this reach and passes through the High Aswan Dam near the Sudan-Egypt border. The Merowe Dam is constructed upstream of the High Aswan dam and is therefore included in the Baseline and Scenario models, but not in the historical calibration model. There are also modeled demand locations that represent aggregations of many water users in this region.

Figure 4.6 the Main Nile (source: ENTRO)

The Eastern Nile River Basin model schematic in fig 4.7 shows all the reservoirs, flows, gage stations and demand locations that are modeled in the HEC-ResSim model.

In the Blue Nile sub-basin three reservoirs, seven flow locations and three irrigation demand locations are modeled. Incremental flows along the main stem of the Blue Nile which was used for the development of the HEC ResSim model. These sites include: BahirDar-Kessie, Kessie-Karadobi, Karadobi-Mandaya, Mandaya-Border,Rahad and Dinder Incremental. The three demand locations considered in this model development were: Upstream Sennar Demand, Gezira Managil Demand, and Downstream Sennar Demand. Reservoirs on the Blue Nile include GERD, Roseries Reservoir and Sennar Reservoir.

The Atbara River originates just North of Lake Tana. The primary tributary to the Atbara River are the Kubur and the Wad El-Hilew Rivers. The principal reservoirs in the Atbara sub-basin is the Khashm El Girba Dam .Two hydrologic inflow locations were included in this model and labeled Tekeze Catchment and Atbara Inflow. Reservoir on the Tekeze-Setit-Atbara considered in the model is Khashm el Girba Reservoir.

The White Nile at Malakal represents the upstream boundary of the modeled region. This gage represents the combined flows from the Sobat and the outflows from the Sudd marshes. Diversion directly from Jebel

Aulia is the demand location considered on the While Nile between Malakal and Khartoum and is quantified as average monthly demands.

The Main Nile is considered to be the reach below the confluence of the White and Blue Nile to the Mediterranean Sea. The Merowe Dam in Sudan and HAD of Egypt are the major water infrastructures which are included. The demand locations that are modeled in on the Main Nile are Tamaniat-Hassanab Demand and Hassanab-Dongola Demand.

Four observed stream gage stations considered were Khartoum, Tamaniat, Hassanab and Dongola stations.

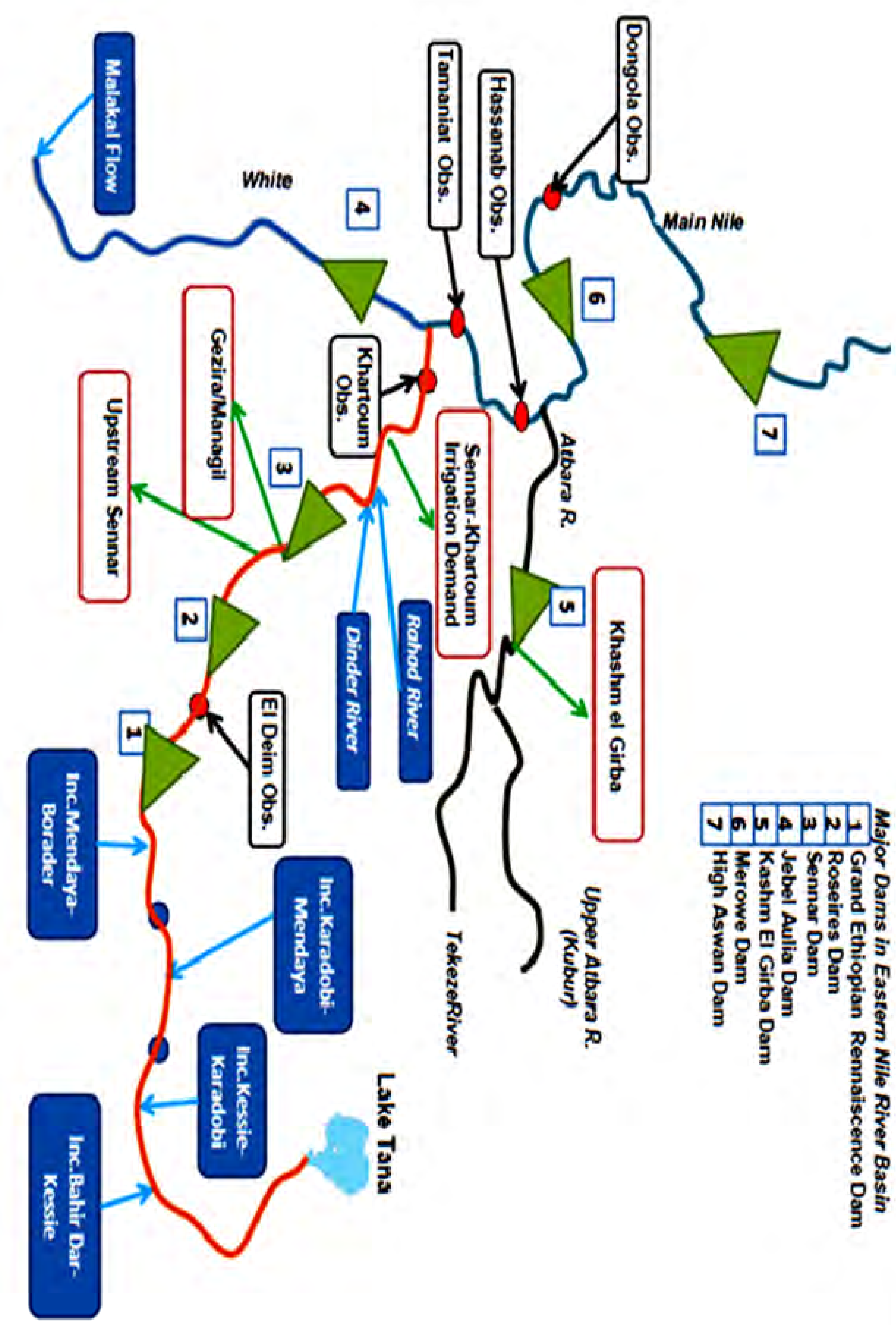


Figure 4.7 Eastern Nile River Basin model schematic

4.11 Hydrologic Inflows

Historical hydrologic inflows were acquired from the monthly flow spreadsheet at ENTRO. The five inflow locations into Lake Tana include: Gilgl Abay, Megech, Ribb, Gumara, and Tana Ungaged Inflow Time series data from five tributary locations include: Didessa, Dabus, Beles, Dinder, and Rahad Incremental flows along the main stem of the Blue Nile were extracted from a monthly flow spreadsheet at ENTRO. These monthly flows were developed through the scoping of the proposed reservoirs. These sites include: Bahar Dar to Kessie -Incremental, Kessie to Karadobi- Incremental, Karadobi to Mandaya-Incremental, and Mandaya to Renaissance-Incremental.

These incremental flows were available for these four sites for the period from 1956 to 2003 and therefore incorporating flows from tributaries already known from gaged data.

Flow records for upstream reaches and tributaries of Tekeze-Setit-Atbara sub-basin are unfortunately limited; therefore this study utilized hydrologic inflows developed through previous modeling efforts. Two hydrologic inflow locations Kubur and Wad El Hilew were included in this model.

Furthermore it appeared that that the inflows from the Atbara were reconstructed to simply meet the historical flows at the gage at kilometer three, hence included the flows from both the Atbara and the Tekeze tributaries. Since neither of these inflows from the monthly flow spreadsheet could be considered reliable, flows in the Tekeze tributary and from the Atbara Wad were obtained from ENTRO staff using the ongoing implementation of WP II Stage II model.

Hydrologic inflows to White Nile reach are strictly from catchment areas entering the reach. The gage at Malakal combines the outflows from the Sobat with the outflows from the Sudd. The historical outflows from the Sudd are ungaged, but can be back-calculated by subtracting the flows on the Sobat at Hillel Doleib from the flows at Malakal. For the purposes of calibration, this provides a perfectly reconciled flow at Malakal. Additional inflows from the Machar Marshes are possible downstream of the Malakal gage, however the magnitudes of these flows are historically insignificant and not deemed reliable for any planning purposes. No intervening inflows are assumed on the remainder of the White Nile before reaching the confluence with the Blue Nile.

Hydrologic inflows into the Main Nile are from three reaches described earlier including the Blue Nile, White Nile and the Tekeze -Setit- Atbara sub-basins. No local inflows are assumed in arid regions.

4.12 Water demands

Data from three demand locations in the Blue Nile were including: Upstream Sennar Demand, Gezira Managil Demand, and Downstream Sennar Demand were obtained from ENTRO are shown in appendix.

Data from the Kashim el Girba Demand location were obtained from ENTRO. These demands were simple repeating patterns and no data on historical inter-annual variability was available and are included in the appendix of this report.

Two demand locations are included on the White Nile between Malakal and Khartoum. Diversions upstream of Jebel Aulia and diversions directly from Jebel Aulia are quantified as average monthly demands.

Two demand locations are modeled in on the Main Nile that represents aggregate consumptive uses along this reach. These are: Tamaniat- Hassanab and Hassanab-Dongola Demand. Since the demands in this location have no effect on reservoir operations, this was considered acceptable for the current model development and analysis.

4.13 Reservoir physical data

Reservoirs on the Blue Nile include GERD Reservoir, Roseries Reservoir and Sennar Reservoir. Elevation- Volume- Area relationships, evaporation rates, tail water rating curve and power generation characteristics were extracted from the High Aswan system diagram final.xlsm spreadsheet and EEPCo GERD project reservoir operation studies report.

The physical characteristics for the Grand Renaissance Dam were extracted from GERD project report RP-1 by EEPCo and reservoir operation studies report. These reports contain detailed information on the turbine characteristics including explicit relationships between operating head, turbine releases and power generation. The operation of GERD is described in detail in RP-1 report.

Reservoirs on the Tekeze-Setit-Atbara include of Khashm el Girba Reservoir .Although data describing these reservoir was compiled from the High Aswan system diagram final.xlsm spreadsheet and the Power Toolkit, significant uncertainty on the operation of these reservoirs remains.

The physical characteristics of the elevation-storage-surface area for the Jebel Aulia Reservoir were obtained from ENTRO and the evaporation coefficients were obtained through the High Aswan system diagram final.xlsm spreadsheet. The operation of the reservoir was understood through the NEC 2003 study and target elevations were developed to reflect the basic logic.

The High Aswan Dam and the Merowe Dam are included in the Main Nile reach in the Baseline, and Scenario models. The physical characteristics and operation of the High Aswan dam are well described in numerous data sources while for the Merowe Dam limited information was identified that describe its future operations. The High Aswan system diagram final.xlsm spreadsheet was the principle source used to describe both reservoirs.

The physical characteristics for the High Aswan Dam and Lake Nasser were extracted from the High Aswan system diagram final.xls spreadsheet.

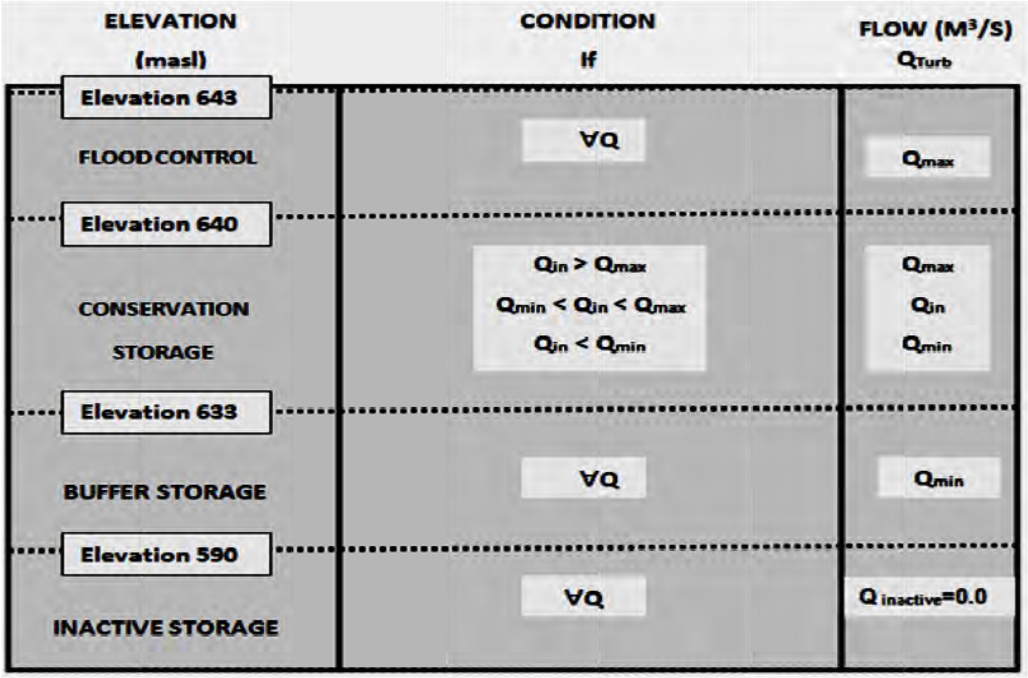
4.14 Reservoir operation

4.14.1 GERD Operation

Reservoir pool elevations are identified and categorized into four elevation zones including an Upper Conservation Storage Zone from 633 masl to 640masl, Lower Conservation Storage Zone from 590 masl to 633 masl, Buffer Storage Zone from 560 to 590 masl and Inactive Storage. No release below 590masl reservoir water level for power generation. Elevations above 640 masl include uncontrolled spillway releases. Releases from GERDP are then determined as a function of both the pool elevation and the inflow state of the reservoir.

Bearing in mind that the aim of the present study is to compare two situations, the present situation without GERDP and the future situation with GERDP, exactly the same water uses values must be considered in Sudan and in Egypt in order to build the comparison on the same basis. The GERDP operation rules which will be applied in the future water management system, will consider that the intention of GERDP is energy generation. Energy will be generated satisfying the monthly demand as long as GERDP water level is above the MOL (590masl). If GERDP water level becomes higher than 640masl, some water volumes will be spilled downstream. To maximize the annual energy produced. The adopted operating rules resulted as follows:

Table 4.2 operating condition of GERDP for maximum Energy



ELEVATION (masl)	CONDITION If	FLOW (M^3/S) Q_{Turb}
Elevation 643		
FLOOD CONTROL	$\forall Q$	Q_{max}
Elevation 640		
CONSERVATION STORAGE	$Q_{in} > Q_{max}$ $Q_{min} < Q_{in} < Q_{max}$ $Q_{in} < Q_{min}$	Q_{max} Q_{in} Q_{min}
Elevation 633		
BUFFER STORAGE	$\forall Q$	Q_{min}
Elevation 590		
INACTIVE STORAGE	$\forall Q$	$Q_{inactive}=0.0$

Where,

Q_{turb} Turbined Flow/Turbine release/

Q_{in} Inflow to the reservoir

Q_{max} Release to 16 Turbine units operating at maximum efficiency according to the available head

Q_{min} Release to one Turbine unit operating at maximum efficiency according to the available head

4.14.2 Roseries Dam Operation

Operational rules for Roseries Dam are based on descriptions provided by ENTRO through both the Aswan system diagram final.xlsm spreadsheet containing detailed operational criteria. Due to the large seasonal variation, relatively small storage volume, and high amount of sediment accumulating in Roseries, the operational criteria is specified to draw down the reservoir starting in mid-January and keep a minimum elevation until the peak flow has passed in September. Therefore, meeting target elevation criteria is the primary guiding rule of the operation of Roseries Dam.

Turbine characteristics were obtained from Aswan system diagram final.xlsm spreadsheet as well. Using Microsoft Excel spread sheet to determine power generation given the relationship between operating head and power coefficient that was obtained from the High Aswan system diagram final.xlsm spreadsheet.

The relationship between operating head and maximum turbine capacity for Roseries was obtained from the Roseries Reservoir.xlsx.

4.14.3 Sennar Dam Operation

Operational rules for Sennar Dam are also based on descriptions provided by ENTRO through both the Aswan system diagram final.xlsm spreadsheet and NEC 2003. Similar to Roseries Dam, a principal operational objective of this reservoir is to achieve drawdown and refill elevations on specified dates. In addition, the Gezira Managil diversion takes water directly from the reservoir for agriculture purposes. The minimum diversion elevation of the Gezira Managil diversion is 417 masl and therefore demands can be met when the pool elevation is greater than this level. All water in the reservoir above this elevation is considered available for diversion. After this goal is met, the reservoir operates to meet the monthly target elevations.

An additional rule is placed on Sennar Dam to increase outflows based on any shortages to the water users downstream of the Sennar Dam. Although this rule is essentially never effective given the small demands of this diversion location relative to outflows from the reservoir, it was included for future multi-objective uses and potential growth in agriculture in this region.

The power coefficients and the maximum turbine releases were available through the High Aswan system diagram final.xlsm spreadsheet.

4.14.4 Khashm el Girba operation

Physical characteristics of Khashm el Girba Reservoir were extracted from the High Aswan system diagram final.xlsm spreadsheet obtained from ENTRO, including elevation-storage-surface area curves, reservoir evaporation rates, and turbine characteristics. Operations were assumed to primarily meet the Khashm el Girba demands and then to achieve the target elevations specified in the High Aswan system diagram final.xlsm spreadsheet, adjusted to limit the drawdown as specified in the NEC 2003 report.

The power coefficients were obtained from the Power Toolkit and the maximum flow was obtained from the High Aswan system diagram final.xlsm spreadsheet.

Power is generated through a low head turbine as water is released to the Khashm el Girba command directly from the reservoir. This is modeled in Hec ResSim as an in-line power plant with a linear turbine release-power relationship ramping up to the maximum discharge of 116 m^3 and a flow power capacity of 7.6 MW as specified in the High Aswan system diagram final.xlsm spreadsheet.

The filling of the Jebel Aulia reservoir starts at the beginning of July and continues increasing to 377.45 masl at October 21. It is then held constant for one month in July until the peak flood of the Blue Nile has passed. In a monthly time step model, the only real effect of this policy is the target elevation at the end of the month of September. If the peak flow at the beginning of September has not passed, then set the September target to the half-way point with the goal of achieving the refill volume by the end of October.

4.14.5 Merowe Dam operation

The Merowe Dam is included in the baseline and scenario models. Data describing the elevation-volume-surface area was acquired through the High Aswan system diagram final.xlsm spreadsheet while the power generation characteristics were obtained from the public web-site of the Sudanese government. http://www.merowedam.gov.sd/en/index.php.

Operational criteria of the Merowe Dam was not identified and therefore assumed to be operated to meet the main aim of hydropower generation. A method was developed to operate this reservoir to principally meet a target power generation of 1250 MW. To achieve this operation, a release vs. head that specifies a turbine release to meet the power generation objective, followed by a flood control rule that spills any water in excess of a specified elevation. A maximum pool elevation of 300 masl and a minimum operation level of 284.90 masl were used as the range over which power could be generated. A HEC ResSim method of overall efficiency was selected to calculate the power given a plant efficiency of 95%.

4.14.6 Jebel Aulia Dam Operations

The Jebel Aulia Dam is included in the baseline and scenario models. Data describing the elevation-volume-surface area was acquired through the High Aswan system diagram final.xlsm spreadsheet.

The filling of the reservoir starts at the beginning of July and continues to 376.5 masl at the end of the month. Operational rules of the Dam are based on descriptions provided by ENTRO through both the Aswan system diagram final.xlsm spreadsheet and NEC 2003. It is operated to meet the target elevation.

4.14.7 High Aswan Dam Operations

The major task of the operation rules is to supply enough water supplies and to avoid river damages in addition to maintaining the dam structural safety. The reservoir operation policies were determined by the Ministry of Water Resources and irrigation of Egypt according to different limitations such as:

1- Maximum allowed water outflow should not exceed 2890 m^3/sec (250 MCM/day) to avoid excessive erosion and banks overtopping.

2- The water levels upstream High Aswan Dam should be kept at 175.00 m at the beginning of water year (January 1st) to fulfill high and low flood requirements, Raising upstream water level at the beginning of the water year may have some positive effects due to the addition water storage availability for next low floods years. However, raising water level may cause some side effects such as increasing water losses, higher risks for future high floods (dam safety risk and higher water discharges damaging).

3- The minimum allowed water discharges should be released to fulfill irrigation, navigation, drinking and other requirements and Sudan abstractions [Sadek and Aziz, 2005].

The physical characteristics for the High Aswan Dam and Lake Nasser were extracted from the High Aswan system diagram final.xls spreadsheet. This spreadsheet contains detailed information on the turbine characteristics including explicit relationships between operating head, turbine releases and power generation. The operation of High Aswan is described in detail in the High Aswan system diagram final.xlsm spreadsheet. Inflows to the reservoir are evaluated and an inflow state is assigned based on a specified range.

In addition to the inflow ranges, current reservoir pool elevations are identified and categorized into four elevation zones including an Upper Conservation Storage Zone, Lower Conservation Storage Zone, Buffer Storage Zone and Inactive Storage. Elevations above 178 masl include Toshka releases. Releases from High Aswan are then determined as a function of both the pool elevation and the inflow state of the reservoir.

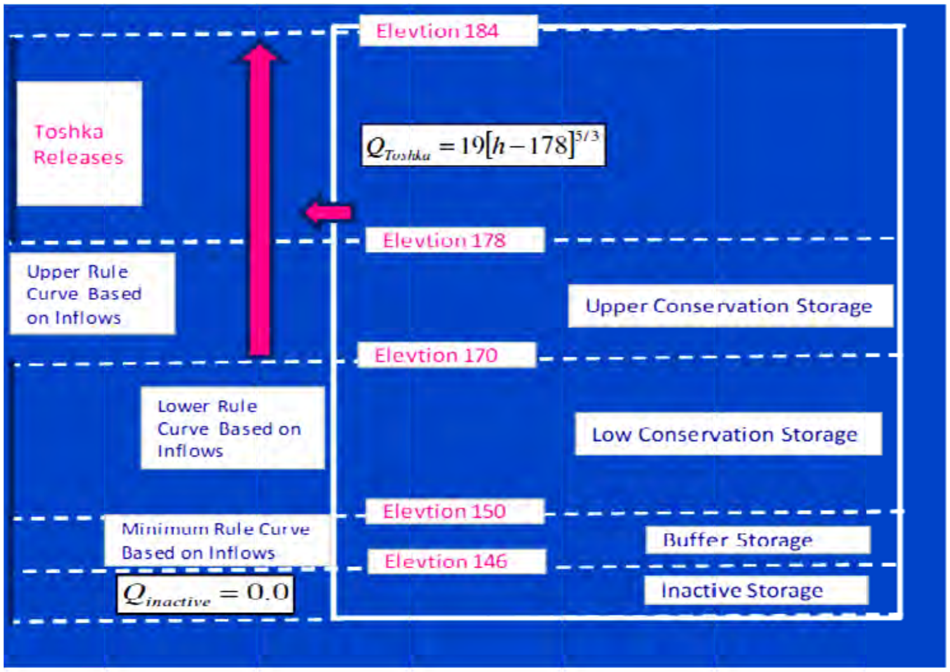


Figure 4.8 High Aswan Dam Operation Zones

4.15 Stream Gage Data

A complete set of stream gage data was available at El Diem and at the Khartoum Soba gage sites. Historical release data from any of the reservoirs on the Blue Nile is inadequate for calibration purposes.

Stream gage data for the Tekeze-Setit-Atbara sub-basin exists for the Atbara at Kilometer 3. This provides a continuous record for calibration of the historical upstream conditions and assumptions. Records of outflows from of Khashm el Girba dam exist, but were considered too incomplete to be used for calibration purposes.

Four stream gage locations were identified on the Main Nile and used in the model development for calibration purposes. The Tamaniat Gage represents the flow at the upstream end of the Man Nile, the Dongola Gage below the Merowe Dam site, and the Hassanab gage.

4.16 Environmental Requirements

An additional augmentation check is available on the release from each of the reservoirs to meet downstream environmental requirements. These demands are specified in the Power Toolkit and are uniform for the entire Blue Nile, and the Tekeze-Setit-Atbara sub basins.

Chapter Five

Summary of Results

5.1 General

This thesis work or study is conducted to simulate the impact of GERDP on other Reservoirs operation in the system of Eastern Nile river basin specifically Roseires, Sennar, Merowe and HAD using HEC-ResSim model. The general objective of the study was to simulate water use and operations of existing and/or planned major water resource projects i.e. Reservoirs on the river basin (GERDP, Roseires, Sennar, Jebel Aulia, Kashm El-Girba, Merowe, and HAD multipurpose reservoirs plus irrigation diversion in Sudan) by using HEC ResSim model.

The HEC-ResSim model has been run for six scenarios including the scenario for calibration of the model by using the hydrologic time series inflow data from 1956-2003 over the period of 48 years and considering six irrigation diversions. Varieties of reservoir characteristics have also been used to refer to the fact on the ground. This chapter illustrates the simulation results of each scenario.

5.2 Simulation assumptions

The simulation made a number of assumptions to simplify the complexity of the actual Operation system and river basin simulations. Some of the basic assumptions must be made:

1. No seepage throughout the reservoir and the body of the dam
2. Seepage and evaporation throughout the reaches are insignificant and assumed to be zero
3. Only free water surface evaporation losses from reservoirs were assumed.

5.3 Model calibration simulation results

HEC-ResSim model was first set up to simulate flow routing without taking into account effects of development and using this set up hydrological time series comparison against flow data available at the basin outlet, i.e. El-Deim, Khartoum station, Tamaniat station, Hassanab station, and Dongola station, has been conducted. A good agreement was observed between simulated and the measured flow. The correlation coefficient R^2 was 0.972, 0.960, 0.949, 0.941, 0.926, and 0.885 at El-Deim, Khartoum, Tamaniat, and Hassanab and Dongola stations respectively.

A summary of the calibration results is presented in Table 5-1. The model configuration generally calibrated well at all gage sites. The inflows used were provided by ENTRO staff and assumed to be the best available illustration of reconstructed conditions.

Table 5-1 Summary of Calibration simulation

Calibration Location	R^2 Value
Blue Nile	
El Diem Station	0.972
Khartoum Station	0.960
Main Nile	
Dongola Station	0.926
Hassanab Station	0.941
Tamaniat Station	0.949

5.4 Scenario Model simulation results

After model calibration, models were developed to simulate five different water resource scenarios in which the first two(without GERDP and including GERDP) to compare operation effect of new reservoir GERDP on the downstream using 48 years time series (1956-2003) after filling phase, the other three phase scenarios are different filling scenarios in different set of years representing the years 2014-2019 namely; Dry consecutive filling years(1981-1987) ,Wet consecutive filling years(1997-2001) and Average consecutive filling years(1972-1977) and compare this results with the normal operation of the system without introducing GERDP upstream.

Simulations are realized at downstream reservoirs (i.e. Rosaries, Sennar, Merowe, and HAD) in the present conditions (without considering GERDP upstream) using the available monthly time series, from January 1956 to December 2003. Initial operating conditions are those reached by the downstream reservoirs once GERDP impounding stage is completed, in order to compare these reservoirs simulations without GERDP and with GERDP influenced simulations: after filling three cases are analyzed for the initial HAD water level and has been assumed to be after 10 consecutive Wet, Dry and Average seasons from the observed Pool level 180.0masl, 158.20masl, 175.61masl respectively. Stored water volume of 149.50BCM, 56.68BCM, and 124.74BCM are the respective cumulative active and inactive storage.

5.4.1 Simulation results of downstream reservoirs in normal operation and without GERDP upstream (present situation):

a) Roseires

- Mean Roseires water level is equal to 472.18 masl. It reaches its maximum value (481 masl) in October, and its minimum values (467.0 masl.) in June, before the beginning of the wet season.
- Average Power generated during these time is 122.86MW
- Average Energy production is around 1,076.23 GWh/year.

b) Sennar

- Mean Sennar water level is equal to 419.40 masl. It reaches its maximum value (421.7 masl) in October, and its minimum values (417.0 masl) in May,
- Average Power generated during these time is 10.57MW
- Average Energy production is around 92.60 GWh/year.

c) Merowe

- Mean Merowe water level is equal to (298.43 masl). It reaches its maximum value (300.17 masl) in September, and its minimum values (294.11 masl) in June, before the beginning of wet season.
- Average Power generated during these time is 822.47MW
- Average Energy production is around 7,204.82 GWh/year.

d) HAD

- Mean HAD water level is equal to 180.26 masl. It reaches its maximum value (181.46 masl) in October, and its minimum values (178.11masl) in July, at the beginning of the wet season.

Nile flows in Egypt are fully regulated by HAD. Moreover, outflows monthly repartition corresponds to the irrigation water use schedule since this water use is satisfied as priority to energy generation.

- Average Power generated during these time is 734.84MW
- Energy production is around 6,437.18 GWh/year.

5.4.2 Simulation results of GERDP after filling:

GERDP operation simulations are realized utilizing monthly inflows time-series from January 1956 to December 2003.

- Mean GERDP water level is equal to 616.46 masl. The minimum value (606.04masl) is reached in June just at the end of the dry season. The maximum value (625.12masl) is reached in October, at the end of the wet season.
- In average, the whole inflow volumes are regulated: annual outflows are equal to annual inflows once losses are deducted (approximately the difference in GERDP water levels at the beginning and at the end of the simulated period). Compared to natural conditions, the monthly repartition of flows is modified with a smoothing effect: outflows decrease during the wet period (July to October) and increase significantly during the rest of the year.

- Average Power generated during these time is 1625.46MW
- Total energy generation is 14,238.99 GWh/year.

5.4.3 Simulation result of downstream reservoirs operation with GERDP upstream /after filling of GERDP/:

a) Roseires

With GERDP upstream, using time series data from 1956-2003 mean Roseires water level is equal to 473.28masl, that is to say 1.10 m higher than and store more water than the mean value without GERD simulation. The minimum value (467masl) is reached in June just before the start of wet season and the maximum value (481masl.) is reached in October. The fluctuation of water level is reduced compared to without GERD simulation results. This is a consequence of the seasonal inflows regime regulation and relatively more constant flows arrive at Roseries throughout the year.

- Energy production will be around 1,439.86 GWh/year, that is to say 33.79 % increase in the Annual energy production due to the presence of GERD.
- Roseires average inflow in the future situation is less than Roseires average monthly inflows in the present situation (i.e. average inflow in the future scenario is 98.38 % of inflow in the current situation /future scenario without GERD/), but the average storage volume increases.

b) Sennar

With GERDP upstream, using time series data from 1956-2003 mean Sennar pool level is equal to 419.88masl, that is to say 0.48 m higher than and store additional 33.51MCM of water than the mean value without GERD simulation. The minimum value (417masl) is reached in May and the maximum value (421.7masl.) is reached in October. The fluctuation of water level is reduced compared to without GERD simulation results. This is a consequence of the seasonal inflows regime regulation and relatively more constant flows arrive at Sennar throughout the year.

- Energy production will be around 100.67 GWh/year, that is to say 8.71 % increase in the Annual energy production due to the presence of GERD.
- Sennar average inflow in the future situation is generally similar with Sennar average monthly inflows in the present situation (i.e. inflow in the future scenario is 97.49 % of inflow in the current situation /future scenario without GERD/) but the average storage volume increases.

C) Merowe

With GERDP upstream, using time series data from 1956-2003, mean Merowe water level is equal to 299.98masl, that is to say 1.55 m higher than and store additional 1.1BCM of water than the mean value of without GERD simulations. The minimum value (299.79masl) is reached in July and the maximum value (300.07masl.) is reached in August. The fluctuation of water level is reduced compared to without GERD simulation. This is a consequence of the seasonal inflows regime regulation and relatively more constant flows arrive at Merowe throughout the year.

- Energy production will be around 9542.34 GWh/year, that is to say 32.44% increase in the Annual energy production due to the presence of GERD.
- Average monthly inflows in the future situation are generally similar with HAD average monthly inflows in the present situation (i.e. inflow in the future scenario is 98.69 % of inflow in the current situation /future scenario without GERD/).

d) HAD

With GERDP upstream and using time series data from 1956-2003 three options are considered:
1-*considering HAD initial pool level/Lookback reservoir level/ at a level to be at the end of 10 year Average flow season (from observed data Pool level is 175.61masl)*;
Mean HAD water level is equal to 181.19masl., that is to say 0.93 m higher than without GERD and store additional 4.12 BCM of water than the mean value of without GERD simulations. The minimum value (180.40masl) is reached in July and the maximum value (181.51masl.) is reached in Mar. The fluctuation of water level is reduced compared to without GERD simulation results. This is a consequence of the seasonal inflows regime regulation and relatively more constant flows arrive at HAD throughout the year.

- Energy production will be around 6,041.78 GWh/year, that is to say 6.14% less than the production considering without GERD. This reduction is a consequence of the average water inflow decrease at HAD, but it will be largely compensated by the additional energy produced by GERDP.
- HAD average monthly inflows in the future situation are generally similar with HAD average monthly inflows in the present situation (i.e. inflow in the future scenario is 97.26 % of inflow in the current situation/ future scenario without GERD/).

2-*considering HAD initial pool level/Lookback reservoir level/ at a level to be at the end of 10 year dry flow season (from observed level 158.2masl)*

Mean HAD water level is equal to 180.76masl., that is to say 0.50 m higher than and store more than 1.66 BCM of water on average yearly than the mean value of without GERD simulations. The minimum value (179.96masl) is reached in July and the maximum value (181.09masl) is reached in December. The fluctuation of water level is reduced compared to without GERD simulation results. This is a consequence of the seasonal inflows regime regulation and relatively more constant flows arrive at HAD throughout the year.

- Energy production will be around 6,115.08 GWh/year, that is to say 5.0% less than the production considering HAD alone. This reduction is a consequence of the average water inflow decrease at HAD, but it will be largely compensated by the additional energy produced by GERDP.
- HAD average monthly inflows in the future situation are generally similar with HAD average monthly inflows in the present situation (i.e. inflow in the future scenario is 98.04 % of inflow in the current situation/ future scenario without GERD/).

3-*considering HAD initial pool level/Lookback reservoir level/ at a level to be at the end of 10 year wet flow (from observed level 180masl)*

Mean HAD water level is equal to 181.22masl., that is to say 0.96 m lower than the mean value of without GERD simulation. The minimum value (180.42masl) is reached in July and the maximum value (181.55masl.) is reached in March. The fluctuation of water level is reduced compared to without GERD simulation results. This is a consequence of the seasonal inflows regime regulation and relatively more constant flows arrive at HAD throughout the year.

- Energy production will be around 6,075.02 GWh/year, that is to say 5.63 % less than the production considering HAD alone. This reduction is a consequence of the average water inflow decrease at HAD, but it will be largely compensated by the additional energy produced by GERDP.
- HAD average monthly inflows in the future situation are generally similar with HAD average monthly inflows in the present situation (i.e. inflow in the future scenario is 98.20 % of inflow in the current situation/ future scenario without GERD/).

5.4.4 Simulation results of downstream reservoirs during filling of GERDP:

During GERDP filling scenarios (i.e. Average, Dry and Wet seasons) the reservoir water level of reservoirs ,power generated and the inflow-outflow from the reservoir using the same operating rules for each scenario are shown below.

5.4.4.1 Simulation result during Average years of filling phase

A comparative analysis of reservoirs operating results for the present and the future situation during GERDP filling, for a period of Average years of filling simulation is presented. The Average period taken as possible future scenario, occurs from 1972 to 1977.

a) Simulation results of GERD during filling phase:

The mean water level of GERD during Average season filling is 608.26masl is less than the normal operation after filling phase which is 616.59masl. The minimum and maximum average pool level is 589.56masl(in June) and 618.54(November) respectively .During these Average years of filling scenario the average inflow to GERD will be 1505.09m^3/s and the outflow from the reservoir will be 1283.88m^3/s. The average energy produced will be 11,314.38GWH/year.

Thus, graphical output the simulations are presented at daily time intervals in appendix.

b) Simulation results of Roseires during filling of GERDP:

The mean water level considering Roseries during this filling phase of GERD (467.58masl) is lower than the mean value without considering GERD upstream (472.18masl) but there is 3.39% reduction of total yearly energy due to flow and Head reduction.

Thus, graphical output the simulations are presented at daily time intervals in appendix.

c) Simulation results of Sennar during filling of GERDP:

The mean water level considering Sennar during this filling phase of GERD (419.88masl) is higher than the mean value without considering GERD upstream (419.40masl) and there is 11.46% increase in the total yearly energy production due to Head increase.

Thus, graphical output the simulations are presented at daily time intervals in appendix.

d) Simulation results of Merowe during filling of GERDP:

The mean water level considering Merowe during this filling phase of GERD (299.81masl) is higher than the mean value without considering GERD upstream (298.43masl) and there is 18.26% increase in the total yearly energy production due to Head increase.

Thus, graphical output the simulations are presented at daily time intervals in appendix.

e) Simulation results of HAD during filling of GERDP:

The mean water level considering HAD without GERD (181.02masl) is lower than the mean value considering HAD influenced by GERDP during filling phase in Average years (172.16 masl) and there will be 3.10% decrease of total yearly energy production. During these extreme Average years of filling scenario the inflow to HAD will reduce by 14.67% and the outflow from the reservoir will also reduced.

Thus, graphical output the simulations are presented at daily time intervals in appendix.

5.4.4.2 Simulation result during Dry years of filling phase

A comparative analysis of reservoirs operating results for the present and the future situation during GERDP filling, for a period of severe drought is presented. The most critical dry period taken as possible future scenario, occurs from 1981 to 1987.

a) Simulation results of GERD during filling phase:

The mean water level of GERD during Dry season of filling is 596.93masl which is less the normal operation after filling phase which is 616.46masl.During these Dry years of filling scenario the average yearly inflow to GERD will be 1,228.12m^3/s and the outflow from the reservoir will be 1,141.15m^3/s. The average energy produced will be 8,974.19GWH/year.

Thus, graphical outputs of the simulations are presented at daily time intervals in appendix.

b) Simulation results of Roseires during filling of GERDP:

The mean water level considering Roseires without GERD (472.18masl) is higher than the mean value considering GERDP upstream during filling phase in Dry years (470.87masl) but there is 7.00% increase in the total yearly energy production, this is a consequence of the seasonal inflows regime regulation and relatively more constant flows arrive at Roseries throughout the year.

Thus, graphical outputs of the simulations are presented at daily time intervals in appendix.

c) Simulation results of Sennar during filling of GERDP:

The mean water level considering Sennar without GERD (419.40masl) is higher than the mean value considering GERDP upstream during filling phase in Dry years (419.88masl) and there will be 9.96% increase of total yearly energy due to reservoir pool level increase.

Thus, graphical outputs of the simulations are presented at daily time intervals in appendix.

d) Simulation results of Merowe during filling of GERDP:

The mean water level considering Merowe without GERD (298.43masl) is lower than the mean value considering GERDP upstream during filling phase in Dry years (299.62masl) and there will be 4.62% increase of total yearly energy due to increase in reservoir pool level.

Thus, graphical outputs of the simulations are presented at daily time intervals in appendix.

e) Simulation results of HAD during filling of GERDP:

The mean water level considering HAD without GERD (177.36masl) is lower than the mean value considering HAD influenced by GERDP during filling phase in Dry years (170.56 masl) and there will be 16.02% increase of total yearly energy due to reservoir pool level increase.783.01

During these extreme Dry years of filling scenario the inflow to HAD will decrease by 4.65% and the outflow from the reservoir will also reduced by 3.51%.

Thus, graphical output the simulations are presented at daily time intervals in appendix.

5.4.4.3 Simulation result during Wet Years of filling phase

A comparative analysis of reservoir operating results for the present and the future situation during GERDP filling, for a period of Wet years of filling simulation is presented. The Wet period taken as possible future scenario, occurs from 1997 to 2001.

a) Simulation results of GERD during filling phase:

The mean water level of GERD during Wet season filling is 612.00masl which is less the normal operation after filling phase which is 616.46masl.During these Wet years of filling scenario the average inflow to GERD will be 1,722.63m^3/s and the outflow from the reservoir will be 1,306.18m^3/s. The average energy produced will be 11,925.61GWH/year.

Thus, graphical outputs of the simulations are presented at daily time intervals in appendix.

b) Simulation results of Roseires during filling of GERDP:

The mean water level considering Roseires without GERD (472.18masl) is higher than the mean value considering GERDP upstream during filling phase in wet years (467.61masl) and there is 4.37% decrease in the total yearly energy production, this is a consequence of the seasonal inflows regime regulation and relatively more constant flows arrive at Roseires throughout the year.

Thus, graphical outputs of the simulations are presented at daily time intervals in appendix.

c) Simulation results of Sennar during filling of GERDP:

The mean water level considering Sennar without GERD (419.40masl) is lower than the mean value considering GERDP upstream during filling phase in wet years (419.88masl) and there will be 24.61% increase of total yearly energy due to the seasonal inflows regime regulation and relatively more constant flows arrive at Sennar throughout the year.

Thus, graphical outputs of the simulations are presented at daily time intervals in appendix.

d) Simulation results of Merowe during filling of GERDP:

The mean water level considering Merowe without GERD (298.43masl) is lower than the mean value considering GERDP upstream during filling phase in Average years (299.89masl) and there will be 25.75% increase of total yearly energy due to the seasonal inflows regime regulation and relatively more constant flows arrive at Merowe throughout the year.

Thus, graphical outputs of the simulations are presented at daily time intervals in appendix.

e) Simulation results of HAD during filling of GERDP:

The mean water level considering HAD without GERD (180.26masl) is higher than the mean value considering HAD influenced by GERDP during filling phase in Average years (177.63 masl) and there will be 14.46% increase of total yearly energy due to the seasonal inflows regime regulation and relatively more constant flows arrive at Merowe throughout the year.

During these extreme Wet years of filling scenario the average inflow to HAD will reduce by 10.35% and the outflow from the reservoir will also reduced.

Thus, graphical output the simulations are presented at daily time intervals in appendix.

Table 5.2.Reservoir summary report average values during filling

Location/Parameter	AVERAGE FILLING	DRY FILLING	WET FILLING
GERD			
Storage (m3)	42,594,677,667.56	26,037,103,523.09	42,849,430,796.59
Elevation (m)	615.28	602.42	614.70
Controlled Release (cms)	1,294.97	1,211.48	1,377.85
Uncontrolled Spill (cms)	13.38	8.69	35.49
HAD			
Storage (m3)	103,734,182,684.52	105,528,383,545.18	140,010,973,233.19
Elevation (m)	170.80	171.67	178.28
Controlled Release (cms)	1,607.89	1,682.87	1,778.07
Uncontrolled Spill (cms)	-	-	-
JEBEL AULIA DAM			
Storage (m3)	2,790,956,567.64	2,787,699,538.09	2,784,092,532.98
Elevation (m)	376.25	376.25	376.24
Controlled Release (cms)	782.78	686.72	875.63
Uncontrolled Spill (cms)	-	-	-
KASHM EL GIRBA			
Storage (m3)	480,170,048.13	468,477,635.57	464,781,083.43
Elevation (m)	471.31	471.16	471.03
Controlled Release (cms)	479.01	345.13	374.72
Uncontrolled Spill (cms)	-	-	-
MEROWE DAM			
Storage (m3)	11,964,827,024.79	11,896,673,223.56	12,025,979,244.73
Elevation (m)	299.83	299.73	299.92
Controlled Release (cms)	2,064.18	1,861.92	2,230.69
Uncontrolled Spill (cms)	143.05	39.57	95.30
ROSEIRES DAM			
Storage (m3)	68,570,271.77	452,982,139.00	217,083,083.97
Elevation (m)	467.63	470.88	468.68
Controlled Release (cms)	1,315.99	1,222.88	1,421.95
Uncontrolled Spill (cms)	-	-	-
SENNAR DAM			
Storage (m3)	303,745,422.57	304,486,174.48	302,116,285.41
Elevation (m)	419.80	419.81	419.78
Controlled Release (cms)	1,099.85	994.99	1,121.23
Uncontrolled Spill (cms)	-	-	-

Table 5.3.Reservoir summary report average values during normal operation

Location/Parameter	AFTER 10 WET YEARS	AFTER 10 AVERAGE YEARS	AFTER 10 DRY YEARS	WITHOUT GERD
GERD				
Storage (m3)	71,674,757,936.74	70,929,435,081.94	70,929,435,081.94	
Elevation (m)	638.63	638.19	638.19	
Controlled Release (cms)	1,649.62	1,650.08	1,650.08	
Uncontrolled Spill (cms)	-	-	-	
HAD				
Storage (m3)	162,782,381,058.47	162,780,775,658.11	162,780,775,658.11	163,478,040,001.24
Elevation (m)	182.00	182.00	182.00	182.11
Controlled Release (cms)	1,867.55	1,929.68	1,929.68	2,248.41
Uncontrolled Spill (cms)	-	-	-	-
JEBEL AULIA DAM				
Storage (m3)	4,010,000,000.00	4,010,000,000.00	4,010,000,000.00	4,008,433,891.77
Elevation (m)	377.40	377.40	377.40	377.40
Controlled Release (cms)	1,000.67	990.27	990.27	993.81
Uncontrolled Spill (cms)	-	-	-	-
KASHM EL GIRBA				
Storage (m3)	656,526,938.79	656,245,808.40	656,245,808.40	654,472,942.39
Elevation (m)	474.00	474.00	474.00	473.98
Controlled Release (cms)	40.60	11.12	11.12	368.58
Uncontrolled Spill (cms)	-	-	-	-
MEROWE DAM				
Storage (m3)	12,087,264,964.28	12,087,358,509.74	12,087,358,509.74	12,130,267,815.70
Elevation (m)	300.00	300.00	300.00	300.07
Controlled Release (cms)	2,259.59	2,280.52	2,280.52	2,189.64
Uncontrolled Spill (cms)	2.73	4.36	4.36	683.34
ROSEIRES DAM				
Storage (m3)	2,037,490,757.46	1,988,556,684.52	1,988,556,684.52	1,757,580,736.13
Elevation (m)	480.72	480.55	480.55	479.43
Controlled Release (cms)	1,734.46	1,795.39	1,795.39	2,331.69
Uncontrolled Spill (cms)	-	-	-	-
SENNAR DAM				
Storage (m3)	481,200,000.00	481,200,000.00	481,200,000.00	428,198,985.11
Elevation (m)	421.70	421.70	421.70	421.25
Controlled Release (cms)	1,287.88	1,370.38	1,370.38	1,871.09
Uncontrolled Spill (cms)	-	-	-	-

Table 5.4.Power summary report average values during filling of GERDP

Location/Parameter	AVERAGE FILLING	DRY FILLING	WET FILLING
GERD-Power Plant			
Generation Efficiency	0.95	0.95	0.95
Power Head (m)	113.81	100.88	113.56
Hydraulic Losses (m)	0.11	0.09	0.1
Energy Generated per Time Step (MWh)	34395.45	28148.54	33985.12
Power Generated (MW)	1433.14	1172.86	1416.05
Plant Factor	0.24	0.2	0.24
Flow Power (cms)	1306.25	1220.26	1287.9
HAD-Power Plant			
Generation Efficiency	0.95	0.95	0.95
Power Head (m)	59.69	60.37	66.87
Hydraulic Losses (m)	1	1	1
Energy Generated per Time Step (MWh)	21566.83	22617.03	23045.58
Power Generated (MW)	898.62	942.38	960.23
Plant Factor	0.43	0.45	0.46
Flow Power (cms)	1609.01	1677.72	1554.67
MEROWE DAM-Power Plant			
Generation Efficiency	0.95	0.95	0.95
Power Head (m)	52.14	52.62	52
Hydraulic Losses (m)	3	3	3
Energy Generated per Time Step (MWh)	23557.02	21505.22	25268.9
Power Generated (MW)	981.54	896.05	1052.87
Plant Factor	0.79	0.72	0.84
Flow Power (cms)	2032.18	1836.09	2183.28
ROSEIRES DAM-Power Plant			
Generation Efficiency	0.83	0.84	0.83
Power Head (m)	20.78	24.25	21.24
Hydraulic Losses (m)	1.7	1.7	3.5
Energy Generated per Time Step (MWh)	2907.81	3233.85	3232.25
Power Generated (MW)	121.16	134.74	134.68
Plant Factor	0.43	0.48	0.48
Flow Power (cms)	710.97	660.13	754.57
SENNAR DAM-Power Plant			
Generation Efficiency	0.95	0.95	0.95
Power Head (m)	14.03	15.96	15.94
Hydraulic Losses (m)	0.5	0.5	0.5
Energy Generated per Time Step (MWh)	280.03	309.38	314.43
Power Generated (MW)	11.67	12.89	13.1
Plant Factor	0.78	0.86	0.87
Flow Power (cms)	88.64	86.07	87.9

Table 5.5.Power summary report average values during normal operation

Location/Parameter	AFTER 10 WET YEARS	AFTER 10 AVERAGE YEARS	AFTER 10 DRY YEARS	WITHOUT GERD
GERD-Power Plant				
Generation Efficiency	0.95	0.95	0.95	
Power Head (m)	135.81	135.81	135.38	
Hydraulic Losses (m)	0.16	0.16	0.16	
Energy Generated per Time Step (MWh)	50057.29	50057.29	49914.68	
Power Generated (MW)	2085.72	2085.72	2079.78	
Plant Factor	0.35	0.35	0.35	
Flow Power (cms)	1649.62	1649.62	1650.08	
HAD-Power Plant				
Generation Efficiency	0.95	0.95	0.95	0.95
Power Head (m)	70.42	70.42	70.32	69.89
Hydraulic Losses (m)	1	1	1	1
Energy Generated per Time Step (MWh)	14680.03	14680.03	15146.45	17476.56
Power Generated (MW)	611.67	611.67	631.1	728.19
Plant Factor	0.29	0.29	0.3	0.35
Flow Power (cms)	933.78	933.78	964.84	1123.63
MEROWE DAM-Power Plant				
Generation Efficiency	0.95	0.95	0.95	0.95
Power Head (m)	52.11	52.11	52.08	51.23
Hydraulic Losses (m)	3	3	3	3
Energy Generated per Time Step (MWh)	26179.01	26179.01	26334.54	24247.49
Power Generated (MW)	1090.79	1090.79	1097.27	1010.31
Plant Factor	0.87	0.87	0.88	0.81
Flow Power (cms)	2249.68	2249.68	2264.72	2147.61
ROSEIRES DAM-Power Plant				
Generation Efficiency	0.86	0.86	0.86	0.86
Power Head (m)	33.16	33.16	32.93	31.38
Hydraulic Losses (m)	1.7	1.7	1.7	1.7
Energy Generated per Time Step (MWh)	5579.26	5579.26	5529.7	5208.06
Power Generated (MW)	232.47	232.47	230.4	217
Plant Factor	0.83	0.83	0.82	0.78
Flow Power (cms)	829.34	829.34	827.86	817.41
SENNAR DAM-Power Plant				
Generation Efficiency	0.95	0.95	0.95	0.95
Power Head (m)	15.49	15.49	15.37	14.7
Hydraulic Losses (m)	0.5	0.5	0.5	0.5
Energy Generated per Time Step (MWh)	320.91	320.91	317.87	300.51
Power Generated (MW)	13.37	13.37	13.24	12.52
Plant Factor	0.89	0.89	0.88	0.83
Flow Power (cms)	92.73	92.73	92.55	91.17

Chapter Six

Conclusion and Recommendation

6.1 Introduction

In concluding the thesis, this final chapter lays down a brief summary of the work undertaken to fulfill the aims of the research study, the conclusions drawn from the analyses carried out in the previous chapters, recommendations derived from the conclusions, limitations of the study and areas for further research.

This research work is conducted to carry out reservoir operation simulation to determine the effect of GERDP on downstream water use and reservoir operation.

In this study reservoir operation is carried out by using HEC-ResSim model to work out the daily reservoir operation in the Eastern Nile river basin system by considering all the major upstream major rivers and tributaries as main inflow to the reservoirs and all major water infrastructure in the Blue, White, and Main Nile sub basins from the river at Malakal and Tana up to HAD of the basin.

The analysis of reservoir operation has been performed on daily time step and various parameters (like reservoir physical characteristics, evaporation rates, operation rules) as main inputs, and considering irrigation (diversions) and power production water requirement. To know the impact of GERDP downstream different alternative scenarios during and after filling of GERDP were examined and the simulation results obtained at daily time steps were evaluated using 48 years inflow data from 1956-2003.

The reservoir operation simulation study main concern was to determine the effect of introducing new hydropower reservoir upstream by utilizing the release rules of each reservoir and water demands on each diversions downstream in the Eastern Nile River Basin.

This study has also considered the downstream benefit depending on the daily power released activity satisfying the maximum energy production from GERDP. In the HEC-ResSim model, the reservoir operation study main concern was to determine the impact by using release rule. This study has considered the downstream benefit (power production, Irrigation requirement and flood protection) depending on the daily power released activity satisfying the maximum energy production from HAD.

6.2 Conclusions of GERDP impacts on the Eastern Nile River system

The analysis reveals that building new large infrastructures in the upper part of the basin would have significant impacts on the operating strategies of the reservoirs: should the operation of the reservoirs be coordinated, the flood peak observed in the Blue Nile is reduced while the low flows are improved. The main beneficiaries are hydropower in Ethiopia and irrigation and Hydropower in Sudan. Moreover, upstream storage in Ethiopia and their regulation capacity will generate positive externalities in Ethiopia and Sudan. In Ethiopia, the production of hydroelectricity is boosted. In Sudan, the regulation capacity would increase irrigation water. Coordinated operation of the reservoirs would also enable an average annual saving of at least 1.8BCM through reduced evaporation losses from the High Aswan Dam. The High Aswan Dam inflows would be reduced and the reservoir would be operated a lower pool elevation but it will still reduce the hydrological risk exposure of Egypt.

The GERDP operation rules which will be applied in the future water management system, will consider that the objective of GERDP is energy generation. Energy will be generated satisfying the monthly demand as long as GERDP water level is above the MOL (590masl.). If GERDP water level becomes higher than 640masl, some water volumes will be spilled downstream or possibly turbined (within the capacity of the installed power). Thus, to satisfy this objective of firm energy generation, GERDP will turbine water at a quite regular rate all over the year. These operation rules will match the three countries water uses requirements:

- In Ethiopia, energy generation will be significantly increased with GERDP;
- In Sudan, as it will be necessary to withdraw water downstream GERDP, there will be no significant change in yearly water volume arriving in Sudan from the Blue Nile. The major modification will concern the seasonal Blue Nile flows distribution which will be more uniform along the year therefore beneficial to flood control in Sudan.
- In Egypt, there will be no significant decrease of the water volumes arriving at HAD because, once GERDP impounding will be completed water will be regularly released from the GERDP reservoir to guarantee energy generation, and these volumes of water will reach HAD.

6.2.1 After impounding of GERDP

With its 6000MW installed capacity of power generation, GERDP will boost Ethiopian power generation by 14,238.99 GWh/year in average. Considering only hydro electric generation, the present Ethiopian installed capacity of 1,579 MW (i.e.Fincha [134MW], Tis-Abay I &II [85MW], Gibe I [184MW], Gibe II [420MW], Beles [460MW] and Tekeze [300MW]). With GERDP and Gibe III, the future hydropower production capacity will be increased more than 5 times. GERDP symbolizes a sustainable socio-economic project for Ethiopia: saving fossil fuels and reducing Carbon emissions, GERDP will significantly contribute to the economic and social development of the country.

In the long term, once GERDP reservoir will be filled, it will have positive impacts on downstream reservoir operation and the impacts:

- ➢ Reduction of evaporation losses at HAD. This reduced evaporation is due to reduction of high fluctuation in the mean monthly water surface level of the reservoir.

- Better coverage of the irrigation water demand with no deficit during dry months (for an Egyptian current irrigation water demand of 55.5 BCM/year). This is due to a better control of water release for irrigation, as a consequence of upstream flow regulation.
- Better flood control in the Blue Nile. The flood storage capacity of the Nile River will be raised with the implementation of GERDP.

Sudanese reservoirs, and as a consequence also the Sudanese irrigation schemes, will be less dependent to hydrological variability, especially during drought periods. Sudanese energy generation may increase significantly because of flow regulation and reduction of spilled water.

Basin Water Management will be easier to optimize with higher storage capacity and upstream regulation capacities.

Regulated flows arriving at HAD; HAD inflows will increase from November to June, and decrease from July to October, and will be more regular. At least, it will offer three benefits:

- The possibility to optimize the Water Resources Management at HAD. Agricultural schedule may be reconsidered to optimize and improve the agricultural production.
- Except for the driest years, the total irrigation demand in Egypt, Sudan and Ethiopia could be increased
- Reduction of the sedimentation loads occurring in the Sudanese Nile Valley, which particularly affects the Sudanese reservoirs with reduced capacity (Merowe, Sennar, Roseries). GERDP reservoir will retain sediment upstream Sudan protecting Sudanese reservoir’s live storage. It may improve Sudanese dam efficiency and water use optimization. Indeed, combined with more regular flows, irrigation schedule can be modified increasing crops production and/or improving water use efficiency.
- Better coverage of the Sudanese irrigation use. GERDP reservoir will provide more constant flows than in the present natural conditions. The mean monthly flow at the Sudan Border will become higher than when compared with present situation (without GERDP).
- More constant flows all over the year will reduce evaporation losses and infiltration along the Blue Nile River.
- Reduction of the threat due to Blue Nile floods in Sudan. Certainly, the high flows during the wet season will be stored in GERDP reservoir and will sustain moderate flows all over the dry season reducing negative impacts on population and infrastructures in Sudan. GERDP will reduce the maximum monthly Blue Nile flow at Sudan border by approximately half and double the minimum flow.

GERDP construction will reduce HAD energy generation by 395.41 GWh/year in average because of the HAD water level reduction. This represents only a decrease of 6.14% of the present HAD energy generation. This is unavoidable but, at the same time, GERDP will generate around 14,238.99 GWh/year which significantly increase the present power production capacity of the whole Eastern Nile Basin. Indeed, the total energy generation of GERDP, Roseries, Sennar, Merowe and HAD will reach at 31,363.63 GWh/yr which represents an increase of more than 111.76% compared to the present average yearly energy generation by Roseries, Sennar, Merowe and HAD.

Finally, it would be advisable that riparian countries especially the three countries (i.e. Egypt, Ethiopia and Sudan) could closely cooperate to optimize the whole Eastern Nile Basin water management system, developing an integrated system will be considerably beneficial for each country and interconnected projects could provide extra energy to Sudan and Egypt from excess of GERDP energy generation.

6.2.2 Impounding/filling/ stage simulations Conclusion

Downstream impacts of GERDP on Roseries, Sennar, Merowe and HAD during filling stage will appreciably depend on the hydrological conditions in which impounding stage will occur:

- During sequences of average and wet sequence of filling years, GERDP impounding will be realized from June 2014 to July 2019. The water demand for Egypt and Sudan irrigation will be equal to situation without GERDP upstream. There will be energy generation increase from Sudan reservoirs (i.e.Roseires, Sennar, and Merowe) due to the seasonal inflows regime regulation and relatively more constant flows arrive at Sennar throughout the year.
- If GERDP impounding stage will occur during a sequence of dry years, it will require more additional year to reach GERDP Normal Water Level (i.e.640masl).

The negative downstream impacts will be only in the short term during GERDP reservoir impounding. These effects will be the reduced energy generation in downstream plants and some temporary irrigation water supply shortage during a sequence of dry years. All these impacts will be more than compensated by the long term benefits.

In order to minimize negative impacts of GERDP impounding on downstream reservoirs operation conditions, if it occurs during a sequence of dry years, the measures which should be implemented could be;

- Introducing temporary limitations in water supply for irrigation in both Sudan and Egypt and/or
- Filling GERDP reservoir in a longer period.

6.3 RECOMMENDATIONS

Sizeable development of the water resources on the Eastern Nile River basin particularly upper Blue Nile sub basin is likely in the coming years including the one which is under construction (GERDP hydropower project). Such development should be well designed, constructed and operated in a more sustainable manner. The two key themes of the recommendations are to strengthen nation's capacity for water resources management, and to bring in the philosophy and practical aspects of Integrated Water Resource Management (IWRM) to Ethiopia and the downstream riparian countries Sudan and Egypt.

The beginning of water resources planning and strategizing with downstream riparian countries is essential to the achievement of the hydropower and irrigation development projects. There are many opportunities for win-win situations, with bargaining chips including energy and food production, regulated stream flow, water conservation through reduced evaporation losses, and redistributed water rights.

This thesis work can be expanded in various ways that involve the climate, hydrology, and water resources components.

Nowadays the sign of climate change and its impact is revealing on different natural and artificial/manmade systems, in one or other ways. Therefore, the study recommends including further refinement of scenarios with impacts of climate change.

Sedimentation is one of the major problems of reservoirs by decreasing the live storage capacity as it is seen in Roseries reservoir downstream of GERDP. To minimize sediment accumulation rate integrated watershed management practice should be done upstream as well as on the downstream of GERDP reservoir to keep the long life of the reservoir and sustainability of the land. This study has not considered sedimentation characteristics from all proposed and existing pools; therefore, the effect of upstream reservoir on sedimentation of downstream reservoirs in Sudan which can alter the storage capacity of reservoirs. Therefore, the study recommends including this parameter in future studies.

This study has not considered seepage loss from all proposed and existing pools; therefore, quantification and simulation of seepage from the reservoir can alter result obtained from HEC-ResSim and mode of operation of a reservoir. Therefore, the study recommends including this parameter in future studies.

REFERENCES

Abu-Zeid, M.A., and El-Shibini, F.Z., 1997, Egypt’s High Aswan Dam, Water Resources Development, Vol. 13, No. 2, pp. 209 - 217.

Abdel-Moteleb,M., and Saad,M.B.A.,2001, “Calibration Of An Ogee Weir”, IAHR Congress, China.

Acres Consulting Services Limited, December 1973, "The Trent Basin: Plan of Operation,” Report to the Department of Indian and Northern Affairs.

Acres Consulting Services Limited, December 1973, "The Trent Basin: Analysis of the System." Report to the Department o f Indian and Northern Affairs.

Amir Mobasher, 2010, “Adaptive Reservoir Operation Strategies under changing Boundary Conditions: The case of Aswan High Dam Reservoir," Ph.D. Thesis, Darmstadt, Germany.

Awulachew S.B.; McCartney M.; Steenhuis, T. S; Ahmed A. A., 2008, “A review of hydrology, sediment and water resource use in the Blue Nile Basin.” Colombo, Sri Lanka: International Water Management Institute. 87p. (IWMI Working Paper 131)

Bather, J.A., 1962, “Optimal Regulation Policies for Finite Dams.” J. Soc.Ind. Appl. Math., 10. pp. 395-423.

Beard, L.R., February1976, “Flood Control by Reservoirs.”Vol.7 of Hydrologic Engineering Methods for Water Resources Development. U.S. Army Corps of Engineers. Hydrologic Engineering Center. Davis, California.

Beard, L.R., September 1975, "Models for optimizing the Multipurpose Operation of a Reservoir System.” Proceedings of the Symposium and Workshops on the Application of Mathematical Models in Hydrology and Water Resources Systems, Bratislava. Czechoslovakia.

Block, P., 2007, Integrated management of the Blue Nile Basin in Ethiopia: hydropower and irrigation modeling, International Food Policy Research Institute, Washington, DC, Discussion Paper 00700.

Buras, N., November 1963, “Conjunctive Operation of Dams and Aquifers.” ASCE, J.of the Hydraulics Div., Vol. 89. No. HY6. p.111.

Dietrich, G. N. and O.P. Loucks, November 1967, "A Stochastic, Model for Operating a Multi-purpose Reservoir," Proceedings, Third Annual American Water Resources Conference, San Francisco, California, pp.92-104.

Eastern Nile Technical Regional Office (ENTRO), January 2008, “One system inventory-OSI kit” Addis Ababa, Ethiopia.

Eichert, B.S., October, 1979, "Reservoir Storage Determination by Computer Simulation of Flood Control and Conservation Systems," Technical Paper NO. 66, HEC. Davis. California.

Ethiopian Association of Civil Engineers (EACE), 1998, Bulletin Vol. 1. No. 1, Addis Ababa.

EEPCo, Ethiopian Power System Expansion Master Plan update (EPSEMPU), 2006.

EEPCo, 2010, 5000 Hydroelectric Project, Basic Design: Vol.I, main report, Studio Pietrangeli (SP), Salini Costruttori.

EEPCo, 2010, 5000 Hydroelectric Project, Basic Design: Vol.VII, Hydrology report, Studio Pietrangeli (SP), Salini Costruttori.

EEPCo, 2010, 5000 Hydroelectric Project, Basic Design: Vol.VIII, Hydraulic calculations, Studio Pietrangeli (SP), Salini Costruttori.

EEPCo, 2010, 5000 Hydroelectric Project, Basic Design: Vol.X, Energy Production and Reservoir operation Studies, Studio Pietrangeli (SP), Salini Costruttori.

EEPCo, 2011, GRAND ETHIOPIAN RENAISSANCE DAM PROJECT: Hydrological and Reservoir Simulations Studies, RP1-002582/Rev C, Tractebel Engineering, Coyne et Bellier.

Evans, T.E., 1996, the effects of changes in the world hydrological cycle on availability of water resources. In F. Bazzaz & W. Sombroek, eds. Global climate change and agricultural production: direct and indirect effects of changing hydrological soil and plant physiological processes pp. 15–48. Rome, FAO; and Chichester, UK, John Wiley.

Fahmy, H., March2001, Modification and Re-Calibration of the Simulation Model of Lake Nasser, Water International, Volume26, Issue1, pages 129-135.

Falkson, M.,1961, "An Application of Howard's Policy - Iteration Method for the Solution of Sequential Decision Processes to the Problem of Determining the Optimal Operation Procedure for a Water Resource System, “seminar paper. Harvard Water Program. Cambridge. Massachusetts.

Frederich, A.J. and L.R. Beard, October 1972, "System Simulation for Integrated Use of Hydroelectric and Thermal Power Generation," Technical Paper No. 33, The Hydrologic Engineering Center, U.S. Army Corps of Engineers.

Gablinger, M. and D.P. Loucks, January 1970, “Markov Models for Flow Regulation,” ASCE, J. Hydraulics Div., Vol. 96, No. HY1, pp. 165-181.

Gablinger, M., March 1971, "Reservoir Regulation, Same Techniques and Results,” Technical Report No. 26, Cornell University Water and Marine Sciences Center, Ithaca, New York, p. 186.

Georgakakos, A.P.,Yao,H.,and Miller,F.,May1997,A Decision Support System For The High Aswan Dam, Waterpower.

Houck, M.H. and J.L. Cohon, 1978, "sequential Explicity Stochastic Linear Programming Models: A Proposed Method for design and Management of Multipurpose Reservoir Systems," Water Resources Res., Vol. 14, No. 2,

Hula, R.L, 1981, “Southwestern Division Reservoir Regulation Simulation Models.”Proceedings of the National Workshop on Reservoir Systems Operations (G.H.Toebes and A.A. Sheppard, Eds.), ASCE, New York.

http://waltainfo.com/EEPCO/about.html. “Milestone in the history of EEPCO” (12.05.2010)

Solomon, S., 1998, Hydropower of Ethiopia: Status, potential and Prospects.

Hydrologic-Engineering Center, 2007, HEC-ResSim, Reservoir System Simulation, User’s Manual Version 3.0:U.S. Army corps of Engineers, Report CPD-82, Davis, Calif.

Also Available online: www.hec.usace.army.mil

Hydrologic Engineering Center, 1998, HEC-5, Simulation of Flood Control and Conservation System, User’s Manual, Report CPD-5, U.S. Army Corps of Engineers, Davis, Calif.

Hydrologic Engineering Center, 2006b, HEC-DSSVue, HEC Data Storage System Visual Utility Engine, User’s Manual, Report CPD-79, U.S. Army Corps of Engineers, Davis, Calif.

Hydrologic-Engineering Center, December 2010, Water Balance and Regulation Alternative Analysis for Kajakai Reservoir using HEC-ResSim, Phase I and II Final Report PR-63, U.S. Army Corps of Engineers, Davis, Calif.

Ibrahim, A. M., 1984, “The Nile: Description, Hydrology, Control and Utilisation,” Dr W. Junk Publishers, the Hague. Printed in the Netherlands, Hydrobiologia 110, 1-13.

Labadie, J. W., Baldwin M. L., and Larson R., 2000, MODSIM: Decision Support System for River Basin Management, Documentation and User Manual, Colorado State University, Fort Collins.

Little, J.D.C., "The Use of Storage Water in a Hydroelectric System,” Operations Res., 3, 1955, p. 197, **Ph.D.** thesis.

Loucks, D.P., April 1970, “Some Comments on Linear Decision Rules and Chance Constraints,” Water Resources Res., vol. 6, No. 2, pp. 662-671.

Loucks, D.P. and L.M. Falkson., June 1970, “A Comparison of Some Dynamic, Linear and Policy Iteration Methods for Reservoir Operation," Water Resources Bulletin, AWRA Journal, Vol. 6, No. 3, pp. 384-400.

MacDonald, Sir M. & Partners. , 1988, Rehabilitation and improvement of water delivery systems in Old Lands, Egypt. Annex A: Water Resources. IBRD/UNDP Project No. EGY/85/012. Washington, DC.

Mahmoud, M.K., April 2005, Improvement the Efficiency of Toshka Spillway Canal, Water Science, Issue No. 37.

Manne, A.S., 1960, “Linear Programming and Sequential Decisions," Management Science, 6, p. 259.

Manne, A.S., 1962, "Product-mix Alternatives: Flood Control, Electric Power and Irrigation," International Economic Review, 3, p. 30.

McCartney, M. P., 2007, Decision support systems for large dam planning and operation in Africa. Colombo, Sri Lanka: International Water Management Institute. 47 p. (IWMI Working Paper 119)

Ministry of Electricity and Energy "MEE", 2005, Annual Report 2004/2005, Cairo, Egypt.

Moussa, A., Soliman, M., and Aziz, M., 2001, Environmental Evaluation For High Aswan Dam Since Its Construction Until Present, Sixth International Water Technology Conference, IWTC, Alexandria, Egypt.

National Electricity Corporation (NEC) Sudan, 2003,” Building of Electricity sector database and long term power system planning study” interim report no.3 the data book.

River System: An Improved Operational Strategy, December 1975, “Proceedings of the Second World Congress on Water Resources, New Delhi, India.”

Roefs.T.G. July 1968, "Reservoir Management: The State of the Art,” IBM, Science Center Rep. 320-2508.

Roefs. T.G. and L. D. Bodin, April 1970, “Multi reservoir Operation Studies.”, Water Resources Res. Vol. 6, No. 2. pp. 410-420.

Schweig, Z. and J.A. Cole, 1968, “Optimum Control of Linked Reservoirs,” Water Resources Res., Vol. 4. No. 3, pp. 479-497.

Sigvaldason. O.T., April 1976, "A Simulation Model for operating a Multi-purpose Multi-reservoir System." Water Resources Res. Vo1. 12. No. 2. pp. 263-278.

Sigvaldason, O.T., R. Ellis and R.B. Allen, May 1975, “Early Experience in Using a Simulation Model for operating the Trent River System.” Proceedings of the Second Canadian Hydro technical Conference, Burlington, Ontario.

Tedrow, A.C., C.S. Liu. D.B. Halton and R.A. Hiney, 1970, New York State Department of Environmental Conservation, Division of Water Resources. “The Use of Systems Analysis in the Development of Water Resources Management Plans for New York State.” Report to U.S. Department of the Interior, Office of Water Resources Research. Grant No. 14-01 -001 -1 536.

Texas Water development Board, July 1972, "Economic Optimization and Simulation Techniques for Management of Regional Water Resource System," River 3asin Simulation Model, SIMYLD II Program Description.

Thomas, H.A., J r. and P. Watermeyer, 1962, "Mathematical Models: A Stochastic Sequential Approach in Design of Water Resource Systems," edited by A. Maass, et al. , Chapter 14, pp. 540-561, Harvard University Press, Cambridge, 4uassachusetts.

U.S. Amy Corps of Engineers, 1971, “HEC-3: Reservoir System Analysis,” Generalized Computer Program Description. The Hydrologic Engineering Center. Davis, California.

UNESCO, December, 2004, World Water assessment program, National water development report for Ethiopia. Addis Ababa.

UNECA, 1995, “Problems and Prospects for Inter-country Cooperation for Integrated Water Resources Development of the Nile River Basin”, Addis Ababa Ethiopia.

U.S. Army Corps of Engineers, 2007, (accessed online), HEC-ResSim:
http://www.hec.usace.army.mil/software/hec-ressim/hecressim-hecressim.html

Vedula,S. and Mujumdar, P.P. ,2006, “Water Resources Systems Modeling Techniques and Analysis.”

Wakena Totoba, 2006, “Operational Analysis of the cascaded Wadecha-Belbela Reservoir system (Ada’a Liben Woreda, in Oromia region),” M.Sc. Thesis, Arba Minch University, Ethiopia.

Watermeyer. P. and H.A. Thomas, J r., 1962, "Queuing Theory and Reservoir design." The Annals of the Computation Laboratory of Harvard University, Vol. 31, Harvard University Press. Cambridge, Massachusetts.

Whittington, D., Wu, X., and Sadoff, C., 2005, Water resources management in the Nile Basin:
The economic value of cooperation, Water Policy, 7, 227–252.

Worede Fantaye Hailemariam, January 2011, “The Challenges of Renewable Energy Resource Development: The Case of Gilgel Gibe III Hydropower Project in Ethiopia” Thesis, University of Oslo, Blindern, Norway.

Wurbs. R. A., and Tibbets, **M. N.,** 1985, ‘‘State-of-the-art review and annotated bibliography of systems analysis techniques applied to reservoir operations.’’ Tech. Rep. No. 136, Texas Water Resources Institute, College Station, Tex.

Wurbs, R.A., James P.W., 2001, “Water Resources Engineering” , First Edition.

Wurbs, R.A., 2005, “Comparative Evaluation of Generalized River/Reservoir System Models.” Tech. Rep, 282, Texas Water Resources Institute, College Station, TX.

Wurbs, R.A., 2009, Salinity Simulation with WRAP. Technical Report 317, Texas Water
Resources Institute, College Station, TX, USA.

Wurbs, R.A. ,1994, “Computer models for water resources planning and management” Tech. Rep, 282, Texas A&M University, Department of Civil Engineering, Environmental, Ocean and Water Resources Division, College Station.

Yeh. W.W-G., et al., February 1978, “Optimization of Real Time Hourly Operations of a Complex Multiple Purpose Reservoir System.” Report to USDI, OWRT. University of California at Los Angeles, School of Engineering and Applied Physics, California.

Yates, David N. and Kenneth M. Strzepek., 1998b, Modeling the Nile basin under climatic change. Journal of Hydrologic Engineering 3(2): 98-108.

Zagona, E.A., Fulp, T.J., R. Shane., T. Magee., and Goranflo, H.M., 2001, "RiverWare:
A Generalized Tool for Complex Reservoir System Modeling." Journal of the American Water Resources Association, 37(4), 913-929.

APPENDIX

APPENDIX-A Physical and Power plant characteristics of Hydropower dams(Source:ENTRO)

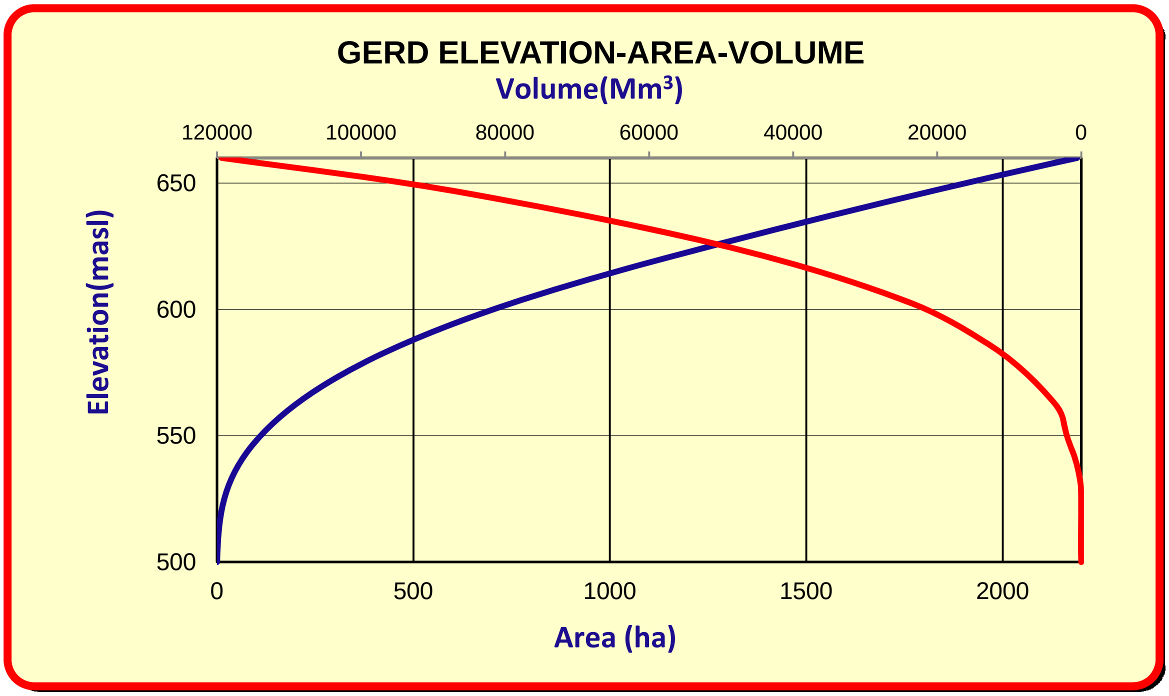


Fig A-1 Elevation-Area and Elevation-Storage curve for GERD reservoir

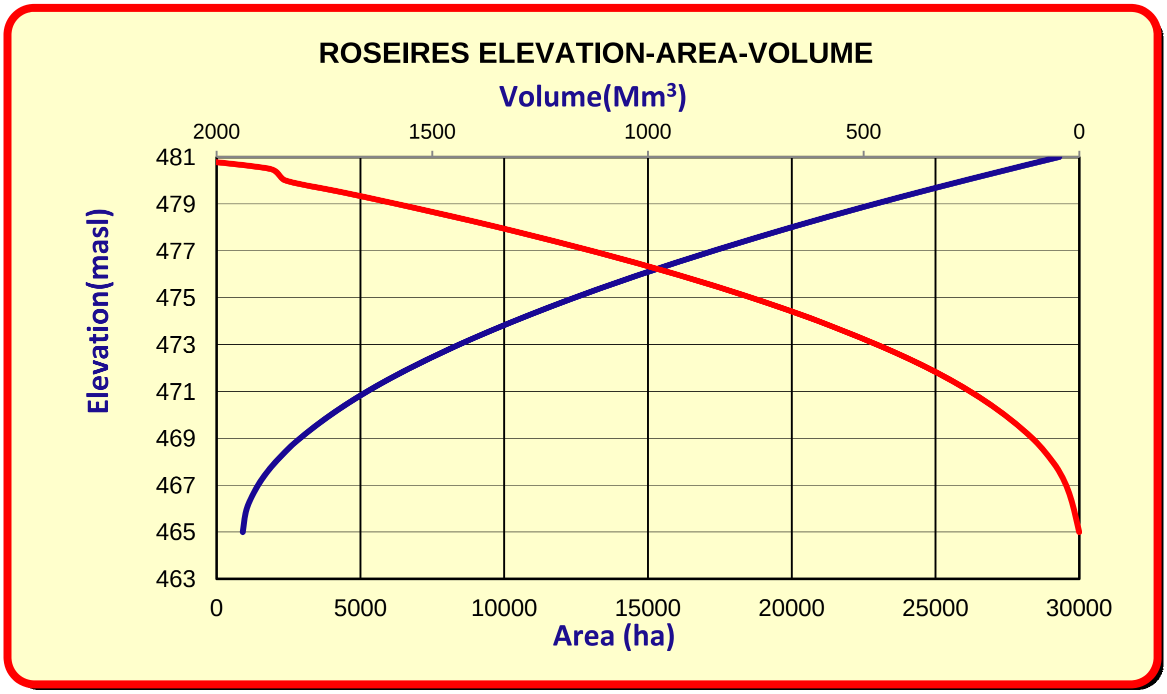


Fig A-~~1~~ Elevation-Area and Elevation-Storage curve for Rosaries reservoir

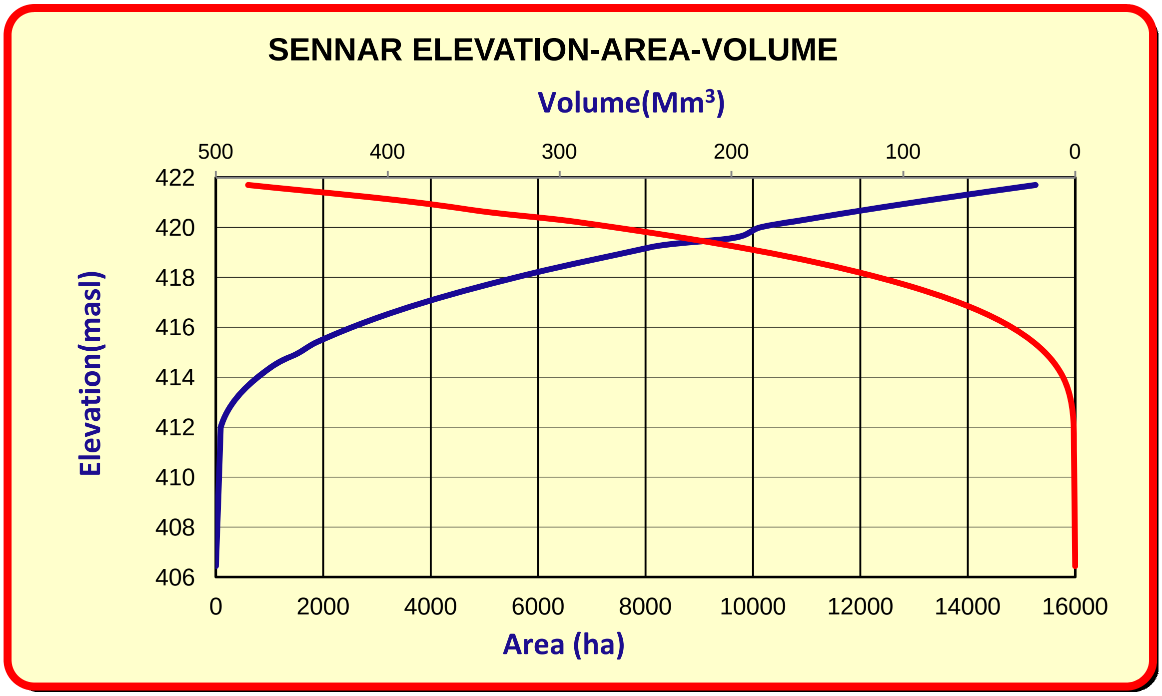


Fig A-1 Elevation-Area and Elevation-Storage curve for Sennar reservoir

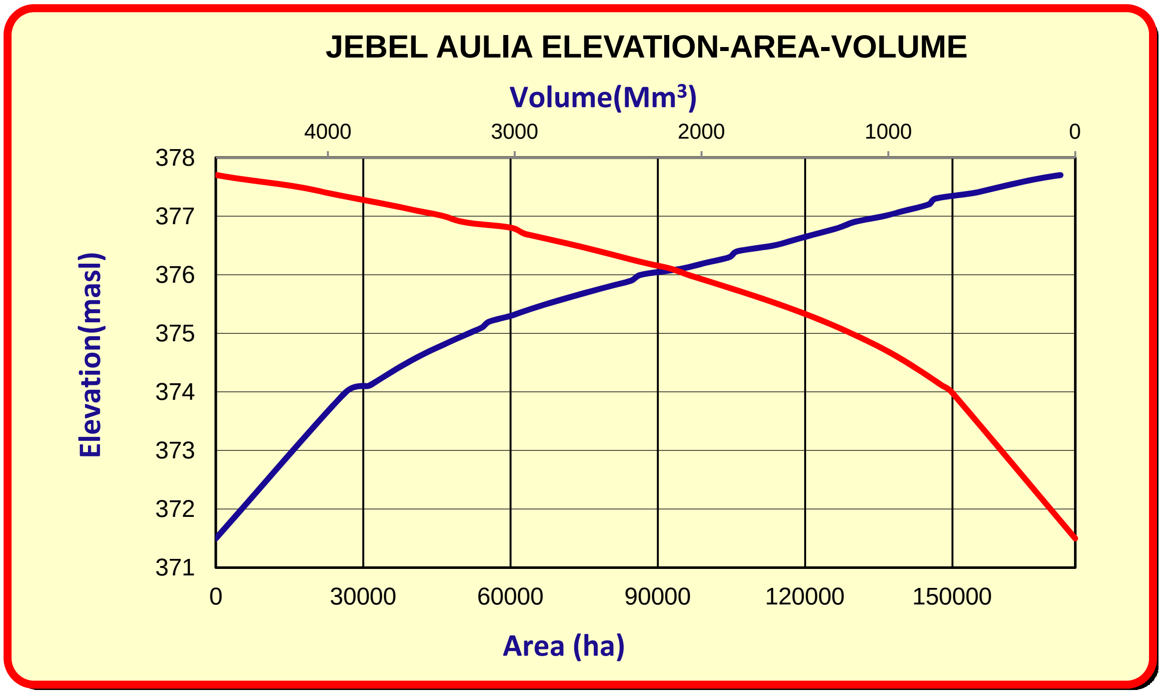


Fig A-1 Elevation-Area and Elevation-Storage curve for Jebel Aulia reservoir

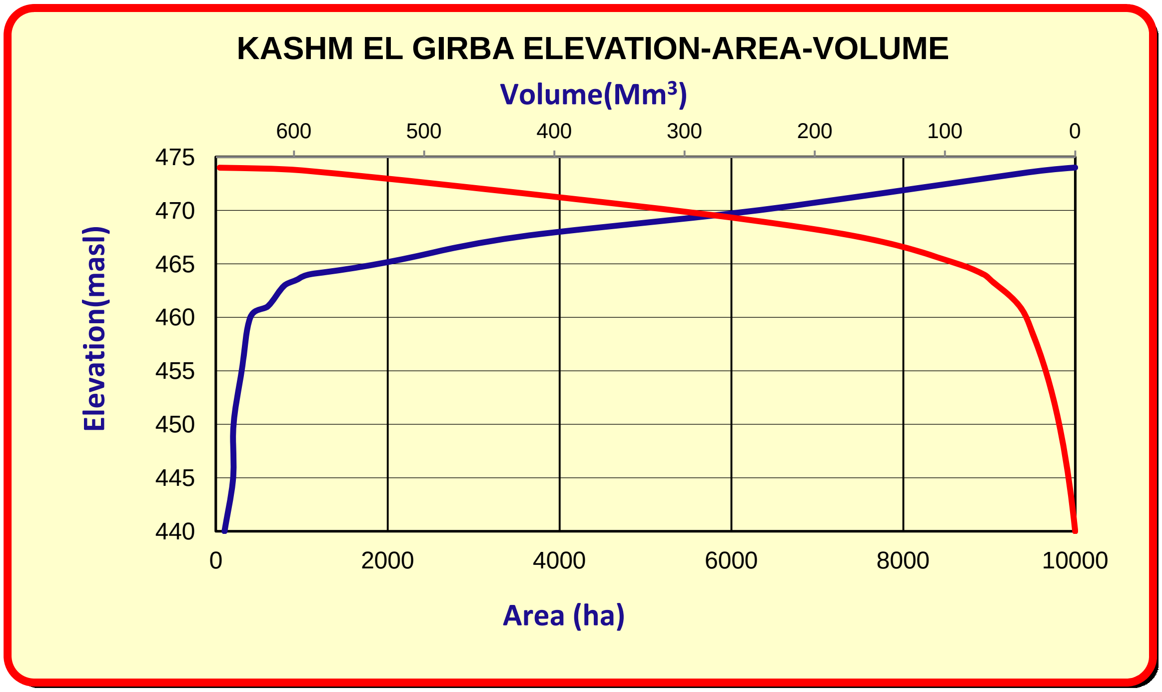


Fig A-1 Elevation-Area and Elevation-Storage curve for Kashm el Girba reservoir

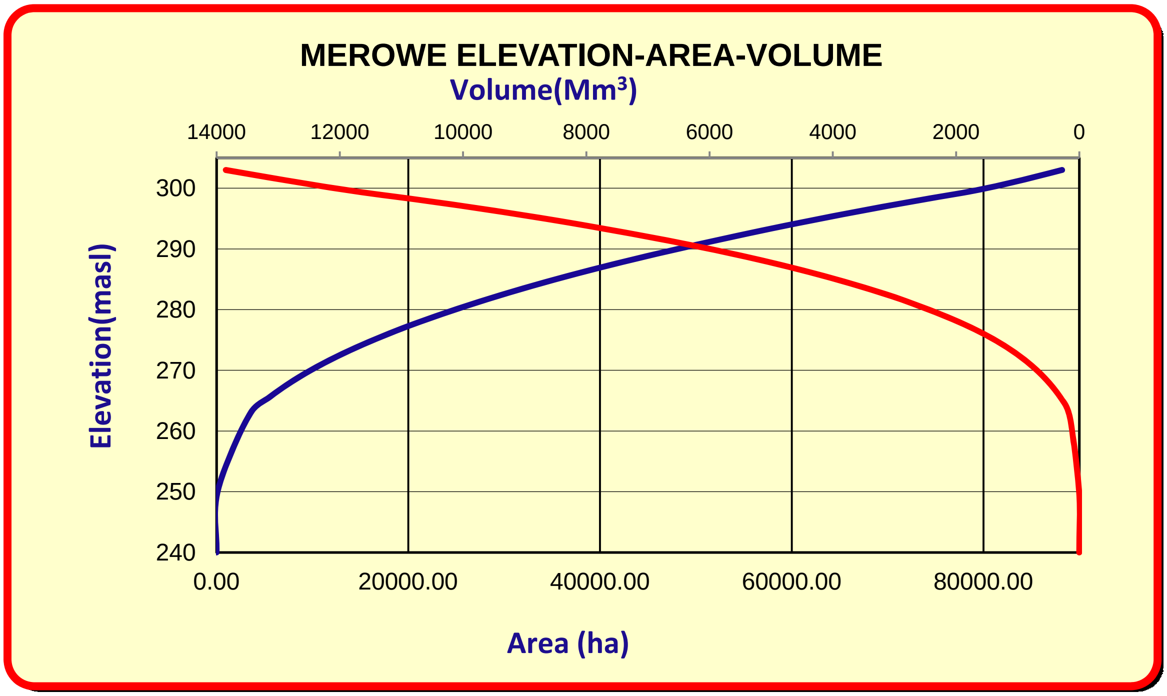


Fig A-1 Elevation-Area and Elevation-Storage curve for Merowe reservoir

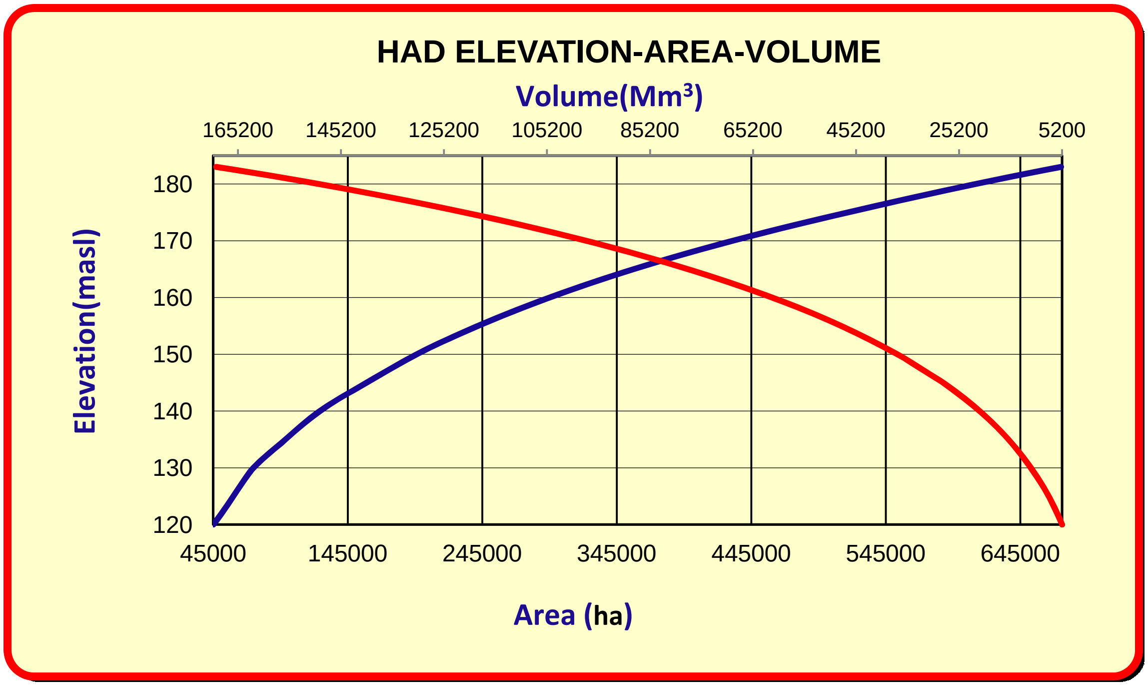


Fig A-1 Elevation-Area and Elevation-Storage curve for HAD reservoir

APPENDIX-B Table of Monthly Evaporation rates (Source: ENTRO)

Month	GERDP	Roseires	Sennar	Jebel Aulia	Kashm El Girba	Merowe	HAD
	Evaporation(mm)	Evaporation (mm)	Evaporation (mm)	Evaporation (mm)	Evaporation (mm)	Evaporation (mm)	Evaporation (mm)
Jan	135	179.8	254.2	189	174	197	123
Feb	136	184.8	265.55	235	204	222	128
Mar	171	226.6	328.6	233	242	295	168
Apr	158	221.1	315	222	248	331	196
May	106	189.1	282.1	229	258	365	243
Jun	42	62.7	228	225	238	340	262
Jul	-3	-27.9	136.4	118	126	314	260
Aug	1	-26	93	115	81	303	254
Sep	14	19.5	105	135	162	317	237
Oct	91	124.9	170.5	152	183	307	214
Nov	114	156.9	234	174	188	231	166
Dec	115	167.4	223.2	171	183	199	133
Annual	**1080**	**1478.9**	**2635.55**	**2198**	**2287**	**3421**	**2384**

APPENDIX-C Tables of Monthly Demands (Source: ENTRO)

Table C-1. Demands on the Blue Nile

Month	U/S Sennar Demand (cms)	D/S Sennar Demand (cms)	Gezira Managil Demand (cms)
Jan	67.46	7.51	202.34
Feb	66.45	8.1	191.27
Mar	44.69	10.42	118.13
Apr	34.87	11.72	30.78
May	35.09	12.39	44.49
Jun	77.06	12.54	180.89
Jul	97.39	9.04	268.64
Aug	93.75	7.22	258.55
Sep	132.38	10.28	337.76
Oct	148.2	11.35	321.77
Nov	141.85	10.11	249.6
Dec	82.78	7.25	185.58

Table C-2. Demands on the Tekeze-Setit-Atbara

Month	Khashm El Gibra Demand (cms)
Jan	42.24
Feb	39.78
Mar	27.43
Apr	16.89
May	19.44
Jun	40.83
Jul	45.56
Aug	51.35
Sep	51.82
Oct	55.41
Nov	46.73
Dec	45.23

Table C-3. Demands on the White Nile between Malakal and Khartoum

Month	u/s of Jebel Aulia (cms)	d/s of Jebel Aulia (cms)	Total Jebel Aulia (cms)
Jan	9.05	20.91	29.97
Feb	9.83	24.72	34.55
Mar	10.73	28.00	38.74
Apr	12.01	31.25	43.26
May	12.04	32.99	45.03
Jun	12.27	35.58	47.85
Jul	9.3	69.22	78.52
Aug	6.74	71.91	78.66
Sep	10.41	135.65	146.06
Oct	10.5	155.89	166.39
Nov	10.15	135.35	145.5
Dec	8.75	36.99	45.75

Table C-4. Demands on the Main Nile

Month	Tamaniat- Hassanab Demand (cms)	Hassanab-Dongola Demand (cms)
Jan	18.85	13.44
Feb	12.85	10.75
Mar	5.34	20.37
Apr	4.63	25.08
May	7.17	25.92
Jun	14.81	23.26
Jul	13.44	18.85
Aug	10.75	12.85
Sep	20.37	5.34
Oct	25.08	4.63
Nov	25.92	7.17
Dec	23.26	14.81

APPENDIX-D Tables of Monthly Target reservoir pool level (Source: ENTRO)

Table D-1. Rosaries Dam Target Elevation

Month	Top Elevation (masl)
Jan	478.78
Feb	475.13
Mar	472.39
Apr	469.78
May	467.09
Jun	467.00
Jul	467.00
Aug	467.00
Sep	471.67
Oct	481.00
Nov	481.00
Dec	481.00

Table D-2. Sennar Dam Target Elevation

Month	Top Elevation (masl)
Jan	421.70
Feb	421.70
Mar	421.70
Apr	421.70
May	417.00
Jun	417.00
Jul	417.00
Aug	417.00
Sep	418.65
Oct	421.70
Nov	421.70
Dec	421.70

Table D-3. Khashm El Girba Dam Target Elevation

Month	Top Elevation (masl)
Jan	474.00
Feb	474.00
Mar	474.00
Apr	474.00
May	474.00
Jun	463.50
Jul	463.50
Aug	463.50
Sep	474.00
Oct	474.00
Nov	474.00
Dec	474.00

Table D-4. Jebel Aulia Dam Target Elevation

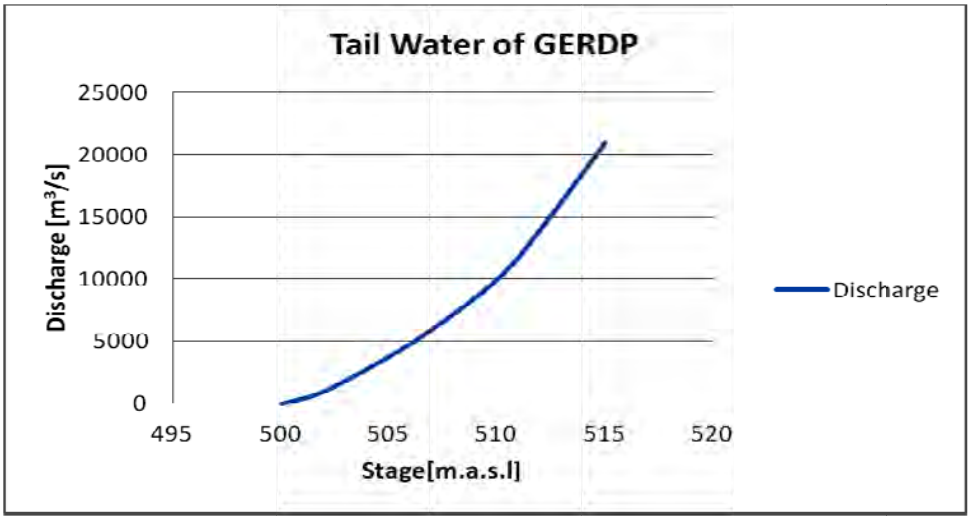
Month	Top Elevation (masl)
Jan	377.40
Feb	377.40
Mar	376.87
Apr	375.43
May	373.94
Jun	372.50
Jul	376.50
Aug	376.50
Sep	377.40
Oct	377.40
Nov	377.40
Dec	377.40

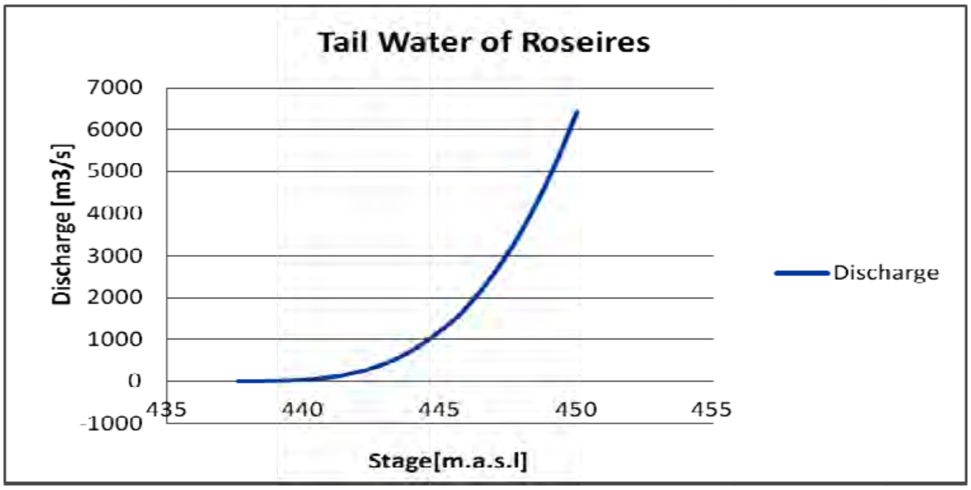
APPENDIX-E Table of Monthly Environmental Demands (Source: ENTRO)

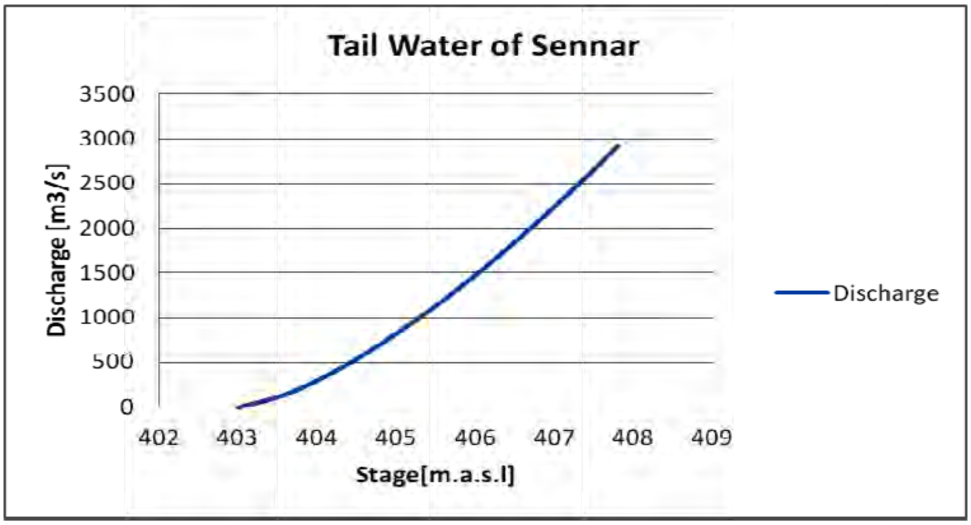
Table E-1. Environmental Demands in the Blue Nile and Tekeze-Setit-Atbara

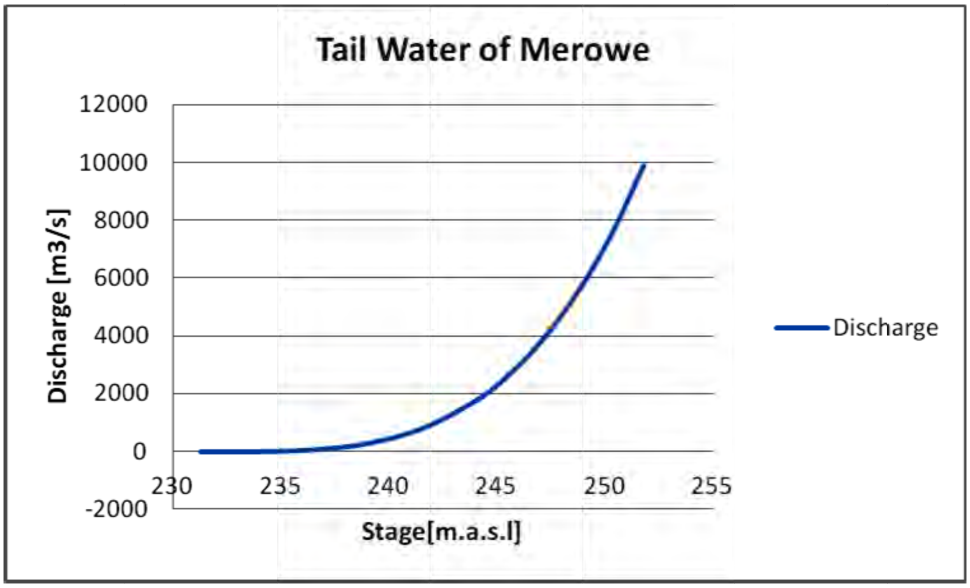
Month	Environmental Demand on Blue Nile (cms)	Environmental Demand on Tekeze-Setit-Atbara (cms)
Jan	64.40	2.47
Feb	64.40	1.59
Mar	64.40	2.43
Apr	64.40	3.72
May	64.40	3.57
Jun	64.40	9.07
Jul	128.80	22.77
Aug	643.80	22.77
Sep	193.20	22.77
Oct	128.80	20.30
Nov	64.40	8.58
Dec	64.40	4.74

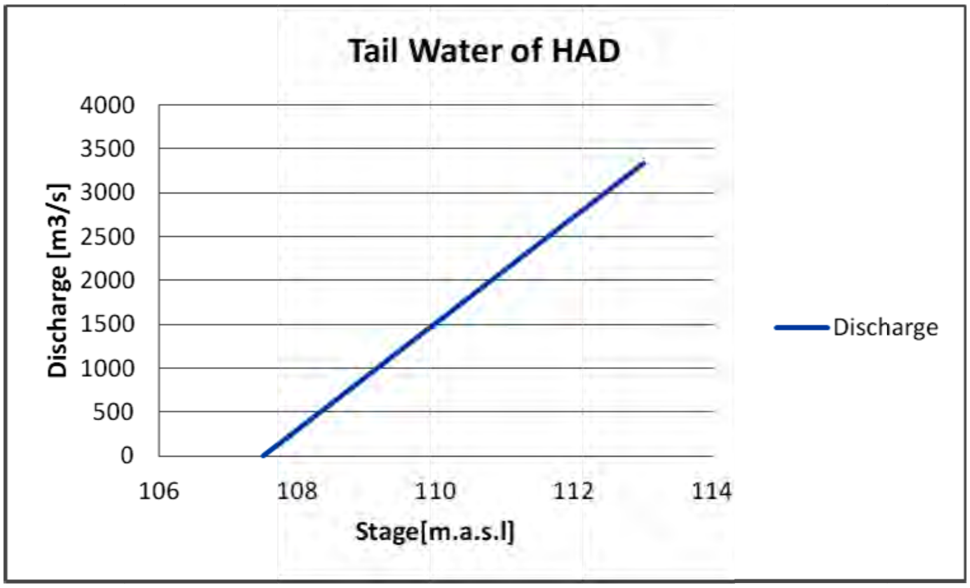
APPENDIX-F Tail water rating curves (Source: ENTRO)





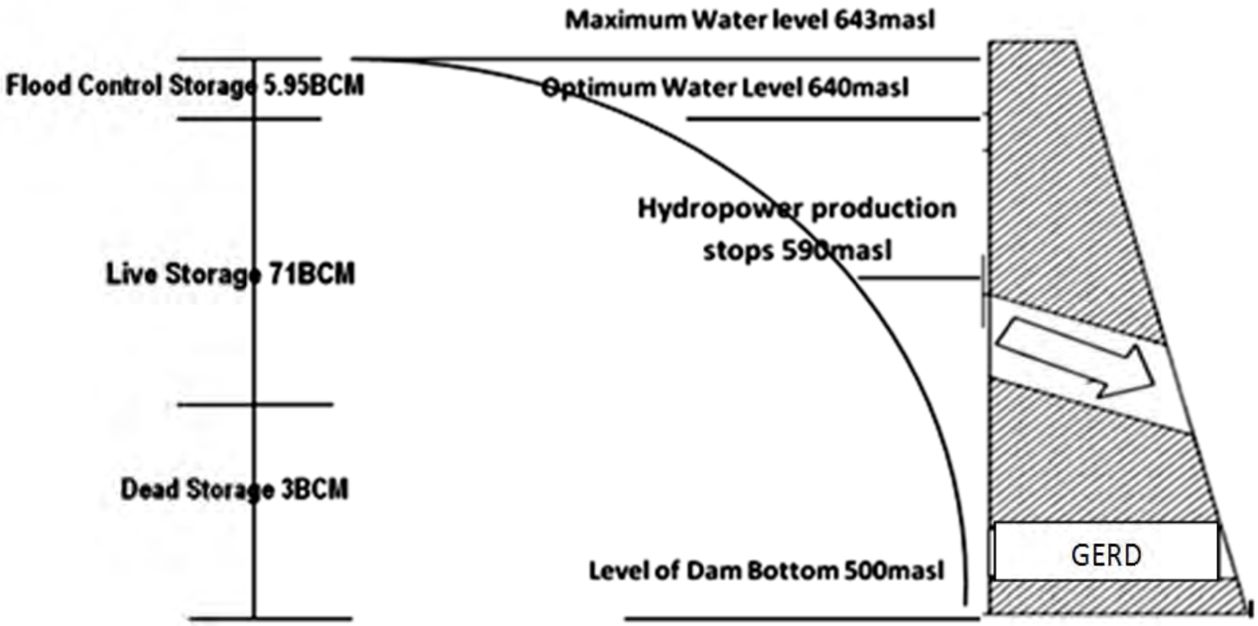



Tail Water of Merowe
12000
10000
8000
6000
4000
2000
0
-2000
230
235
240
245
250
255
Discharge [m3/s]
Stage[m.a.s.l]
Discharge

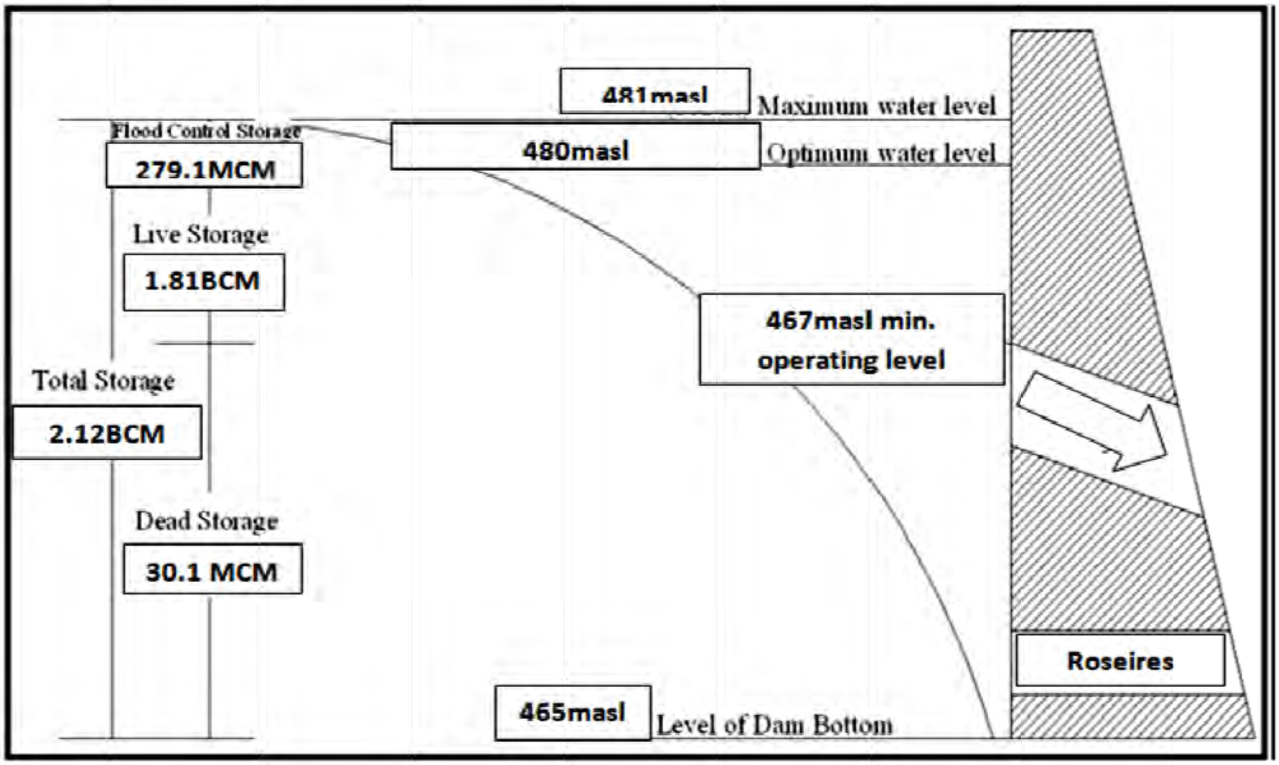

Tail Water of HAD
4000
3500
3000
2500
2000
1500
1000
500
0
106
108
110
112
114
Discharge [m3/s]
Stage[m.a.s.l]
Discharge

APPENDIX-G Dam characteristics

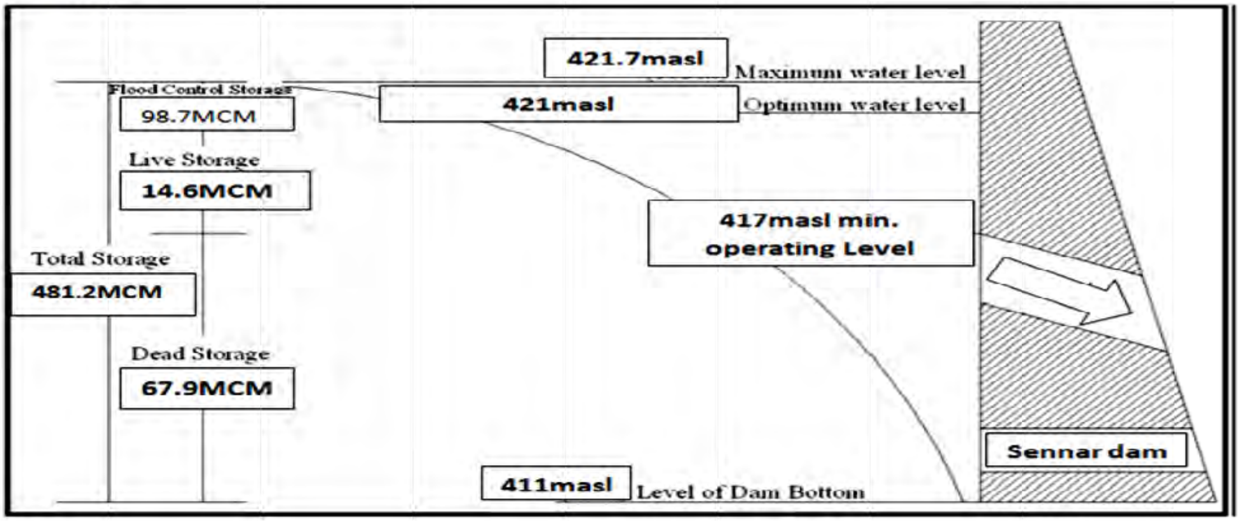
A- GERD



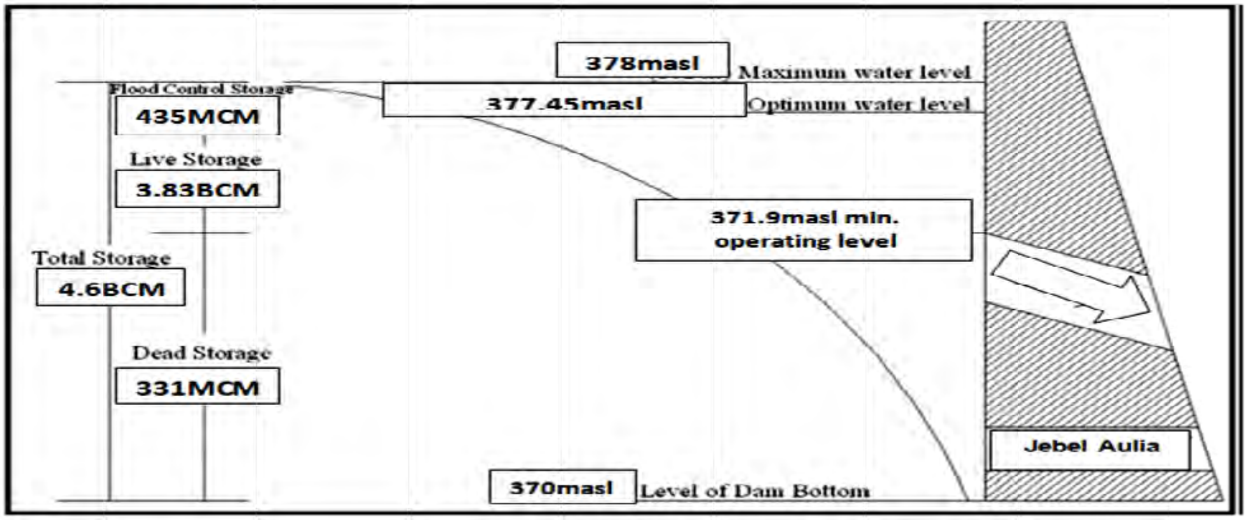
B-Roseires



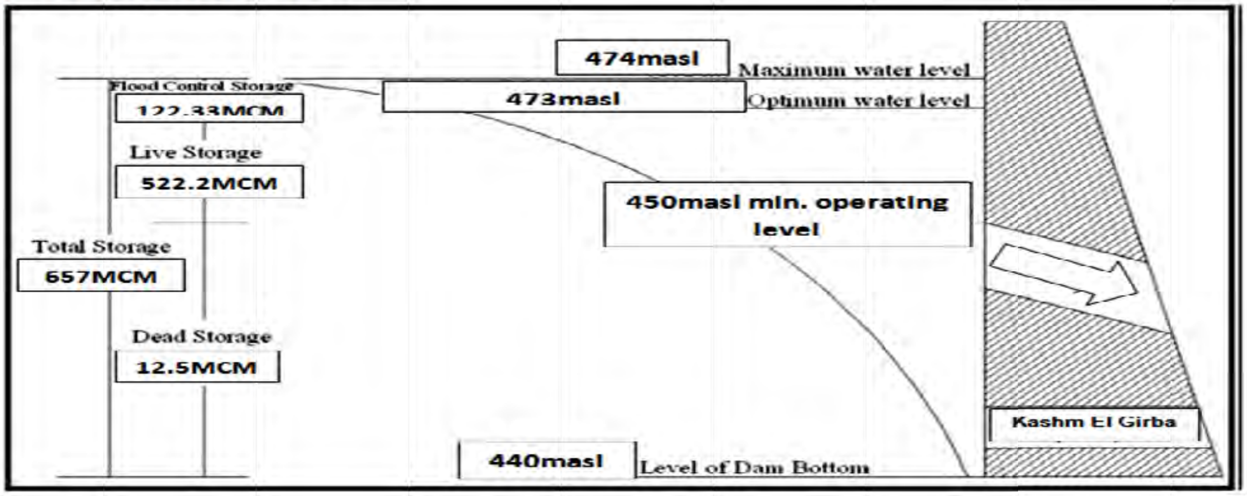
C-Sennar



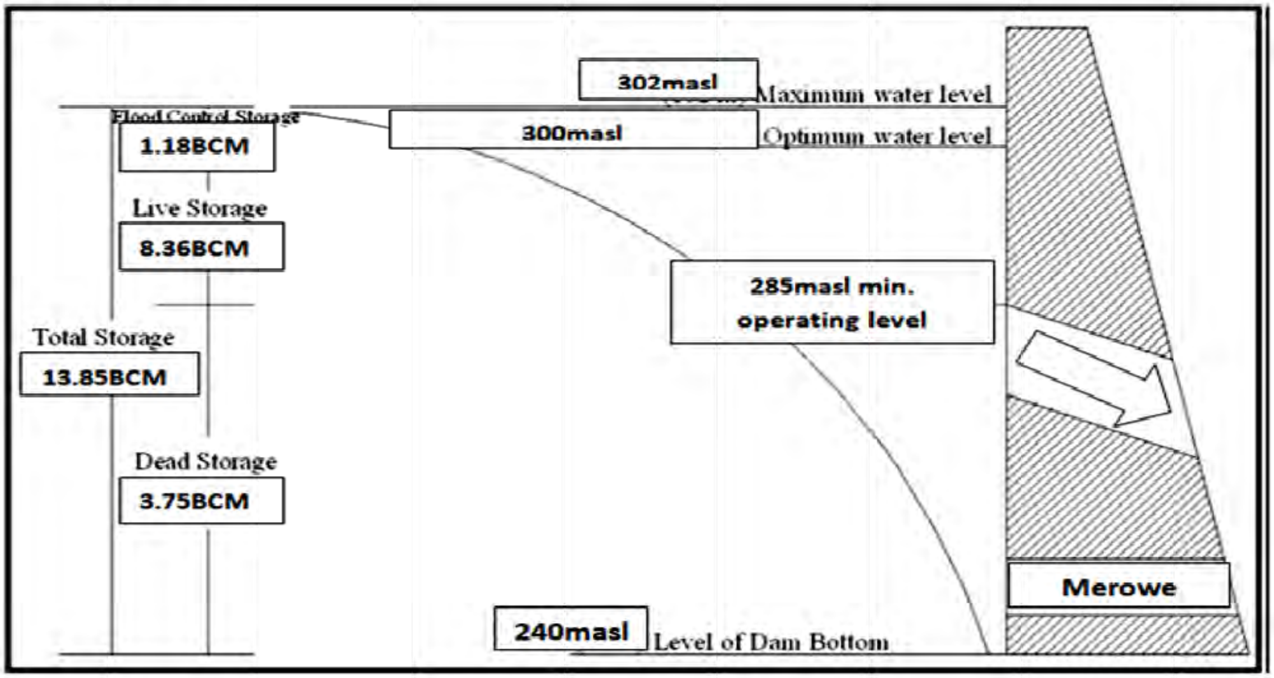
D-Jebel Aulia Dam



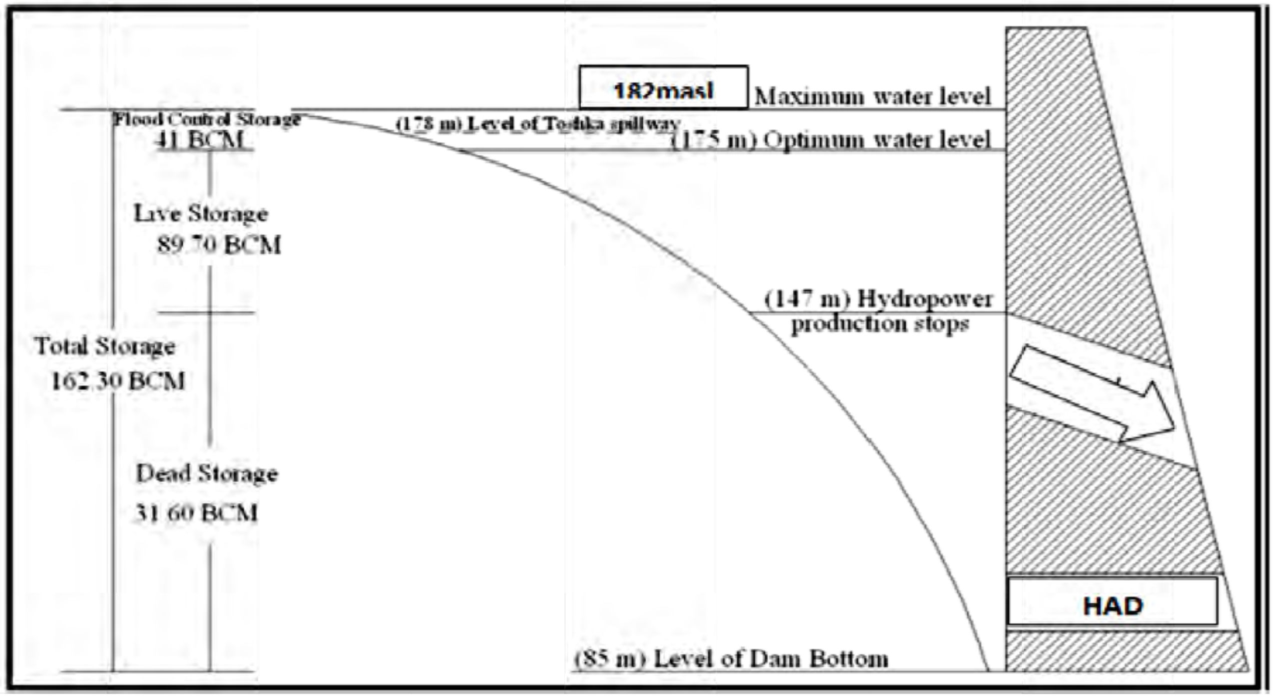
E- Kashm El Girba Dam



F- Merowe Dam



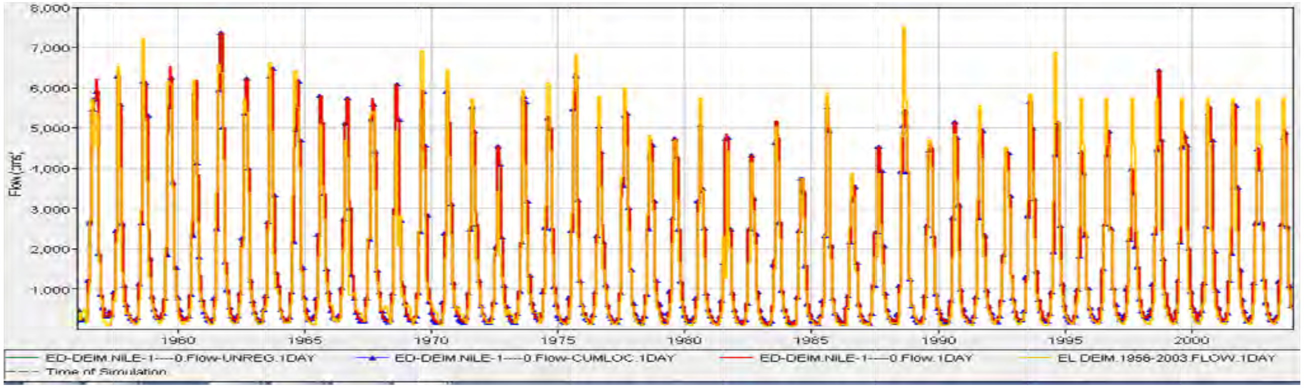
G- HAD



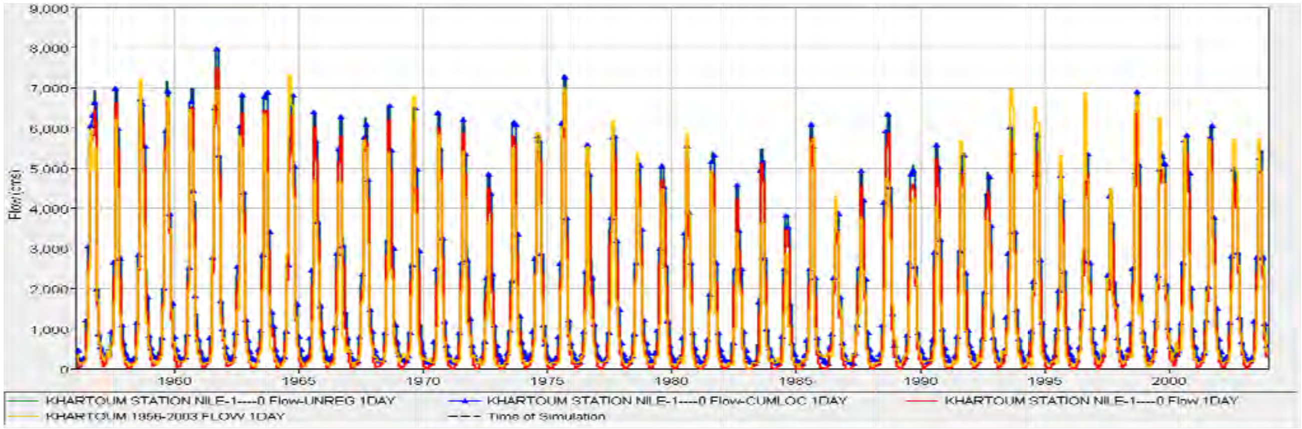
APPENDIX-H Standard Graphic Output Graph from HEC-ResSim Model

Model Calibration simulation results

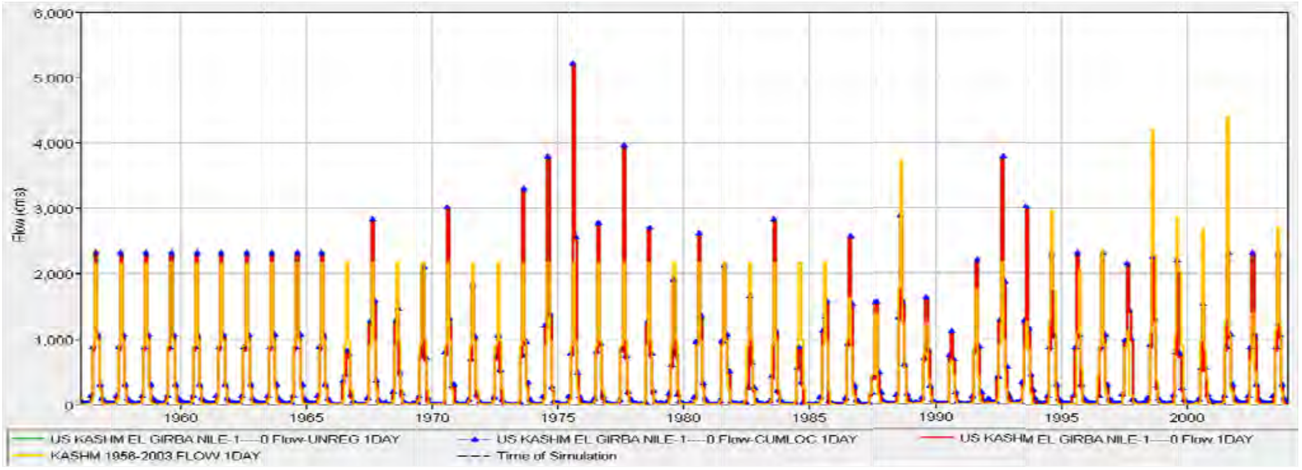
Time Series Calibration of the Blue Nile at El Diem Gage



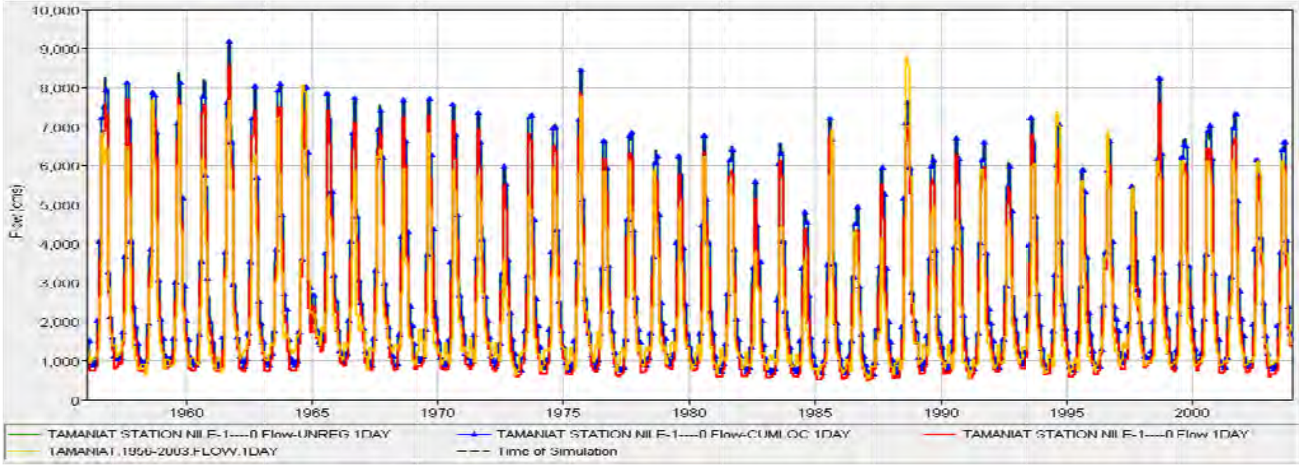
Time Series Calibration of the Blue Nile at Khartoum Station



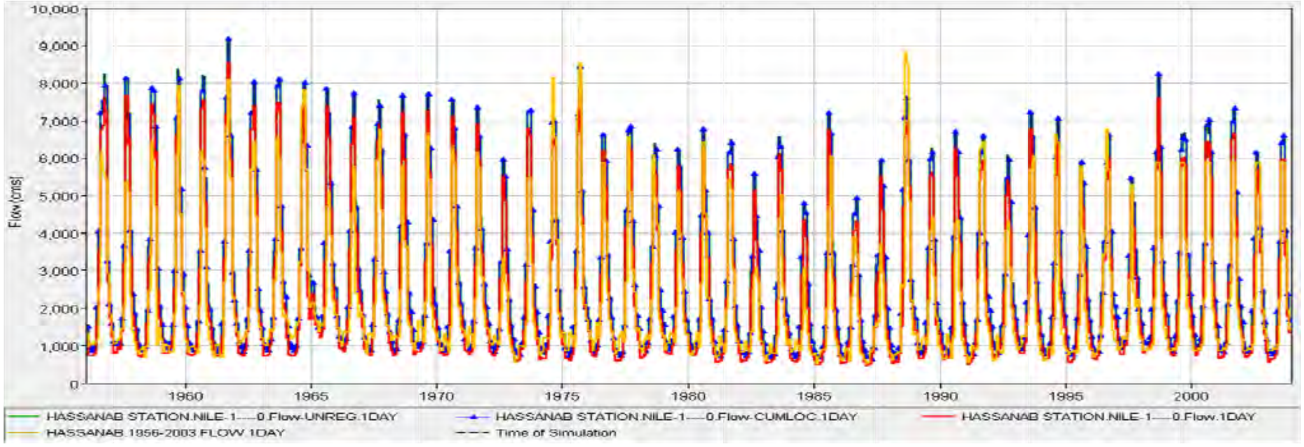
Time Series Calibration of the Blue Nile at Kashm El Girba



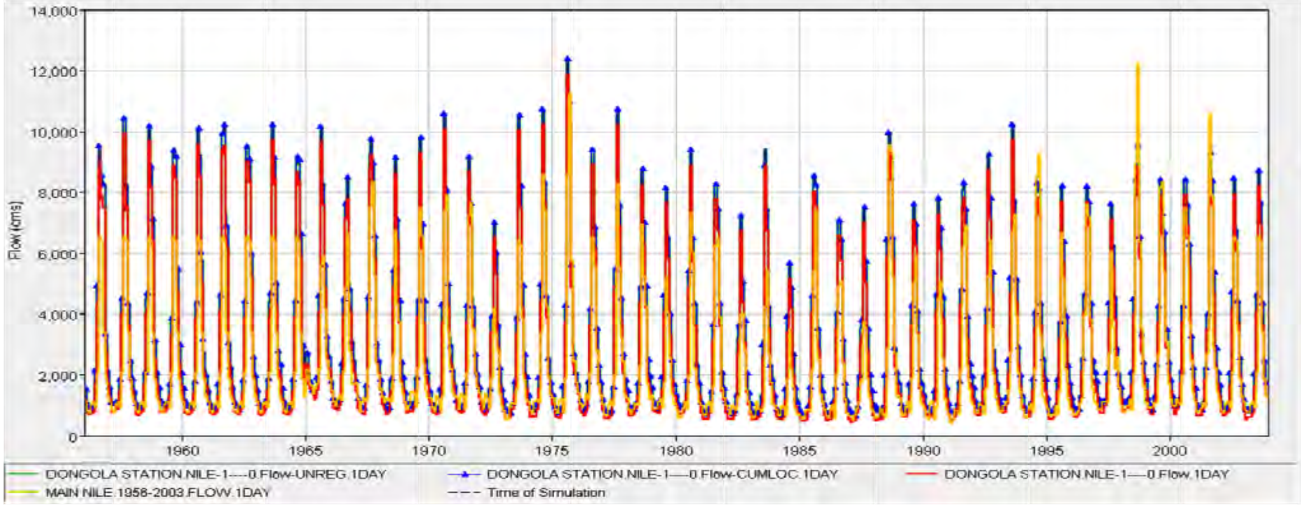
Time Series Calibration of the Blue Nile at Tamaniat Station



Time Series Calibration of the Blue Nile at Hassanab Station

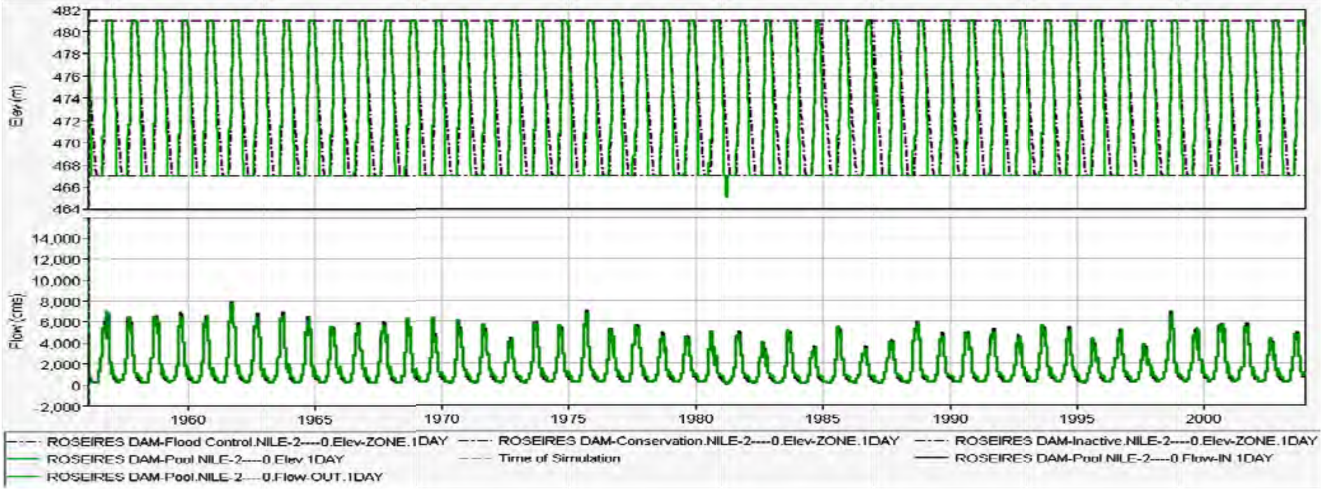


Time Series Calibration of the Main Nile at Dongola Station

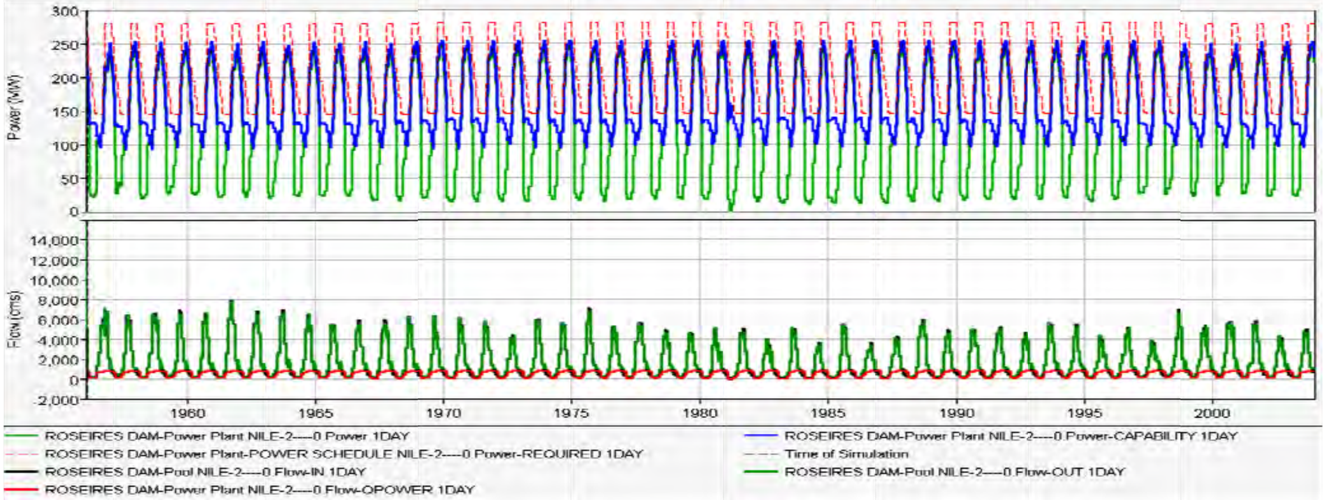


Simulations results in the present conditions (without considering GERDP)

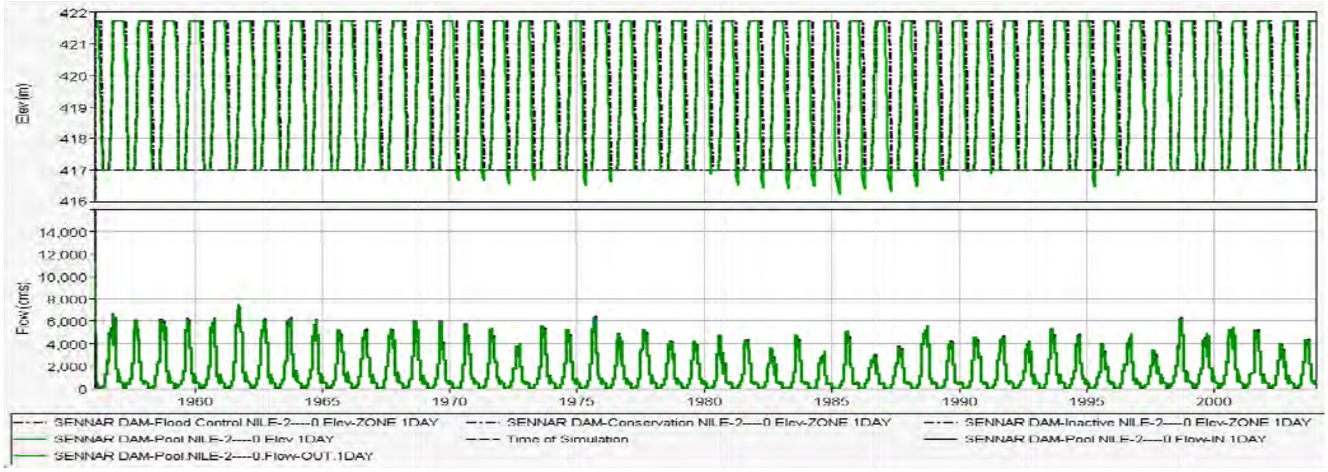
Rosaries Reservoir Modeled Pool Elevation and flow



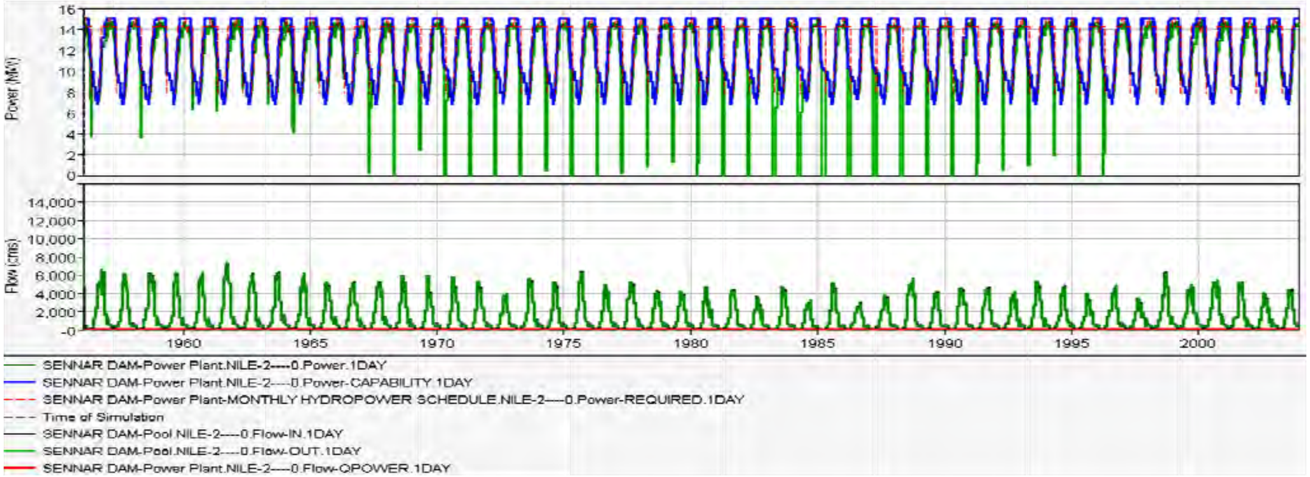
Rosaries Modeled Power



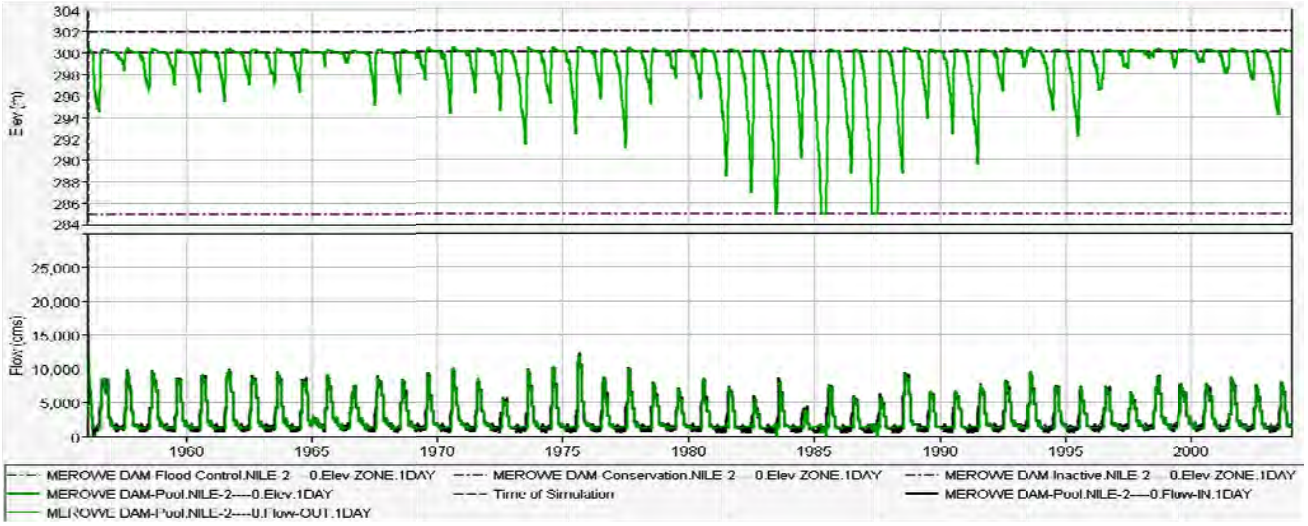
Sennar Reservoir Modeled Pool Elevation and flow



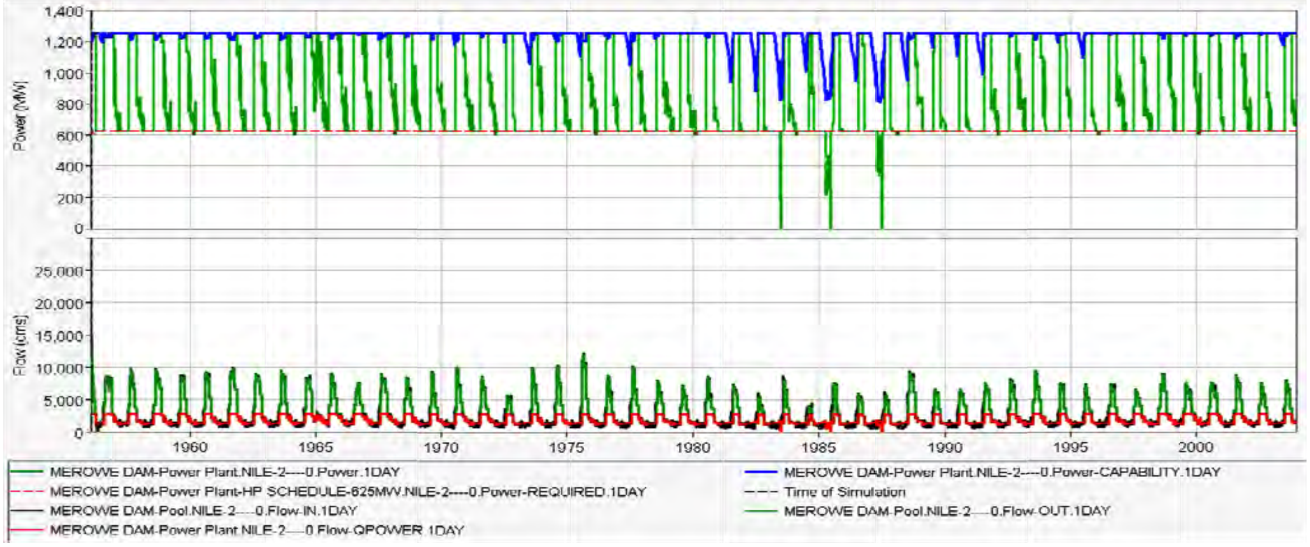
Sennar Modeled Power



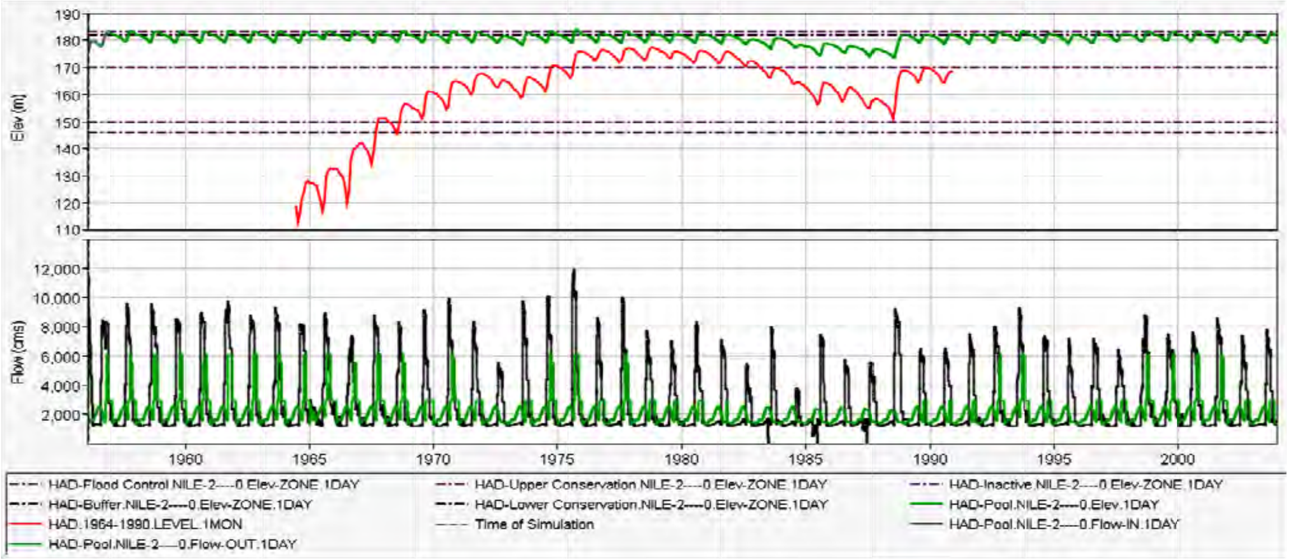
Merowe Reservoir Modeled Pool Elevation



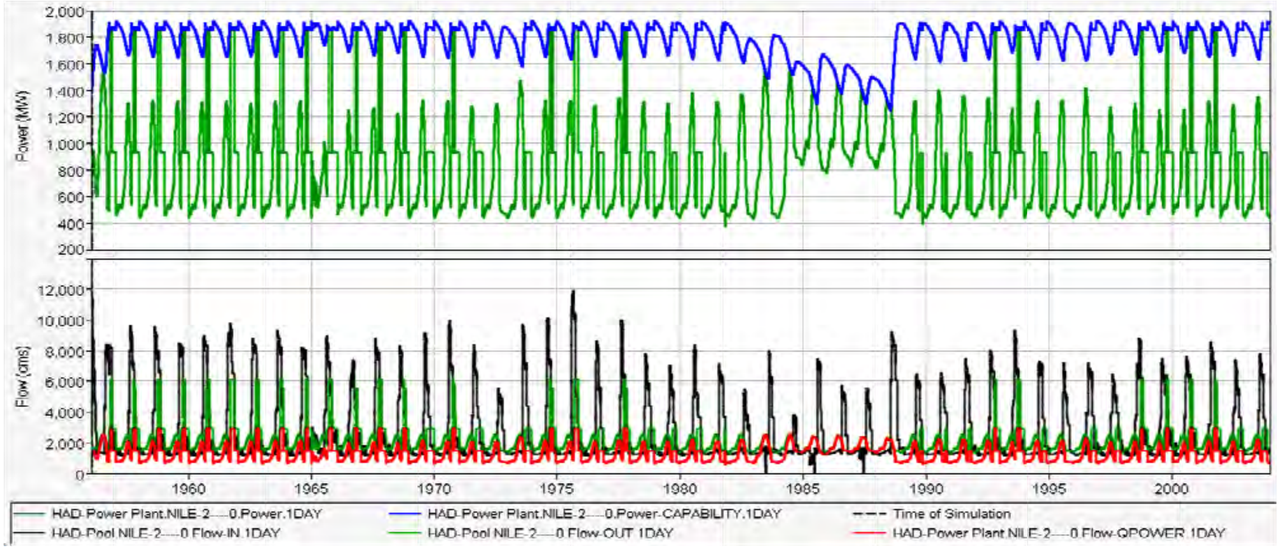
Merowe Modeled Power



HAD Reservoir Modeled Pool Elevation and flow

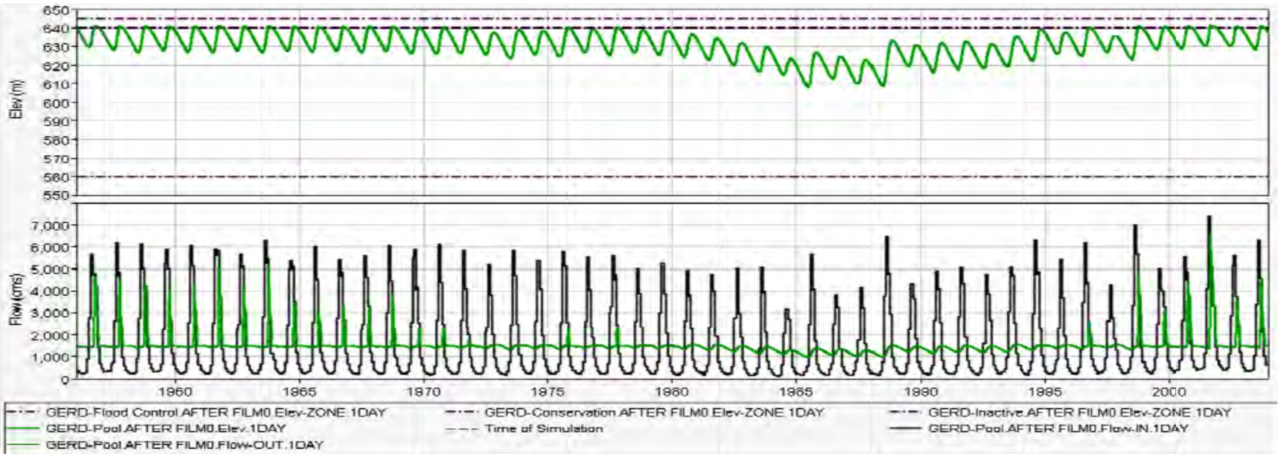


HAD Modeled Power

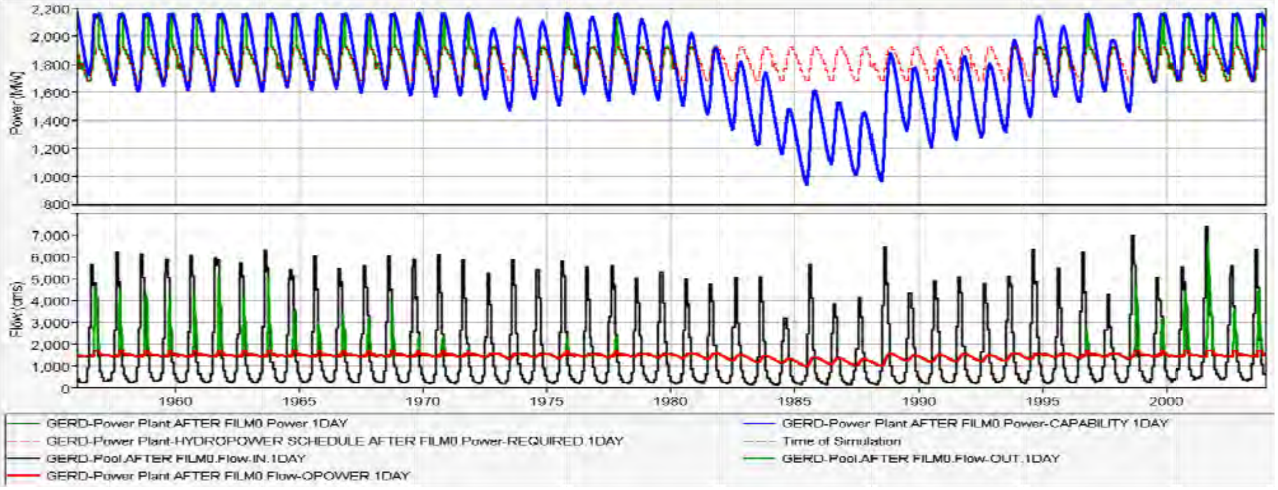


Simulations results in the future conditions (considering GERDP upstream) utilizing inflow time-series from January 1956 to December 2003

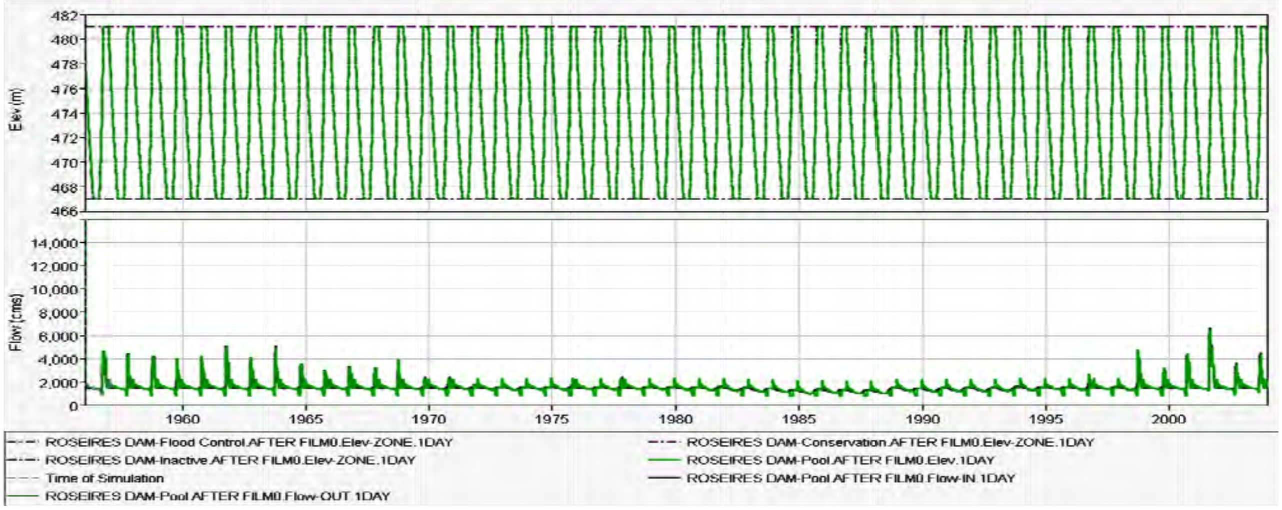
GERD Reservoir Modeled Pool Elevation



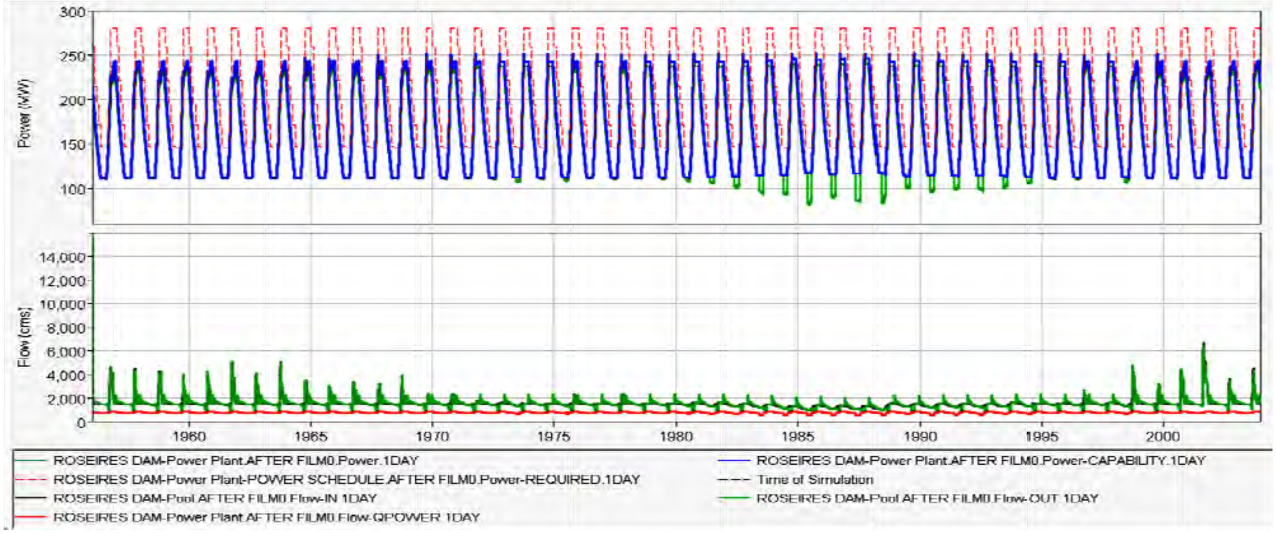
GERD Modeled Power



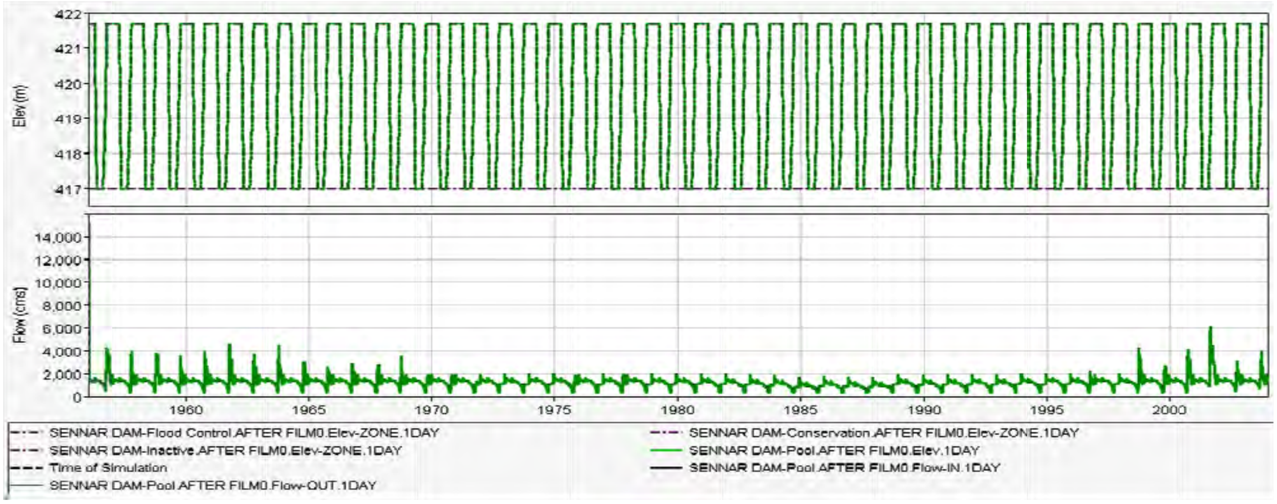
Rosaries Reservoir Modeled Pool Elevation and flow



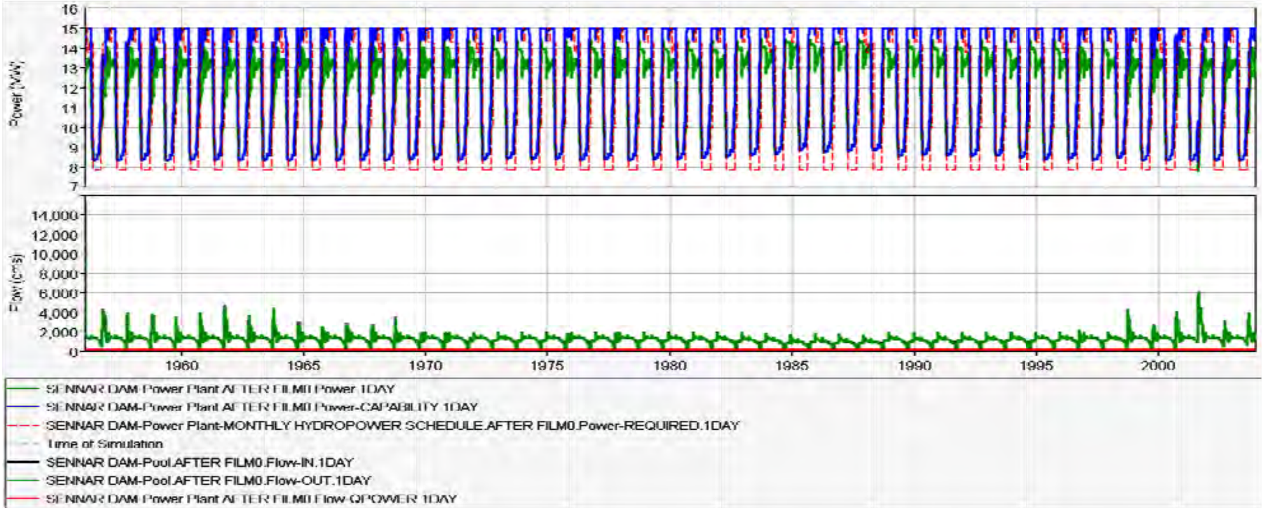
Rosaries Modeled Power



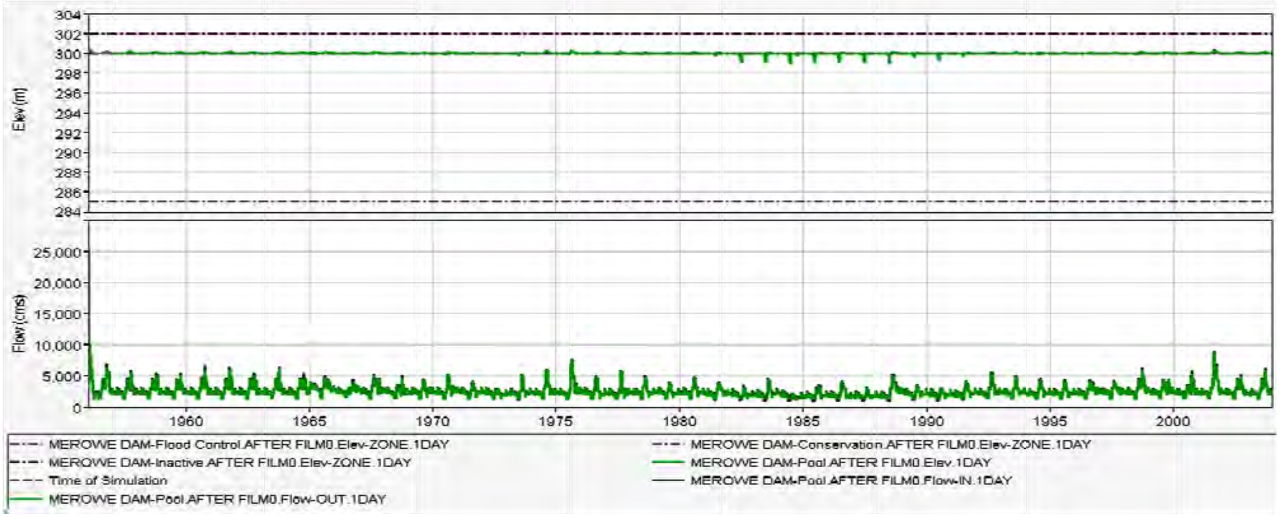
Sennar Reservoir Modeled Pool Elevation and flow



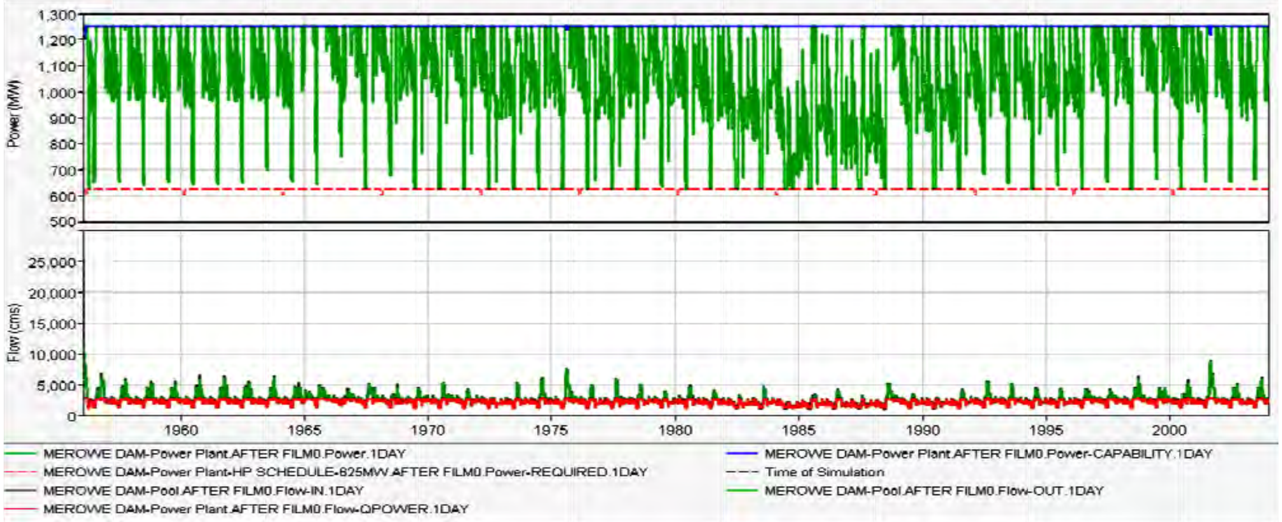
Sennar Modeled Power



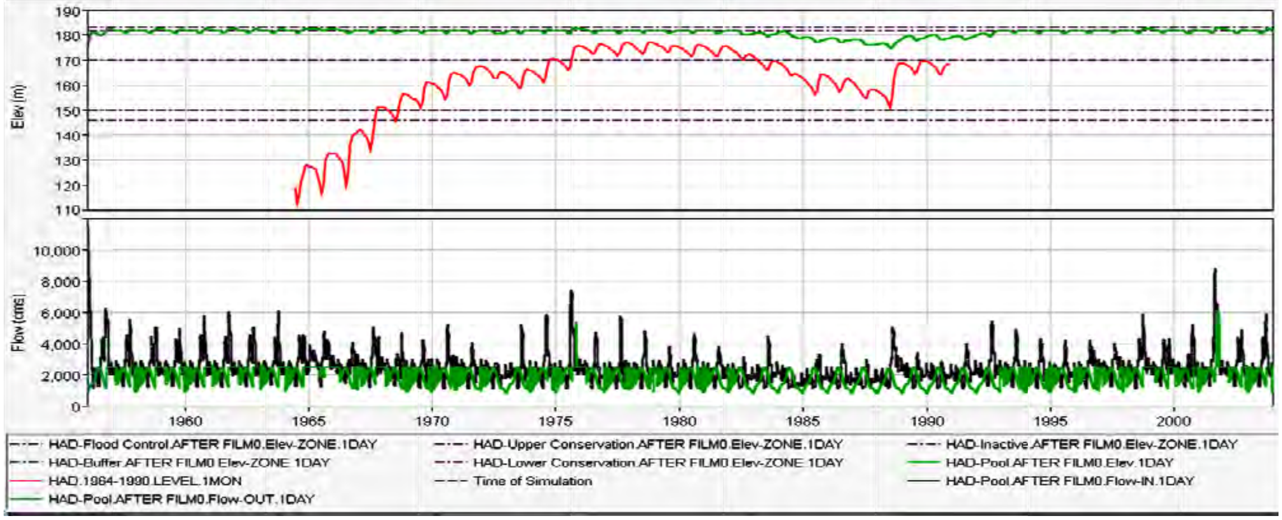
Merowe Reservoir Modeled Pool Elevation



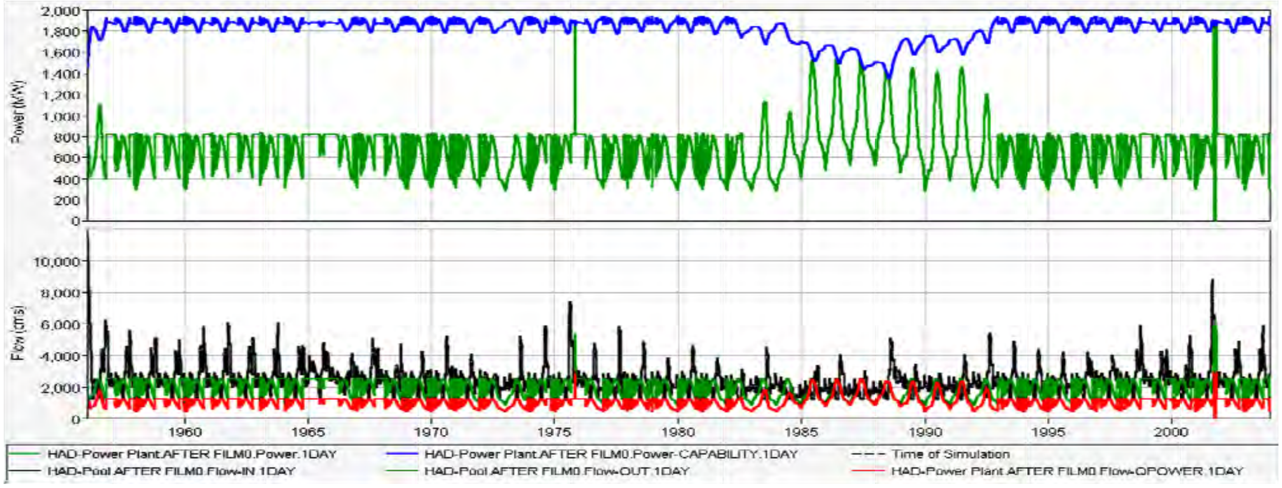
Merowe Modeled Power



HAD Reservoir Modeled Pool Elevation and flow



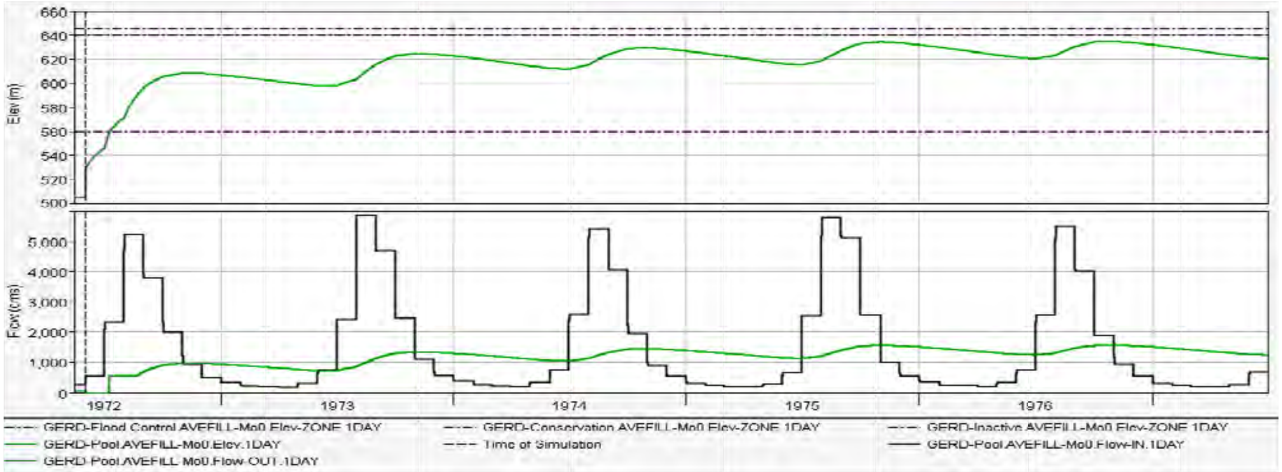
HAD Modeled Power



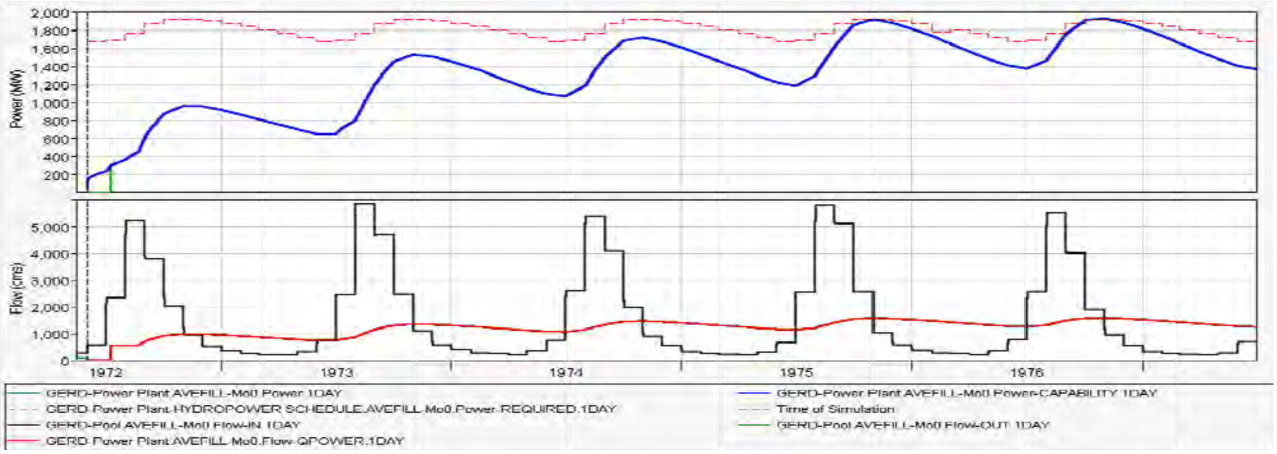
Simulation result during Average, Dry and Wet filling Years

Simulation result during Average filling Years

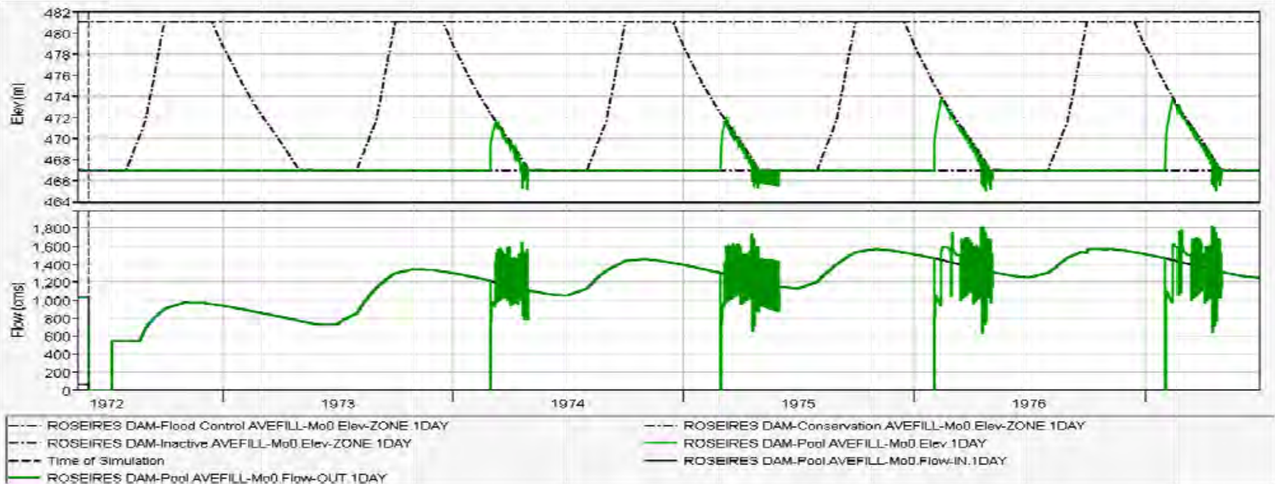
GERD Reservoir Modeled Pool Elevation



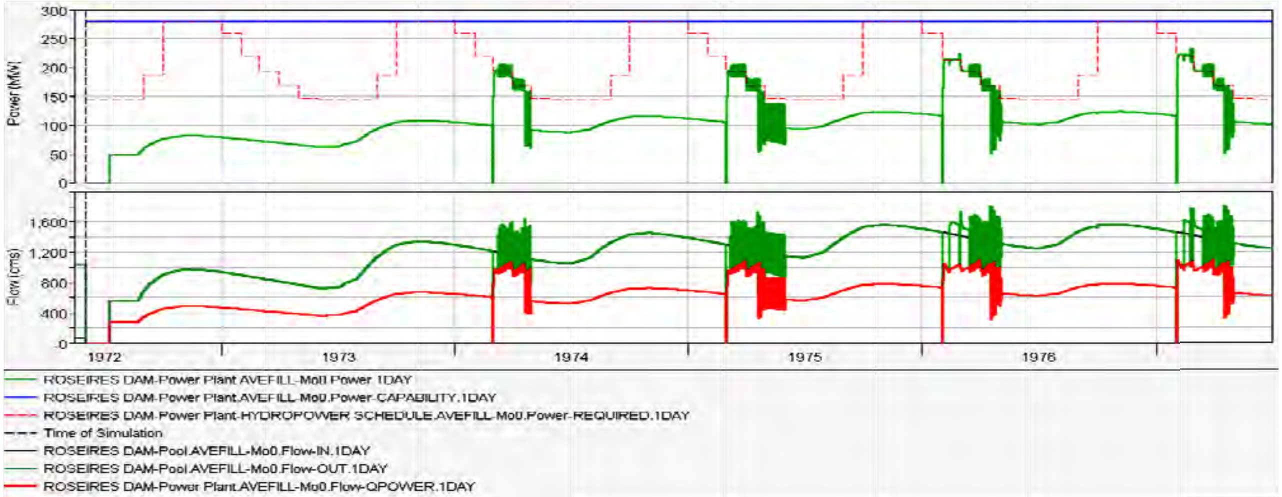
GERD Modeled Power



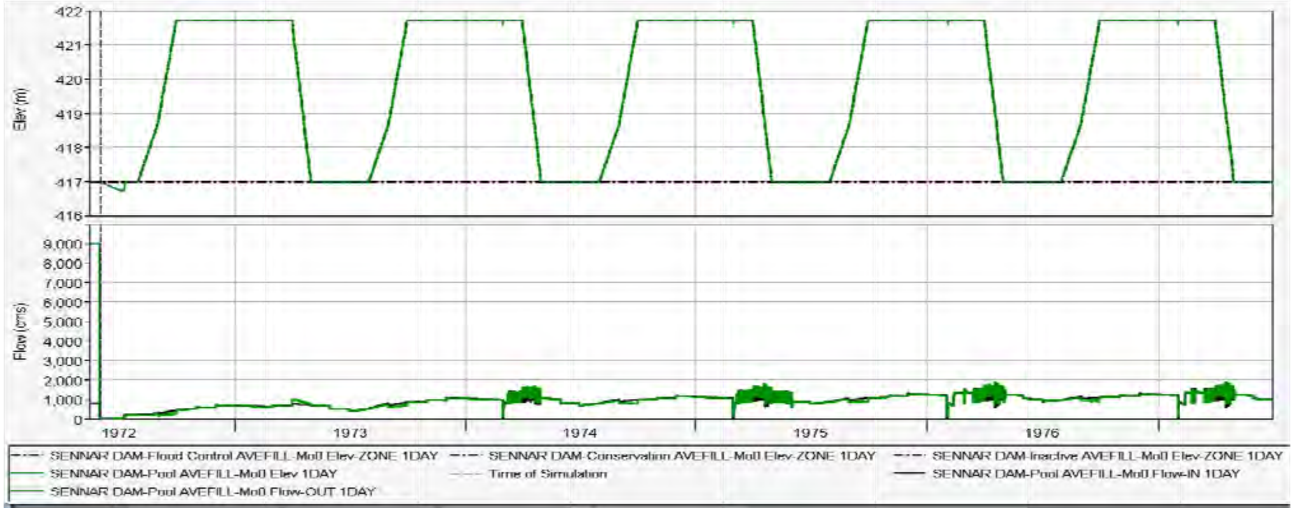
Rosaries Reservoir Modeled Pool Elevation and flow



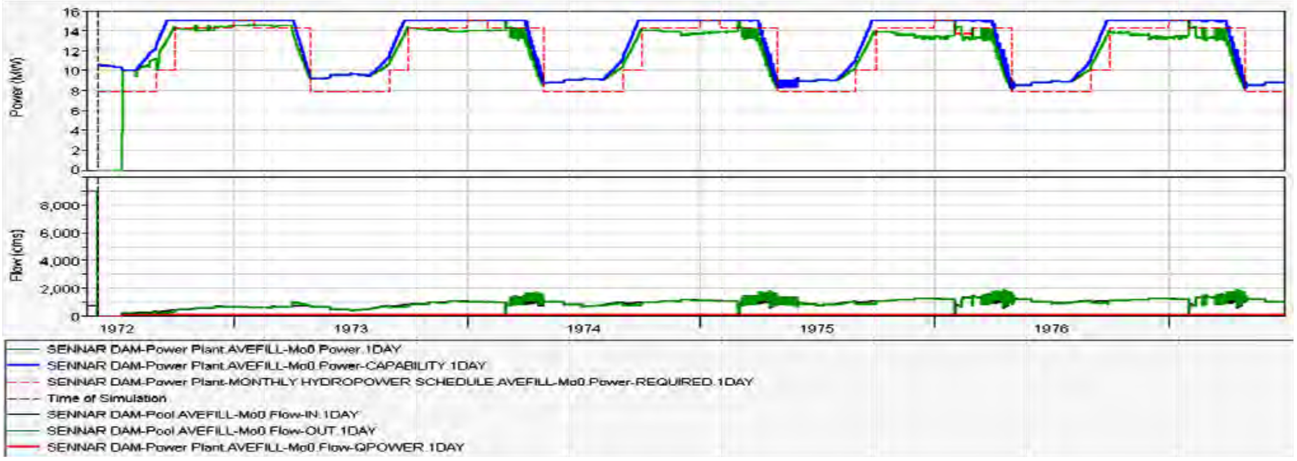
Rosaries Modeled Power



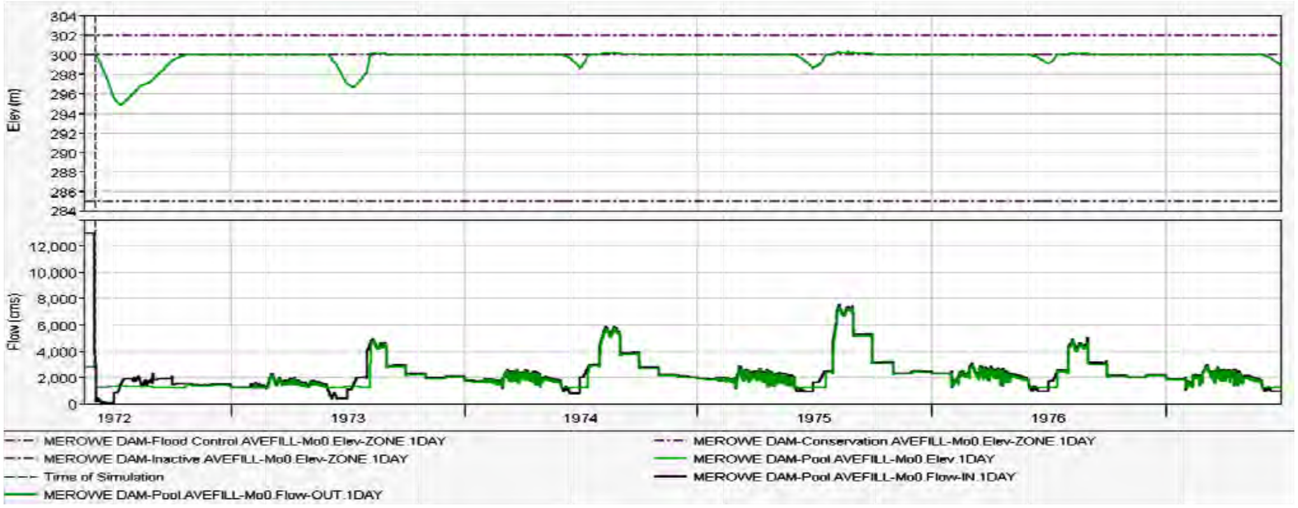
Sennar Reservoir Modeled Pool Elevation and flow



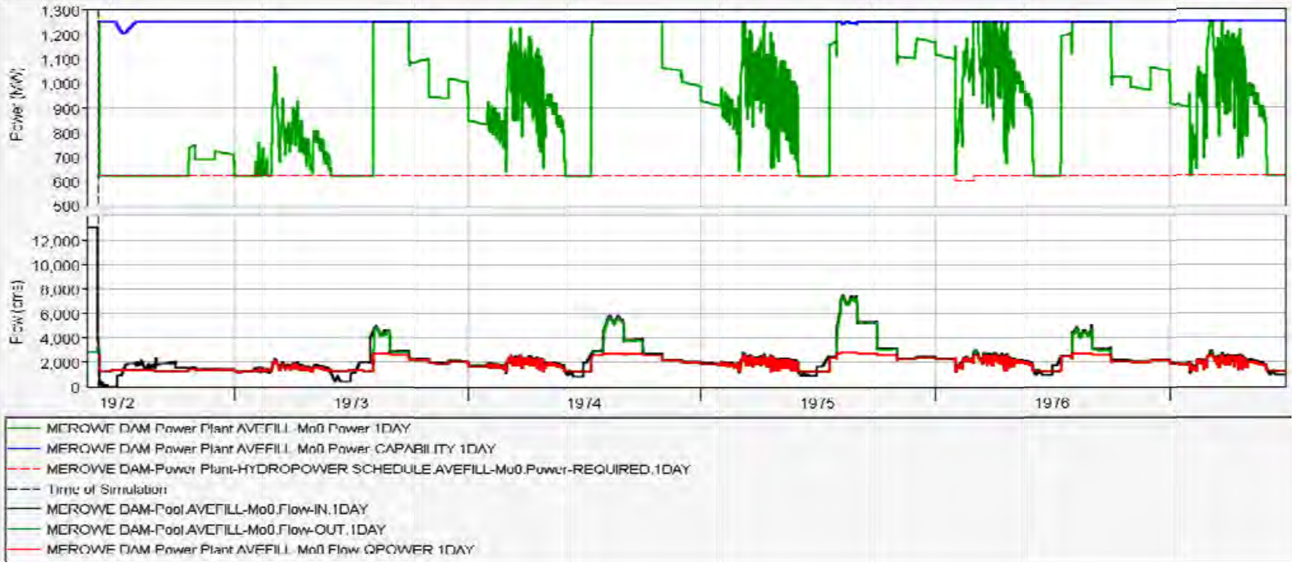
Sennar Modeled Power



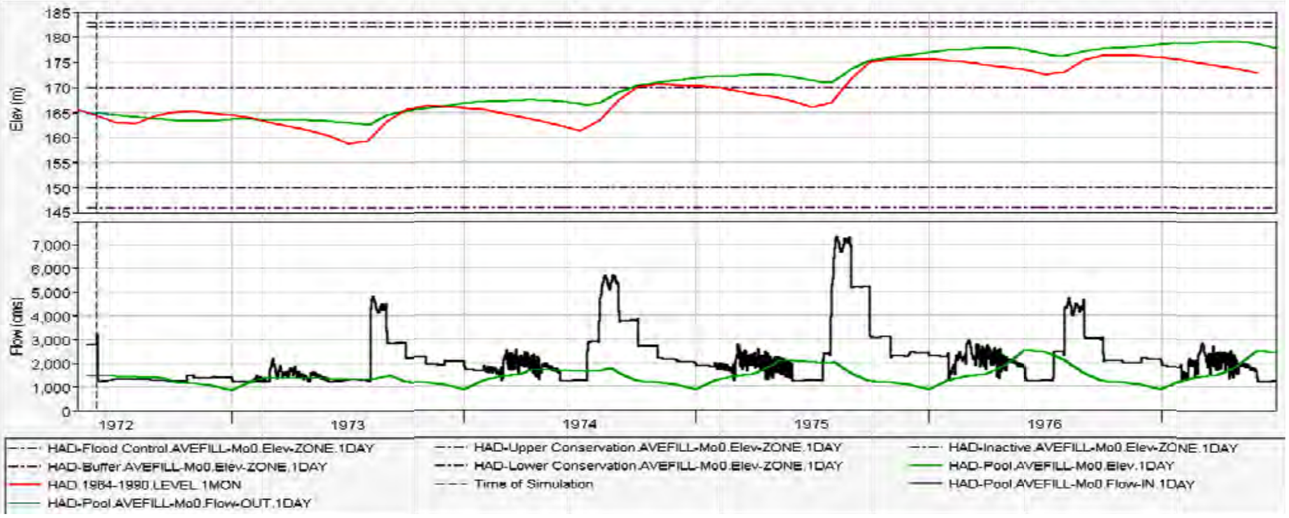
Merowe Reservoir Modeled Pool Elevation



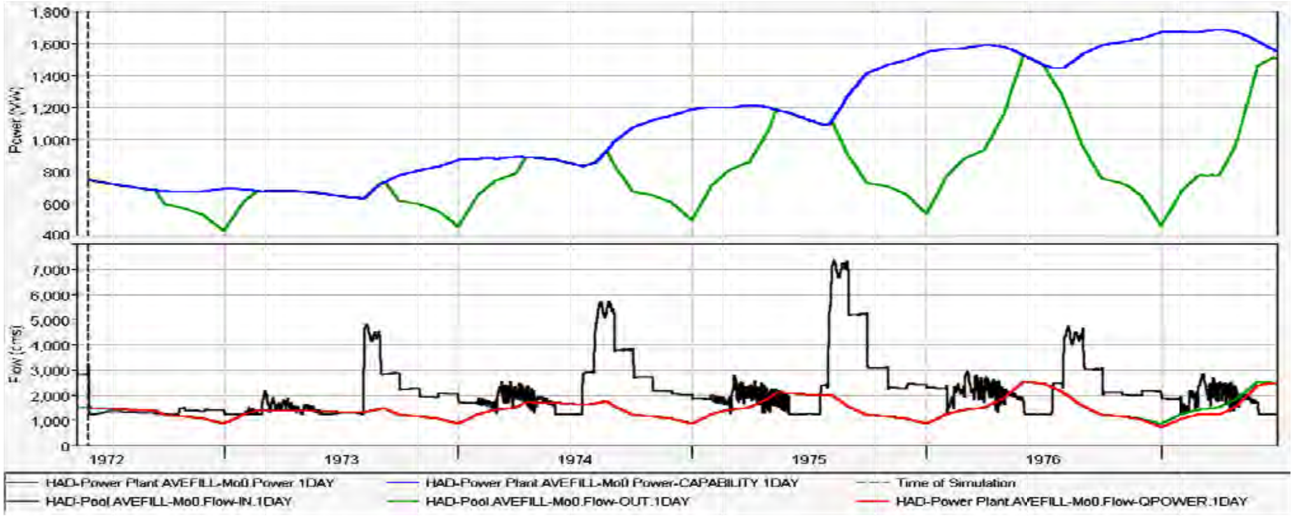
Merowe Modeled Power



HAD Reservoir Modeled Pool Elevation and flow

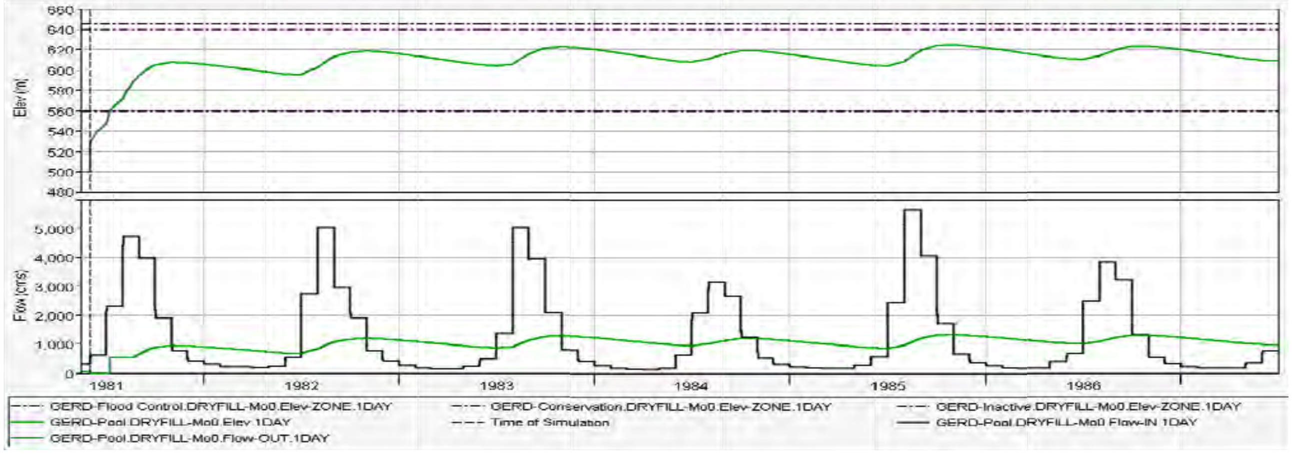


HAD Modeled Power

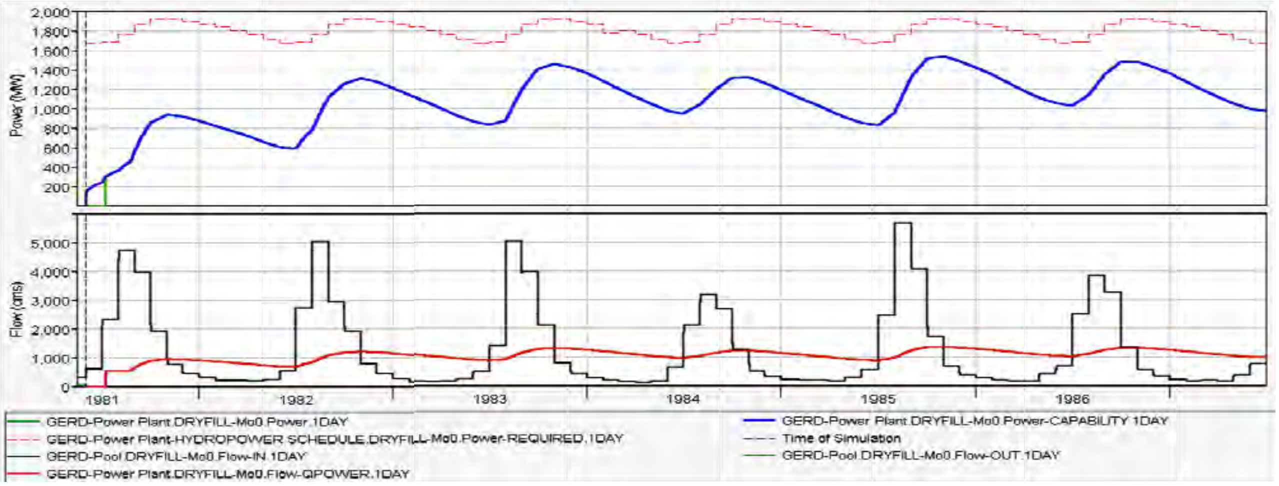


Simulation result during Dry filling Years

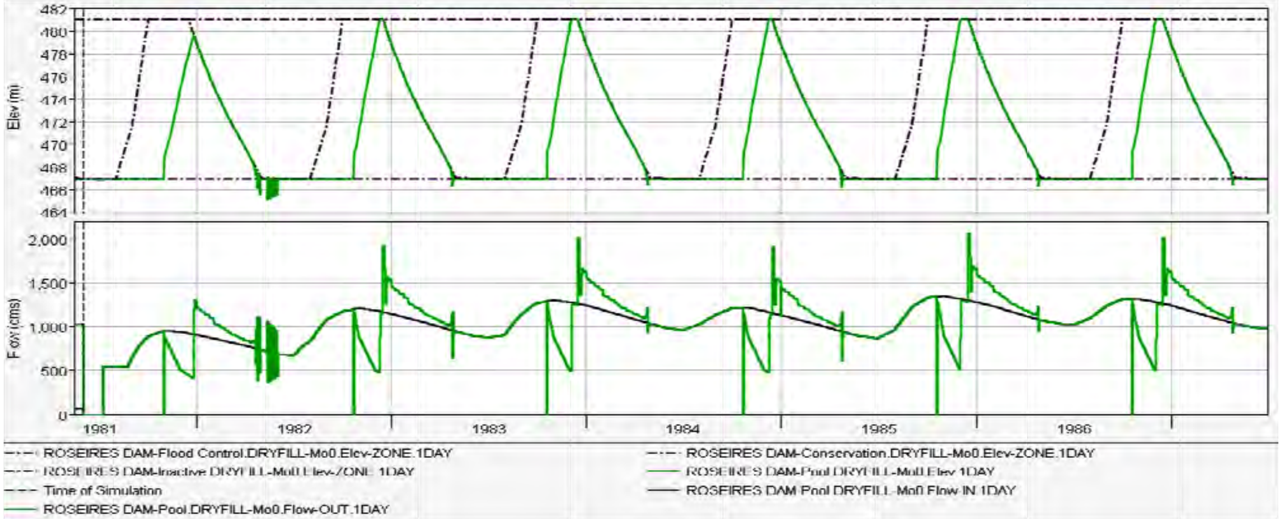
GERD Reservoir Modeled Pool Elevation



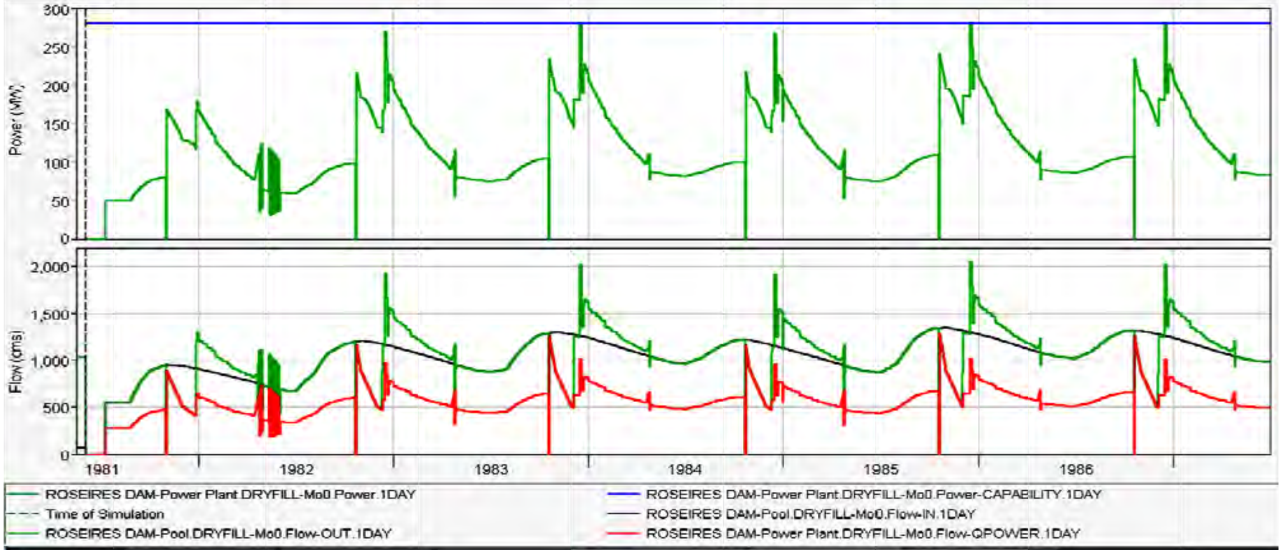
GERD Modeled Power



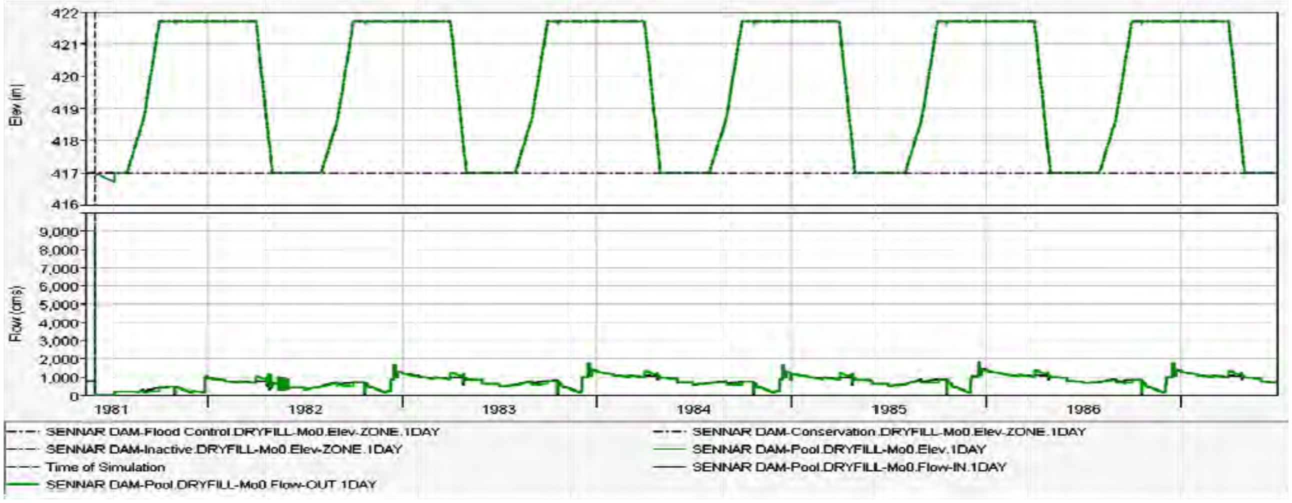
Rosaries Reservoir Modeled Pool Elevation and flow



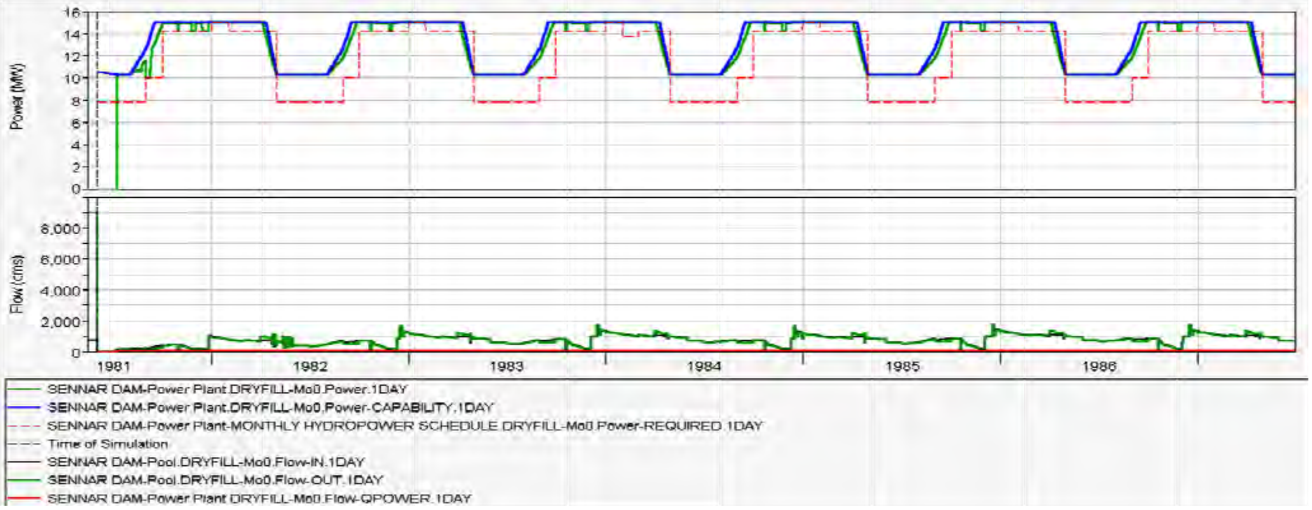
Rosaries Modeled Power



Sennar Reservoir Modeled Pool Elevation and flow



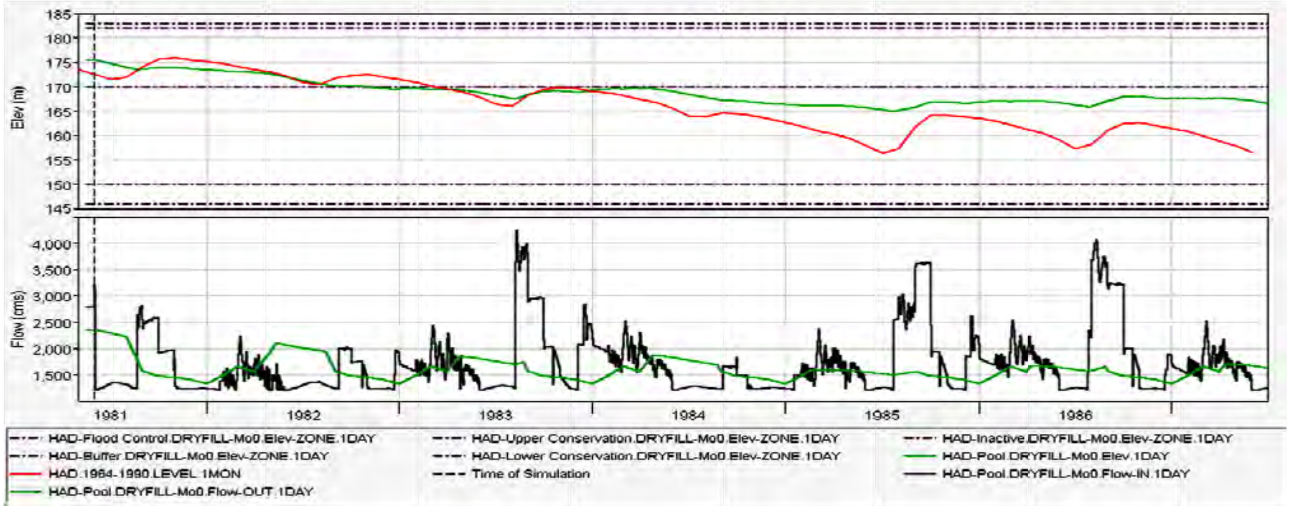
Sennar Modeled Power



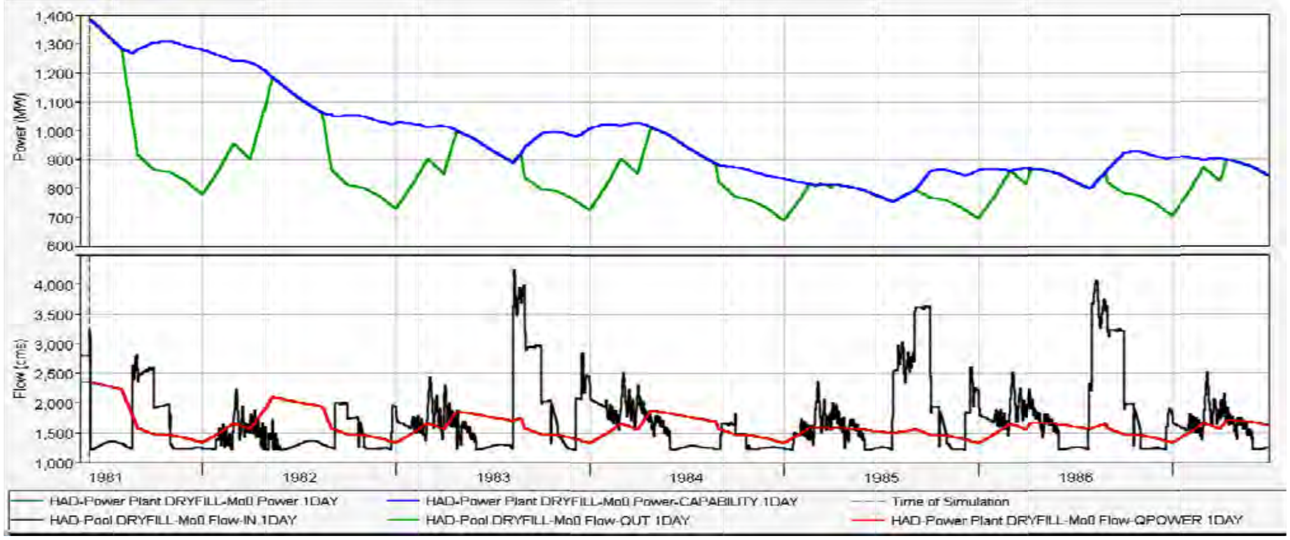
Merowe Reservoir Modeled Pool Elevation

Merowe Modeled Power

HAD Reservoir Modeled Pool Elevation and flow

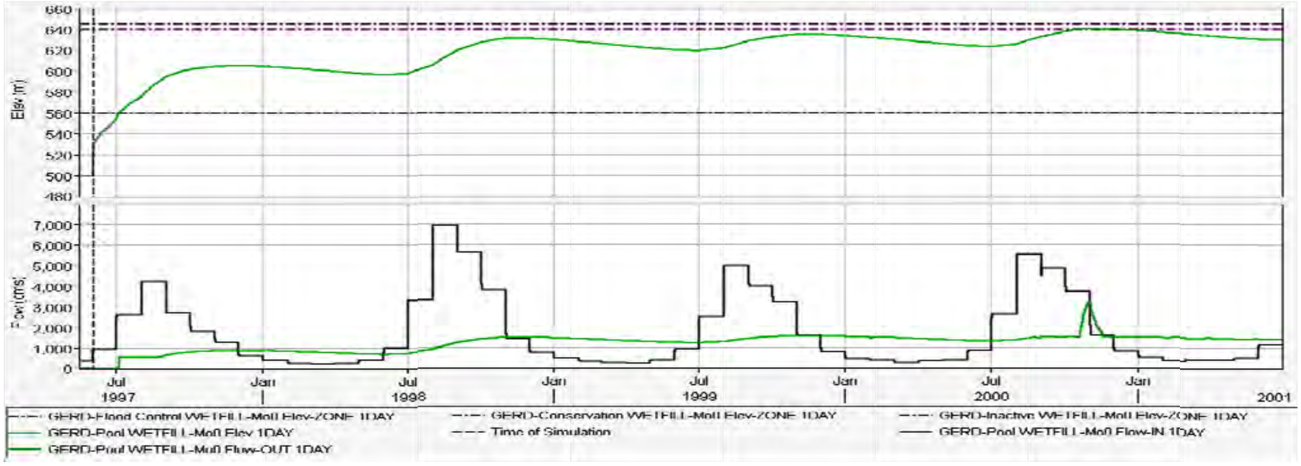


HAD Modeled Power

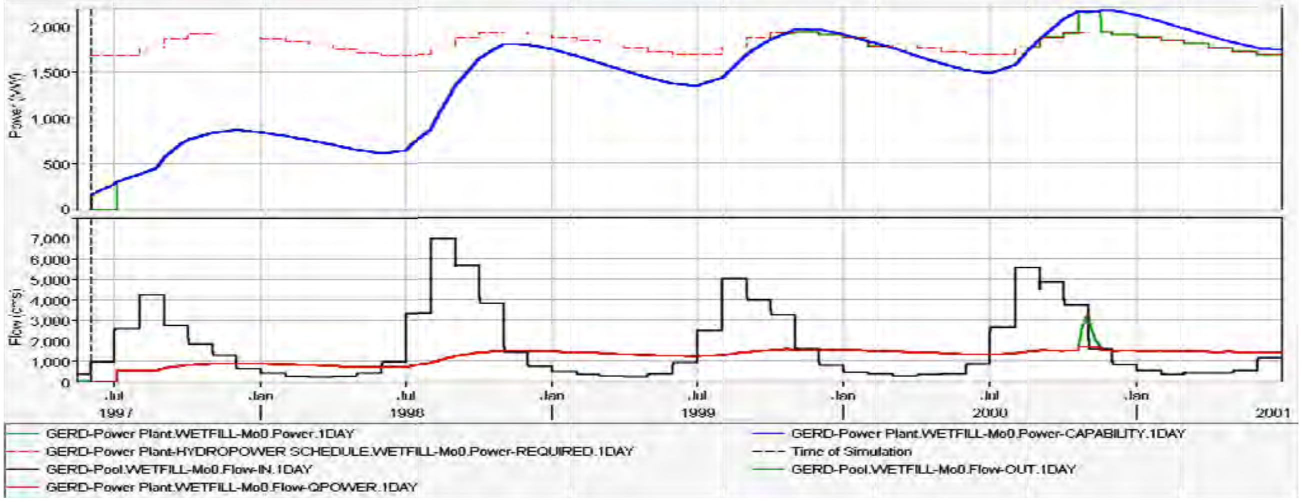


Simulation result during Wet Years of filing

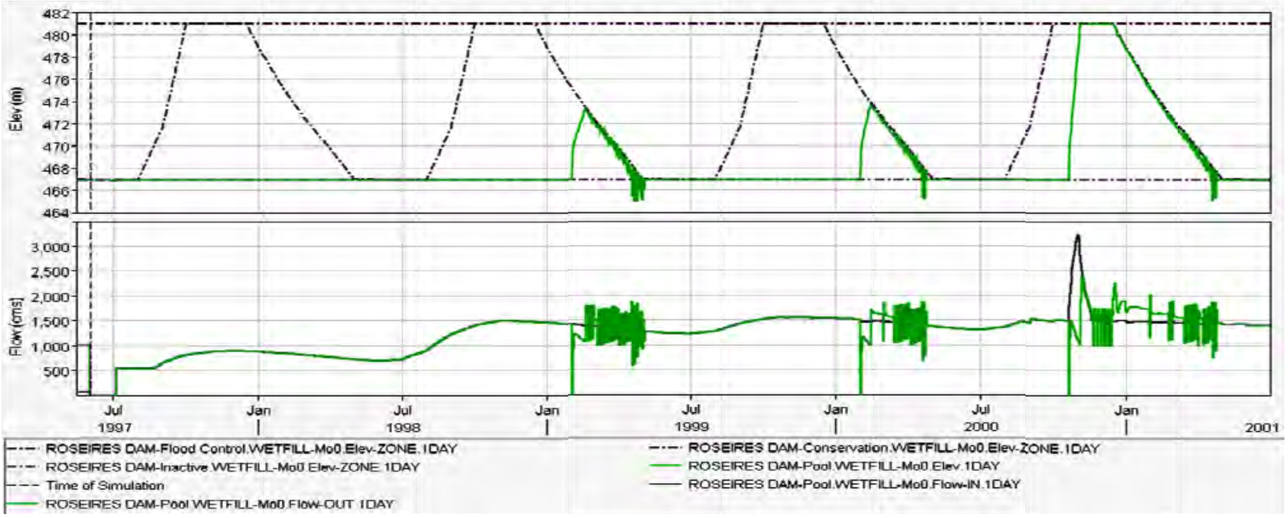
GERD Reservoir Modeled Pool Elevation



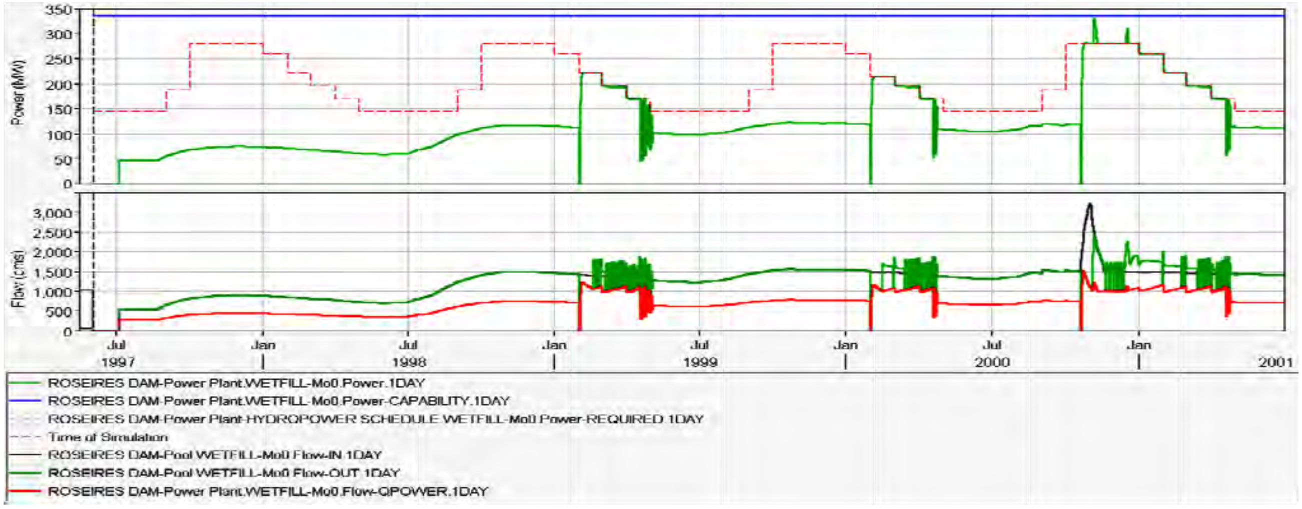
GERD Modeled Power



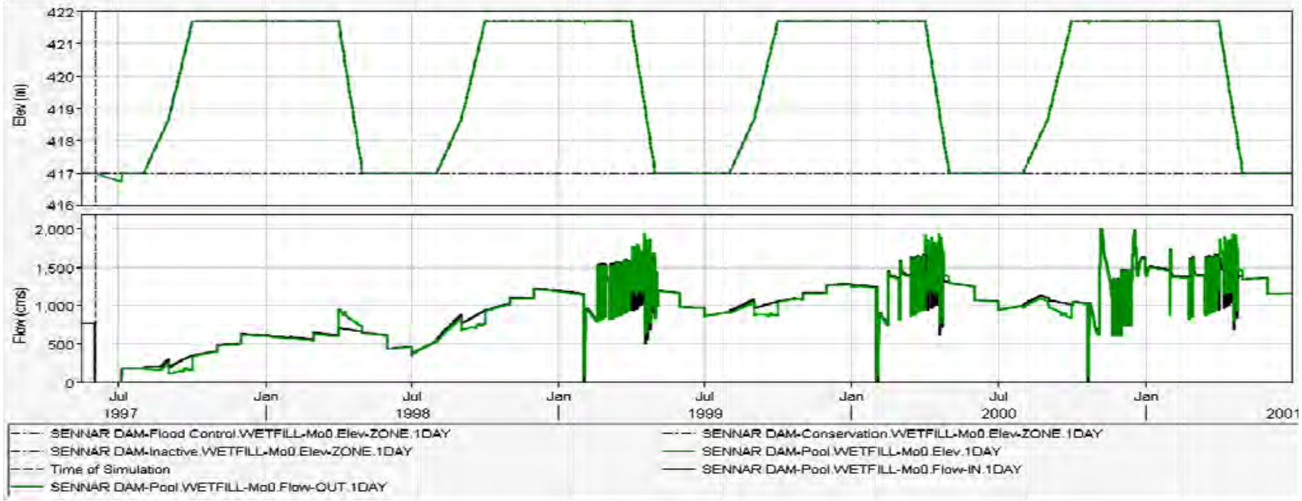
Rosaries Reservoir Modeled Pool Elevation and flow



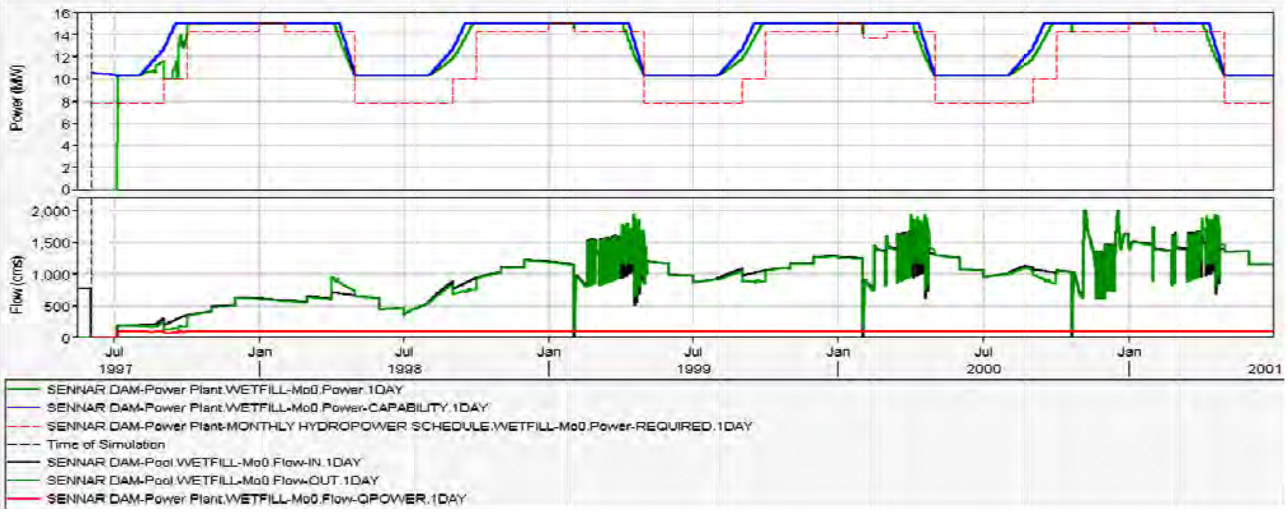
Rosaries Modeled Power



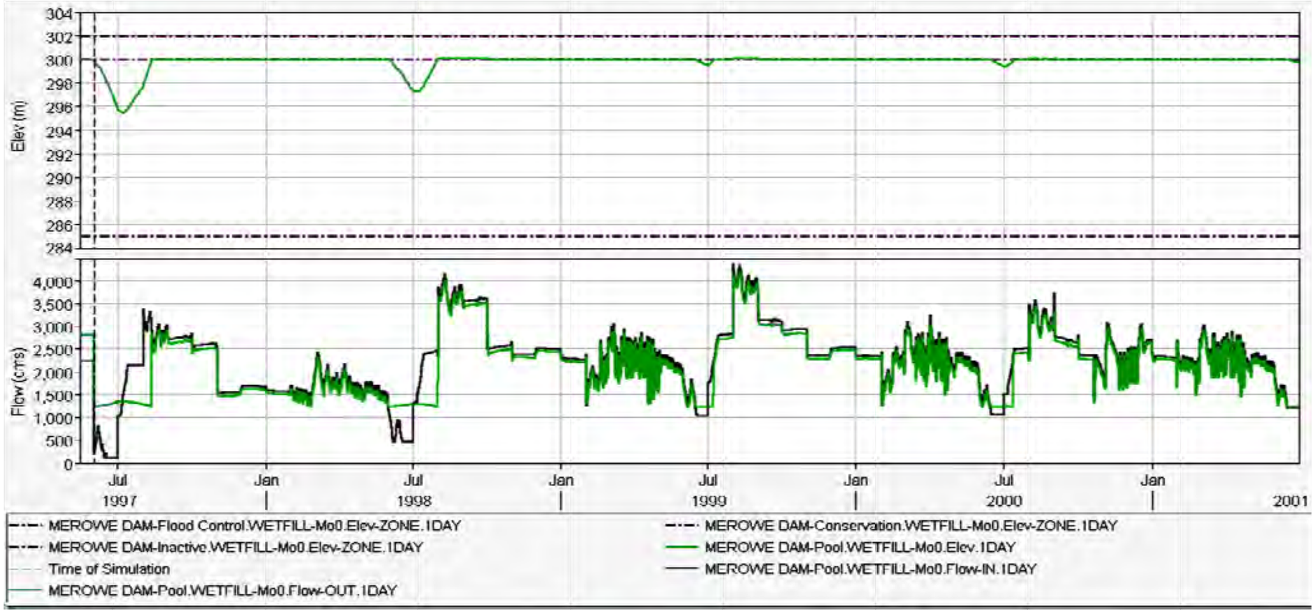
Sennar Reservoir Modeled Pool Elevation and flow



Sennar Modeled Power

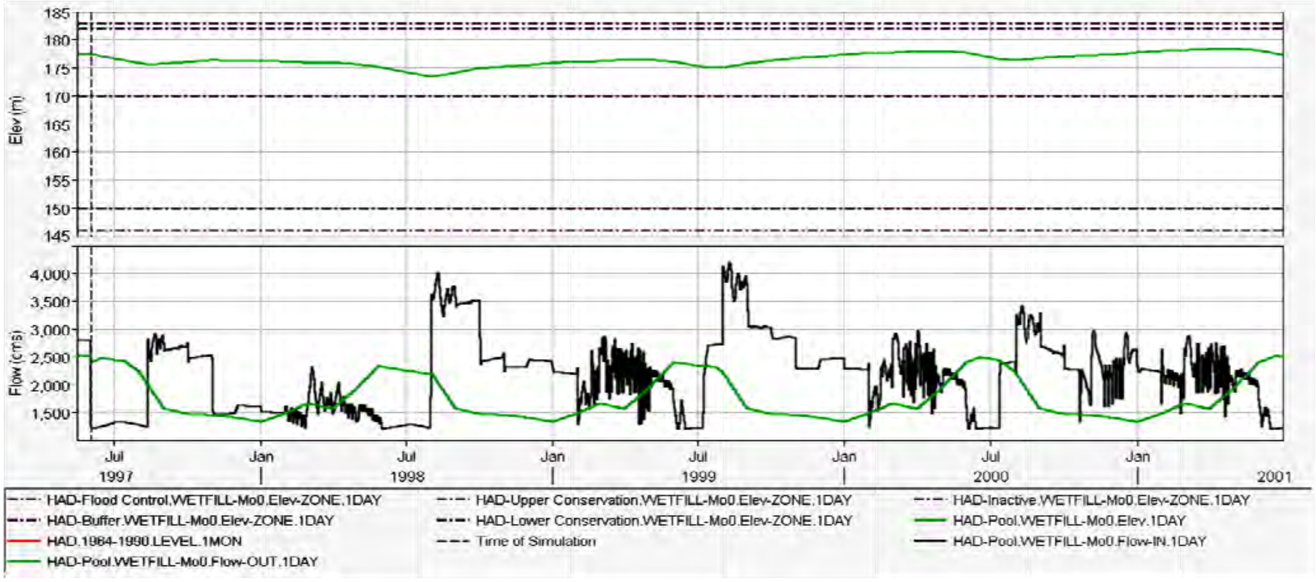


Merowe Reservoir Modeled Pool Elevation

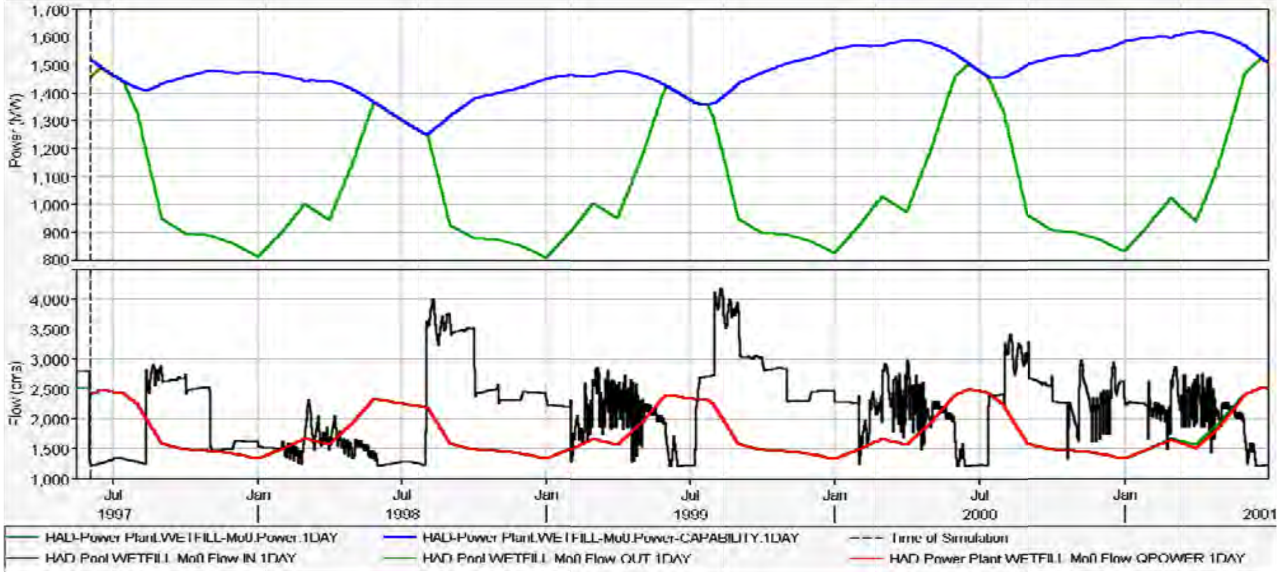


Merowe Modeled Power

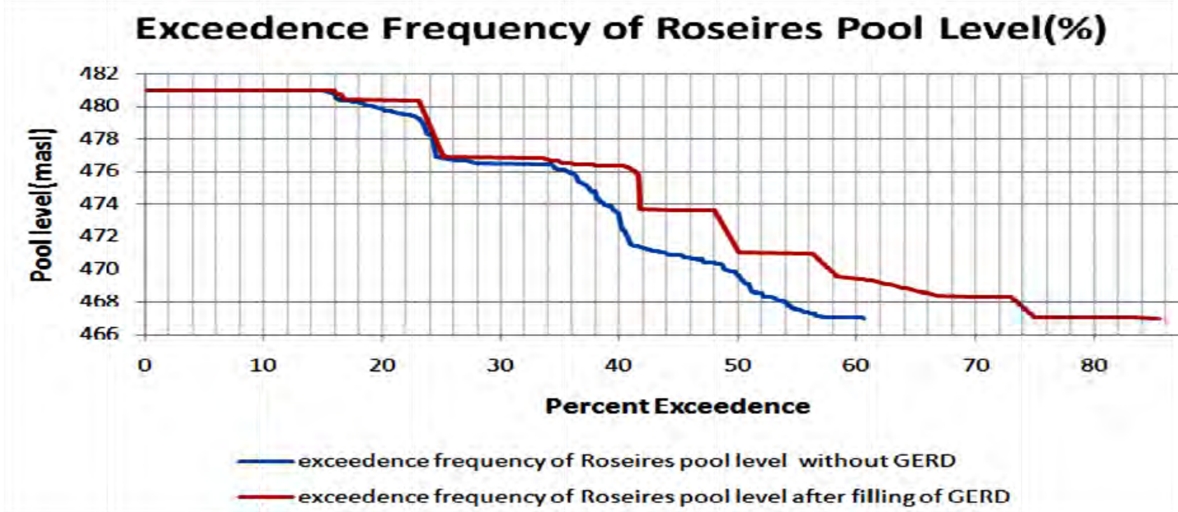
HAD Reservoir Modeled Pool Elevation and flow

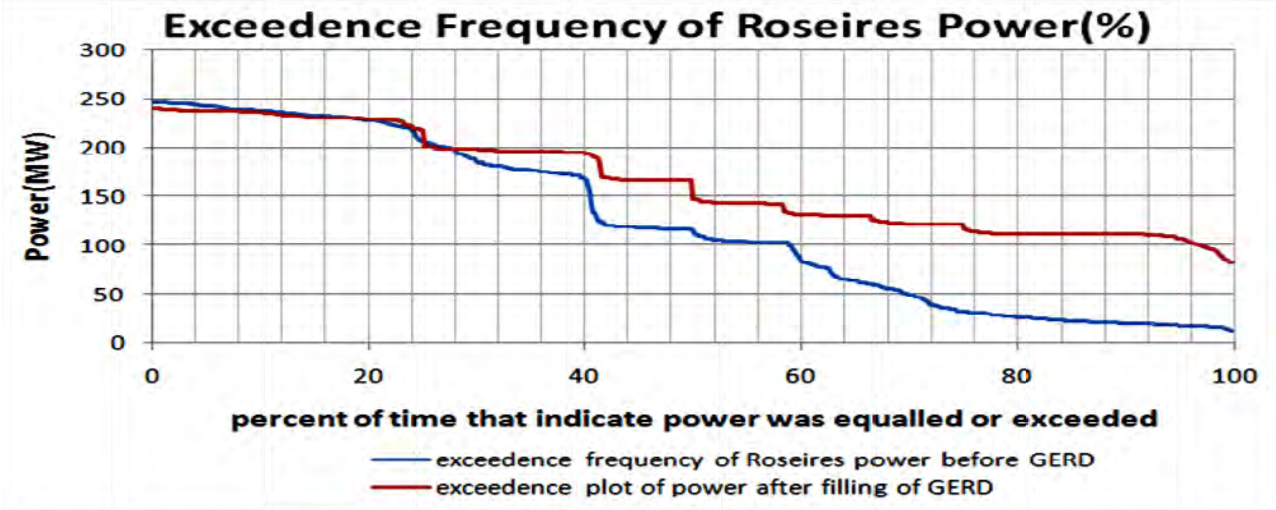


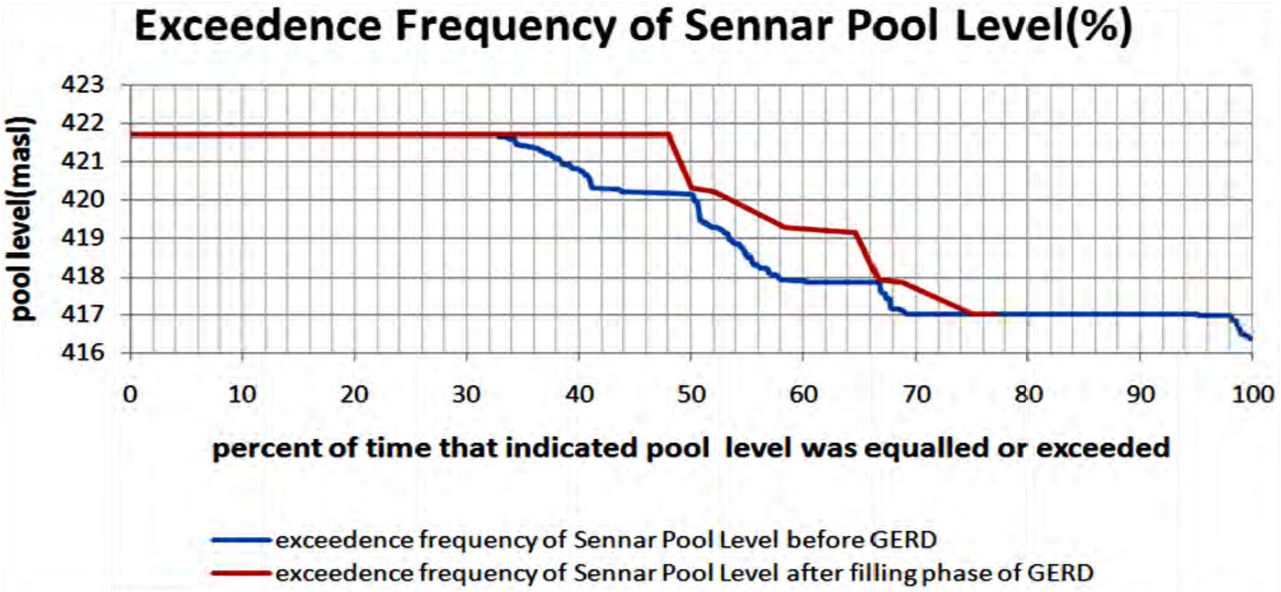
HAD Modeled Power

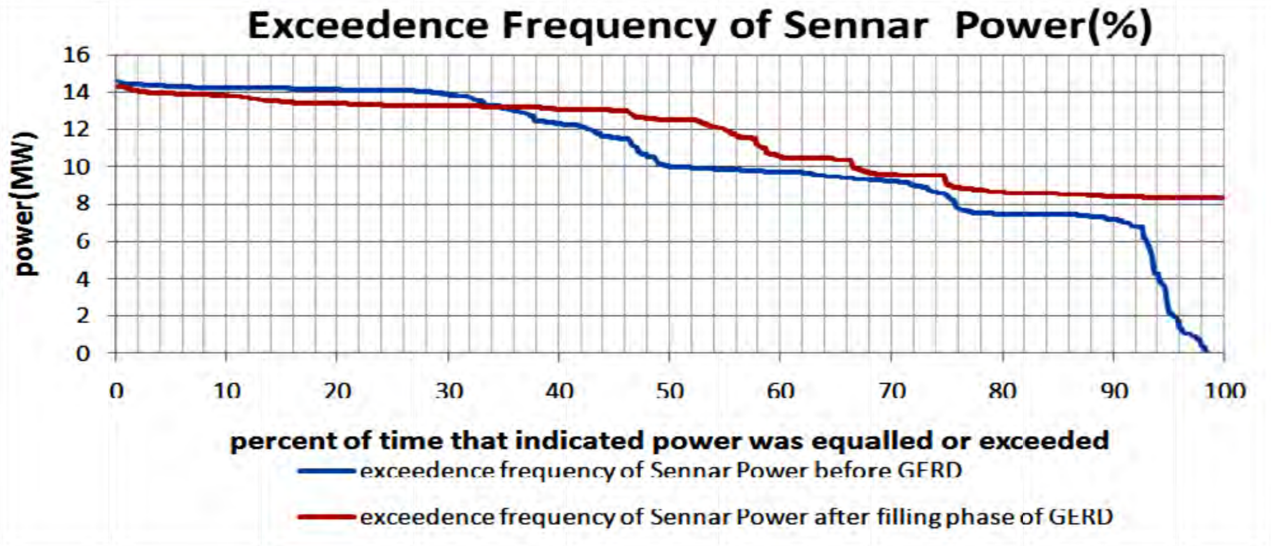


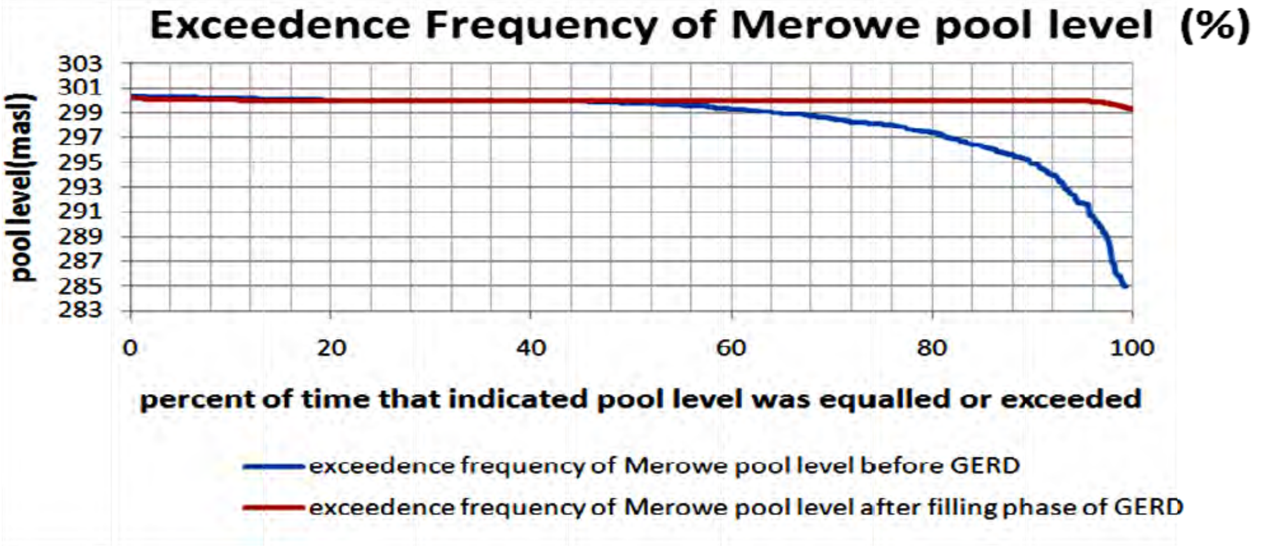
APPENDIX-I Exceedence plot of Reservoir pool level and Power

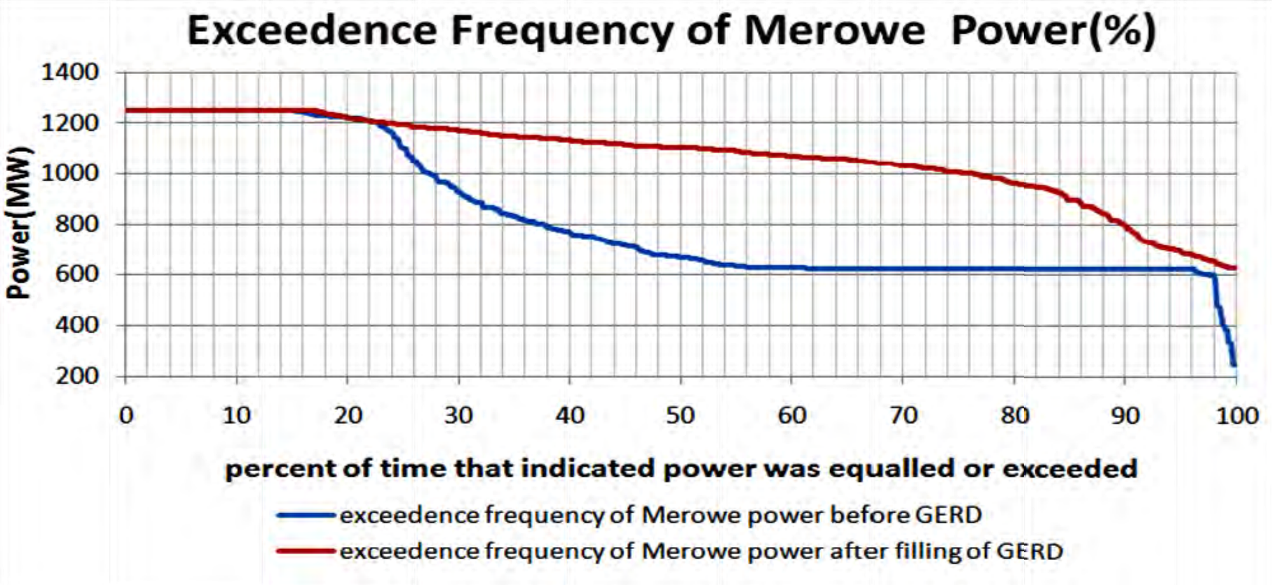


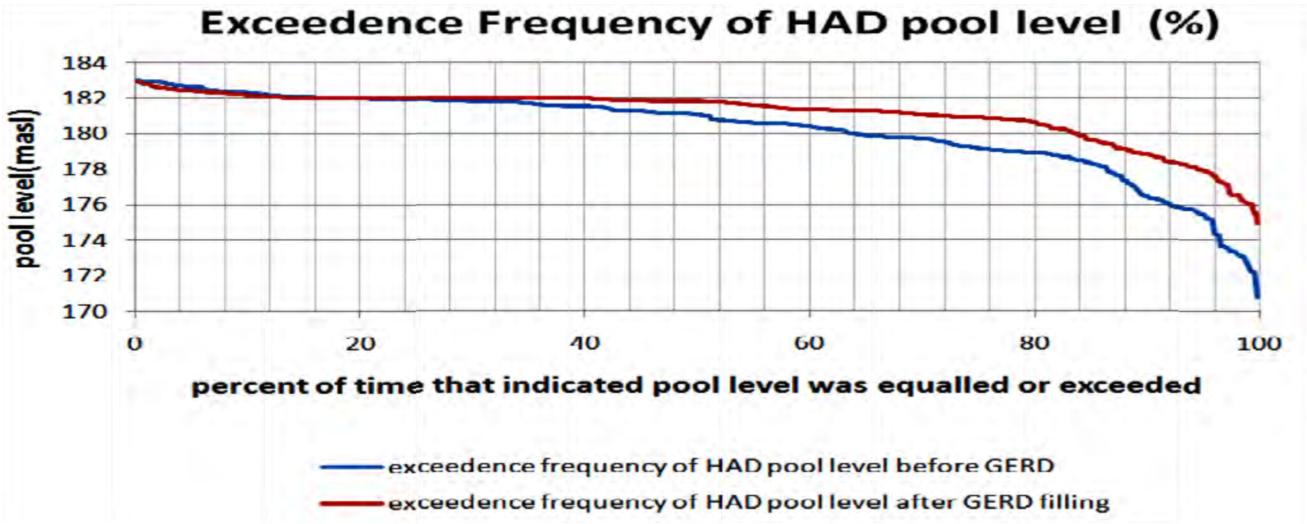


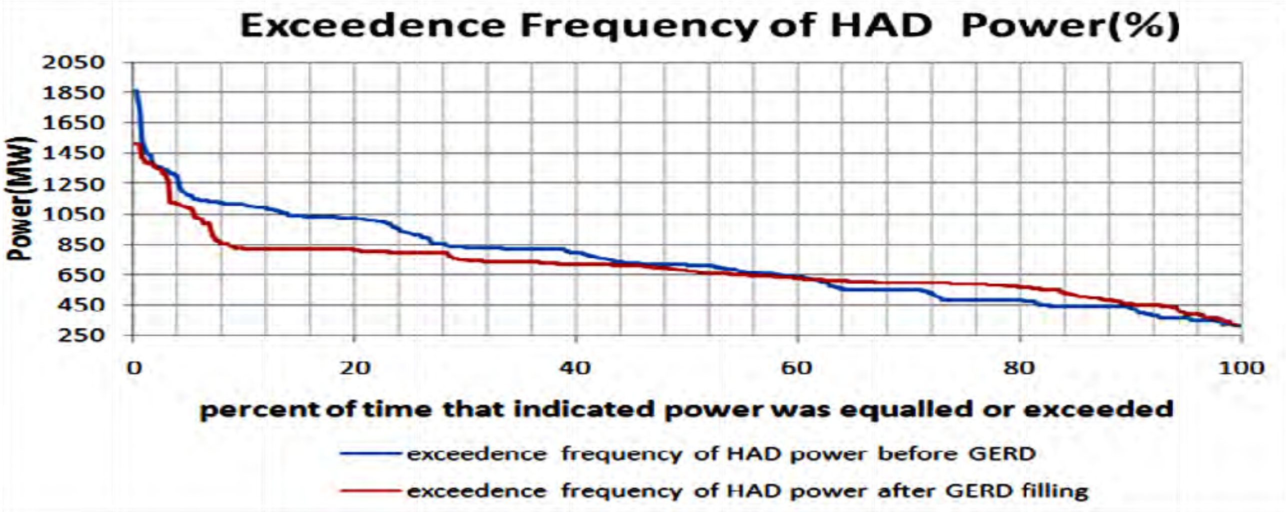


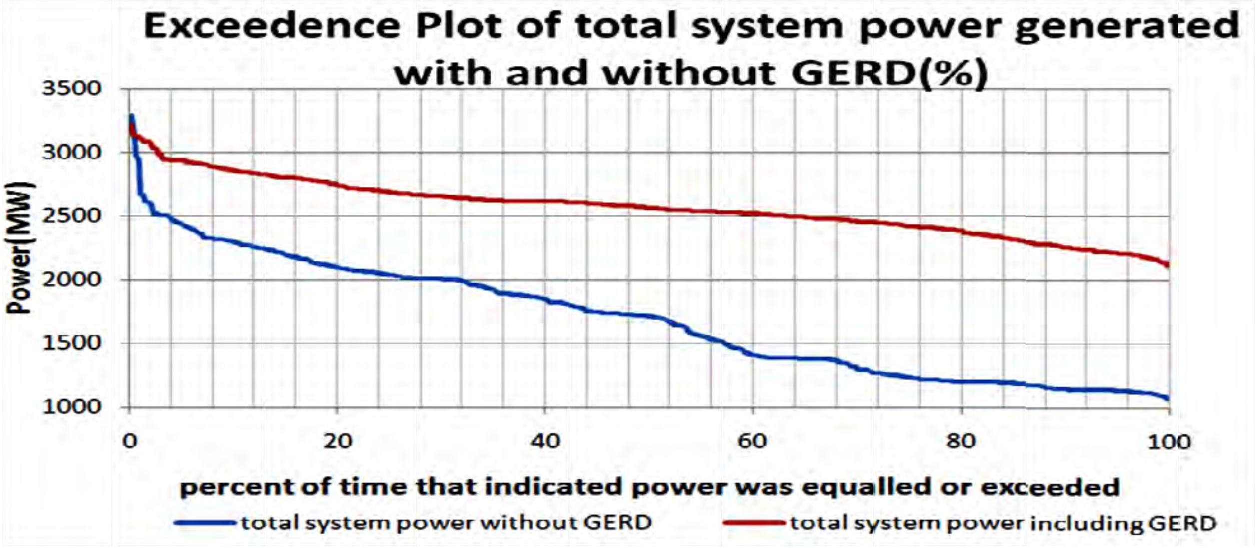

Exceedence Frequency of Sennar Power(%)
power(MW)
16
14
12
10
8
6
4
2
0
0
10
20
30
40
50
60
70
80
90
100
percent of time that indicated power was equalled or exceeded
exceedence frequency of Sennar Power before GERD
exceedence frequency of Sennar Power after filling phase of GERD


Exceedence Frequency of Merowe pool level (%)
pool level(masl)
303
301
299
297
295
293
291
289
287
285
283
0
20
40
60
80
100
percent of time that indicated pool level was equalled or exceeded
exceedence frequency of Merowe pool level before GERD
exceedence frequency of Merowe pool level after filling phase of GERD


Exceedence Frequency of Merowe Power(%)
Power(MW)
1400
1200
1000
800
600
400
200
0
10
20
30
40
50
60
70
80
90
100
percent of time that indicated power was equalled or exceeded
exceedence frequency of Merowe power before GERD
exceedence frequency of Merowe power after filling of GERD


Exceedence Frequency of HAD pool level (%)
pool level(masl)
184
182
180
178
176
174
172
170
0
20
40
60
80
100
percent of time that indicated pool level was equalled or exceeded
exceedence frequency of HAD pool level before GERD
exceedence frequency of HAD pool level after GERD filling


Exceedence Frequency of HAD Power(%)
Power(MW)
2050
1850
1650
1450
1250
1050
850
650
450
250
0
20
40
60
80
100
percent of time that indicated power was equalled or exceeded
exceedence frequency of HAD power before GERD
exceedence frequency of HAD power after GERD filling


Exceedence Plot of total system power generated with and without GERD(%)
Power(MW)
3500
3000
2500
2000
1500
1000
0
20
40
60
80
100
percent of time that indicated power was equalled or exceeded
total system power without GERD
total system power including GERD