WATER RESOURCE SYSTEM MODELING OF EASTERN NILE RIVER BASIN

by

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PhD Dissertation submitted to Graduate School of Addis Ababa University, Addis Ababa Institute of Technology, School of Civil and Environmental Engineering in partial fulfillment of the requirements for the

Degree of

Doctor of Philosophy, PhD

In

CIVIL ENGINEERING

Addis Ababa University

Addis Ababa, Ethiopia

June 2015

The thesis committee of

Addis Ababa University (AAU), in Addis Ababa Institute of Technology (AAiT) certifies that this is the approved version of the following thesis

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Abstract

WATER RESOURCE SYSTEM MODELING OF EASTERN NILE RIVER BASIN

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Civil and environmental engineering (hydraulic engineering

This study was conducted to quantify the likely impacts and benefits of current and future development options in the Blue Nile basin using simulation approach. Four cases studies were investigated under different scenarios; i) the filling strategy of the under-construction Great Renaissance Dam (GERD), ii) the long term GERD operation case study iii) strategic development perspective case study that includes all proposed dams upstream of GERD in Abbay-Blue Nile and iv) future irrigation development in the Eastern Nile. Mike Basin and Mike Hydro River Basin Simulation Models were used.

The results indicate 6 years filling period is mostly sufficient to fill the GERD reservoir with no impact on the current irrigation water use of Egypt. However, if a rare scenario of 6 years dry consecutive sequence of flow that was observed in the 1980s occurs, the filling strategy need to be revised. Analysis of the hypothetical scenarios within -/+ 20 flow variation from the long term mean indicates the 6 years filling sequence lower than the normal (mean) flow by up to 10% will be in the tolerable range of filling.

In terms of long term analysis, once GERD reservoir is filled and started operation, it imposes no threat to the existing agricultural water use on downstream countries (Sudan and Egypt). However, the annual energy production from HAD may be reduced by 6 to 8% due to the reduction in the head available at the Dam in Egypt. Overall, the presence of GERD renders more regional benefit than before. The mean energy in Eastern Nile region could increase by more than 120%. If additional proposed dams are developed as strategic option in the Abbay-Blue Nile sub basin, up to 56,000 GWh/year of energy can be produced without significant

impact on regional agricultural water uses. The upstream country Ethiopia can generate as much as 38200 GWh of Energy and the energy production in Sudan increases by 38%.

However, expansion of irrigated agriculture in the Eastern Nile basin generally may impact both the hydropower and existing agricultural water uses downstream of GERD. Analysis based on planned irrigation development in the basin indicates, water availability is a major constraint that limits irrigated agriculture expansion. The planned irrigation development in Sudan and Ethiopia may reduce water availability for agriculture by as much as 26.3% in the Eastern Nile basin. The possibility of more large-scale irrigation exists in the basin, but it is not close to the extent of planned development. As the study utilized the planned irrigation development by the countries, comprehensive regional planning and coordinated water management scenario, which is not covered under this study, may yield a better overview of irrigation expansion in the basin.

This study is a comprehensive analysis of the impacts and benefits of hydropower and irrigation development in the Eastern Nile basin and may lay a basis for future scientific engagement in the basin. Hydropower development in the upper reaches of Abbay-Blue Nile basin is enormous and renders distinct possibility for future development beyond the completion of GERD. However, planned large scale expansion of irrigated agriculture introduces water deficit to both energy and agriculture production and requires coordinated regional planning and analysis for optimal economic and social returns to the basin. The future holds a great deal of uncertainty in terms of socio-economic and political changes that influence development decisions. To take full advantage of the water resources of the basin it is necessary the basin be managed as a single system which requires the establishment of an effective institutional mechanism that aim to develop the river in a shared-vision and cooperative way. Furthermore, future climate change may put additional uncertainties to the Eastern Nile basin development. Therefore, it is suggested that analysis of water resources development in Eastern Nile Basin shall explore opportunities using probabilistic approaches under various level of regional cooperation scenarios.

ACKNOWLEDGEMENTS

I would like to express my special appreciation and thanks to my advisor Dr. Semu Ayalew Moges, you have been a tremendous mentor for me. I would like to thank you for encouraging my research and for allowing me to grow as a research scientist. Your advice on both research as well as on my career have been priceless. I am also thankful to the School of Civil and Environmental Engineering of AAiT, Addis Ababa University for smoothly facilitating my PhD work throughout my study period. Words cannot express how grateful I am to my beloved wife Kumneger Genene who spent sleepless nights with and was always my support in the moments when there was no one to answer my queries. Thanks my sons Hiruy, Yosef and Estifanos Asegdew for all of the sacrifices that you've made on my behalf.

I would like to thank the Directorate of Hydrology and Water Quality and the library staffs of the Ministry of Water and Energy, who provided me with the needed hydrological data and literature. Especial thanks are also due to the ENTRO staffs especially to Dr. Yosif Ibrahim and Azeb Mersha for providing me with the opportunity of the internship program at ENTRO.

Finally, I am using this opportunity to express my gratitude to everyone who supported me throughout the course of this PhD thesis. I am thankful for their aspiring guidance, invaluably constructive criticism and friendly advice during the research work. I am sincerely grateful to them for sharing their truthful and illuminating views on a number of issues related to the project. I am particularly thankful to all of my friends Temesgen Enku, Fitsum Tesfaye, shimels Assefa and Belete Birhanu who deserve special thanks for their continuous support and encouragement.

Declaration

By submitting this dissertation, I declare that the entirety of the work contained herein is my own, original work, that I am the sole author. The work contains no material that has been accepted for the award of any other degree or master in any university and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text.

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Asegdew Gashaw Mulat	________________________	June 8/2014
Name of the Author	signature	Date

Dedication

This work is dedicated to

The Almighty, my Wife, Children and Friends

For dedicating their life for me and my wellbeing with endless love and support

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Abbreviations

AAiT	Addis Ababa Institute of Technology
ARMA11	Autoregressive Moving average
ARMP	Abbay River Master Plan
ASCE	American Society of Civil Engineering
BAL	Bekoabo low
BCEOM	Bureau Central d’Etudes pour les Equipements d’Outre-Mer
BCM	Billion Cubic Meter
DSS	Decision support system
DHI	Danish Hydraulic Institute
EDF	Electricity de France
EEPCO	Ethiopian Electric Power Corporation
ENB	Eastern Nile Basin
EN MSIOA	Easter Nile Multi Sectorial Investment Opportunity Analysis
ENTRO	Eastern Nile Technical Regional Office
ESRI	Economic and Social Research Institute
FAO	Food and Agricultural Organization of the United Nation
FDL	Full Development Level
FEWS	Flood Early Warning System (Sudan)
FRL	Full Reservoir Level
FSL	Full Supply Level
GAMS	General Algebraic Modeling System
GCM	Global Circulation Model
GDP	Gross Domestic Product
GERD	Grand Ethiopian Renaissance Dam
GHC	Greenhouse gas
GLUE	Generalized Likelihood Uncertainty Equation
GWh	Giga Watt Hour

GWh/y	Giga watt Hour per Year
ha	Hectare
HAD	High Aswan Dam
HRS	Hydraulic Research Station
IDF	Intensity Duration Frequency
IMPEND	Investment Model for Planning Ethiopian Nile Development
IPCC	Intergovernmental Panel On Climate Change
IWMI	International Water Management Institute
JICA	Japan International Cooperation Agency
LL	Lower Limit
MAF	Mean Annual Flood
m.a.s.l	Meter Above Sea Level
MMC	Million meter cube
MODSIM	Modeling and Simulation
MOL	Minimum Operation Level
MoWR	Ministry of water resource
MoWE	Ministry of water and energy
Mt	Metric ton
MW	Mega Watt
MWRI	Ministry of Water Resource and Irrigation (Egypt)
Mm^3y-1	Million meter cube per year
NBI	Nile basin initiative
NEOM	Nile Economic Optimization Model
NFS	Nile Forecast System
Nile-DST	Nile Decision Tool
NLWRA	National Land and Water Resource Audit
NMSA	National metrology service agency
NTU	Nephelomeric Turbidity Unit
NWL	Normal Water Level
PE	Potential Evaporation
PET	Potential Evapotranspiration

RegCM3	Regional Climate Model Version 3
RIBASIM	River Basin Simulation Model
SAP	Subsidiary action program
SEI	Stockholm Environment Institute
SRES	special Report on Emissions Scenarios
SUFI-2	Sequential Uncertainty. Fitting, ver. 2
SWAT	oil & Water Assessment Tool
TAS	Tekeze -Atbara-Setite
TF	Thomas Ferrying
TWh	Terra watt hour
UL	Upper Limit
UNEP	United Nations Environment Programme
UNESCO	United Nation Education Science and Culture Organization
UNESCO-IHE	International Institute for Hydraulic and Environmental Engineering
USBR	United states Bureau of Reclamation
WATBA	Water Balance
WaBaMo	Water Balance Model
WEAP	Water Evaluation And Planning
WEF TMDL	Water Environment Federation nutrient total daily loads
WMO	World Metrology Organization

Chapter One

Introduction

1.1. Background

In most international river basin systems, the runoff variability caused by natural or anthropogenic factors is a serious concern in water resources management of all riparian countries. Trans-boundary Rivers can bring cooperation or conflict. Unilateral development of hydropower or irrigation projects without cooperation usually associated with these international rivers disputes. Susanne (2010) states that, the study of hydro politics originates from the question whether the fact that watercourses are often shared by several nation states with diverging interest in how to use, exploit or protect water and related resources necessarily to conflict or even violence or can be mitigated through cooperation. There are two main branches of thought: neo-realistic or Malthusian approach, focusing on the conflictive potential of trans-boundary watercourses and an institutionalized or Cornucopia branch, emphasizing the cooperative potential of water.

The Nile River Basin is a typical example of these disputes. There is emerging water use disputes between the upstream and downstream countries (Whittington, 2004; Waterbury and Whittington, 1998 and Wolf, 1998). The Nile basin countries are Burundi, Democratic Congo, Egypt, Eritrea, Ethiopia, Kenya, Rwanda, Tanzania, South Sudan, Sudan and Uganda. Egypt and Sudan are the lower riparian countries while the rest of the countries are referred as upper riparian countries. In terms of the river system, the Nile consists of Equatorial Nile, the Eastern Nile and the main Nile system.

The water resources availability and uses are unevenly distributed amongst the riparian countries. Ethiopian highlands supply over 85% of the water of the Nile from three main sub-basins of the Nile: The Abbay-Blue Nile, Barro-Akobo and Tekeze sub-basins. The Abbay-Blue Nile sub-basin where this study is focused contributes about 60 % of the flow to the Nile flow. The Equatorial Nile supplying about 15% of the Nile. The lower riparian’s of Sudan and Egypt literally supply insignificant amount to the Nile flow.

In terms of water use, Egypt and Sudan are the largest water consumers while the equatorial Nile countries and Ethiopia uses negligible amount of water from the Nile. Both Egypt and Sudan are dependent on Nile water significantly for their agricultural production (Waterbury, 2002). In contrast, the rest of the other countries use insignificant amount of water from Nile. For instance Ethiopia has developed less than 5% of the irrigation and less than 3% of the hydropower potential of the basin (Block et al. 2007). As indicate in the recent master plans, Ethiopia possesses enormous water resources and hydropower potential. To meet the growing demand for food and energy, the Nile riparian countries are attempting to further develop their water resources. While there is little existing irrigation upstream in the Nile, there are large ambitions for more irrigation. The Ethiopian government for instance, is pursuing ambitious plans and programs to develop hydropower and irrigation in the Ethiopian part of the Nile.

There are several existing and ongoing project developments in the Nile basin system. High Aswan Dam (HAD), completed in 1970, is the largest man-made reservoir and produces 2100 megawatts (MW) of electricity. It was planned to resolve both floods and droughts and irrigate about 283,000 ha. Sudan built two dams, which led to the development of the 1929 treaty: the Sennar in 1926 was built primarily to irrigate cotton, while the Jabal Aulia was built in 1936 for both power and irrigation. Later, the Roseires Dam was added to the Nile system by Sudan. The Khashm Al Gerba on the Atbara River was built in 1964 to irrigate the Al-Gerba agricultural scheme and generate 70 MW of power. Recently, Merowe Dam, which is the largest dam in Sudan, was constructed for hydropower purpose on the main Nile.

In the Abbay-Blue Nile River Basin large hydropower plants and irrigation areas are being planned with the ultimate goal of boosting the production of hydropower and increasing food security (Guariso and Whittington, 1987 (cited in Waterbury and Whittington 1998); Block et al. 2007; Block and Strzepek, 2010; Georgakakos, 2006; Nile Basin Initiative, May 2010a).

Ethiopia's first big dam, the Finchaa Dam, was completed in 1973 on the Finchaa River that feeds into the Abbay River. The Tekeze Dam on the Tekeze River was completed and began operating in 2009 with 300 MW generation capacities. On the Abbay River, downstream of Lake Tana, the Tis-Abbay I hydroelectric project began to transmit power in 1964; later, the

Chara-Chara weir in 1997 was built to boost power supplies and in 2001 another weir, Tis-Abbay II was commissioned to boost power supplies by another 20 per cent (Awulachew et al. 2009)

Currently, the Ethiopian government is developing plans and programs to significantly increase both irrigation and hydropower in the basin, with the aim of increasing food security, reducing poverty and driving socio-economic development. Since the beginning of the 20th century, large-scale projects have been on the drawing board to develop the Abbay Blue Nile river basin (Whittington, 2004). Ethiopia has at least three new proposed and one under construction dams on the Abbay-Blue Nile River. The Grand Ethiopian Renaissance Dam (GERD) is under-construction gravity dam on the Abbay-Blue Nile River in Ethiopia. It is located close to Ethiopia-Sudan boarder will form the largest hydropower producing dam in Africa with over 60000 MCM of active reservoir storage. When completed, it is anticipated to produce maximum of 6000 MW of hydropower energy (Verhoeven, 2011).

Due to GERD and other proposed dams on the Abbay-Blue Nile there is a growing concern GERD and other dams would have potential impacts on downstream countries. This study is therefore an attempt to assess and quantify the likely impacts and benefits of the GERD dam on the current water use of the downstream riparian countries mainly on Egypt and Sudan during the filling and long term development phases of the reservoir. The study also addresses strategic policy options during the filling phase of the reservoir in the event of unlikely extreme drought scenario. Further analysis is also included to evaluate future additional cascaded hydropower and irrigation development. To achieve this, a basin-wide integrated water resource simulation model has been developed using Mike Basin and Mike Hydro Models on monthly time scale.

1.2. Research Questions

The thesis attempts to answer the following pertinent research questions.

1. Does GERD have any potential impacts on the socioeconomic sectors dependent on the Nile flow downstream of the GERD in the short and long term perspectives?
2. If it does which socio-economic sector does it affect, irrigation or hydropower?

3. If GERD doesn't have impacts, does it have any additional benefits to downstream socio-economic sector?
4. If Ethiopia proceeds to develop additional cascades of dam upstream of GERD, what will be the long term outcomes of these developments?
5. How much more large-scale irrigation is possible in the Eastern Nile?

1.3. Scope of the Research

The scope of the research is to provide a basis for sustainable water resource development through establishing appropriate river basin model; studying water balance dynamics at different spatial and temporal scales in a river basin; and developing scenarios for Eastern Nile river basin management. The study provides an insight into how this synthesis can help in developing sustainable water management strategies that encompasses hydropower and irrigation water use. The scope of the research is limited to assessment of the impacts and benefits of the infrastructure development in the Abbay-Blue Nile system, future irrigation development and expansion, proposed operational rules on the basis of existing historical and stochastic time series flow data and simulation based approach.

1.4. Research Objectives

The main objectives of the thesis is to evaluate the potential short term (filling) and long term impacts/benefits of GERD and additional cascaded developments upstream of GERD on the eastern Nile socio-economic sector specifically on irrigation and hydropower sectors.
The study evaluates three main objectives:

i. Assessment of impacts of GERD on the performance of downstream water used during the filling (impounding) stage of the reservoir under different hydrological realizations (dry, normal and wet flows)
ii. Assessments of long term impacts/benefits of GERD after filling stage of the reservoir
iii. Evaluation of additional proposed cascaded development upstream of GERD on the Eastern Nile System including GERD
iv. Assessments of the impacts of future irrigation and hydropower development on the availability of water in the Eastern Nile using stochastic flow sequences

1.5. Organization of the Thesis

In order to achieve the above objectives, the thesis is organized into 9 chapters

Chapter 1 presents introduction including the background, problems, research question and objectives.

Chapter 2 presents water resource development and management challenges in the Easter Nile, review of water resource modeling in the Eastern Nile, irrigation and impacts of climate change assessment on water resource management.

Chapter 3 presents description of the study area and data required for the thesis work.

Following this, chapter 4 presents a model setup and configuration of the Eastern Nile basin, description of Mike basin, schematization of the Eastern Nile nodes, scenario analysis and model performance analysis.

Chapter 5 present results of Grand Ethiopian Renaissance Dam (GERD) impacts on downstream structures especially on High Aswan Dam (HAD) during the impounding phase.

Chapter 6 presents the results of evaluation of Grand Ethiopian Renaissance Dam (GERD) impacts on High Aswan Dam (HAD) and reservoirs in Sudan during the operation phase.

Chapter 7 present results of future Upper Blue Nile (Abbay) River Basin Cascades Development upstream of GERD.

Chapter 8 present the analysis of future irrigation development plans on the availability of water in the Eastern Nile using stochastic time series flow data

Chapter 9 presents summary, conclusions and recommendations.

Chapter Two

Literature Review

2.1. Challenges in the Eastern Nile

2.1.1. Socio-Economic and Hydro-Political Challenges

Many of the Nile Basin countries are classified as some of the poorest in the world in terms of GDP and food security (FAO, 2010). Most people lack electrical power and the necessary means of obtaining electricity; average electrification rate is 30 per cent. This is a very low proportion; according to Economic Consulting Associates (2009). Hydropower is underexploited in most of the basin countries affecting growth and development. Nile Basin economies are heavily dependent on agriculture which accounts for more than half of the gross domestic product and employs more than 80% of the workforce. However, lack of water supply infrastructure, climate variability, and poor cultivation practices have seriously restrained economic growth (Georgakakos 2004).

According to Howell and Allen (1994), the Nile faces many socio-economic and hydro-political challenges. Some of the main challenges are poverty and uneven water use, contentious issues in the past Nile treaties which weaken effective communication and information exchange between the riparian countries. Despite it has been increasingly recognized among the riparian states that, cooperation on development and management of the Nile water resources can yield major benefits from the river on food and energy production, and will underpin many other benefits for the welfare of the basin inhabitants, there is poor cooperation between the upstream and downstream countries. There is a lack of clear and comprehensive agreement binding all riparian states (Amare, 1997). The water use prevailing in the basin currently is a lopsided one favoring mainly downstream countries of Egypt and to some extent Sudan. This inequitable use coupled with pressure from population growth, poverty, data scarcity, climate change and environmental degradation are presenting a formidable challenge to the sustainable use of the river Nile. Especially the recent desire of socio-economic development by the upstream riparian countries poses hydro-political threat in the Nile basin.

According to Abraham (2006), there is imbalance of water allocation in Nile basin stating that, the upstream countries as supplier and the downstream countries as user. Egypt, the most downstream country of the basin consumes about 80% of the Nile waters, while Ethiopia has a negligible consumption, even though 85% of the Nile waters come from the Ethiopian Highlands (Wu and Whittington, 2006; and Johnson and Curtis 1994).

Egypt has signed agreements in1929 with Great Britain, which represent Sudan, Kenya, Tanzania and Uganda and with Sudan in 1959 after its independence to secure its share of the Nile waters. The agreements were very controversial between upstream and downstream countries (Egypt and Sudan). The 1959 agreement between Egypt and Sudan assumes that, given an agreed upon annual average of 84 BCM of Nile yield, the allotment for Egypt is 55.5 BCM while Sudan receives 18.5 BCM. 10 BCM are left for evaporation losses (Haynes and Whittington 1981).

Allocation of the Nile waters has been a controversial topic for decades and currently is becoming more complex issue. As all Nile countries gain their independence, they demand rights to use the water resource, declaring the previous agreements no longer valid and never been recognized (Okidi, 1994; Nicol, 2003). Several riparian nations, especially Ethiopia, state that they were not included in the 1929 and 1959 treaties and the treaties violate their right to equitable utilization. The upstream countries with their own development issues do not feel that they need Egyptian permission to use Nile water. Ethiopia is not bound by an agreement with Egypt or the Sudan over the sharing of Nile waters (Ashok, 1997).

Arsano (1996) argue that shared resource based economic co-operation should be regarded as a key factor in economic development, conflict prevention and political harmonization. Basin-wide dialogue between countries has been initiated in 1997 with the Nile Basin Initiative (NBI). This organization aims at providing a framework to develop the river in a cooperative way, sharing socio-economic benefits and promoting regional security and peace. The NBI has successfully developed a number of so called shared-vision, and subsidiary action projects. However, the dialogue of the Nile riparian on a unified legal framework has not yet been completed and Sudan and Egypt strongly opposed (Nile Basin Initiative, May 2010a).

2.1.2. Hydrological Challenges

2.1.2.1. Flood

The ENB has a long recorded history of flooding (Walsh et al. 1994). The region is characterized by highly variable river flows and a significant proportion of the annual runoff volume of the Eastern Nile, contributing over 86% of the total River Nile flows, which occur in only three months, July to September. During high rainfall periods, major rivers in the region often give rise to large scale riverine flooding, particularly in the floodplains of the Sudan and Ethiopia, with devastating effects on lives, livelihoods, and properties (Ahmadul, 2012).

2.1.2.2. Drought and water Scarcity

The Nile basin, because of its size and variety of climates and topographies, constitutes one of the most complexes of all major river basins. However, the river's annual discharge is relatively small. The river is distinguished from other great rivers of the world by the fact that half of its course flows through countries with no effective rainfall. Almost all the water of the Nile is generated on an area covering only 20 percent of the basin, while the remainder is in arid or semi-arid regions where the water supply is minimal and where evaporation and seepage losses is very large (Dianar, 2000).

According to Georgakakos (2004), most Nile countries are close to water stress, if not already below the water scarcity threshold of 1000 m^3 of water per inhabitant per year. Water stress is compounded by rapid population growth, occurring at nearly twice the average global rate. Severe water scarcity conditions are looming over most Nile countries.

Egypt is a very arid country where rainfall is virtually non-existent. Two of the worst droughts occurred in 1067-1072 and 1199- 1202 (Ahmadul, 2012). The droughts that occurred in 1199-1202, referred to as “the years of starvation” were due to very low levels of the Nile. In the beginning of the 20th century there was also a prolonged drought following the years 1913, 1914 and around the years 1939-1942. The years 1972 -1973 were dry and the period 1979- 1984 coincided with the drought in the Sahel that extended to Ethiopia and the Sudan. In 1913-1914, Egypt suffered one of its worst droughts in recorded history (since 1695). The natural yield of the river at Aswan was 42 Bm^3 (Fahmy, 2006). The available storage water plus the natural summer flow were too little to fulfill the irrigation requirements at that time which badly affected agriculture.

Per capita fresh water availability in Egypt dropped from 1893 cubic meters per person in 1959 to 900-950 cubic meters in 2000 and tends to decline further to the values of 670 cubic meter by 2017 and 536 by 2025 (UN CCA 2001 and MWRI, 2002). Egypt's per capita share of water has dropped from 20,000 cubic meters per year at the beginning of the 19th century to less than 1000 cubic meters per year at the close of the 20th century. The increase in population is responsible for the sharp decline in the country's per capita share of water.

2.1.2.3. Salt Water Intrusion

Egypt has a relatively long coast line, including more than 950 km along the Mediterranean Sea in the north and 1200 km along the Red Sea in the east (Fahmay, 2006). The coastal region is one of the most densely populated areas in Egypt facing the challenges due to sea level rise. The most important coastal lowland in the Nile basin lies along the Mediterranean Sea and there is possibility of hydraulic contact between the Nile Delta aquifer system and underlying the formations directly by embedded faults.

Previous studies have predicted that relative rise in sea level in the Mediterranean Coast could lead to increased flooding and saltwater intrusion. The current simulation of the compaction phenomena has provided understandable view about the saline water near the base of the Nile Delta aquifer within the fresh water part at south of Delta as a geologic evolution is the main sources of the salt in groundwater aquifer system (Fahmay, 2006). One of the reasons for low productivity in Sudan's irrigation areas is salinization and an unfavorably hot climate (Bastiaanssen and Perry, 2009).

2.1.2.4. Sedimentation and Surface Water Quality

A report prepared by ENTRO (2006) estimates the total soil eroded within the Abbay Basin alone is nearly 302.8 million tons per year) and erosion from cultivated land is estimated to be 101.8 million tones/year (33%).Thus about 66 per cent of soil being eroded is from noncultivated land (Molden et al., 2010). About 45 per cent of this reaches the stream system annually causing heavy siltation of downstream reservoirs.

Erosion from steep cultivated lands of Ethiopia especially at the beginning of rainy season (in July) is a major problem, reducing agricultural productivity and causing rapid sedimentation in downstream reservoirs (Awulachew et al. 2008).

The sediment load at the Ethio-Sudan border is estimated at 140 million tons/year. An annual average of 21 and 11.56 million tons of sediment is deposited at Roseires and Sennar reservoirs respectively. The Dindar and Rahad rivers, downstream of the Sennar reservoir, yield a mean annual sediment inflow of 9.2 million tons/year. An estimated of 99 million tones/year sediment reaches at Khartoum (ENTRO, 2006a). The Sennar lost 66%, the Girba 60% and the Rosaries 30% due to sedimentation from Ethiopian high lands (Ahmed, 2006; Gibb and Coyne Et Bellier report (1996).

Together the Blue Nile and Atbara contribute on average about 97 % of the Nile's annual suspended sediment load (with about 72 % from the Blue Nile and 25 % from the Atbara) and the White Nile the remaining 3.0 % (Foucault and Stanley, 1989). Suspended sediment flux is dominated by the summer flood in the Blue Nile and Atbara catchments (Williams *et al*., 1982).

In the main Nile at Aswan the sediment wave tends to peak in August before the main flood peak. The suspended sediment concentrations for the summer flood of 1955 at Gaafra (near Aswan) peak at over 5500 mg l^{-1} in mid-August and then decline steadily to <500 mg l^{-1} by the end of October (El Manadely *et al*., 2002 and Shahin, 1985).

The rate of erosion in the Blue Nile headwaters during the 70 years before completion of the Aswan High Dam was 0.12–0.24 mm year^{-1}. In contrast, in the 1970s annual soil loss from parts of the Ethiopian Plateau was roughly 0.4–1.0 mm/year (Hurni, 1999). This represents a two orders of magnitude increase in the rate of soil loss, a rate that is much faster than corresponding rates of soil formation.

Several areas and cities in the ENB depend on the Nile system for their drinking water. Watershed erosion and heavy sediment movement during flood season especially the flood season cause high turbidity and suspended solids in the Nile River water making the water unsuitable for domestic use and drinking purposes. For example at Khartoum, the turbidity has tremendously increased during the last decade. It was increased from 5000 NTU to above 20,000 NTU during the floods of 1999 to 2003 (Ahmed, 2006). Many water treatment plants have been affected by such heavy sediment load. For example, the Khartoum water treatment plant, which was designed initially to treat raw water of maximum turbidity of 8000 NTU (Ahmed, 2006), now produces water of poor quality when the sediment dose is greater than the maximum allowable quantity. Besides sedimentation discharge of untreated or partially treated industrial and domestic wastewater, leaching of pesticides and residue of fertilizer as well as navigation are often factors that affect the quality of water of the Nile River.

2.1.3. Temporal and Spatial Distribution of Water Flow

According to Lars (2006), of the total runoff reaching the main Nile around 80 % stem from the Ethiopian plateau and almost 20 % from the equatorial Lakes Plateau. Nearly all of the river's water is generated on an area covering 20% of the basin, while the remainder is arid or semiarid regions with minimal water supplies and very large evaporation losses (Karyabwite, 2000).While the average outflow of Lake Albert, the last of a chain of lakes in the Equatorial Plateau, is 31.4 km^3 , half of the water running off from the Equatorial Lakes plateau is evaporated in the Sudd area in southern Sudan (Sutcliffe and Park., 1999; Tate et. al. 2004; Mohamed, 2005). The size of the Sudd area is varying according to season and year (Mohammed, 2005; Sutcliffe and Park, 1999).

The inflow to Lake Nasser shows a sharp seasonal pattern: between July and November the flow is above 2.32 m^3/s which reach a peak in September 8.10 m^3/s). During the rest of the year the flow is below 2.32 m^3/s with minimum flows close to 0.58 m^3/s during the peak of the dry season between April and May. The main contribution to runoff from July to November stems from the Blue Nile and Atbara River. Annual runoff shows high variability as well. The average flow before 1871 and 1898 was 102109 m^3/year, between 1899 and 1971 is 88109 m^3/year, and between 1972 and 1986 it was 77109 m^3/year (Evans, 1994).

According to Nicol (2003) Nile basin is highly diverse environment. Nevertheless, the complexity of the number of states, combined with the uneven distribution of the basin between states and the complex hydrology of the system, poses significant technical and institutional challenges both for the management of shared waters and, in the future, for ascertaining where and how benefits can and should be shared within and outside the basin.

That the flow could vary from year to year as well as seasonally has been recorded for many thousands of years and the awareness of Egypt's cycles of lean years followed by years of plenty was part of the way of life of people residing in the lower Nile valley before the filling of Lake Nasser/Nubia in the 1960s (Sutcliffe and Lazenby, 1990).

The second major feature of the hydrological system is the huge seasonality of the Blue Nile's flows, concentrated from July to October in a spectacular flood. From the point of view of basin development the main interest in the hydrology of the Blue Nile within Ethiopia is for flood forecasting for reservoir operation and to give warning of possible inundation in Khartoum and in the agricultural areas downstream (Sutcliffe and Lazenby, 1990)

Over the years, fluctuations in the flow of the Blue Nile have contributed changes in mean annual discharge of plus or minus 20 percent, with very severe consequences for water management in Egypt and Sudan (Conway and Hulme, 1996). A third major feature of the river system is caused by virtue of the river's situation in hot, arid areas where evaporation losses are high. By far the most significant losses are in the Sudd in southern Sudan. Between entry and exit the river loses up to 50 percent of its original flow. This loss to the system for Egypt and Sudan has meant significant shortfalls in summer months, when flows from the Blue Nile reach their lowest point (Nicol, 2003).

2.1.4. Abbay-Blue Nile Runoff Data and Flow Variation

Because of the vast size of the basin and the scarcity of data it is difficult to apply complex hydrological models without making many assumptions about parameter values and without using a monthly time step.

A major requirement of any modeling attempt is the availability of climatic and hydrological data. Much of the data management environment to date has focused on river flows, addressing the problems of water management. By its size, physiography, political divisions, and history the Nile Basin is very complex. Therefore, although there are several projects operating actually in the region, it is still difficult to obtain reliable data, at detailed scales (Conway 1997). The Upper Blue Nile, only a limited number of observation sites are available over a very large area (Conway, 1997).

Although good quality long-duration records exist for the Blue Nile at a number of sites in Sudan (Evans, 1990; Walsh et al*.* 1994; and Sutcliffe and Parks, 1999), there is very little published hydrologic data for the Blue Nile and its tributaries in Ethiopia upstream of the El Deim gauge. River flow data are limited because of the remoteness of many of the catchments, the lack of economic resources and infrastructure to build and maintain monitoring sites.

Lake Tana levels and outflows from August 1920 through February 1926 and from January 1928 through December 1933 are the earliest records for the Blue Nile in Ethiopia (Hurst and Phillips, 1933) (cited in Sucliffe and Park, 1999). According to USBR (1964) a staff gauge was installed on the Blue Nile near Kessie during the 1935-1941, but no records were available for that period. A new staff gauge was installed at this site in July 1953 and runoff records are available from July 1953 to September 1954. Most of these gauges, however, were probably operational for only one or two years. In addition, because the records are so short it is unlikely that they are representative of the long term mean conditions (Conway, 2000).

The daily flows up to 1962 were published in the 1961 and 1962 Abbay Basin Hydrologic Summary (USBR, 1964). According to Admasu (1996) (cited in Sucliffe and Park, 1999) a total of 102 gauges have been installed on tributaries in the basin at some time, but he estimates that at least 25 per cent of the gauging network was abandoned or is non-operational.

The seasonal distribution of runoff varies considerably owing to differences in the seasonality of rainfall and catchment physiographic. Peak flows usually occur in August, one month after the rainfall maximum. These runoff patterns reflect the variation in rainfall distribution in the basin (Conway, 2000). Comparison with the annual rainfall series shows close agreement. There is an increasing trend up to 1964 followed by a prolonged decline until 1984 since when flows have generally increased (Conway, 2000). Fluctuations in Blue Nile flows have been the main cause of fluctuations in Main Nile discharge of up to ±20 per cent which have had important consequences for water resource management in the downstream riparian (Conway and Hulme, 1996; Anon, 1994).

2.2. River Basin Modelling in Nile River Basin

Efficient utilization of the water resources in the Nile Basin demands a good understanding of the past and current hydro-climates and also how these interact with the geography and geology of the basin to produce the hydrologic characteristics of flow that is observed at different sections of the basin.

Since the beginning of intensive water resources management efforts in the Nile, hydrologists have recognized the importance of treating the system as one geographical unit. The Century storage scheme and the musings of planners such as Hurst reflected this preoccupation, and were motivated by a need to overcome the high natural flow variability and seasonality of the Nile flood (Hurst, 1952 (cited in Sutcliffe and park, 1999)). Currently several basin-scale hydrologic models have been developed to further describe the river. There are simulation model like Nile-DST, Nile-Sim, Nile Forecast System (NFS) etc. which seek replications of historically observed flows. There are also optimization models which aim to guide future water resources planning, for instance, Nile-DST, NEOM, IMPEND etc. In addition, there are a number of smaller sub-basin models designed to address questions that apply to specific portions of the basin.

According to Strzepek and McCluskey (2007), a general rainfall-runoff model called WatBal, which simulates changes in soil moisture and runoff and has been applied to many hydrology problems, including those of the Nile. The model contains two components: the first is a water balance for a conceptualized basin (precipitation inflows and evapotranspiration, surface runoff and subsurface runoff outflows), and the second calculates potential evapotranspiration over spatial grid cells using the Food and Agriculture Organization (FAO) Penman-Monteith approach. Another such model is the NFS, a grid-based hydrological model developed in 1992 covering the White Nile to Malakal, the Blue Nile to Khartoum, and the Atbara basin, combined with a routing model for the Main Nile (Sayed and Nour, 2006).

2.2.1. Potential and Impact Assessments in the Nile Basin

According to Barrett (1993) (cited in Levy and Baecher, 1999), one of the first such technical simulation models of the Nile was built by the US National Weather Service. The primary purpose of this model was to develop and implement a river forecasting system for use in operation of the Aswan High Dam. In 1964 (during the construction of HAD) the USBR performed a thorough investigation and study of the hydrology of the upper Blue Nile basin (Block, 2008). The USBR's study included preliminary designs of dams for irrigation and hydropower along the Blue Nile and Atbara Rivers (USBR, 1964). The four major hydroelectric dams along the Blue Nile, as proposed by the USBR, are Border, Mendya, Mabil and Karadobi. These four dams would impound a total of 73.1 BCM, which is equivalent to approximately 1.5 times the average annual runoff in the basin and can generate up to 5570 MW of power.

The Karadobi Dam is located 385 km downstream of Lake Tana just upstream of the Guder River confluence and would be responsible for controlling a draining area of nearly 60,300 square kilometers (USBR, 1964). The Mabil Dam would site 145 km further downstream, 25 km downstream of the confluence with the Birr River. The Mendya and Border Dams would be constructed about 175 km and 21 km upstream of the Sudan-Ethiopia border, respectively (USBR, 1964).

Preliminary plans ordered the construction of the dams to be from upstream to downstream, beginning with Karadobi and finishing with Border. More recent schemes, though, have altered the construction order to be: Karadobi, Border, Mabil, and finally Mendya (Harshadeep, 2006 (cited in Block, 2008)).

Grand Ethiopian Renaissance Dam (GERD) previously called Border is under construction before all other Dams with improved capacity and design. Original Mendya is now replaced bay upper Mendya which located above the confluence of Dedesa river. There is no Mabil dam in the current situation which is replaced by Bekoabo. The total storage capacity of reservoirs in

Abbay-Blue Nile River will be more 190 BCM which about 2.7 times the USBR study. The most recent studies reveal that the expected energy production large difference from the previous studies. The implementation order is also changed, Border (Grand Ethiopian Renaissance Dam) construction comes first and the total installed capacity at design head would be 13000 MW of power, more than twice the USBR's value.

Yao and Georgakakos (2003) developed Nile Decision Support Tool (DST) used for hydrological simulation and scenario assessment. It is designed to support sub-basin and basin-wide planning purpose to process the data and quantify the response of the basins for alternative hydrologic, water use, and development/management scenarios. The routing models in the DST are based on linear regression methods. The authors find that the simple regression techniques lead to water flow descriptions that compare favorably with historical observations and are considerably more parsimonious than models based on neural network approaches. Nile-DST also includes a module capable of solving scenarios designed to meet downstream flow requirements and irrigation demands given a specified set of upstream hydropower projects and a historical flow.

Guariso and Whittington (1987) (cited in Whittington et al. 2005) developed a linear model based on average annual flows for optimizing the generation of hydropower in Ethiopia, based on construction of the four largest USBR recommended dams, and found that they would augment the amount of downstream water available for irrigation in Sudan and Egypt.

Block et al. (2007) develops an optimization model called IMPEND (Investment Model for Planning Ethiopian Nile Development) to analyze the cost-benefit implications of stochastic modeling of climate, incorporating the downstream ramifications of the transient stages (filling stages) of planned Abbay River reservoirs, and their associated flow retention policies. IMPEND is written in GAMS, requiring a single input file including stream flow and net evaporation at the four dam locations and Rosaries. The model thus encompasses the Blue Nile River from its headwaters at Lake Tana to the Rosaries Dam. IMPEND weighs the tradeoff value of hydropower and water for irrigation with the total present worth of benefits as the objective value.

IMPEND focuses on the impact of implementing four dams, identified by the Bureau of Reclamation, US Department of the Interior (1964), in Ethiopia for irrigation and hydropower purposes. IMPEND assessed the transient period between different phases of the dams and irrigation projects implementation which the most important features of this model unlike previous models that assumed the four dams become operational simultaneously.

The time horizon, albeit adjustable, is assumed to be 100 years, 2000-2099, for all scenarios. This includes a period of construction of seven years (2000-2006) for the first dam and three years (2004-2006) for the irrigation system before any benefits may be realized. The 30- year transient portion of the model thus starts at 2007, when water may first be impounded, and continues until 2036. Benefits for each dam may begin post-construction of that dam. Full benefits for each dam may or may not be reached in the transient period, again, depending upon hydrologic conditions. He found that explicit consideration of the time required for filling greatly reduces benefit-cost ratios and that climate uncertainty implies there is considerable risk in implementing such projects.

The Nile Economic Optimization Model (NEOM) is another model which focuses more on economic aspects. NEOM is written in the General Algebraic Modeling System (GAMS) language. NEOM aims to optimize economic benefits from a basin-wide perspective assuming perfect cooperation (Whittington et al. 2005). NEOM's main purpose was to maximize the overall benefit of Nile River water allocated to irrigation and hydropower generation among basin countries in cooperative and non-cooperative game settings. NEOM is formulated with the objective of maximizing the net economic value of allocating Nile River water for irrigation and hydropower sectors, taking into account resource degradation and various climate change scenarios, and the possibility of introducing basin-wide water trade.

Analysis conducted with NEOM suggests that cooperation between different basin countries would be beneficial. NEOM considered only two hydropower plants in Ethiopia and hydropower and irrigation projects in Sudan. NEOM is different from the previous model by focusing on three Eastern Nile countries (Ethiopia, Sudan, and Egypt) that have strategic importance in establishing a basin-wide agreement and water trade, and includes existing and new major water demand projects. NEOM addressed the economic impact of resource degradation and the impact of its inclusion in the objective function on the basin water allocation and welfare distribution; and analyze the impact of climate change on the economic welfare of the basin.

Goor et al. (2010) studied the optimal operation of a multipurpose multi-reservoir system in the Eastern Nile River Basin by considering four development scenarios. They developed basin-wide integrated hydro-economic model. They used an algorithm, Stochastic Dual Dynamic Programming (SDDP). The objective was to evaluate the impacts of upstream development in the Blue Nile Basin on the allocation decisions and reservoirs operating strategies and to assess the economic value of regulation (reservoirs) in Ethiopia. The model integrates essential hydrologic, economic and institutional components of the river basin in order to explore both the hydrologic and economic consequences of various policy options and planned infrastructural projects. The analysis focused on two economic sectors: irrigation and hydropower generation.

They adopted a stochastic programming formulation in order to understand the effect of the hydrologic uncertainty on management decisions, determine allocation policies that naturally hedge against the hydrological risk, and assess the relevant risk indicators. According to them, the development of four mega dams in the upper part of the Blue Nile Basin would change the drawdown refill cycle of the High Aswan Dam. And a possibility of an average saving of more than 2.5 BCM water through reduced evaporation losses from the Lake Nasser if the operation of the reservoirs is coordinated. Moreover, the new reservoirs in Ethiopia would have significant positive impacts on hydropower generation and irrigation in Ethiopia and Sudan: at the basin scale, the annual energy generation is boosted by 38.5 TWh amongst which 14.2 TWh due to storage. Moreover, the regulation capacity of the above mentioned reservoirs would enable an increase of the Sudanese irrigated area by 5.5%. This study gives more recent results but with limitation on using updated data. For instance the installed capacity of Border is 1400 MW which is the USBR study. The updated capacity is 6000 MW.

In Whittington et al. (2005), a deterministic hydro-economic model was developed for the entire Nile River Basin and several development scenarios were analyzed. Their study revealed, amongst other things, that the annual benefits of cooperation between the Nile countries can be as high as 4.9 billion US$/year. In Georgakakos (2006), a DSS is developed for the Nile River Basin: the model can simulate the Nile response to different hydrological scenarios and provide reservoir operating strategies for real-time control through the Extended Linear Quadratic Gaussian (ELQG) optimization algorithm. Recently, Block and Strzepek (2010) analyzed the transient conditions associated with the period of filling some of the proposed dams in Ethiopia, under climate change scenarios. Huge increase in basin-wide benefits due to the new hydropower stations in Ethiopia and irrigated areas in Sudan.

Awlachew et al. (2009) reported that, Water Evaluation and Planning (WEAP) model was used to simulate planned hydropower and irrigation development scenarios of Lake Tana. The simulation results revealed that, if the full future development occurs, on average, 2,207 $GWhy^{-1}$ of power could be generated and 548 Mm^3y^{-1} of water could be supplied to irrigation schemes. However, the mean annual water level of the lake would be lowered by 0.33 meters with a consequent decrease of 23 km^2 in the average surface area of the lake. Later, McCartney *et al.* (2010) reported that the natural environment around Lake Tana has been affected by the variability in lake levels caused by the weirs.

The most recent study is the Model-Based Optimization of Downstream Impact during Filling of a New Reservoir (Mendya) on the Blue Nile River by taking Mendya and Roseires as a case study (Hassaballah et al. 2011). But this study didn’t include currently under construction dam (GERD) which is located between Mendya and Roseires.

There are also a number of smaller sub-basin models, geared mainly towards supporting operation of specific control structures on the Nile. Yao and Georgakakos have created DSTs to guide operation of a few reservoirs and control projects, including the Owen Falls and the High Aswan Dams (Yao and Georgakakos, 2003). A model developed in several phases at Kobe University in Japan allows simulation of the Roseires and Sennar Dams in Sudan, for the purpose of guiding irrigation planning; specifically, the model uses a recession-forecast equation based on Blue Nile flows observed early in the rainy season to aid decision-making on the total area of wheat to be planted in a given year without experiencing deficits in timely irrigation water

(Mishra et al. 2003; 2004). A number of similar reservoir-specific models have been designed to analyze proposed Abbay River reservoirs and project options in the Ethiopian Master Plans (USBR, 1964; Norplan-Norconsult, 2006; EDF, 2007).

A number of commercial-type and public-access models that do not appear in the published literature for the Nile are nevertheless used in some form by planning agencies - the Ministry of Water Resources in Ethiopia (MoWR), the Ministry of Irrigation and Water Resources (MIWR) in Sudan and the Ministry of Public Works and Water Resources (MWRI) in Egypt - in Eastern Nile countries, as evidenced through recent country-specific reviews of models commissioned by ENTRO (Ahmed, 2006). Other models have been used by consultants doing specific Master Plan studies but are not generally used or well documented.

For Sudan, Ahmed (2006) describes use of several models for water resources management and planning purposes. These include the Surface Water Modeling System (SMS), the Galway real-time Flow Forecasting System (GFFS), the Flood Early Warning System (FEWS), the Nile-DST, and Dam Break (DAMBRK). With the exception of the Nile-DST, which is used extensively at the MIWR, most of these models have only received limited use in specific case studies. The SMS model has been used by UNESCO for modeling the complex dynamics of flow at the White Nile – Blue Nile confluence in Khartoum.

Forecasting models include the NFS and the Stochastic HAD Inflow Forecast Model, which both suffer from data gaps but could be used for rainfall-runoff modeling and flow routing of the entire Nile Basin.

2.2.2. Water Balance Modelling

Most of water balance analyses are focused on Lake Tana basin. Setegn et al. (2008) reported that, the SWAT2005 model was applied to the Lake Tana Basin for modeling of the hydrological water balance. The main objective of the study was to test the performance and feasibility of the SWAT model for prediction of stream flow in the Lake Tana Basin. The model was calibrated and validated on four tributaries of Lake Tana; Gumara, Gilgel Abbay, Magic and Ribb rivers using SUFI-2, GLUE and ParaSol algorithms. The sensitivity analysis of the model to sub basin delineation and HRU definition thresholds showed that the flow is more sensitive to the HRU definition thresholds than sub basin discretization effect. SUFI-2 and GLUE gave good result.

Kebede et al. (2006) studied the water balance of Lake Tana and found that; the annual water budget of Lake Tana is determined from estimates of runoff, rainfall on the lake, measured outflow and empirically determined evaporation. Simulation of lake level variation (1960-1992) has been conducted through modeling at a monthly time step. Despite the 20% rainfall variations in the Blue Nile basin in the last 50 years, the lake level remained regular. A preliminary analysis of the sensitivity of level and outflow of the lake suggests that they are controlled more by variation in rainfall than by basin-scale forcing induced by human activities. The analysis shows that a drastic (40-45%) and sustained (7-8 years) rainfall reduction is required to change the lake from out flowing to terminal (cessation of outflow).

According to Conway (1997, 2005), Climate is dominated by the influence of elevation in the river basin. Estimates of potential evapotranspiration (PE) and rainfall were predicted for 10-minute resolution grid cells for input to the model. The estimates were based on multiple regression models using latitude, longitude and elevation. The model is calibrated to reproduce mean monthly runoff over a 37-year period (1953-1987), and validated by its ability to simulate sub-catchment runoff and historical variations in Blue Nile runoff. The model was used to investigate spatial variability in the sensitivity of runoff to changes in rainfall and PE. The sensitivity was greatly affected by the runoff ratio of the model grid cells and it increases as grid cell runoff ratio decreases. The sensitivity is also affected by the seasonal distribution of rainfall.

Wubet et al. (2008) applied Mike Basin model to analyze Water Uses on Large River taking Abbay Basin as a case study. The objective of the research was to simulate water allocation for major production activities (existed and planned) in the Abbay basin. Configuration and model set up for various river basin elements and water use elements.

They reported that, water extracted to irrigate 220416 ha of land was 1.624 BCM per year, inducing for Abbay an average annual flow reduction of about 3.04% at Sudan Border. The overall mean annual flow from the mean monthly data of the main stream gauges was estimated as 50.45 BCM at the Sudan border. They concluded that as compared to the result of scenario 1 of the master plan to irrigate a command area of 440804 ha and to generate 9519 GWh, the border flow reduction which was 7% is compatible with the output of this study. In this study Abbay basin was considered for selected projects and focuses on evaluation of master plan yet fail to adequately address critical aspects, including the implications of stochastic modeling of variable climate and climate change. They also recommended further study on the un-gauged rivers and other detailed studies on the gauged tributaries to fully assess the impacts of irrigation and hydropower potential of the basin on the border flow by applying the modeling technique of rainfall-runoff simulation.

2.3. Water Resources Models

The water resources of a river basin represent a single entity, and must be treated as a whole to avoid conflicts over the utilization of this increasingly finite resource. Water resources management of a river basin requires the optimal utilization of the available resources given the competing demands, both natural and manmade. The water demands must be matched with the resources, with their own temporal and spatial distribution.

Allocation models are typically divided into two categories, simulation and optimization models. Linear and non-linear programming models for integrated hydro-economic modeling have been used in many rivers basins (Rosegrant et al. 2000 and Rodgers et al. 2002). Those tools will provide the optimum solution for a particular problem. Simulation models are widely used by managers for planning and management of complex systems. Simulation based water allocation models use mass balance principles to allocate resources in a river system, as in MODSIM-DSS (Fredericks et al. 1998), Mike Basin (DHI, 2001), WEAP (Yates et al. 2005), etc. A simulation model is not intended to provide optimum solution to a specific problem. Rather, its aim is to evaluate changes managers might like to make to a complex system.

2.3.1. Optimization and/or Simulation

For determining the best design and operating policy variable values in river basin systems the use of both optimization and simulation models can be advantageous. Optimization is often useful, not for finding the very best solution, but for eliminating the worst alternatives from further consideration. The remaining ones can then be analyzed in greater detail, using more detailed simulation models. Simulation by itself begs the question: ‘What to simulate?’ Optimization by itself begs the question: ‘Is the solution really the best?’ (Daniel and Eelco, 2005; Simonovic, 2009)

Simulation models describe how a system operates, and are used to predict what changes will result from a specific course of action. Such models are sometimes referred to as cause-and-effect models. They describe the state of the system in response to various inputs, but give no direct measure of what decisions should be taken to improve the performance of the system. Therefore, simulation is a problem solving technique. It contains Development of a model of the system, Operation of the model and observation and interpretation of the resulting outputs the following phases (Daniel and Eelco, 2005; Simonovic, 2009). The essence of simulation is modeling and experimentation. Simulation does not directly produce the answer to a given problem (Daniel and Eelco, 2005; Simonovic, 2009).

The complexity involved in river basin planning requires both approaches (Daniel and Eelco, 2005; Simonovic, 2009). However, applying optimization requires simplifications, in particular with respect to spatial and temporal detail. For this reason, simulation models should be applied to check and refine the infrastructural designs and operating policies as well as to develop detailed management options. Both optimization and simulation modeling approaches require a description of the natural resource system and related infrastructure, and a description of the socioeconomic functions in the river basin (Daniel and Eelco, 2005; Simonovic, 2009).

In a simulation approach, the analyst will have to specify the values of the decision variables. The ‘best’ values of these decision-variables will have to be determined by sensitivity analyses, i.e. by changing these variables and seeing what the output will be in terms of the objective functions. Hence, simulation is a ‘trial-and-error’ approach. More complicated systems can be simulated by using generic computer packages for river basin planning, such as RIBASIM (WL Delft Hydraulics, 2004; Mike Basin; DHI, 2003; and WEAP-21, SEI, 2007; Daniel and Eelco, 2005; Simonovic, 2009).

Integrated basin-wide models are typically built around arcs and nodes: the former may represent natural inflows to the system, canals, the river network, whereas the nodes are used to represent confluences, reservoirs, abstraction points, demand sites, etc. (Harou et al. 2009). River basin simulation packages support the development of a model schematization consisting of a network of nodes connected by links. The links transport water between the different nodes. The network can be adjusted to provide the level of spatial and temporal detail required. The river basin is represented as a network schematization superimposed over a vector or raster map.

2.3.2. Some Available Water Resource Models and Their Functionality

2.3.2.1. Mike Basin

Mike Basin is software developed by Danish Hydrologic Institute, DHI. Mike Basin is an integrated water resource management and planning computer model that integrates GIS with water resource modeling (DHI, 2008). Mike Basin addresses water allocation, conjunctive use, reservoir operation, or water quality issues. It couples the power of ArcGIS with comprehensive hydrologic modeling to provide basin-scale solutions.

According to Progea (2003) in terms of actual DSSs, one may consider Mike Basin as a first example of a more comprehensive tool. Developed by the Danish Hydraulic Institute (DHI) as a Versatile Decision Support Tool for Integrated Water Resources Management and Planning, Mike Basin has been integrated into the ArcView GIS environment. This ensures to maintain the full functionality of the ESRI Tool and apply its standard facilities to water resource modeling. The model can operate in Arc GIS environment and is well-organized into modules and a great package for data management.

In Mike Basin, the emphasis is on both simulation and visualization in both space and time, making it appropriate for building understanding and consensus. This gives managers and stakeholders a framework within which they can address multi-sectorial allocation and environmental issues in a river basin. In general terms, Mike Basin is a mathematical representation of the river basin, including the configuration of the main rivers and their tributaries, the hydrology of the basin in space and time, and existing as well as potential major water use schemes and their various demands for water.

2.3.2.2. RIBASIM

RIBASIM (River Basin Simulation Model) is a generic model package for analyzing the behavior of river basins under various hydrological conditions (WL Deflt Hydraulics 2004). The model package is a comprehensive and flexible tool which links the hydrological water inputs at various locations with the specific water users in the basin (Van der, 2010).

2.3.2.3. WEAP

WEAP ("Water Evaluation And Planning" system) is a user friendly software tool that takes an integrated approach to water resources planning. Allocation of limited water resources between agricultural, municipal and environmental uses now requires the full integration of supply, demand, water quality and ecological considerations. The Water Evaluation and Planning system, or WEAP, aims to incorporate allocation of limited water resources between different sectors into a practical yet robust tool for integrated water resources planning. WEAP is developed by the Stockholm Environment Institute's Boston Center at the Tellus Institute. It provides a comprehensive, flexible and user friendly framework for planning and policy analysis.

2.3.2.4. MODSIM

MODSIM is a generalized river basin Decision Support System and network flow model developed at Colorado State University designed specifically to meet the growing demands and pressures on river basin managers today. MODSIM’s graphical user interface (GUI) allows users to create any river basin system topology by simply clicking on various icons and placing system objects in any desired configuration on the display. MODSIM can also be used with geographic information systems for managing the intensive spatial data base requirements of river basin management.

2.3.2.5. RiverWare

A general UNIX based river and reservoir modeling application with both operational and planning applications. This system offers multiple solution methodologies that include simulation, simulation with rules, and optimization. RiverWare can accommodate a variety of applications, including daily scheduling, operational forecasting, and long-range planning.

Modeling framework is non-spatial (not GIS based). Because of its object-oriented nature, the modeling framework allows for the generation of new modeling methods that could include economically driven demand modeling. The tool is most appropriately used to model resource demands on complex water systems governed by water law and intricate operating rules. Uncertainty modeling related to parameter variance provides estimates of uncertainty in model output.

2.3.2.6. Conclusive Remark

The Mike Basin philosophy is to keep modeling simple and intuitive, yet provide in-depth insight for planning and management. In Mike Basin, the emphasis is on both simulation and visualization in both space and time, making it appropriate for building understanding and consensus. Mike Basin is a quasi-steady state mass balance model, however allowing for routed river flows. It adds the time dimension to the spatial information stored in the GIS and is therefore a great package for data management.

Mike Basin allows integrating technical infrastructure like large reservoir operation and water users. Mike Basin software is equivalent to couple of the economic model (GAMS) with WEAP model. Mike Basin model is a powerful tool for water resource management considering the impact of climate variability. It is a coupled dynamic hydrologic-economic model for water policy scenario analysis. The model accounts for national water management strategies that can be used as a supportive tool for trans-boundary water management. Furthermore, Mike Basin is currently used by the NBI for Nile DSS tools, so for future application and to access data and information regarding Nile basin it is preferable to apply the software. The table below summarizes the functionality of some model.

Table 2-1: Functionalities of model (source Strzepek, 2008)

Model	System yield planning	Operation and Development planning	Water quality	Hydrologic analysis	Ground water
Ribasim	√	√	√	√	√
Water ware	√	√	√	√	√
Mike basin	√	√	√	√	√
WRSM	√	√	-	√	-
Riverware	√	√	√	-	-
WEAP	√	√	√	weak	√
Hec-Resim	√	√	-	-	-

2.4. Irrigation Developments in the Eastern Nile

Except for Egypt and Sudan, the other Nile Basin countries have relied more on rain-fed agricultural potential for their available water resources because of different reasons (Table 2-2). The total irrigated area in the Nile Basin is estimated to be 4.3 million ha (Water Watch, 2008). Egypt and Sudan are almost completely dependent on Nile water for irrigated agriculture. Total irrigated area of the basin is estimated to range from 4.9 million to 6.4 million ha (Table 2-2).

Table 2-2: Currently irrigated area (1000 ha) in the Eastern Nile from different sources

	Irrigated (1000 ha)		
Country	FAO (2010)	Awlachew et al. (2012)	Bastiaanssen and perry, 2009
Egypt	5117	3324	2963
Sudan	1207	2176	1749
Ethiopia	15	16	91
Total	6339	5516	4803

2.4.1. Irrigation Schemes in Egypt

In Egypt, total agricultural area in the Nile Valley and Delta exceeds 3 million ha; double cropping means that over 5 million ha are planted annually (Table 2-2). Water is provided by the HAD and seven barrages diverting water into an extensive network of canals (32000 km of canals) with complementary drainage systems. Availability of water for agriculture in Egypt is determined predominantly by the volumes arriving at, and released from, the AHD. FAO (2005) estimated total withdrawals in Egypt as 68.3 BCM/year, with 59 BCM diverted to agriculture. A later study by FAO (2010) estimated annual water use for irrigation in the Nile Basin in Egypt at 65.6 BCM. Blackmore and Whittington (2008) report Egypt's current total water use as 55.5 BCM based on government estimates. A much lower agricultural demand of around 43.2 BCM is estimated by Awlachew et al. (2012). In addition, at least 6-8 BCM of flow from the delta to the Mediterranean are needed to mitigate saline intrusion and preserve the salt balance of the Nile Delta (El-Arabawy, 2002).

Different sources reported different estimation of the discharge from the Nile to the Mediterranean. The outflow is about 28 BCM (Bonsor et al., 2010; Karimi et al., 2012; McCartney et al., 2012). Hamza (2009) estimated that total annual releases are as low as 2-4 BCM; similarly, El Shabraway (2009) reports that annual outflows decreased from about 32 BCM before construction of AHD to 4.5 BCM after. The uncertainty surrounding estimates of total water use within Egypt thus remains very high.

Water productivity in the Nile Basin, and found that overall productivity in irrigated systems in Egypt is high, with intensive irrigation, high yields and high-value crops (Karimi et al. 2012). Bastiaanssen and Perry (2009) point out that there is great variability in productivity between different irrigation districts, with some functioning very poorly, but some of the systems in the Delta ranking among the best in the world

2.4.2. Irrigation Schemes in Sudan

In Sudan, irrigation schemes totaling around 1.5 million ha have been developed on the White Nile (0.08 million ha), New Halfa (0.16 million ha) and on the Blue Nile (1.25 million ha). There is low productivity in Sudan's irrigation areas is attributed to a range of factors including poor farming practices, problems with water delivery resulting from siltation of reservoirs and lack of flexibility due to the requirements of releases for hydropower, poor condition of canals, drainage problem, salinization and an unfavorably hot climate (Bastiaanssen and Perry, 2009).

The Rahad scheme which is 122000 ha and intended to use water from Roseires Dam in 1960 is plagued by siltation and irrigation inefficiency, and yields have been below average (Wallach, 2004). The Khashim el Girba Dam built for the New Halfa scheme silted too quickly and was poorly planned (El Arifi, 1988). In the 1990s Sudan had a 2 million ha modern irrigation system developed in a fertile valley south of Khartoum between the Blue and White Niles. Generally, yields are poor, partly due to government policies, poor canal maintenance, and lack of irrigation water and inefficient use of water (Molden et al., 2011).

Reported irrigated area ranges from 1.2 million to 2.5 million ha (Table 2-4); Availability of water for agriculture in the Nile Basin depending on assumptions made about per hectare application rates, channel losses and return flows, total demand exceeds 12.5 BCM and could be as high as 22 BCM/year (Table 2-4). Water shortages do occur in both Gezira and New Halfa, but these are due to inadequate seasonal storage and siltation of reservoirs (Bastiaanssen and Perry, 2009). Since 2009, there have been additional evaporative losses from Merowe Dam, estimated at 2.1 BCM annually (Blackmore and Whittington, 2008); and the current expansion of Roseires Dam will also result in increased evaporative losses (DIU, 2011).

2.4.3. Current and Future Irrigation Schemes in Ethiopia

In Ethiopia current demand is minimal compared with available resources. Ethiopia has about 3.7 million ha that can be developed for irrigation; about half of this is in the Nile Basin, but only 5-6 per cent has been developed so far (Arseno and Tamrat, 2005) (Awulachew et al., 2007, 2009). The current irrigated area is about 250000 ha, with less than 20000 ha in the Nile Basin; most of the current agricultural production is rain-fed.

The water potential of the country was not accurately known until recently. Possible Ethiopian irrigation projects have been investigated over a number of years (Lahmeyer, 1962; USBR, 1964; JICA, 1977 and 1997; EVDSA, 1991; WAPCOS, 1990; BCEOM, 1998) and the total potential irrigated area is estimated to be 815581 ha comprising 45.856 ha of small-scale, 130,395 ha of medium-scale and 639330 ha of large-scale schemes. Of this, 461000 ha are envisaged to be developed in the long term (BCEOM, 1998). In the 1960s and 1970s, comprehensive reconnaissance and feasibility studies were carried out on the Abbay (Blue Nile). Extensive studies were undertaken for the water resource potential of the Abbay River basin by Lahmeyer in 1962 and USBR in 1964.

In the late 1980s, an Indian firm, WAPCOs, prepared a preliminary master plan for water development for the whole country (WAPCOS 1990). On a smaller scale, pre-feasibility and reconnaissance studies of watersheds and subsidiary river valleys have been undertaken at the initiative of WRDA and EVSDA in the 1980s. These include the Birr, Koga and, Gilgel Abbay, There have been different estimates of the irrigation potential of the country. According to Awlachew et al. (2012), one of the earliest estimations was made by the World Bank in 1973, which suggested a figure of between 1.0 and 1.5 million hectares; Ministry of Agriculture in 1986, the total irrigable land in the country measures 2.3 million hectares; and the International Fund for Agricultural Development (IFAD) in 1987 gave a figure of 2.8 m.

The Indian engineering firm Water and Power Consulting Services' 3.5 m ha is the highest estimate so. Most of these figures are derived by adding up the irrigation potential of the country's eight river basins. Currently envisaged irrigation projects will cover a total of more than 174000 ha, which represents 21% of the 815581 ha of potential irrigation estimated in the basin (BCEOM, 1998). Currently, the MoWR (Ministry of Water Resources) has identified 560 irrigation potential sites on the major river basins. The total potential irrigable land in Ethiopia is estimated to be around 3.7 million hectares.

Table 2-3: Ethiopian irrigation potential (hectares) from different sources

River	ENTRO	WAPCOS (1995)	MoWE (recent master plan)
Abbay	978000	1001000	815581
Tekeze	313000	31700	83350
Baro-Akobo	749000	98500	1019523
Total	2040000	1131200	1918454

Data and information are not uniformly available to accurately know the existing irrigation schemes. While it is possible to capture the medium and large schemes data accurately, it is difficult to account for the small-scale irrigation development, particularly, the traditional irrigation development and the privately developed household-based irrigation schemes which use traditional diversions, water harvesting and ground water development.

There is very little irrigation in the Ethiopian Blue Nile catchment. Currently the only major irrigation scheme in the Ethiopian part of the catchment is the Finchaa sugar cane plantation and Koga irrigation project. In addition to the above, however, recent development in Ethiopia through Tana-Beles intra basin transfer enables generation of 460MW power production and potential of development of irrigation of about 40,000ha in the Beles Basin. Furthermore, additional small dam projects around Lake Tana expected to improve the profile of development of irrigation access of water in the basin.

2.4.4. Future Irrigation Development of Eastern Nile

All Nile countries have ambitious proposals to expand irrigated agriculture to meet growing food demands and boost economic development. Based on national planning documents (Awlachew et al 2012), the overall increase will be more than 10 million ha in the Nile Basin, doubling from current levels of around 5 million ha.

The question is whether such plans are feasible, Availability of water for agriculture in the Nile Basin where the limits to development lie in terms of the balance between demand and availability of water for irrigation in the basin, and at what stage withdrawals by upstream countries will impact upon Egypt. The upper basin proposed irrigation development would change patterns of water availability in the Eastern Nile (Blackmore and Whittington, 2008; McCartney et al., 2010; Awlachew et al. 2012; McCartney et al., 2012).

The potential for irrigation in the EN region based on identified national projects is estimated to be around 7.3 to 9.9 million ha (Table 2-4 below) and currently (2014) around 4.7 to 5.5 million ha which highlight the challenge and constraint of water availability due to established water uses.

Table 2-4: Eastern Nile irrigation development trajectories: irrigation area (1000 ha)

ENTRO spreadsheet				
Country		**Current**	**Medium-term development**	**Long-term development**
Egypt		3139	3302	3313
Sudan		1399	1939	2517
Ethiopia		140	1028	1392
South Sudan		0	13	118
Total		4678	6282	7340
Ahmed Famy (2010)				
Egypt		3078	-	4420
Sudan		1935.2	-	2750
Ethiopia		23.16	-	2220
Total		5036.26	-	9390
McCartney et al., 2012 (only Blue Nile)				
Egypt		-	-	-
Sudan		1305	2126	2190
Ethiopia		10	210	461
South Sudan		-	-	-
Total		-	-	-
Awlachew et al., 2012				
Egypt		**3324**	**3765**	**4205**
	Nile valley	3324	3521	3718
	El-salam	0	130	260
	Toshoka	0	113	227
Sudan		**2176**	**3575**	**4503**
	Blue Nile	1305	2126	2194
	White Nile	349	587	796
	Tekeze Atbara	391	412	732
	Main Nile	131	450	781
Ethiopia		**16**	**344**	**1216**
	Blue Nile	16	217	490
	Baro-Akobo	0	72	537
	Tekeze Atbara	0	55	186
T0tal		5516	7684	9924

2.5. Climate Change and Variability in the Nile Basin

This section concerns fluctuations in rainfall and river flows in the Nile basin since the beginning of modern gauge measurements of river flows began. The source areas for the Nile are the humid highlands of East Africa and Ethiopia, Neither region experiences particularly high inter-annual rainfall variability, however, marked fluctuations in rainfall have occurred over decadal timescales with significant consequences for Nile flows. As it is possible to explain most of the variability in Nile flows by considering the Blue Nile (Ethiopian highlands) and Lake Victoria (East Africa, main component of the White Nile system) this section reviews and presents a hydro climatic analysis of both regions and their integrated effects on the overall flows of the Nile.

Climate change will hit Africa worst, according to Waako et al. (2009), who states that climate change is now becoming a key driver in considerations over food and energy security in the Nile. Models have been developed to prepare for climate change, but there are different results and inconclusive (Conway and Hulme, 1993, 1996; Conway 2005; Kim et al. 2008; Beyene et al. 2009; Kizza et al. 2010; Taye et al. 2010).

Climate fluctuations dramatically change the structure and the regime of the Nile River (Mohamed et al. 2009). A number of papers have looked at the implications in Nile flows for water resources in Egypt, particularly since a prolonged period of low flows during the 1970s and 1980s. Abu-Zied and Biswas (1991) and Conway and Hulme (1993) considered the implications of climate fluctuations for water management with emphasis on the Nile. They stressed the uncertainties involved in predicting future climate change and that existing planning processes and hydrologic methodologies need to be improved to deal with such challenges. They also emphasized the importance of fluctuations in river flow over the historical period for managing water resources.

Hulme (1990) reviewed the factors affecting precipitation over the Nile basin at different temporal and spatial scales. He presented future changes in temperature and precipitation. Conway and Hulme (1996) used hydrologic models of the Blue Nile and Lake Victoria to assess the magnitude of potential impacts of future climate change on Nile flows. The impacts were largely dependent on the wide range of inter-model differences in future climate, particularly associated with the direction and magnitude of rainfall change.

According to Nicol (2003) and Anon (1994) the north–south orientation of the River Nile on the African continent ensures extreme variability in climate between the extremes of the basin. The Nile Basin receives annually an average rainfall of about 650 mm, or a total of about 1,900 BCMs per year. Long-term mean annual flow at Aswan is about 85 BCM per year, making the annual runoff coefficient of the basin around 4.5 percent which is considered to be small. The reason for this is found largely in those parts of the basin belonging to the arid and hyper-arid zones that are large in surface area, and contribute only negligibly to basin runoff. With losses from major swamp areas as well, up to 30 percent of the rainfall the Nile Basin receives in an average year is lost before being used for any purpose.

Sayed (2004) recognized that there is an increase in the temperature rates over the eastern Nile during the last 20 years. The results predicted a warming of about 3.5° C spreading uniformly over the seasons, with most of the Mediterranean basin showing an increase in precipitation in winter and increase of rainfall over the eastern Nile basin (Sayed, 2004). Recent and predicted future precipitation changes over the Nile basin, and monitoring of the upper White Nile catchment, upper Blue Nile catchment, and Middle Nile Basin from 1880 to 1989 showed declination in the total precipitation, however; it was recognized that there is an increase in the precipitation over the Eastern Nile (Sayed, 2004). The short period of flood months (5 months from June-October) makes the Nile basin vulnerable to floods and droughts as well. So, within the Nile basin, climate change can be seen as a threat or as an opportunity. He also recognized the temperature increase over the Eastern Nile and at the same time the increase of the overall runoff of the Nile. This increase can be attributed to the increase of precipitation rates that is accompanied by severe watershed degradation that leads to the increase of the net runoff.

The water resources of the Lake Tana catchment are highly vulnerable to changes in rainfall and temperature. In a study of possible impacts of climate change on the hydrology of the Gilgel Abbay River, it was estimated that by 2080 mean annual runoff into the lake could be reduced by approximately 3% with much greater reduction in some years (Shaka, 2008). It is also probable that climate change will affect the temporal distribution of runoff (Deksyos and Abebe, 2006; Shaka, 2008) and this could also affect both water availability and irrigation demand.

Global circulation models (GCM) for 1861 - 1988 show an overall warming of 0.5° C for this period, this increase have been verified by observed data from 1990 to 2004 (Sayed, 2004). Conway (2005) has shown that for the Blue Nile basin, a slightly increasing trend in rainfall was observed between 1905-1965, followed by a prolonged decline reaching its minimum in 1984, and then recovering significantly during the 1990s.

A similar finding was reported by Funk et al. (2005), who examined rainfall patterns in Ethiopia since 1960 for June-September. Funk et al. (2005) also noted that the months of March-May had experienced a sharp decline in rainfall over Ethiopia since 1960. They argued that this was most likely because positive temperature anomalies in the southwestern Indian Ocean may have increased oceanic precipitation and reduced rainfall over eastern Africa.

According to Elshamy et al. (2009), Downscaled precipitation and potential (PET) scenarios for the 2081– 2098 period were constructed for the upper Blue Nile basin to drive a fine-scale hydrological model of the Nile Basin to assess their impacts on the flows of the upper Blue Nile at Diem. For no change in rainfall, increasing PET thus leads to a reduced wet season runoff coefficient. The ensemble mean runoff coefficient (about 20% for baseline simulations) is reduced by about 3.5%. Assuming no change or moderate changes in rainfall, the simulations presented here indicate that the water balance of the upper Blue Nile basin may become more moisture constrained in the future. White and the Blue Nile behave quite differently to climatic change scenarios (Singh, 1995).

In recent decades a noticeable decrease of rainfall has been recorded at Ethiopia highlands, which almost provides about 80% of the Nile waters (Howell and Allen, 1994). Temperature, on the other hand is likely to increase and as a consequence overall evaporation is likely to increase as well because of this IPCC (2001) estimates that the net change of runoff in the Nile Basin will be zero. Strzepek et al. (2001) on the other hand, presents different scenarios. Eight of them predict a lower Nile flow (at Aswan) until 2100; two even predict a reduction of over 75 %.

Strzepek et al. (1996) used a spatially aggregated monthly water balance model to explore the sensitivity of Nile flows to climate change. They argue that the Nile flow is extremely sensitive to ambient temperature and precipitation changes, and it is possible that the effects of climatic fluctuations would be severe. They found that there was divergence between climate model results for the Nile basin; from a sample of four models two produced increases and two produced decreases in flows, with one producing a decrease of over 70% of annual flow.

Yates and Strzepek (1998) found that five out of six climate models with a doubling of CO_2 produced an increase in Nile flows at Aswan, with only one showing a small decrease (-15%). Strzepek et al. (2001) use a purpose designed software system to produce a sample population of climate change scenarios for the basin that incorporate uncertainties due to differences between climate models, a range of climate sensitivity estimates, emission pathways. They selected nine representative scenarios from the full range which were translated into future Nile flow scenarios using a suite of water balance models. The results showed a propensity for lower Nile flows (in eight out of nine scenarios).

Eman et al. (2008) said that in general the RegCM3 can efficiently simulate the climatology of the Blue Nile, reproduce the spatial and temporal pattern of temperature, the seasonality and spatial pattern of precipitation, and provide inputs to the NFS model which accurately predicts stream-flow observed at Diem. For the Sobat basin, it was apparent that the model requires some adjustment and additional investigations.

Moges and Bimrew (2009) reported the impacts of climate change and variability on the water availability changes for hypothetical scenarios of precipitation and evapotranspiration changes of Blue Nile catchments. They consider 10 out of the major 16 catchments, which are considered to have good data sets, and hypothetical climate change scenarios varying from -30 to +30 for both rainfall and PET for the analysis. The sensitivity of the impacts on water availability was tested using HBV hydrological model.

They found that Chacha in lowland part (west) and Sechi in the highland part of Blue Nile (east) were found most sensitive catchments. All catchments in the north and center are relatively less sensitive. They concluded that catchments contributing to the left bank and lower side of the main river appear to be more vulnerable than all catchments joining the main river to the right bank and upper side of main river.

According to Mohamed et al. (2005), the Global Precipitation Climatology Center (GPCC), providing monthly rainfall data at 1^0 resolutions, interpolated from conventional gauged observations. The model accurately captures seasonality of the rains over the 4 sub-basins. On the White Nile the model underestimates the rain during the period from March to June. The RMSE of precipitation for the 4 sub-basins: Nile, Atbara, White Nile and Blue Nile are 0.47, 0.52, 0.65 and 0.95 mm/day, respectively.

2.6. Conclusions

Numerous hydrologic and water resource models have been developed to assess hydropower and agricultural irrigation potential within the Nile River basin. However, they often fail to adequately address critical aspects, including impounding stages of large-scale reservoirs with recent information, relevant flow retention policies and associated downstream ramifications, and the implications of stochastic modeling of variable climate and climate change. Nile River basin is a complex river basin hosting countries with myriads of socio-economic challenges of which the main challenges are poverty and uneven water use, contentious issues in the past Nile treaties which weaken effective communication and information exchange between the riparian countries. The basin is also characterized with recurrent history of flooding, drought, sedimentation and water quality, and salt intrusion from Mediterranean Sea. Many researchers highlighted the importance of cooperation and communication in the Nile basin. The water demand riparian countries are gradually increasing and there is obvious sign of conflict. Especially the construction of ongoing GERD dam in Ethiopia has intensified the conflict. This study evaluates current and future water resources development scenarios in the Eastern Nile with the view of to provide comprehensive analysis for planned projects in the basin. As shown in section2.3.2, various water resources simulation models were investigated and Mike Basin River Basin model was found suitable for this study.

Chapter Three

Description of Eastern Nile Basin and the Data

3.1. Description of Eastern Nile

3.1.1. Location

The Nile River, with an estimated length of over 6,800 km, is the longest river flowing from south to north over 35 degrees of latitude. The basin extends from 4^0S to 32^0 N, stretching over different geographical, climatologic and topographical regions (Mohamed et al. 2005).The river originates from two distinct geographical zones, the basins of the White and Blue Niles. The source of the White Nile is in the Great or Equatorial Lakes Region, and is also fed by the Bahr-el-Jebel water system to the north and east of the Nile-Congo Rivers divide. The Blue Nile originates in the highlands of Ethiopia, as do the other major tributaries of the Nile, the Atbara and the Sobat. About 85% of the Nile's waters originate in Ethiopia, while the majority of the river's water is used in the Sudan and Egypt.

The Nile Basin includes two main sub-basins: the Eastern Nile sub-basin (Egypt, Ethiopia, Eritrea, the Sudan and South Sudan) and the Equatorial Lake sub-basin (Burundi, the Democratic Republic of Congo, Kenya, Rwanda, South Sudan, Tanzania and Uganda). The total area of the Nile basin represents 10.3% of the area of the continent or an area greater than 3349000 km^2 and spreads over eleven countries.

The Eastern Nile Basin lies between latitudes 7º N and 31º N and covers an area of 1809606 km^2 of which Egypt contributes 4%, Ethiopia 22% the South Sudan 13% and Sudan 61%. A very small part of Eritrea is also included in the Nile system. The location of the Eastern Nile Basin (ENB) is shown in Figure 3.1.

3.1.2. Topography

Elevation of the ENB ranges from 0 m.a.s.l to around 4300 m.a.s.l. About 5% area of the basin is very low lying areas, most of the area (around 70%) falls in the ranges of 300-600 m.a.s.l. Another 20 % is between 600-2000 m.a.s.l and the remaining 5% is with very steep slope (2000-4300 m.a.s.l).

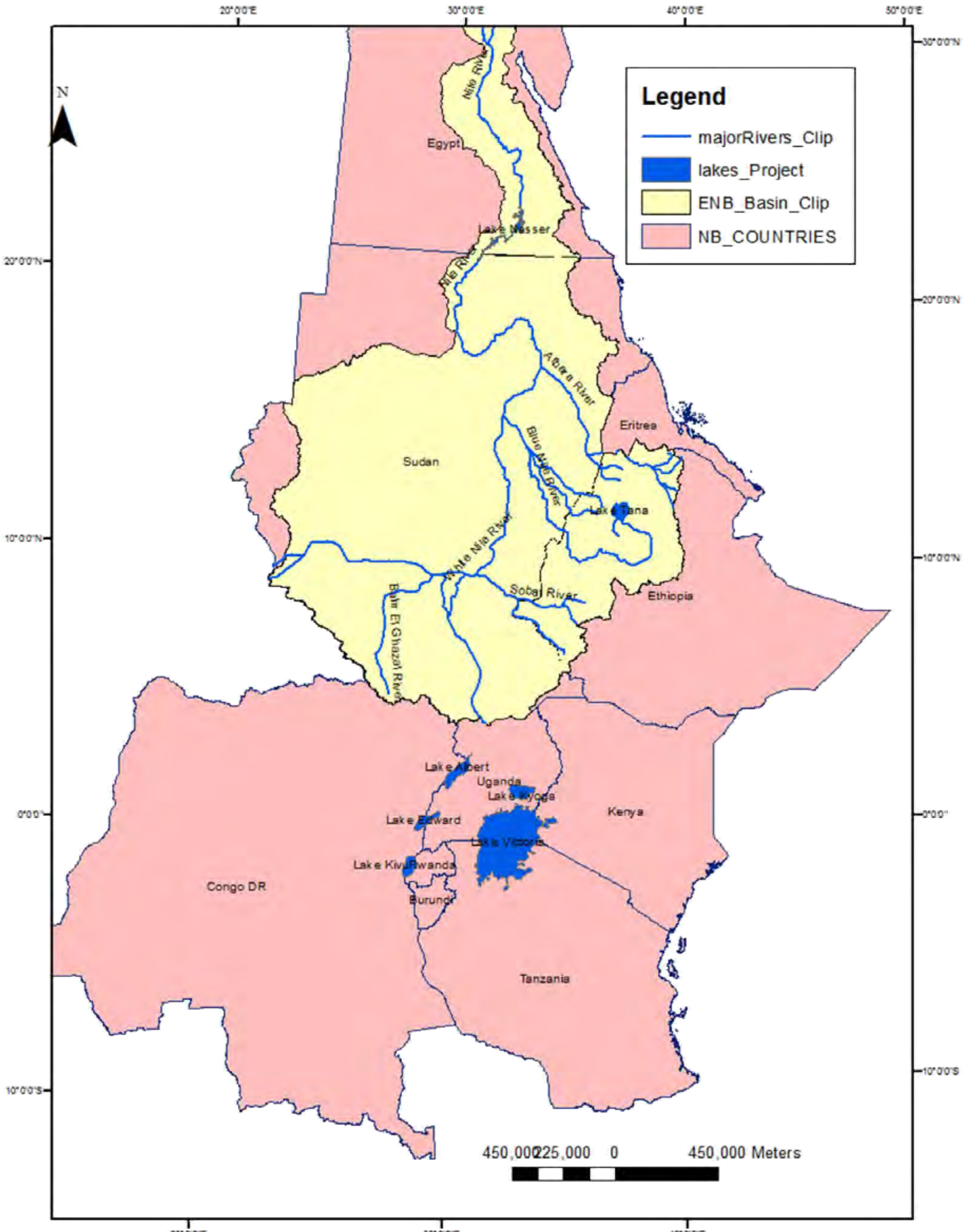

Figure 3-1: Location map of the Eastern Nile

3.1.3. Climate

The climate and vegetation cover in the Nile basin are highly related to the amount of precipitation. Precipitation increases southward and with altitude. The common area with average high precipitation of about 1200-1600mm/years is on the highlands of Ethiopia and the Equatorial lakes plateaus. The potential Evaporation over the basin increases as one move downstream which show opposite trend to the precipitation (Mohamed, 2013).

The average rainfall over the basin is 615 mm adding up to around 1845 km^3. The Runoff at Dongola, the last discharge station before the Nile enters Lake Nasser is around 83 km^3. This means that the total runoff coefficient for the basin is 0.045. This is quite low compared to other basins (Rhine: 0.41) or to the global average of 0.35 (Dai and Tenberth, 2002). The precipitation amount varies greatly during the year and inter-annually. The records between 1830 and 1980 show, precipitation in the upper Nile basin was significantly lower during El Niño years and higher in La Niña years (Whetton and Rutherford, 1994).

3.2. Sub-basins of Eastern Nile Basin and River Networks

The Nile is a major north-flowing river in north-eastern Africa, generally regarded as the longest river in the world. The ENB is divided into four sub-basins that include the Main Nile, the Baro-Akobo-Sobat- White Nile, the Abbay-Blue Nile, and the Tekeze-Atbara-Setite. The location map of the ENB including the four sub-basins is shown in Figure 3-2.

The Main Nile is the largest sub-basin of the ENB covering 44% of its total area while the Tekeze-Atbara-Setite is the smallest sub-basin covering 13% of the area. Among the sub-basins the Abbay-Blue Nile and the Main Nile are the most heavily populated accounting for 82% of the ENB population. The Baro-Akobo-Sobat-White Nile sub-basin and the Tekeze-Atbara-Setite have 8% and 10% of the ENB population respectively (ENTRO, 2006a).

The major rivers of the Nile River Basin are the Main Nile, the Blue Nile, the Atbara, the White Nile, Rahad, Dindir, Sobat, the Akobo and the Baro, which are shown in Figure 3-1. The length and the slope of all major rivers in the ENB are given in Table 3.1. The longest river is the Main Nile (3006 km) and the Akobo River has the highest slope (6.695 m/km). Among the major rivers, the smallest is the Baro River (280 km) and the White Nile River has the flattest slope (0.011 m/km).

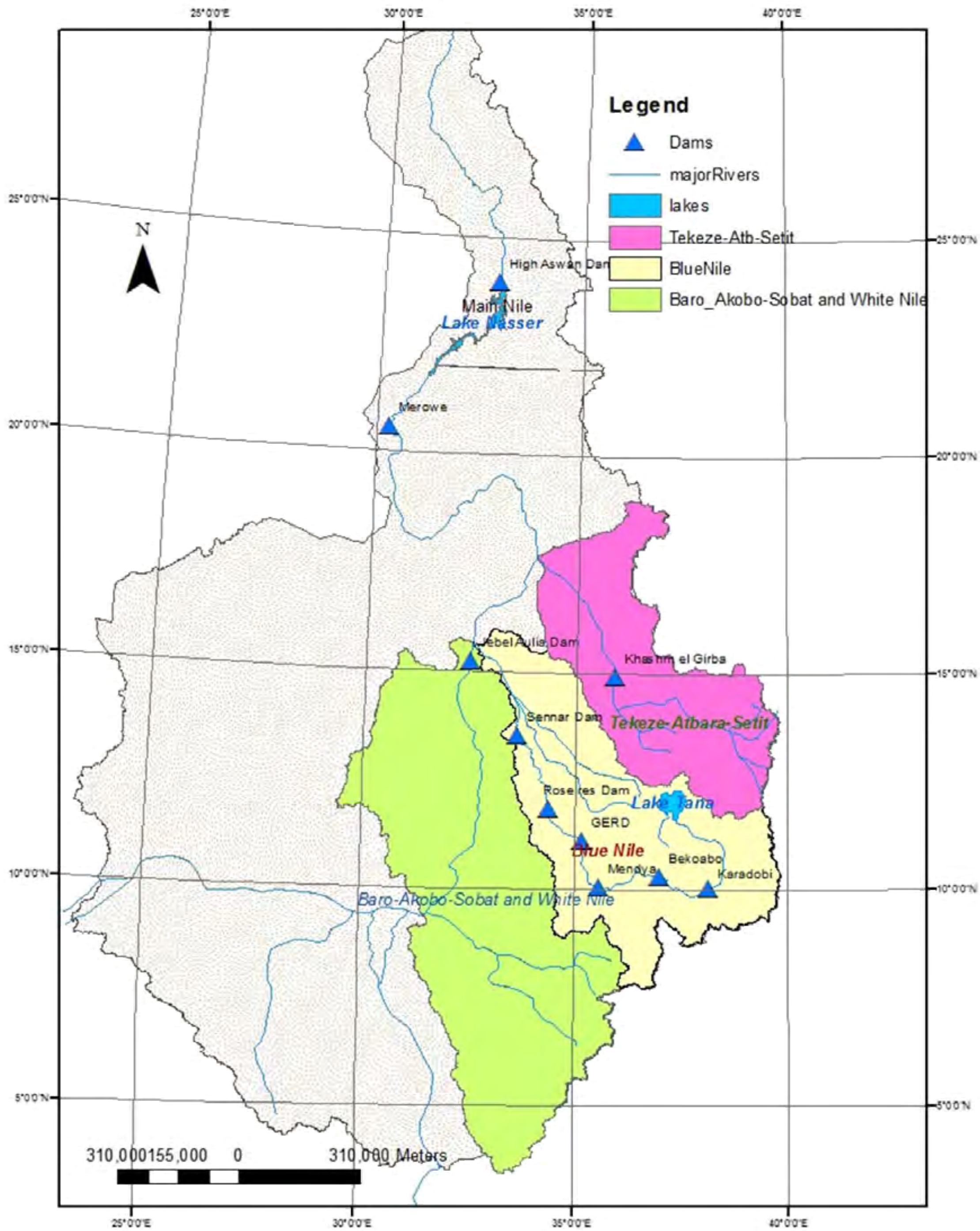

Figure 3-2: Eastern Nile sub-Basin with main sub basins and Reservoirs in the main river

The Akobo and the Baro are two rivers in the upper part of ENB. The Baro Originates at an elevation of 2200 m and the Akobo at an elevation of 1,000 m. These two rivers meet the Sobat River which joins the White Nile. The Blue Nile originates at Lake Tana at an elevation of 1800 m which meets the White Nile at Khartoum at an elevation of about 350 m and commonly regarded as Main Nile. Finally it falls in the Mediterranean Sea. In the Main Nile the High Aswan Dam is one of the major interventions where river elevation falls about 100 m.

Table 3-1: Major river reaches, their length and slope River reach name Length (km) Slope (m/km)

River Reach Name	Rahid	Dinder	Blue Nile	Baro	Akobo	Sobat	White Nile (ENB part)	Atbara	Main Nile
Length (km)	646	702	1708	280	348	338	447	683	3006
Slope (m/km)	0.283	0.412	0.751	3.29	6.695	0.032	0.011	1.013	0.135

3.2.1. The Blue Nile Sub-Basin

3.2.1.1. Location and Topography

The Blue Nile sub-basin, located in the middle east of the ENB, is the largest contributor of the system (56BCM/year) accounting for 67% of the inflow at Aswan (ENTRO, 2006a; Awulachew *et al*., 2008). The Blue Nile headwaters emanate at the outlet of Lake Tana in the Ethiopian highlands. Geographically, the Abbay-Blue Nile sub-basin extends from 32^0 27' east to $39^0$50' east and from 16^0 5' north to 7^0 40' north (the location map is given in Figure 3.2).

The Blue Nile sub-basin covers two countries: Ethiopia and the Sudan. It stretches nearly 850 kilometers between Lake Tana and the Sudano- Ethiopian border, with a fall of 1300 meters; the grades are steeper in the plateau region, and flatter along the low lands. It is joined by many important tributaries, draining the central and southwestern Ethiopian highlands before it reaches the lowlands and crosses into Sudan. The total area of the sub-basin is 311382 km^2 of which Ethiopia comprises about 64% and the Sudan comprises the remaining 36% (ENTRO, 2006a).

The mountainous topography largely located in the Ethiopian highlands lies in its eastern portion and the flat low-lying areas of the sub basin starting close to the Ethio-Sudan border and extending westwards into the Sudanese land to Khartoum from the mouth of the sub basin. The low-lying areas have an altitude that ranges from 500 m.a.s.l around the border to 340 m.a.s.l around Khartoum (ENTRO, 2006a).

The elevation of the Blue Nile sub-basin ranges from 369 m.a.s.l to 4035 m.a.s.l. About 35% of the land is below 500 m.a.s.l which is mainly swamp and wetland area. 62% of the sub-basin falls from 500 to 3000 m.a.s.l and some 3% of area falls at an elevation that ranges from 3000 to 4035 m.a.s.l.

3.2.1.2. River System, Drainage and Catchment

The Abbay River is flows out of Lake Tana at Bahir Dar, and spirals first south, then west, and finally north-west into the Sudan. In contrast to the more steady White Nile, considerable seasonal flow variations characterize the Abbay/Blue Nile - ranging from 302 million m^3/month in February to a peak of 13151 million m^3/month in August (annual peak flow occurs in July-October) (ENTRO, 2006a).

The Abbay, with the channel length of 922 km, falls 1295 meters to the Sudan border (490 m.a.s.l), beginning with the spectacular Tisa Falls in Lake Tana (1785 m.a.s.l). There is a 10-fold increase in discharge between Lake Tana and the Sudan border (ENTRO, 2006a). In the Ethiopian part, the Abbay is subdivided into 16 major watersheds: Dedesa, South Gojjam, Guder, Anger, Lake Tana, North Gojjam, Dabus, Beshilo, Fincha, Mugger, Jemma, Welaka, Wombera, Beles, and Rahad and Dinder at the border, constituting a total of 202884 km^2.

In the Sudan the Abbay is known as the Blue Nile which has three watersheds namely: the Blue Nile, the Rahad and the Dinder with an estimated area of 110663 km^2. A wide variety of effective runoff is generated by the watersheds. It varies from 276 mm (Dinder) to 651 mm (Dedesa sub-watershed). Considering the records of 1980 to 2000, the mean annual inflow at the Kessie is estimated at 17.6 Bm^3 that has a drainage area of 65784 km^2 which indicates an effective runoff of 265 mm generated by the watershed upstream of the Kessie station. Rainfall and effectiveness of rainfall decrease in the north direction.

3.2.1.3. Climate

The climate of the Blue Nile is dominated by two factors: its near-equatorial location and an altitude ranging from below 500 m.a.s.l at its mouth to more than 4000 m.a.s.l in the highland plateaus of Ethiopia. The influence of these factors determines the rich variety of local climates, ranging from hot and desert like along and downstream of the Sudan border, to temperate climates on the highland plateaus and cold climates on the mountain peaks. The climate in the Blue Nile River basin varies greatly between its inception in the highlands of Ethiopia and its confluence with the White Nile River.

The climate of the Blue Nile basin varies from humid to semi-arid. Most precipitation occurs in the wet (Kiremt) season (June through September), and the remaining precipitation occurs in the dry (Bega) season (October through January or February) and in the mild Belg season (February or March through May) (Block and Rajagopalan, 2006). Most of the highlands of Ethiopia, at elevations between 1500 and 3000 meters, are wet, lush and green, and have daily mean temperatures that fluctuate between 15°-18° Celsius. As the Blue Nile drops into the lowlands and into southern Sudan, rainfall decreases and evaporation increases, resulting in a significant net loss. Temperatures also increase in variability, and reach substantially higher levels than at Lake Tana. The Sennar region, located in the southeastern part of Sudan, experiences evaporation rates that total 2500 mm per year, yet only receives 500 mm of rain annually; mean daily temperatures approach 30° Celsius (Sutcliffe and Parks, 1999).

3.2.1.4. Hydrology and Water Balance

The mean annual flow at the Ethio-Sudan Border and the El-diem Dam is 48832 BCM and 47041 BCM respectively, indicating a loss of 1.79 BCM between the border and the Ed-diem station. Annually 7.96 BCM is abstracted from the Sennar reservoir for irrigation purposes while the Rahad-Dindar contributes 3.6 BCM and finally the annual mean flow of the Blue Nile at Khartoum becomes 42.68 BCM. The Blue Nile contributes 65% of the inflow to the Main Nile (ENTRO, 2006a). Blue Nile flow varies from less than 30 BCM to more than 70 BCM, according to Awulachew et al. (2007).

3.2.1.5. Lake Tana Basin

The headwaters of the Blue Nile are formed by the basins of the rivers draining to Lake Tana. In 1995-1996 the Chara Chara weir at the outlet of Lake Tana at Bahir Dar was put in operation for hydropower production (Tis-Abbay HPP I & II with 77 MW installed capacity). The weir controls a volume of 9.1 BCM in the lake (2.4 x average annual outflows) between the levels

1784 and 1788 m.a.s.l. Currently the weir is also used to divert water from the lake to the Tana-Beles system. At present in the Gilgel Abbay basin the Koga irrigation system exists, with a gross command area of 7000 ha.

Lake Tana is the main watershed of the Abbay-Blue Nile sub-basin and has an area of 15320 km^2. The lake is situated at an average altitude of 1800 m.a.s.l and fed by four major tributaries, Gilgel Abbay, Rib, Gumara and Magic. The long term (1964- 2003) average lake water level is estimated at 1786.13 m.a.s.l (Figure 3-3). Mean annual rainfall over the watershed is estimated at 1100 mm. The annual inflow contributed by the Gilgel Abbay to the Lake Tana reservoir is averaged at 1.8 BCM, the Rib and the Gumara at 0.68 BCM and 0.83 BCM respectively, and the Megech at 0.45 BCM.

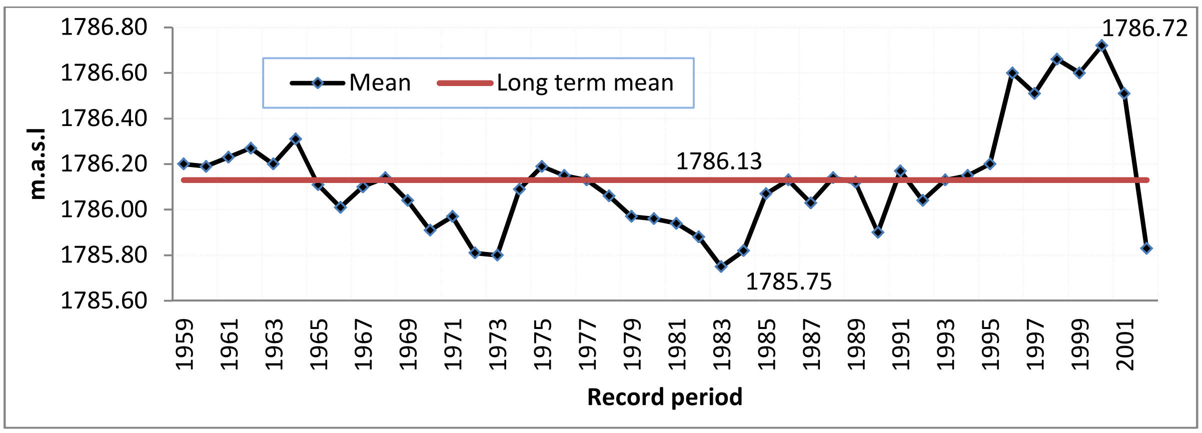

Figure 3-3: Lake level annual series at Lake Tana (1964-2003) (source: ENTRO Database)

Mean annual inflow to the Blue Nile system at the Lake outlet (Bahir Dar) is averaged at 3.8 BCM. Seasonal outflow distribution is presented in Figure 3-4 (collected from MoWE). The maximum flow occurred during September-October.

3.2.1.6. Abbay at Kessie

The gauging station is located at Millennium Bridge (220 km from Addis Ababa). Discharge was measured at Kessie started from 1953 to present. From 1980 to 2000, the average annual flow of the Blue Nile at the Kessie station was 16.98 BCM which was 4.25 times the flow of the Lake Tana outlet. The seasonal flow distribution at the Kessie station is shown in Figure 3-5 (collected from MoWE).

3.2.1.7. Blue Nile at Border

The seasonal distribution of flow collected from MoWE is presented in Figure 3-5. The time series shows an increase in flow in recent years. This trend is also observed at the Kessie station. Seasonal distribution of runoff indicates that there is minimum flow from January to May. The flow starts increasing from June and reaches its peak level during August.

3.2.1.8. Blue Nile at El-Deim

Long term (1980-2000) average annual flow of the Blue Nile River at El-Deim is 45.4 BCM and average monthly maximum flow is 14 BCM. The seasonal distribution of flow collected from ENTRO Spreadsheet is presented in Figure 3-5.

Like stations Kessie and Border, the time series shows an increase in flow in recent years. This trend is also observed at the Kessie station. Seasonal distribution of runoff indicates that the flow is low from January to May. The flow starts increasing from June and reaches its peak level during August

3.2.1.9. Blue Nile at Khartoum

Discharges measuring station for Blue Nile immediately upstream its junction with the White Nile. The flow at this station contains seasonal flow Dinder and Rahad which originated in the highlands of Ethiopia in addition to flow from Sennar. The monthly time series of 1980 to 2000 shows the average annual flow of the Blue Nile at Khartoum to be 39.6 BCM. The long-term inflow (1900 – 1995) has an average of 48.7 BCM, which is considered as a long-term mean annual flow of the Blue Nile at Khartoum (Sutcliffe and Parks, 1999).

The seasonal distribution of flow is shown in Figure 3-5 (from ENTRO Spreadsheet). Inflow at the Khartoum station for the periods of 1980 to 1985 is observed to be drier than the average. In recent years, an increasing trend is observed though not as highly pronounced as it is in the case of the Abbay at the Kessie and El-Deim stations.

3.2.1.10. The Rahid and Dinder Rivers

The Rahid and Dinder rivers originate from the north-western highlands of Ethiopia and join the main stem of the Blue Nile downstream of the Sennar Reservoir with mean annual inflow of 4.0 BCM. The seasonal distributions of the flows of these two rivers are shown in Figure 3-4. The runoff is concentrated in the wet period (June – Oct) with little flow coming in November and December. Almost no flow enters the Blue Nile in the months of January to May.

3.2.2. The Baro-Akobo-Sobat-White Nile Sub-basin

3.2.2.1. Location and Topography

Geographically, Baro-Akobo-Sobat-White Nile sub-basin it extends from 15^0 47' 40" to the north down to 3^0 25' 52" in the south. It extends from 29^0 24' 43" to the west up to 36^0 18' 27". The Baro-Akobo-Sobat-White Nile Sub-basin covers 468216 km^2 (84% of the area is in the Sudan and South Sudan and 16 % in Ethiopia) (ENTRO, 2006c). The location of the Baro-Akobo-Sobat-White Nile sub-basin is shown in Figure 3-2.

The altitude of this sub-basin ranges from above 3000 m.a.s.l in its eastern tip to 400 m.a.s.l at Khartoum, its mouth. More than 65% of the sub-basin falls below 500 m.a.s.l and some 25% falls at an altitude that ranges from 500 m.a.s.l to 1000 m.a.s.l. More than 88% of the sub-basin land is identified to have land slope of less than 5% indicating its tremendous potential for irrigated agriculture (ENTRO, 2006c).

3.2.2.2. River System, Drainage and Catchment

The main tributaries of the Sobat are the Baro, the Pibor and the Akobo that rise on the Ethiopian Plateau at some 3300 m.a.s.l. The Baro-Akobo-Sobat-White Nile sub-basin consists of nine major watersheds: the Pibor watershed, the Nuba Hills watershed, the Machar marshes, the North White Nile watershed, the Baro watershed, the East White Nile, the Akobo watershed, the South White Nile and the Sobat watershed which in total form a drainage area of 468216 km^2. The Baro, the Akobo (north eastern side of the watershed) and the Gillo all originate from the southwestern highland plateaus of Ethiopia and the Pibor together with the southern half of the Akobo watershed and the Machar wetland constitutes the major water system of the sub basin.

3.2.2.3. Climate

The Baro-Sobat-White Nile sub-basin within Ethiopia is well-watered. However, spatial variation of the mean annual rainfall is considerable due to the great range in elevation across the basin. Average annual precipitation ranges between 600 mm in the lowlands (less than 500 m.a.s.l) and 3000 mm in the highlands (over 2000 m.a.s.l). The highest rainfall occurs in June-September (ENTRO, 2006c). In the White Nile sub-basin rainfall decreases northwards from 750 to 250 mm near the junction of the White and Blue Nile. The temperature range is about 27.5^0C below 500 meters elevation on the floodplain to about 17.5^0C at 2500 meters in the highlands (ENTRO, 2006c).

Mean annual evaporation within this sub-basin is observed to vary from below 1000 mm in the highland plateaus of Ethiopia to 6815 mm at Khartoum. As a result, average evaporation loss at Jubil Aulia reservoir with a total storage capacity of 3.5 BCM is 2.12 BCM per year (ENTRO, 2006c).

3.2.2.4. Hydrology and Water Balance

The main tributary of the BaroAkobo-Sobat is Baro River. From year 1976 to 2000, the mean annual runoff of Baro at Gambella has been estimated at 12.41 BCM. The seasonal distribution of runoff of the Baro River at Gambella is shown in Figure 3-4. The hydrologic variability for the annual series is 12.8 % and for the seasonal series, it ranges from 46% (May) to 12% (August) (ENTRO 2009b).

The White Nile system starting from the Malakal station is formed from the Sobat River and the outflow of the Sudd. The mean annual runoff entering the White Nile system at Malakal is recorded to be 30.214 BCM (1980-2000). The runoff at Malakal starts peaking in June and recedes in January reaching its minimum in April (Figure 3-5).

This seasonal distribution is different as compared to the inflows coming from the Ethiopian highlands. This could be factored due to the presence of the floodplain/wetlands upstream of the Sobat confluence, such as Machar and the vast seasonally flooded low land plains from the eastern watershed side and the presence of the Sude floodplain/wetland u/s of Malakal from the basins in the southern direction. These floodplains have a considerable routing effect on the inflows and could widen the base of the inflow hydrograph, which has resulted in delays for peaks and a relatively smooth and mild slope in the rising limp of the hydrograph. The mean annual inflow from the Sude to the White Nile at Malakal has been estimated as 16.82 BCM and together with the Sobat system it is estimated to produce a mean annual inflow of 30.50 BCM to the WN system. The White Nile system contributes about 30% of the Nile flow at Aswan (ENTRO 2009b).

3.2.3. The Tekeze-Atbara-Setite Sub-basin

3.2.3.1. Location and Topography

The Tekeze-Atbara-Setite sub-basin, located at the most north-eastern portion of the ENB, covers an area of 227128 km^2. Sixty percent of the sub basin falls in the Sudan and 40 % falls in Ethiopia (ENTRO, 2006d).

Elevation of the Tekeze-Atbara-Setite sub-basin ranges from 347 m.a.s.l to 4262 m.a.s.l. Forty percent area of the Tekeze-Atbara-Setite sub-basin has almost flat slope ranges from 350-500 m.a.s.l, 27% of area falls at an elevation ranges from 500-1000 m.a.s.l, 30% of the basin falls in the range of 1000-2200 m.a.s.l and the remaining 3% is with very steep slope ranges from 2200-4300 m.a.s.l.

3.2.3.2. River System, Drainage and Catchment

The length of the Atbara and Tekeze rivers are 683 km and 668 km respectively. The Tekeze-Atbara-Setite sub-basin has three major tributaries namely, the Tekeze called “Setite” in the Sudan, the Angereb, and the Goang called “Atbara” in the Sudan. All three tributaries originated from the central north and north western highland plateaus of Ethiopia.

3.2.3.3. Climate

The climate in the Tekeze-Atbara-Setite sub-basin is the tropical type with the wettest season limited to less than three months (June/July to August/ September). Hydrological variability is significant and highly seasonal. Seasonal distribution is more erratic and variable affecting agricultural production significantly. The upper course of the Tekeze- Atbara-Setite watershed is identified as one of the most drought prone areas in Ethiopia (ENTRO, 2006d).

The spatial distribution of temperature values is strongly related to altitude. The area located in the highlands of Ethiopia is characterized by lowest minimum mean monthly temperatures that range between 3^0C and 21^0C that occur between December and February.

3.2.3.4. Hydrology and Water Balance

The Atbara River contributes 12.7 % of the total discharge of the Main Nile. The average discharge at the Kashm El Girba station (1986-2000) has been found to be 11.45 km^3. Most of the Tekeze-Atbara-Setite water comes from Ethiopia, even though 50% of the sub basin is located in the Sudan. Rainfall in the sub-basin ranges from about 2120 mm/year in the highlands of Ethiopia to less than 50 mm/year at the junction with the Main Nile at the Atbara. The Tekeze-Atbara-Setite sub-basin, with mean annual inflow of 12 BCM at the Atbara, is the least contributor in the ENB system. The upstream reach of the sub-basin (the Ethiopian highland watershed portion) contributes 80% of the sub-basin inflow at the Atbara. The seasonal distribution of Atbara wade and Kubre are shown in Figure 3-4.

3.2.4. The Main Nile sub-basin

3.2.4.1. Location and Topography

The Main Nile sub-basin covers 656398 km^2 (89% is in the Sudan and 11 % in Egypt) from the confluence of the Blue and White Niles in Khartoum to the delta in Egypt in the north (ENTRO, 2006b). Geographically, it extends from 30^0 30'35" to the north down to $13^0$7' 20" in the south (ENTRO, 2006b).

3.2.4.2. River System, Drainage and Catchment

The length of the Main Nile River is 3006 km. The Main Nile sub-basin in the ENB system starts at Khartoum right after the confluence of the White Nile and Blue Nile systems/sub-basins. From Khartoum the Main Nile flows in a general northward direction before it meets its first tributary, the Tekeze-Atbara-Setite sub basin, and then flows to the general north-west direction to the Mediterranean Sea.

3.2.4.3. Climate

Mean annual rainfall at Khartoum is below 200 mm, reduced to less than 20 mm at Atbara, and almost less than 5 mm at Dongola and the Aswan High Dam. At Cairo it is 25mm and increases to 200 mm (Alexandria) in the coastal line of the Mediterranean Sea (ENTRO, 2006b). Temperature in this sub-basin is the hottest owing to the prevalence of 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). Evaporation is observed to be considerably high. The Main Nile is a losing system, with high transmission losses due to evaporation and channel infiltration (NWRC, 2007).

3.2.4.4. Hydrology and Water Balance

The inflow to the main Nile system at the Khartoum junction is estimated to be 74 BCM. At Atbara, some 300 km downstream of the Khartoum junction, the Atbara-Setite-Tekeze sub-basin contributes mean annual inflow of 12 BCM, which increases the inflow of the main Nile downstream of the Atbara confluence to be more than 84 BCM. The seasonal flow distribution of main Nile at Dongola is presented in Figure 3-5.

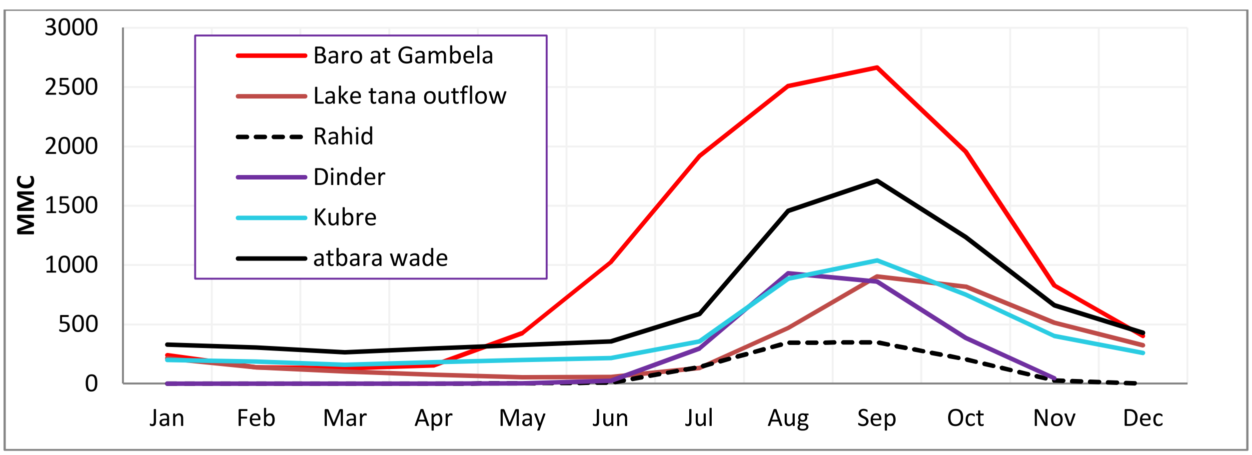

Figure 3-4: Seasonal distribution of some selected rivers in the Eastern Nile basin.

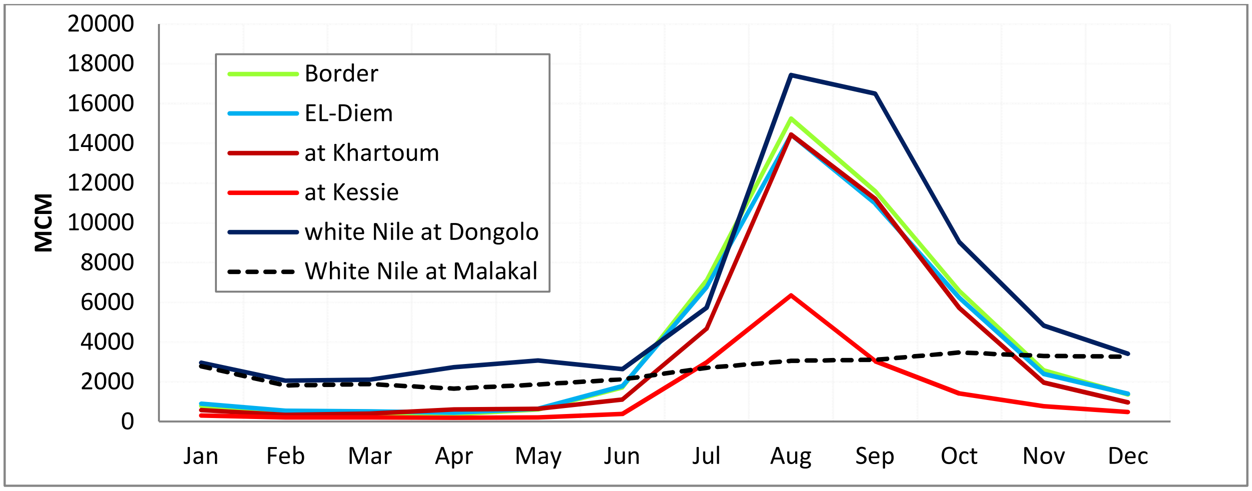

Figure 3-5: Seasonal distribution of Eastern Nile Basin at selected stations

3.3. The Data

3.3.1. Historical Stream Flows

Finding consistent set of discharge data in the Nile basin is more challenging because the published discharge data are limited and most observed data have short periods (Johnson and Curtis, 1994; Conway, 2000). Most of hydrometric stations in Abbay-Blue Nile river basin are located in small streams that may not represent the true characteristics of the sub-basins and have short recording periods with missing data (Conway, 2000; UNESCO, 2004).

According to WMO recommendations (BCECOM,1999),the number of stations are more than satisfactory ,i.e. 1 station should cover 1800 km^2, but most of the stations are not working properly, full of missed data and stopped functioning. The source of available hydrological data is from Ministry of Water and Energy (MoWE). In the study data from 50 stations were collected and analyzed. The data were checked for possible errors, inconsistencies and filled to generate a consistent set of input series for the modeling purpose.

3.3.1.1. Stream Flow Data Generating for Un-Gauged Area of Abbay River Basin

As it is found from Water Resource and Energy Minister of Ethiopian, Hydrometric discharge measuring stations within the Abbay river basin are 124 in number. Most of the stations were located in small streams that are not represent of the spatial characteristics of the hydrology of the Abbay-Blue Nile sub-basin. Apart from short recording periods with missing data, the qualities of the data of some stations were compromised. Therefore, 50 stations were selected for the further analysis of available water resource as well as modeling purpose. The first step in the analysis of the data was to generate concurrent set of monthly time series data for the 50 stations using transformation method as described below. The generated data was compared at selected stations with previous studies.

Transformation Method

It is assumed that similar catchments in the same area will produce a similar time series of flows. Consequently, if the flows and the relevant catchment characteristics are known for a gauged sub-catchment, then flows for an un-gauged sub-catchment with similar catchment characteristics may be determined.

There are several available methods for distributing flows from gauged to un-gauged sites, ranging from the very simple to the complex and laborious. On the simple side, the most widely used method is the distribution of flow in proportion to drainage area. In this case, the stream flow per unit area of watershed is assumed constant, and the naturalized flow at the un-gauged site is calculated as the naturalized flow at the gauged site multiplied by the ratio of un-gauged to gauged areas. On the other extreme, there are generalized computer models of watershed hydrology that are able to compute sequences of daily or monthly stream flows for a given precipitation unit.

To estimate monthly average runoff of the un-gauged river catchments from gauged river catchments the following equation can be used (Jamshid, 2003).

$$Q_{ungauged} = \left(\frac{A_{ungauged}}{A_{gauged}}\right) \times Q_{gauged} \times \frac{P_{ungauged}}{P_{gauged}} \qquad (1)$$

Where,

$Q_{un\text{-}gauged}$ = discharge at un-gauged site (m^3 /s)

$A_{un\text{-}gauged}$ = drainage area of un-gauged site (km^2)

$P_{un\text{-}gauged}$ = areal rainfall at the un-gauged site (mm)

Q_{gauged} = discharge at gauged site (m^3/s)

A_{gauged} = drainage area at gauged site (km^2)

P_{gauged} = areal rainfall at the gauged site (mm)

For gauged rivers, the discharges from gauge sites were transferred to the site of interest using the following formula (Thomas et al. 1993; Sumioka, 1997)

$$Q_{site} = \left(\frac{DA_{site}}{DA_{gauged}} \right)^{n} \times Q_{gauged} \qquad (2)$$

Where:

Q_{site} = discharge at site of interest

Q_{gauge} = discharge at gauge site

DA_{gauge} = drainage area at gauge site

DA_{site} = drainage area at site of interest

The exponent n varies between 0.6 and 1.2. If the DA_{site} is within 20% of the DA_{gauge} (0.6≤DA of site divided by / DA of gauge ≤1.2), n value equal to 1 is used, otherwise the value 0.6 is used. The slope exponent (*x*) accounts for the difference between the ways in which larger basins and smaller basins react to precipitation. Larger basins usually have smaller peak discharges per unit area than smaller basins, because of differences in the amount of water storage in ponds and soils, time of concentration, and spatial differences in precipitation during a storm. The exponent *n* is approximately the same value as the average exponent on basin area in the regional regression equation for that flood region.

If necessary, it is possible directly to determine the value of the exponent for any subset of gauges simply by plotting the flow estimates from flood frequency analysis for a given recurrence interval (dependent variable) against drainage area (independent variable) and fitting a power function through the data.

Then runoff volume per month at the un-gauged site was estimated using the following way. Both gauged and un-gauged catchment areas were calculated. In order to drive mean monthly flow on an area basis, the historic mean values at each station can be plotted against respective catchment area as shown in Figure 3-9. A fitted linear (aA+ c) or power (bA^{n}) offer a convenient method for establishing a regional flood relationship which can be applied to predict the expected mean annual flood (MAF) as a function of catchment area (A) for any point of interests in the region.

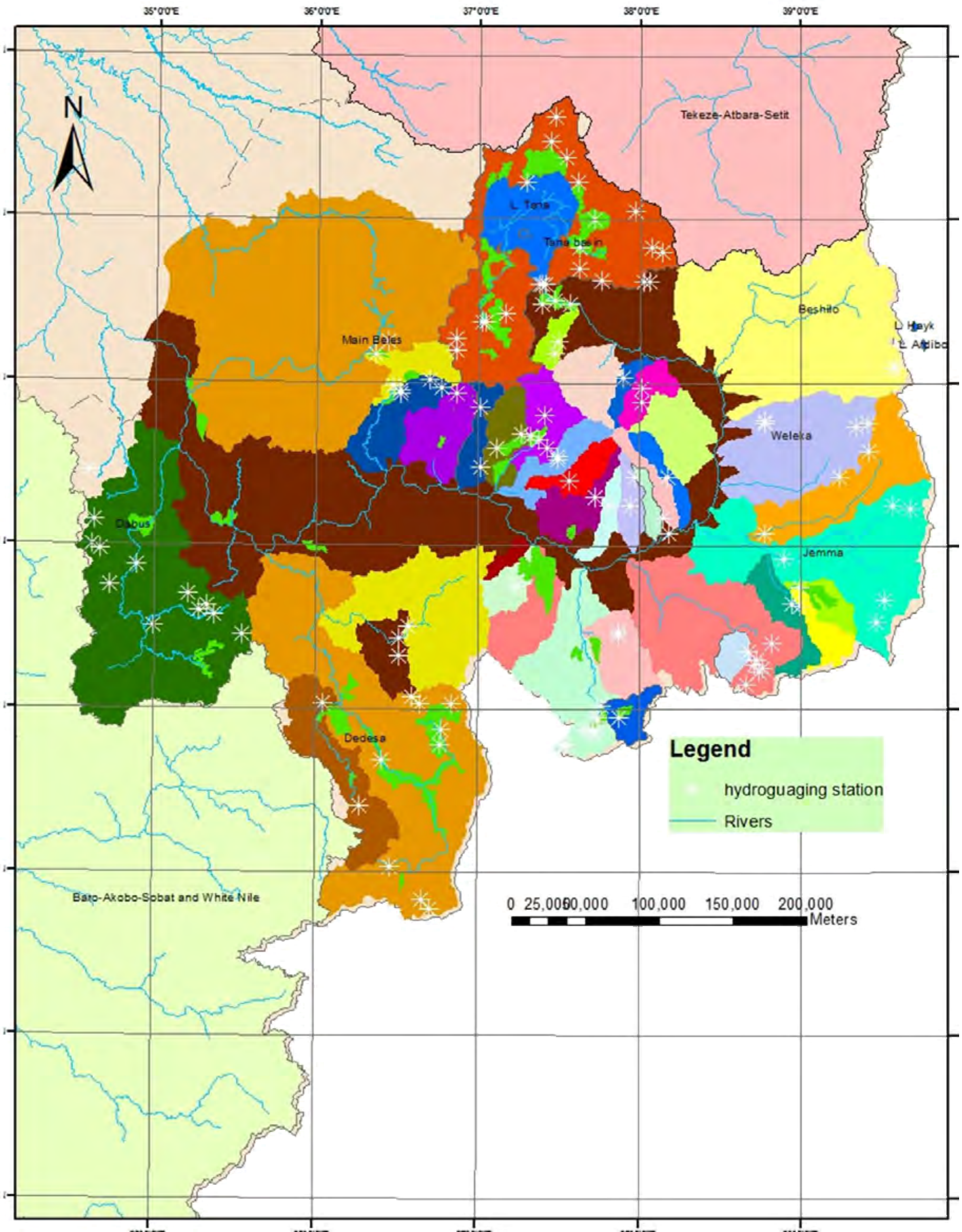

Figure 3-6: Selected catchments of Abbay River basin for stream flow generating

Selected stations which have complete runoff series, relatively long and reliable records for this study are station Kessie and station 6000 at Rosaries which is located after 50 km downstream of the Ethio-Sudan border with a catchment area of 185000 km^2 (5% greater than that at Border).

Data generation was undertaken by considering two areas;

- the first is for the catchments located below station Kessie and above Ethio-Sudan border,
- the second is catchments below Bahir Dar (Lake Tana outlet) and above station Kessie

The stream flow data for rivers within these locations are generated as in the following case. The generated data were checked at Abbay Kessie for the stream flow above Kessie and below Bahir Dar; at Border for the stream flow data generated for the catchments below Kessie. Finally the performance analysis were undertaken for the generated data with the gauged data at Abbay at Kessie and Border using the three performance measures; Nash and Sutcliffe coefficient of efficiency (NS), Root mean square error (RMSE), Mean Absolute Error (MAE), coefficient of determination (R^2) and graphical comparisons. Figure 3-6 shows the selected catchments of Abbay river basin. Appendix Figure A-1 and A-2, show the stream flow diagraph of the station 6000 at Rosaries and station Kessie respectively.

3.3.1.1.1. For catchments below Kessie

There are 27 selected catchments below Abbay at Kessie because of their importance for the study. The area ratio and mean annual flow relations are shown in the Figure 3-7. For the selected Abbay river data set, which includes both tributary and main stream stations commanding the whole catchment area up to the border, is well defined with a correlation coefficient of 0.99 and 0.98 for linear and power curve respectively.

The results show that neighbor catchments can contribute to provide forecasts of good quality at un-gauged sites, especially with the transfer of parameter sets for model simulation. There are two conditions to be considered for the application of the above equations. These are: when the ratio is less than one and greater than one. If the ratio is less than one and if we use power less than one, the result will be aggravated this does not represent the reality. That is, most of the time the un-gauged area contribute less amount of run off as compared to the gauged area because there are located at downstream area of the catchment that has less contribution for base flow. The point here is that there should be good relation between area ratio and the annual flow. Then, the equation can be adjusted depending on the area ratio value. If it is less than one the power should be greater than one and the vice versa. If the ratio is much higher than one the leaner equation gives better result.

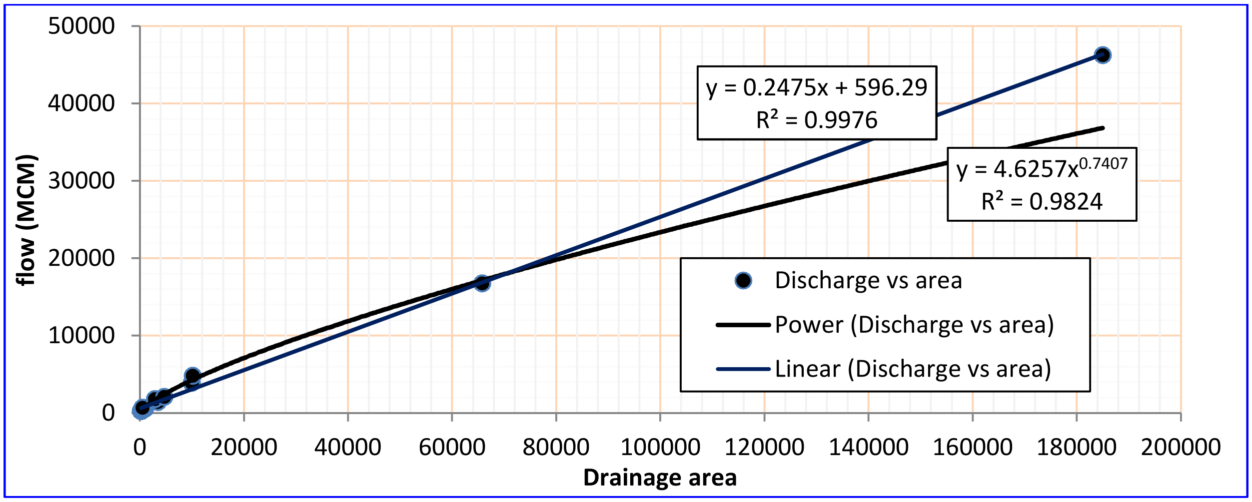

Figure 3-7: Drainage area (km^2) verses flow data (MCM)

Using gauged and un-gauged area of the catchment and the constant 0.74 for power, mean monthly flow of un-gauged catchment can be found by:

$$Q_{for\ un-gauged} = Q_{gauged} \times \left(\frac{A_u}{A_g} \right)^{0.74}$$

Where:

A_U = area of un-gauged (km^2)

A_g = area of gauged (km^2)

The power equation also used by taking the constant 0.6 and 1 depending on the un-gauged to gauge area ratio. The un-gauged area could be the whole drainage area of the considered catchment if data generation is from Rosaries or the un-gauged portion if the gauged area of the catchment itself is used for data generation.

And using the constant 0.25 as a multiplier of gauged to un-gauged area the mean monthly flow of un-gauged area has been found using the equation:

$$Q_{for\ un-gauged} = 0.25 \times \left(\frac{A_u}{A_g} \right)^n$$

After finding the un-gauged stream flow for each catchment, the next is to extend the data for required length of year. Here from 1961 to 2002 (42 years data) is considered for this study. From the above catchments only seven catchments have the required length of data (Chemoga, Jedeb, Temcha, Birr, Dedesa, Anger and Guder). Hence, it is necessary to drive the data from these catchment by the selecting the most correlated catchment. The following table shows the best correlating equation for the catchments.

Table 3-2: Types of equations and coefficient used to transfer stream flow data from Rosaries

Catchment	Total Area	Un-gauged	Gauged	Un-gauged: gauged (Ratio)	Used Equation	Coefficient (n)
Teme	456	156	300	0.52	power	1.2
Bogena	836	166	670	0.25	power	0.6
Yeda	708	125	583	0.21	power	0.6
Chemoga	1462	364	1098	0.33	power	1.2
Jedeb	1006	701	305	2.30	power	0.6
Gu+Tem	706	58	648	0.09	power	0.6
Birr+Leza	1747	594	1153	0.52	power	1.2
Lah	1492	1204	288	4.18	linear	0.25
Fetem	1057	300	757	0.40	power	1.2
Missini	2127	2111	16	131.94	linear	0.25
Dura	2073	750	1323	0.57	power	1.2
M/Beles	12821	9390	3431	2.74	linear	0.25
G/Beles	1295	620	675	0.92	power	1.2
M/Abbay	17286	65784	65784	0.26	linear	0.25
Dabus	14762	4623	10139	0.46	power	1.2
Debena	3628	347	3281	0.11	power	1.2
Dedesa	16396	6415	9981	0.64	power	1.2
Anger	7127	2455	4672	0.53	power	1.2
Uke	690	488	202	2.42	linear	0.25
Neshi	366	44	322	0.14	power	0.6
Amerti	932	680	252	2.70	linear	0.25
Fincha	2082	691	1391	0.50	power	1.2
Guder	4362	3838	524	7.32	linear	0.25
Debis	857	58	799	0.07	power	1.2
Duber	1994	1769	225	7.86	linear	0.25
Muger	6646	6157	489	12.59	linear	0.25
Aleltu	265	236	29	8.14	linear	0.25

Table 3-3: The best correlation coefficient of catchment for data transferring from gauged area to un-gauged area for the location below Kessie

S. No	Catchment needs extended flow	Catchment With more than 42 years data	Equation	R^2	Data Length (Year)
1	Teme	Temcha	$0.183x^{0.869}$	0.82	18
2	Bogena	birr	$0.1233x^{0.97}$	0.72	7
3	Yeda	Abbay Kessie	$0.006x^{0.825}$	0.58	15
4	Lah	Temcha	$0.49x^{1.013}$	0.89	32
5	Fetem	Temcha	$2.142x^{0.783}$	0.90	17
6	Missini	Temcha	$0.38x^{1.1802}$	0.77	15
7	Dura	Temcha	$2.951x^{0.777}$	0.77	40
8	Main Beles	Temcha	$2.062x^{0.85}$	0.68	40
9	Gilgel Beles	Dedesa	0.195x	0.75	21
10	Dabus	Anger	$21.34x^{0.596}$	0.65	32
11	Debena	Anger	$1.67x^{0.831}$	0.93	32
12	Uke	Guder	$0.992x^{0.808}$	0.74	33
13	Neshi	Guder	$0.361x^{0.86}$	0.84	40
14	Amerti	Guder	$0.3011x^{0.8919}$	0.83	21
15	Fincha	anger	$0.0.699x^{0.762}$	0.78	9
16	Debis	Guder	0.179x	0.86	6
17	Duber	Abbay Kessie	0.009x	0.75	6
18	Muger	Guder	$0.302x^{1.1}$	0.80	33
19	Aleltu	Guder	$0.016x^{0.97}$	0.75	22

Performance Analyses

Once obtained, the results were tested by comparing the generated data with observed data at Sudan border which has only nine years data (1969, 1971 to 1974 and 1999 to 19202). Model performance was evaluated using the Nash-Sutcliffe coefficient (NS) the deviation from measured data. The NS Equation is a measure of model efficiency that compares simulated values to corresponding measured values. The Nash–Sutcliffe model efficiency coefficient is used to assess the predictive power of hydrological models. Its definition is identical to the coefficient of determination R^2 used in linear regression.

$$NS = 1 - \left(\frac{\sum_{i=1}^{n} (Q_i - \hat{Q}_i)^2}{\sum_{i=1}^{n} (Q_i - \overline{Q})^2} \right) \qquad (3)$$

Where Q_i is the measured value (stream discharge), Q_i’ is the simulated value, $\overline{Q}$ is the average measured value, and n is the number of data points.

The NS can range from −∞ to 1; improved model performance is indicated as the NS approaches 1, while a value of zero indicates that simulated values are no better than the mean of observed values. Based on many documents; NS values greater than 0.75 signify good model performance, while those between 0.36 and 0.75 signify acceptable model performance (Van et al. 2003). Values of NS greater than 0.4, have also been considered to indicate acceptable model performance (Ramanarayanan, 1997). Other criteria presented include 0.65–0.75 (fair) and 0.75–0.85 (good) with values above 0.85 representing very good model performance (Donigan and Love, 2003).

Within these general ranges the criteria established will often depend on the model and nature of the application, thus what is considered acceptable will vary among projects (Engel et al. 2007). These general guidelines were used in further evaluating model performance. Values not meeting either criterion (acceptable or good) were comparable across the methods. In this work the NS value, graphical comparison and statistical parameters like mean, standard deviation etc. were used for comparing of the two methods (transferred from Rosaries and gauged area) with actual data and the mean annual and NS are show in the Table 3-4. From the table, generated data perform well which has NS value of 92% and 93% at generated data from area ratio and transfer from Rosaries respectively. The cumulative annual mean flow is as well nearly similar with the observed data.

Table 3-4: Relation of generated data with available actual data at border for years (1969, 1970 to 1974 and 1999 to 2002)

Model (equation)		$Q_{un-gauged} = a \times \left(\frac{A_u}{A_g}\right)$ or	$Q_{un-gauged} = Q_{gauged} \times \left(\frac{A_u}{A_g}\right)^n$
Checking site		Generated from gauged area	Generated from Rosaries
NS		0.92	0.93
Mean annual flow (MMC)	Estimated	49544	50102
	observed	49698	49698
	Difference	-154	404

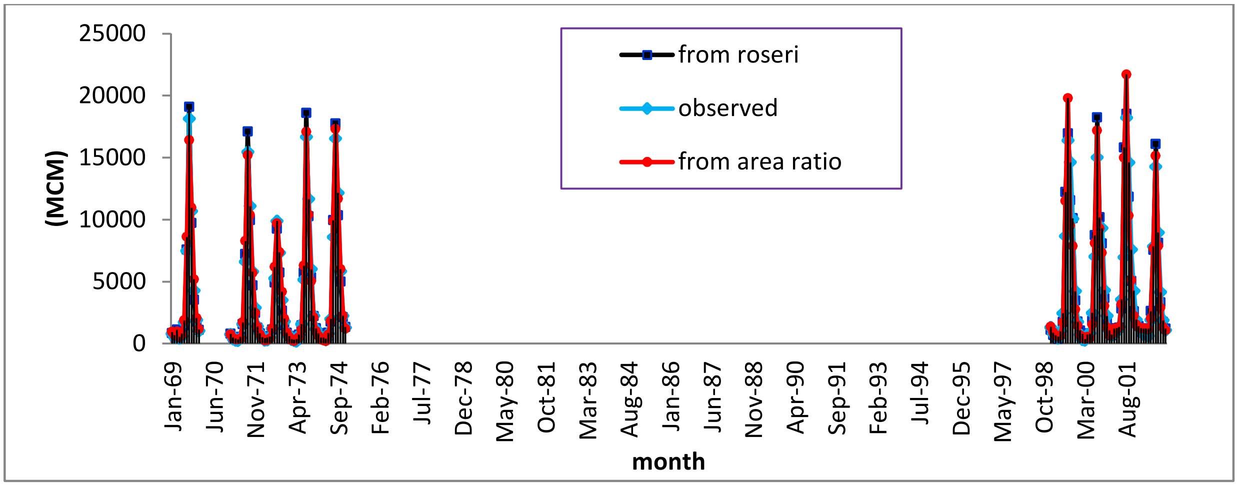

Figure 3-8: Time series data of generated and observed (there is no gauged data in 1970, from1975 to1998)

From the above graphs, tables and NS values the data generated from Rosaries station are more appropriate than the data generated from area ratio method, and thus selected for the catchments below Kessie.

3.3.1.1.2. Above Kessie

There are 15 catchments above Kessie and below Bahir Dar. In this region few stations has relatively good quality and coverage of gauging. But most of them have less coverage (less gauged area). So, it was necessary to estimate the stream flow from the gauged catchments like Abbay at Kessie. There are two conditions of area ratio to mean annual flow relation i.e., two graphs for two groups of catchments as show below.

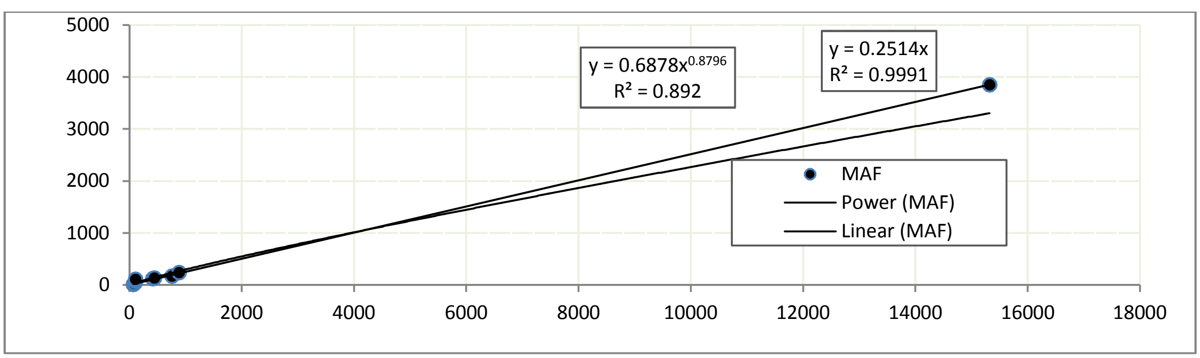

Figure 3-9: Drainage area (km^2) verses flow data (MCM) for station located between station Kessie and Lake Tana outlet for right side of the river

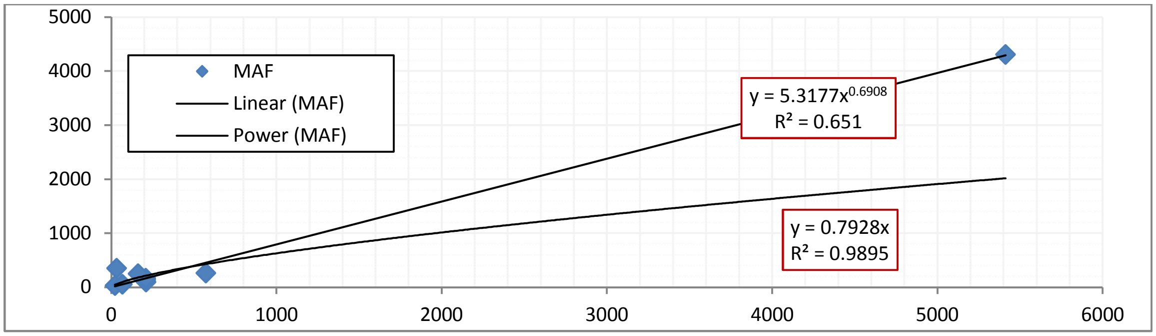

Figure 3-10: Drainage area (km^2) verses flow data (MCM) for station located between station Kessie and Lake Tana outlet for left side of the river

Table 3-5: Equations and coefficients used to generate data for catchments above Kessie

Catchment	Total area	Gauged area	Un-gauged area	Area ratio	Used equation	coefficient
Weleka	5808	-	5808	0.117	power	0.7
Wonchit	4106	-	4106	0.083	power	1
Jema	8306	-	8306	0.168	power	1
Beshilo	13319	-	13319	0.269	power	1
M/Abbay	6774	-	6774	0.137	linear	0.25
Azuari	941	209	732	3.5	linear	0.8
Sede	456	209	247	1.18	power	0.7
Aleltu-Jema	1352	447	905	2.02	linear	0.25
R/Jida	885	762	123	0.16	power	1.2
Andasa	603	573	30	0.0524	linear	0.8
Muga	737	375	362	0.97	power	1.2
Suha	720	359	361	1.01	power	0.7

The coefficients and the equations were used according to the area ratio that is, for ratio less than one power with coefficient of 1.2 or linear with 0.25 were used. For ratio greater than one power with 0.8 or 0.7 were used. Table 3-5 shows the coefficient used and the selected independent catchment. To use the Abbay at Kessie first the data at Bahir Dar was deducted to minimize the storage effect of Lake Tana and the drainage area also be considered accordingly, which is 49463 km^2 (64784-15321 = 49463).

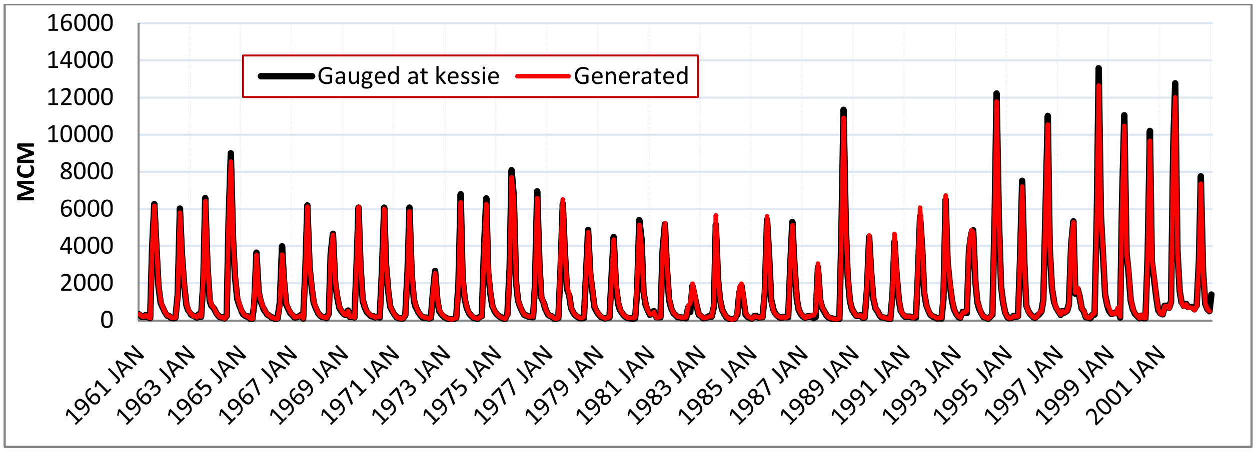

Figure 3-11: Time series data of generated and gauged at Abbay Kessie

The observed and simulated monthly time series flows at station Kessie can be seen in Figure 3-11. As shown in graph there is very good agreement between the generated and observed flow data. After finding the un-gauged stream flow for each catchment, the next is to extend the data for required length of year. Here from 1961 to 2002 (42 year data) is considered for this study. Hence, it is necessary to drive the data from these catchment by the selecting the most correlated catchment.

Table 3-6: The best correlated relation between catchments

S. No	Catchment need extended flow	Data Length (Year)	Catchment with more than 42 years record	Equation	R^2
1	Aleltu-Jema	20	Abbay Kessie	$0.001\,x^{0.1.173}$	0.74
2	Robi Jida	33	Abbay Kessie	$0.122x$	0.73
3	Robi Gumero	33	Abbay Kessie	$0.017x$	0.74
4	Muga	23	Abbay Kessie	$0.02x$	0.80
5	Suha	18	Abbay Kessie	$0.009x$	0.74
6	Sede	16	Andasa	$0.1011\,x^{1.52}$	0.82
7	Azure	18	Andasa	$0.64\,x^{1.20}$	0.78

3.3.1.2. Comparing the Generated Data with Stream Flow Generated by Other

There are different organizations and consultants generated and studied the stream flow data of Abbay river basin. Some of reviewed here are; Karadobi project study (Norplan), GERD study (Coyne ET BELLIER), MoWE. All of these organizations generate data for the Abbay River at the Ethio-Sudan border. Stream flow data of MoWE is found from the master plan study of Abbay basin, Norplan's is from the Karadobi project feasibility study and that of Coyne ET BELLIER is from study of GERD. The reviewed and generated data are shown in the Table 3-7.

Finally the performance analysis was undertaken for the generated data with the gauged data using the three performance measures: Nash and Sutcliffe coefficient of efficiency (NS) (equation 3), root mean squared error (RMSE) and mean absolute error (MAE).

$$RMSE = \sqrt{\frac{1}{n} \times \sum_{i=1}^{n} (Q_i - \widehat{Q}_i)^2} \qquad (4)$$

$$MAE = \left| \sum_{i=1}^{n} \frac{1}{n} \times (Q_i - \widehat{Q}_i) \right| \qquad (5)$$

Where Qi is the measured value (stream discharge), Q_i' is the simulated value, $\overline{Q}$ is the average measured value, and n is the number of data points.

As shown in Figure 3-12, Figure 3-13, Table 3-8 and Table 3-9, the data used by Coney and Norplan are more different from MoWE as compared to the other results. And they have similar statistical characteristics. This is because they used the same flow data source (Abbay at Kessie) to transfer the data but the coefficients are slightly different.

Table 3-7: Mean annual flow of Abbay River studied by different organization and their difference from the WoWE

Site	*Mean Annual flow (BCM)*	*Difference (%) from MoWE*	*Remark*
MoWE	50322	0	
Transferred from Rosaries	48192	4.2	
Generated from gauged area	48505	3.6	
Coyne ET BELLIER (GERD Study)	47615	5.34	Same data sources used but different transformation coefficient
Norplan (Karadobi project study)	46655	7.27	

Table 3-8: Stream flow data statistical parameters of Abbay River studied by different organizations

month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Transferred from Rosaries													
Mean	855	570	570	567	835	1877	7913	15805	10243	5295	2319	1343	**48192**
Std	212	127	206	235	591	2072	2829	4107	2965	2117	758	385	**9224**
CV	0.25	0.22	0.36	0.41	0.71	1.10	0.36	0.26	0.29	0.40	0.33	0.29	0.19
Ministry of water and Energy													
Mean	925	630	465	463	700	2067	7421	14753	11768	6711	2854	1566	**50322**
Std	223	214	166	201	305	692	1898	2205	2356	1986	825	463	**7954**
CV	0.24	0.34	0.36	0.43	0.44	0.33	0.26	0.15	0.20	0.30	0.29	0.30	0.16
Coyne													
Mean	866	523	431	447	665	1861	7960	13071	11187	6421	2793	1390	**47615**
Std	216	183	151	170	275	506	2670	4603	2328	2054	1045	435	**8572**
CV	0.25	0.35	0.35	0.38	0.41	0.27	0.34	0.35	0.21	0.32	0.37	0.31	0.18
Norplan													
Mean	838	556	417	447	643	1861	7703	12649	11187	6214	2793	1345	**46655**
Std	209	197	146	171	266	506	2584	4455	2328	1988	1045	421	8377
CV	0.25	0.35	0.35	0.38	0.41	0.27	0.34	0.35	0.21	0.32	0.37	0.31	0.18
Generated From Gauged Area													
Mean	977	644	572	574	813	1934	7650	14722	10157	5908	2914	1641	48505
Std	205	156	230	274	652	2105	2501	4133	2466	1719	713	397	10069
CV	0.21	0.24	0.40	0.48	0.80	1.09	0.33	0.28	0.24	0.29	0.24	0.24	0.21

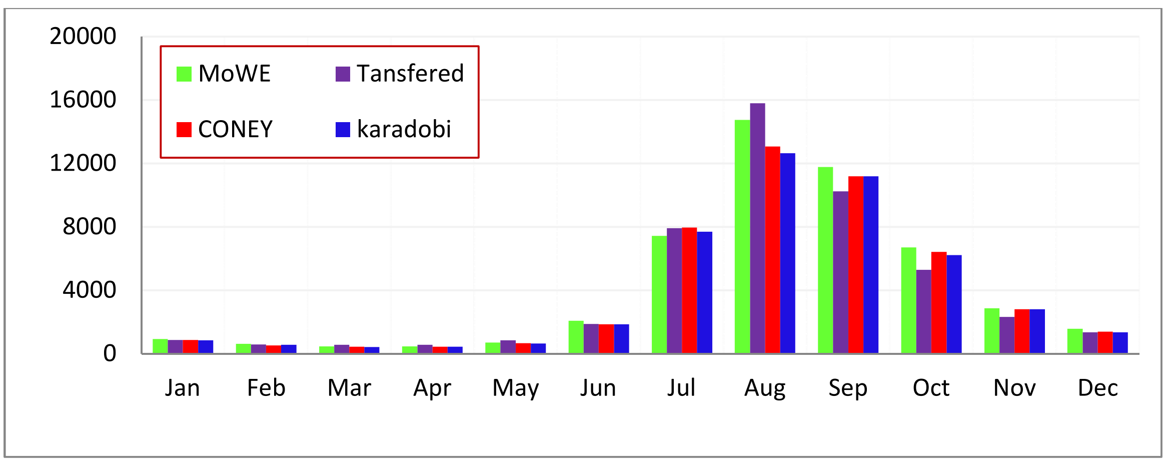

Figure 3-12: Mean monthly Stream flow data of Abbay River studied by different organizations (MCM)

3.3.1.3. Comparing the Generated Data with Stream Flow Generated by Other and Observed Data at Sudan Border

Figure 3-13 show graphical comparison of data generated with data used by Norplan, Coyne ET BELLIER and that of MoWE. There are only nine years data which actually gauged by MoWE (1969, 1970 to 1974 and 1999 to 2002) and are used to see the reliability of the generated data. The statistical values and performances of generated data as compared to the observed data are shown in the Table 3-9.

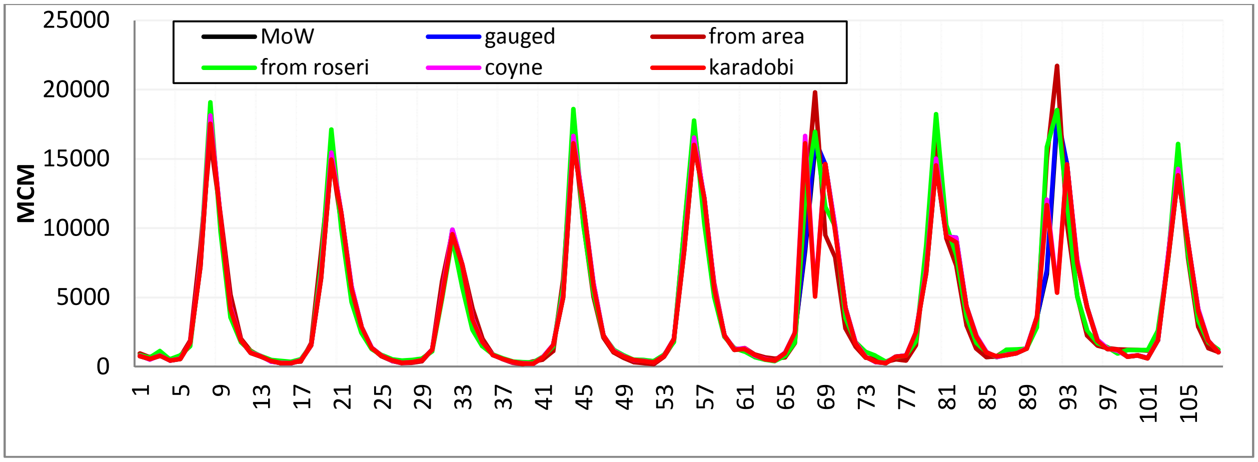

Figure 3-13: Comparison of time series data of Abbay at Sudan border for the years 1969, 1970 to 197 and 1999 to 2002

As shown in the Table 3-9, all generated data perform well however that of data generated from Rosaries has higher performance. The 100 % performance of the MoWE is due to that the presented data is the gauged data itself.

Table 3-9: Performances of the generated data as compared to the observed data

Performance measures	From area ratio	From Rosaries	Coyne	Karadobi (Norplan	Mow
NSE	0.92	0.93	0.86	0.86	1
MAE	13	34	99	181	84
RMSE	1344	1251	1864	1861	174

3.3.1.4. Generated Stream Flow Data at Border

Figure 3-14 shows the generated monthly time series and annual stream flow data of Abbay river basin at Border. Catchment runoff represents locations in the model where water is introduced directly to the stream system. The hydrological analysis that will be under taken during the study requires the collection and review of hydrometric data associated with the Eastern Nile River.

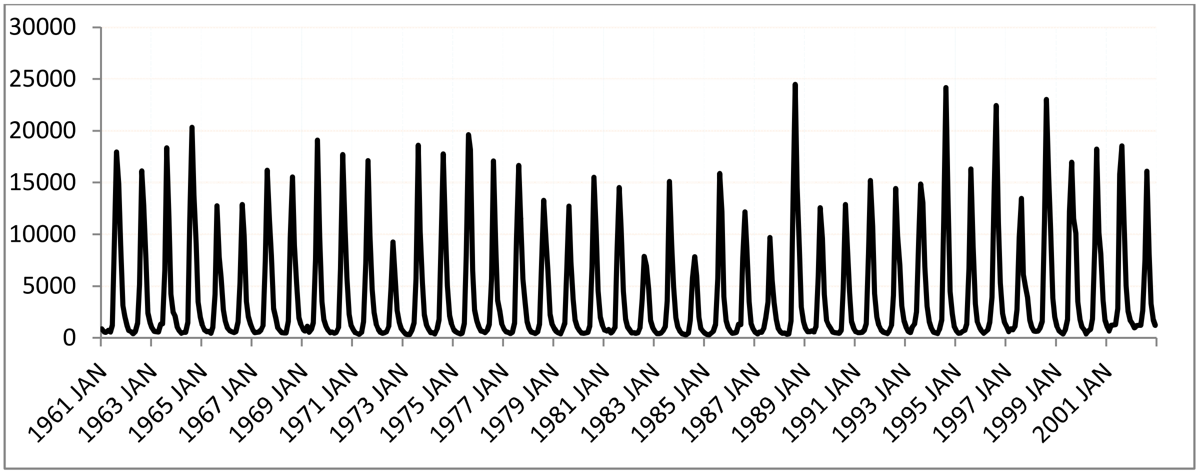

Figure 3-14: Monthly Abbay stream flow data at Border (MCM)

The monthly flows were developed through the scoping of the proposed reservoirs. These sites include: Bahir Dar to Kessie Incremental, Kessie to Karadobi Incremental, Karadobi to Mendya Incremental, Mendya to Border/Renaissance Incremental, Melaka, Kubur, Atbara wade, Rahid and Dinder. These incremental flows were available for the period from 1961 to 2002 and were developed from simple subtractions of mainstream gauges, therefore incorporating flows from tributaries already known from gauged data.

3.3.2. Stochastic Time Series Flow for Future Irrigation Development Analysis

In areas where there are variations record lengths of flow data, the flow generation using minimum data would bring unrealistic estimates and the water resources work based on this estimates may be failed. An observed time series can be assumed as the realization of a stochastic process. Once we understand how the process operates, we can develop a mathematical model to predict the future values of the time series. Understanding the underlying structure of the time series by breaking it down to its components, and to fit a mathematical model and then proceed to forecast the future is the main goal of time series analysis.

Time series of monthly naturalized flow data, obtained from the MoWE, and stochastic time series were generated for the incremental flow between water resource development structures. Hundred years of stream flow data were generated using Autoregressive Moving average (ARMA11) and Thomas-Fiering were used. Both Graphical and numerical performance measures were applied in the comparison of generated and historical data. The graphical evaluation includes comparison of the simulated and observed hydrograph, and comparison of the simulated and observed accumulated runoff. The numerical performance measures include the overall water balance error (i.e. the difference between the average simulated and observed runoff), and a measure of the overall shape of the hydrograph based on the coefficient of determination or Nash-Sutcliffe coefficient. In coefficient of determination is above 0.82 which indicates very good performances of the models. In the graphical comparison, all peaks and minimum flows are captured. The third flow data which extracted from ENTRO's data sheet (Easter Nile Multi Sectorial Investment Opportunity Analysis (EN MSIOA) and Ribasim Model) were used for future irrigation development. The flow time series are presented in appendix A.

3.3.3. Irrigation Water User Data

3.3.3.1. Current irrigation water demands

Large percentage of the irrigated land is located in Egypt. Sudan is the next nation with maximum irrigated land. In Egypt, the annual water demand downstream of the High Aswan Dam was taken as 55.5 km^3 as indicated in 1959 bilateral agreement with Sudan. This volume of water is primarily used for irrigation purposes.

HAD outflows aim to satisfy Egyptian irrigation water demand as priority to energy generation. 55.5 BCM/year are allocated to Egyptian irrigation supply downstream of HAD. 18.5 BCM/year is allocated to Sudan for irrigation supply. Thus, the value of 18.5 BCM/year corresponds to the remaining water volume of the natural Nile flow arriving at HAD (84 BCM/year in average) once Egyptian waters use for irrigation (55.5 BCM/year) and HAD evaporation losses (10 BCM/year) are subtracted.

This 18.5 BCM/year of water are tapped at two different points upstream of HAD in the water system model. 9.33 BCM/year are deducted on the Blue Nile River to irrigate lands around Sennar; 9.17 BCM/year are deducted on the intermediary catchment (on the White Nile River and on the Atbara River) Water volumes for irrigation in Sudan are deducted from the Nile upstream of HAD, and thus are prevented to enter in HAD reservoir in the proposed model. Table 3-10 shows water demand data.

Table 3-10: Current Water demand input data used for modeling (m^3/sec)

Month	Sobolka	Downstream Sennar	Upstream Sennar	Gizira	Dongola	Khashim EL Gibra	Jubial Aluia	HAD
Jan	18.85	7.51	67.46	202.34	13.44	45.56	29.97	988
Feb	10.75	8.1	66.45	191.27	10.75	51.35	34.55	1291
Mar	20.37	10.42	44.69	118.13	20.37	51.82	38.74	1623
Apr	25.08	11.72	34.87	30.78	25.08	55.41	43.26	1662
May	25.92	12.39	35.09	44.49	25.92	46.73	45.03	2130
Jun	23.26	12.54	77.06	180.89	23.26	45.23	47.85	2790
Jul	18.85	9.04	97.39	268.64	18.85	42.24	78.52	2835
Aug	12.85	7.22	93.75	258.55	12.85	39.78	78.66	2448
Sep	5.34	10.28	132.38	337.76	5.34	27.43	146.06	1748
Oct	4.63	11.35	148.2	321.77	4.63	16.89	166.39	1394
Nov	7.17	10.11	141.85	249.6	7.17	19.44	145.5	1286
Dec	14.81	7.25	82.78	185.58	14.81	40.83	45.75	1220

3.3.3.2. Future irrigation water demand

There is potential for additional exploitation, and both Ethiopia and Sudan plan to further develop the water resources of the river. Consequently, both countries are planning significant development of the East Nile River water resources in the future.

In Ethiopia, current planning is focused primarily on the Dedesa Arjo, Tekeze, Baro, Rahad, Dinder, location between Lake Tana and Karadobi, Lake Tana and the Beles River catchments which have been identified by the government. In addition the study explores the possibility of further expansion in irrigation on the Baro and Tekeze Rivers.

Sudan is also planning to increase the area irrigated in the BNB. Additional new projects and extension of existing schemes is anticipated to add an additional 889,340 ha by 2025. The major planned intervention is the heightening of the Roseires dam by about10 m. Unless irrigation efficiencies are significantly better than those currently achieved in the Gezira and other schemes, this will require approximately 9,300 Mm^3 more water than is abstracted at present.

The water withdrawals for irrigation schemes were derived from a variety of sources, including the Ethiopia Basin master plan. For the medium-term and long-term scenarios, the sizes of planned irrigation development schemes were derived from the basin master plan for the Ethiopian Blue Nile, Baro-Akobo and Tekeze and from ENTRO spreadsheet as well as from the JMP1 system Inventory. For the Sudanese schemes, information on likely completion dates was obtained from ENTRO spreadsheet, Awlachew et al. (2012) and McCartney et al., (2012).

The medium-term scenario includes the irrigation projects anticipated to be implemented before 2050. New schemes, proposed extension of existing irrigation schemes were identified and presented in appendix C.

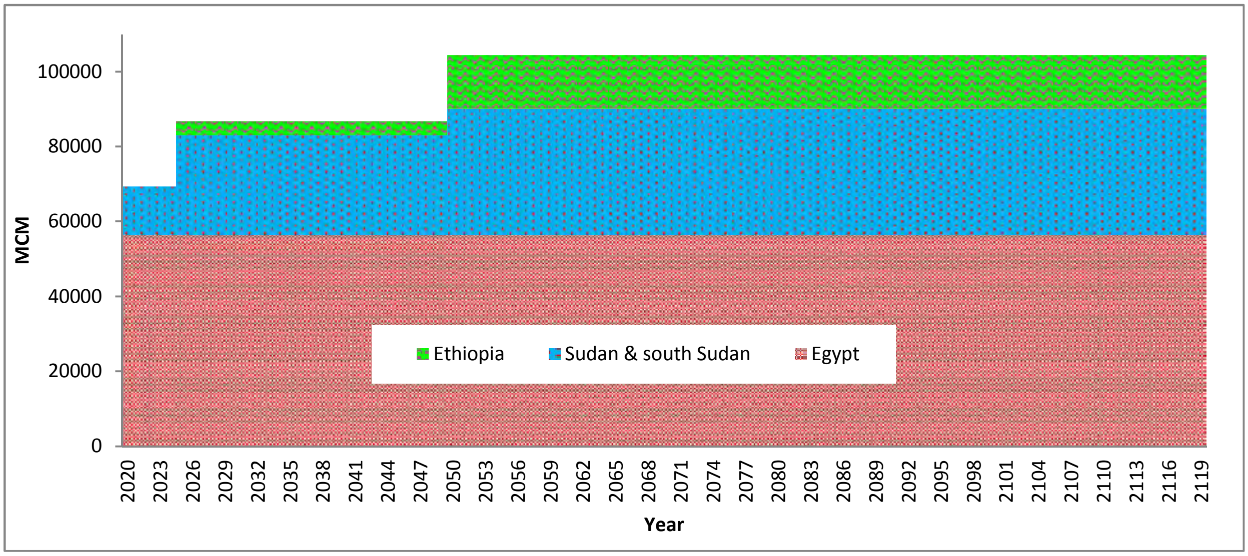

Figure 3-15: Irrigation development trajectory of Eastern Nile: irrigation water demand in the Eastern Nile (MCM)

3.3.4. Hydropower Data

Hydropower data were supplied by Ethiopian Electric Power Corporation (EEPCO) Grand Ethiopian Renaissance Dam Project study and ENTRO power toolkit. For power generation at GERD during impounding the input data is the water level and tail water level with the amount of water delivered to the turbine according to the power unit installed. So, amount of power generated will depend on these input data. But for operation time the power input is 6000 MW installed capacity and 95% engine efficiency. Table 3-11 shows, proposed and implemented Hydropower plants in the Eastern Nile (installed and target power in megawatt (MW) and tail water in meter above sea level (m.a.s.l)

Table 3-11: Proposed and implemented Hydropower plants in the Eastern Nile

Hydropower plant	Hydro power (MW)		Tail water level (m.a.s.l)	Country (location)	remarks
	Installed capacity	Target Power			
Tana Beles	460	460	1356	Ethiopia	In operation
Karadobi	1600	933	890	Ethiopia	Under study
Bekoabo	1940	1329	800	Ethiopia	Under study
Upper Mendia	1700	802	640	Ethiopia	Under study
Bekoabo Low	935	514	603	Ethiopia	Under study
GERD	6000	1807	500	Ethiopia	Under construction
Rosaries	425	200	437	Sudan	In operation
Sennar	15	15	406	Sudan	In operation
Merowe	1000	650	240	Sudan	In operation
Tekeze	300	180	967	Ethiopia	In operation
Jebil Aluia	28.5	15	300	Sudan	In operation
HAD	2100	783	120	Egypt	In operation

3.3.5. Reservoirs Data

For evaluating GERD impacts only existing reservoirs were considered. The reservoirs udder studies are only considered as future cascades development. The physical characteristics of the Reservoirs were provided by ENTRO power tool kit, Ministry of Water and Energy (MoWE). Table 3-12, provides basic physical characteristics of the reservoir sequentially from upstream to downstream. The reservoirs elevation-area-storage curve are provided in the Appendix B

Table 3-12: Main reservoirs in Eastern Nile

Reservoir	River bed (m.a.s.l)	MOL (m.a.s.l)	FRL (m.a.s.l)	Storage capacity (MCM)		Country (location)	Remarks
				at FRL	Active		
Lake Tana	1762.9	1784	1787	32270	9030	Ethiopia	Lake
Karadobi	910	1100	1146	40200	17000	Ethiopia	Under study
Bekoabo high	800	1010	1062	31682	17400	Ethiopia	Under study
Bekoabo Low	800	870	910	1751	1240	Ethiopia	Under study
Mendya	640	760	800	27702	10315	Ethiopia	Under study
GERD	505	590	640	74000	60000	Ethiopia	Under construction
Rosaries	438.59	467.7	481	2020	1850	Sudan	Existing
Sennar	406.44	417	421	480	413	Sudan	Existing
Merowe	240	285	300	12087	8356	Sudan	Existing
Tekeze	967	1096	1140	9293	5293	Ethiopia	Existing
Jebel Aluia	370	374	377.4	4595	389	Sudan	Existing
Gibra	440	464.5	474	657	617	Sudan	Existing
HAD	120	147	183	169420	141120	Egypt	Existing

3.3.5.1. Lake Tana

The Tana-Beles hydropower project was completed in May 2010 and is represented in the baseline and scenario models, but not included in the historical calibration model. The project diverts water directly from Lake Tana but returns back to Abbay before GERD.

If the elevation of Lake Tana is above 1787.0 m.a.s.l or the elevation is above 1786.3 m.a.s.l and it is still rising, then the flow to the Tana-Beles hydropower diversion is 160 m^3/s. If the elevation of Lake Tana is below 1784.0 m.a.s.l and the if elevation is decreasing, then the flow to the hydropower diversion is turned off. If the reservoir is between these two dynamic ranges, then the flow to the hydropower diversion is set to 77 m^3/s (EEPCO, 2010; Salini and Mid-day. 2006).

3.3.5.2. Rosaries Dam

Due to the large seasonal fluctuation, relatively small storage volume, and high amount of sediment accumulating in Rosaries, the operational criteria is specified to draw down the reservoir starting in mid-January and maintain a minimum elevation until the peak flow has passed in September. Therefore, meeting target elevation criteria and satisfying irrigation water demand is the primary guiding principle of the operation of Rosaries Dam.

3.3.5.3. Sennar Dam

Similar to Rosaries Dam, a primary 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 417.0 m.a.s.l 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 objective is met, the reservoir operates to meet the monthly target elevations.

3.3.5.4. Jebel Aluia

The Jebel Aulia dam built forty kilometers upstream of Khartoum in 1937 to store water for later use in Egypt. The rapid silt up of this reservoir and the construction high Aswan dam in Egypt in 1965 stopped its function (Shahin, 2002).

The filling of the reservoir starts at the beginning of July and continues to 376.5 m.a.s.l at the end of the month. It is then held constant for one month 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. A rule was incorporated to evaluate if the peak flow at the Khartoum Soba gage has passed, and if so, set the outflows from the Jebel Aulia dam immediately to meet the refill volume. 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.

3.3.5.5. Khashm El Girba Operations

The Khashm El-Girba Dam is gravity and embankment composite dam on the Atbarah River about 4 km south of Khashm El Girba in Eastern Sudan. The primary purpose of the dam is irrigation and it is equipped with canal head works on its left bank which diverts water into a canal. The main portion of the dam is an earthen embankment while the spillway and irrigation head works sections are concrete gravity. The dam has a small hydroelectric power station, which was upgraded between 2002 and 2004, and has an installed capacity of 10 MW. Operations were assumed to primarily meet the Khashm El Girba irrigation water demands by achieving the target elevation of 374 m.a.s.l.

3.3.5.6. Tekeze Dam Operations

Physical Characteristics describing the elevation-storage-surface area relationships, reservoir evaporation rates and turbine characteristics of target and maximum power generation were extracted from the Power Toolkit provided by ENTRO. No operational guidelines could be located; therefore a method was developed to operate this reservoir to primarily meet a target power generation of 112MW, with a maximum power capacity of 300 MW. To accomplish this operation, a rule was written 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 1140 m.a.s.l and a minimum operation level of 1096 m.a.s.l is used as the range over which power could be generated.

3.3.5.7. Merowe Dam Operations

The Merowe Dam is recently constructed; therefore it is not included in the historical validation of model but is included in the baseline and scenario models. Data describing the elevation-volume-surface area was acquired through ENTRO. Operational criteria of the Merowe Dam was not identified and therefore assumed to be operated to meet the primary objective of hydropower generation. A method was developed to operate this reservoir to primarily meet a target power generation of 625 MW, with a maximum power capacity of 1250 MW. To accomplish this operation, a rule was written 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 m.a.s.l and a minimum operation level of 284.90 m.a.s.l is used as the range over which power could be generated.

3.3.5.8. High Aswan Dam Operations

The physical characteristics for the High Aswan Dam and Lake Nasser/Lake Nubia were extracted from information provided by ENTRO. This information contains descriptions of the turbine characteristics including explicit relationships between operating head, turbine releases and power generation. At HAD, as long as HAD water level is equal or greater than the Minimum Operating Level (147 m), water volumes for Egyptian irrigation are supplied at a monthly time-step according to the repartition presented in Table 3-10. In case HAD water level reaches 183 m, any additional water volume is spilled.

3.3.5.9. Losses from reservoirs

Losses/gains were placed at reservoirs locations within the basin to account for reservoirs gains due to precipitation and losses due to Evaporation. These losses represent the difference between gross precipitation on the reservoir and natural losses due to before the creation of the reservoir. All available demands are average monthly values and do not indicate any inter-annual variability. Table 3-13 shows the net evaporation loss from reservoirs.

Table 3-13: Monthly net reservoir evaporation (mm/day) (source, ENTRO power tool kit and Coyne ET BELLIER and TRACTEBEL report)

Reservoir	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
HAD	4.6	5.6	8.9	10.6	12.7	13.5	13.7	13.6	11.6	9.3	13.4	5.3
GERD	6.3	6.8	5.1	4.9	3.7	-0.6	-7.3	-6.6	-1.1	2.7	4.7	5.8
Elgibra	5.8	6.8	8.1	8.3	8.6	7.9	4.2	2.7	5.4	6.1	6.3	6.1
J/Aluia	6.1	8.1	7.5	7.4	7.4	7.5	3.8	3.7	4.5	4.9	5.8	5.7
Rosaries	5.8	6.4	7.3	7.4	6.1	2.1	-0.9	-0.8	0.7	4.0	5.2	5.6
Sennar	6	6.2	7.6	7.4	6.3	2.1	-0.9	-0.9	0.7	4.2	5.2	5.6
Merowe	6.4	7.7	9.5	11.0	11.8	11.3	10.1	9.8	10.6	9.9	7.7	6.6
Tekeze	4.8	5.4	5.3	5.6	6.0	3.8	-2.6	-3.5	2.9	4.5	4.7	4.6
Karadobi	5.7	5.8	4.5	4.4	3.3	-0.5	-6.5	-5.8	-0.9	2.6	4.2	5.4
Mendya	6.4	6.1	4.9	4.5	3.5	-0.7	-7.3	-5.0	0.6	3.9	4.9	6.0
Bekoabo	5.6	5.4	5.1	4.2	2.1	-2.2	-4.6	-1.5	0.3	2.2	3.9	4.8
Lake Tana	4.5	4.4	3.3	2.6	2.6	-1.2	-5.1	-6.1	-1.2	3.8	4.7	4.9

3.3.5.10. The GERD reservoir filling strategies

According to the envisaged construction and first impounding schedule (Coyne ET BELLIER and TRACTEBEL Engineering, 2011) it is considered that:

- GERD impounding stage will start in January 2014;
- Energy generation can start once water level reaches 560 m.a.s.l.
- Construction of GERD will be completed in June 2017
- The impounding stage will be considered complete when GERD water level will reach its Normal Water Level (640 m.a.s.l.) and then will not decrease below 622 m.a.s.l.

Chapter Four

Methodology

4.1. Model Setup for the Eastern Nile Water Resources System

Mike Basin (DHI, 2001) is a multipurpose, GIS-based river basin simulation package, designed for analyzing water sharing problems and environmental issues at international, national and project scale, and between competing groups of water users. Mike Basin is powerful, yet simple to use, with lots of analysis capabilities for water resources engineering. It provides a framework for managers and stakeholders to address multi-sectoral allocation and environmental issues in river basins.

Mike Basin operates on the basis of a schematic river network, which is made up of building blocks or objects. These typically included river reaches, water user nodes, reservoir nodes, irrigation nodes, hydrological catchments, hydropower nodes and channels which link the various nodes. The characteristics of the individual building blocks and the interactions between them are governed by user defined operating rules. The wide range of modeling routines embedded in the Mike Basin model, allowed the simulation of various multi-purpose water resource project scenarios.

Mike Basin can accommodate multiple multipurpose reservoir systems or individual reservoir to simulate the performance of specified operating policies using associated operating rule curves. The reservoirs set in Mike Basin model can be run either as rule curve reservoirs, allocation pool reservoir, or as lake. The general and operation properties consist of elevation-area-capacity table, characteristics levels of reservoirs, losses, rule curves, flood control zones, minimum operating zones, reduction level and reduction percentages, remote flow rule, and priorities to operate reservoirs as per management policies

Mike Basin can be used for providing solutions and alternatives to water allocation and water shortage problems, improving and optimizing reservoir and hydropower operations, exploring conjunctive use of groundwater and surface water, evaluating and improving irrigation performance, solving multi-criteria optimization problems, establishing cost-effective measures for water quality compliance.

The natural river system of the Easter Nile River Basin (ENRB) was schematized and represented with a node-branch structure. In the simulation, only two major water demand sectors were considered: irrigation and hydropower. The major irrigation system in the basin is gravity flow (normally from reservoirs). The schemes were then allocated to the nearby nodes for their water withdrawals, and return flows from established schemes were directed to the immediate downstream nodes. Two flow series will be considered in the schematization, representing the input to the potential reservoir and the flows to water demand (irrigated) area.

The total river basin is subdivided into a number of sub-basins, which represent hydrological entities and are chosen such that it can represent various small water users within the sub-basin. For each of the sub-basins a separate water balance can be prepared. The links transport water between the different nodes. Such a network represents all of the basin's features which are significant for its water balance. The river basin network schematization of various nodes and links representing existing and potential (inactive) infrastructure or water users, and associated source priority list the characteristics of all nodes and links including operation rules and water allocation priorities. Figure 4-1, Figure 4-2 and Figure 4-3 show the schematization of Eastern Nile River Basin for GERD filling and operation phases, for future developments of cascades and future irrigation development in the Abbay river basin respectively.

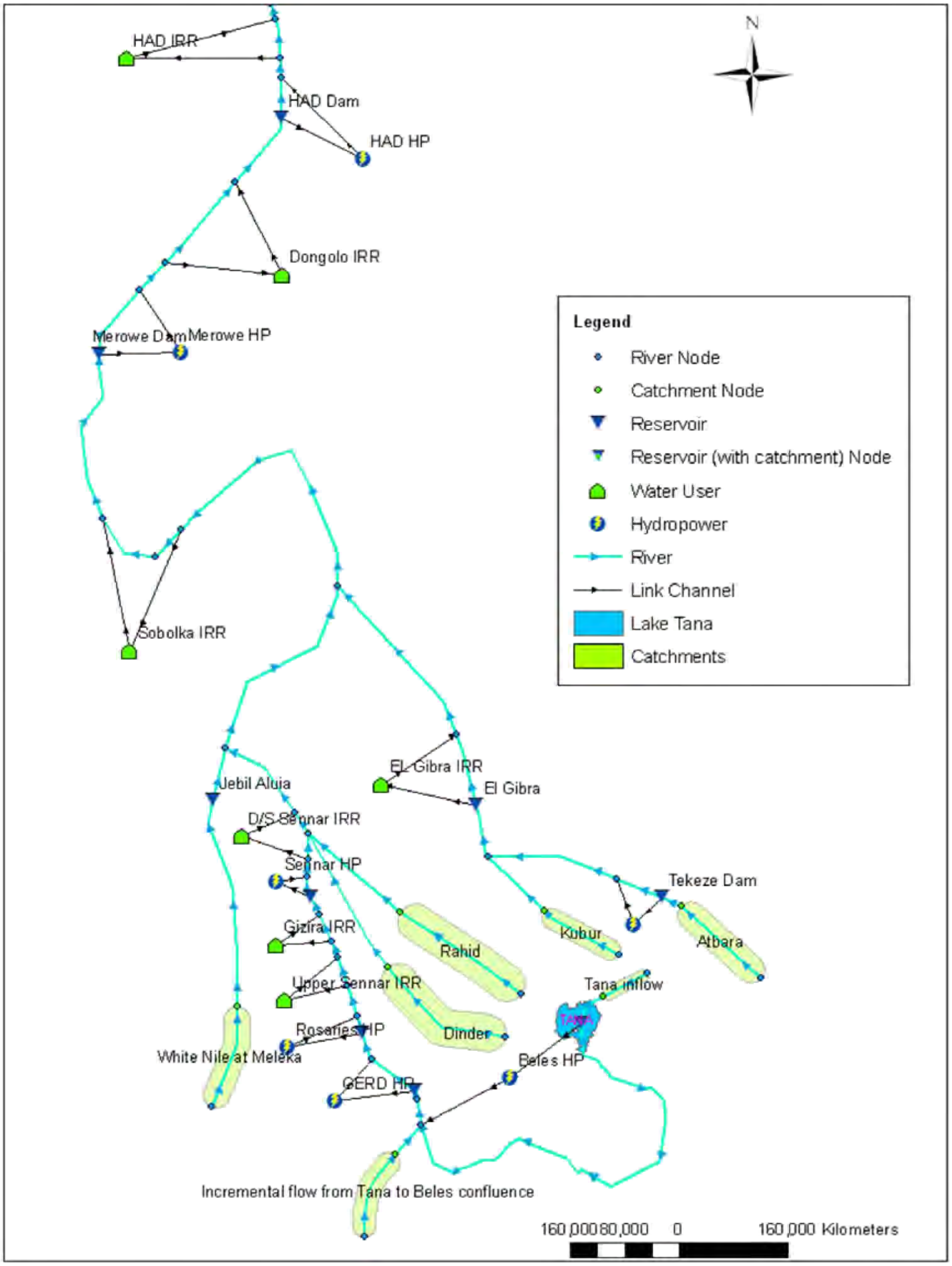

Figure 4-1: Schematization of Eastern Nile for filling and operation phases of GERD

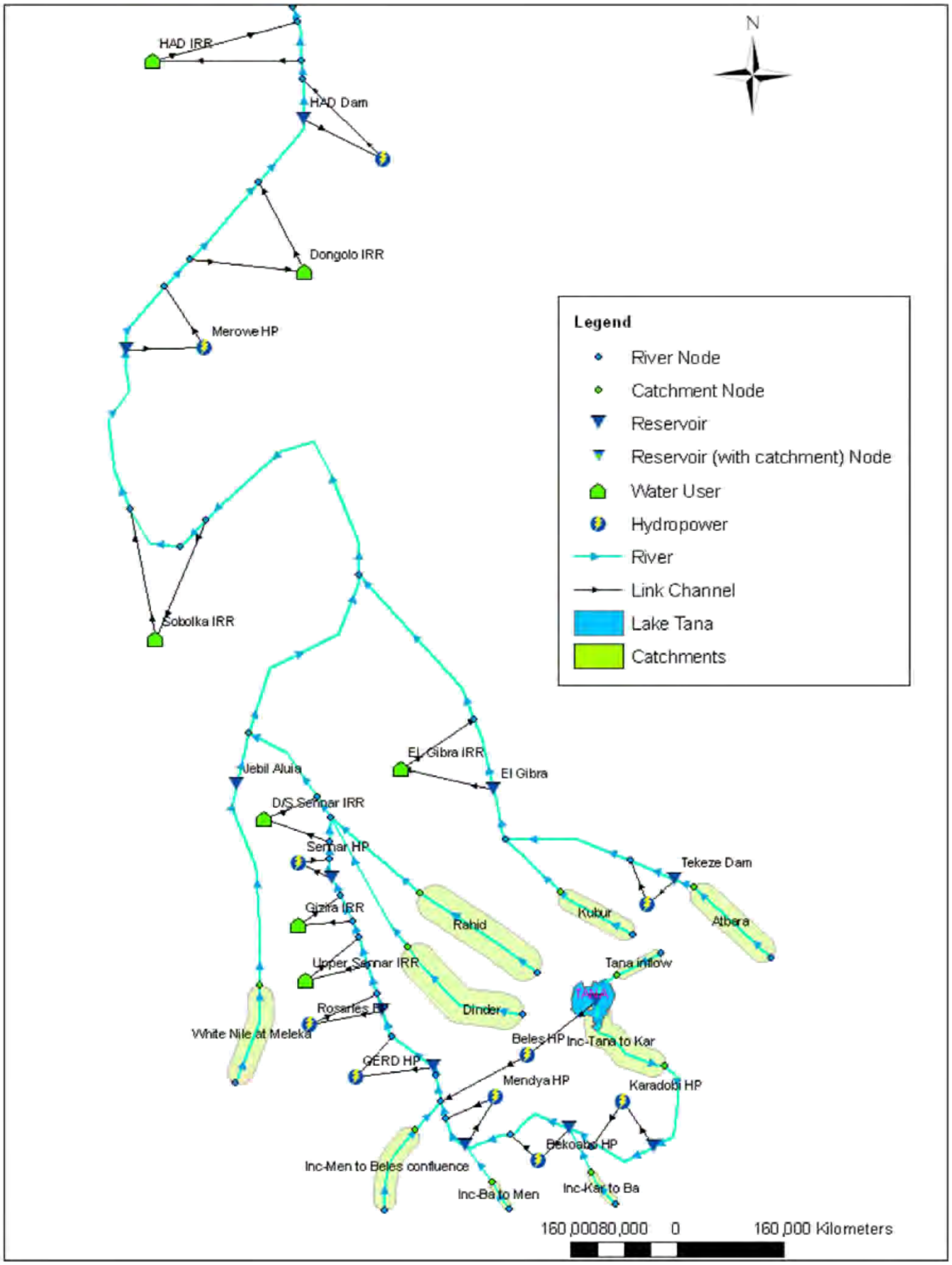

Figure 4-2: Schematization of Eastern Nile for upper cascaded simulation (including Karadobi, Bekoabo and Mendya)

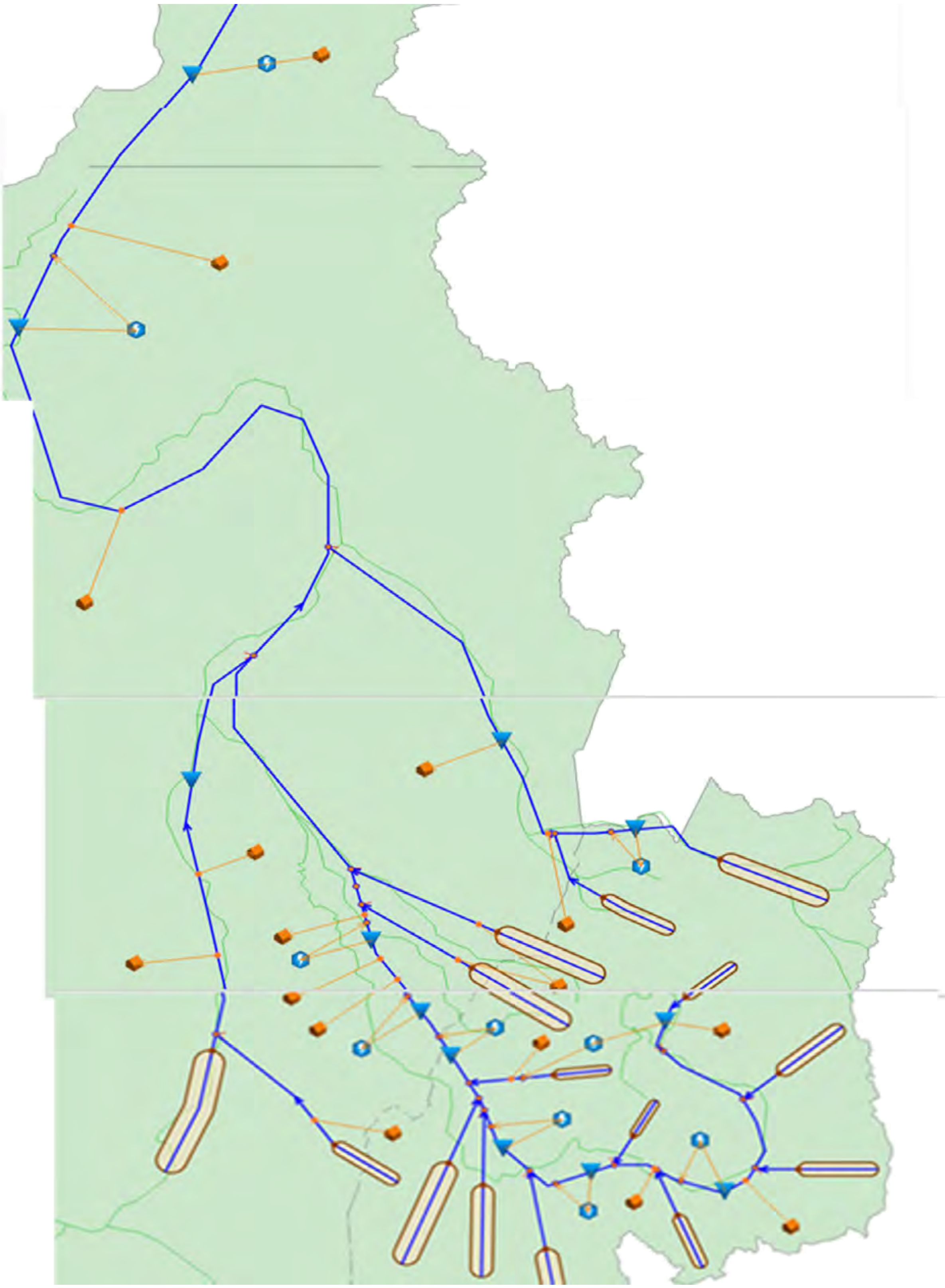

Figure 4-3: Schematization of Eastern Nile for future irrigation development

4.2. Simulation Scenarios

Scenarios are used to compare various "what if" cases and provide a structured method of thinking about possible future water resource development and management options, opportunities and risks, and how these might interact. The results are useful for consensus building and decision making. During this study, an investigation has been conducted to assess the future probable changes in the inputs of the water balance model which may impact on the spatial and temporal distribution of water availability in the basin. It is not a forecast; rather, each scenario is one alternative image of how the future can unfold. It is used in estimating the probable effects of one or more variables, situation analysis and long-range planning. In other words, a scenario is externalities which change the resource availability and distribution, and influence management decision.

There are two types of scenarios, which are exogenous scenarios and endogenous scenarios. The exogenous scenarios are scenarios which depend on natural events such as droughts, floods and others which occur naturally. The endogenous scenarios include water resource management aspects modified induced by human beings. For example, dams and related water diversion structures implemented for consumptive and non-consumptive water use modify the hydrology and water management aspects of the basin. These constitute endogenous scenarios. Table 4-1 presents sets of exogenous and endogenous scenarios considered in this study.

4.2.1. Exogenous Scenarios

Six exogenous scenarios have been considered to simulate water availability using the Mike basin and Mike Hydro models. Based on flow condition three exogenous scansions are extracted from the historical inflow sequence and considered to understand the impacts of flow variability during the filling stage of GERD. These are the normal flow, driest season flow and the wettest flows conditions during the 6 year filling phase of GERD. The normal flow scenarios constitute 6 years period average flow at HAD, which is equivalent to the long term historical average flow at HAD (~ 84 BCM). Details of the period and flow sequences are described in section 5.1. The dry flow scenario constitutes the worst flow sequence which is below the normal flow condition. In this scenario, worst dry flow conditions of 7 to 10 years were considered in the analysis (section 5.2). The wet flow scenario constitutes the flow period with the maximum 6 years flow sequence as described in section 5.3. In the filling stage, the study further investigated hypothetical flow scenario varying from +/– 5% to +/-20% to understand the extent of GERD influence during the filling phase (section 5.4).

Another exogenous scenarios included in this study is assessment of long term impacts/benefits of GERD over the coming 42 years period using the 1960 to 2002 historical time series data as one of possible ensemble scenarios that represents future inflow condition to GERD (Chapter 6). The other flow scenarios are stochastic time series flow scenarios (Moving average (ARMA11), EN MSIOA and Thomas-Fiering) as described in chapter 3 and 8. These flows are used to simulate future irrigation development in the Eastern Nile using Mike Hydro model (chapter 8).

4.2.2. Endogenous Scenarios

The endogenous scenarios considered in this study include existing and proposed dams and related hydraulic structures that divert water for consumptive and non-consumptive uses. Around 15 dams were constructed to divert irrigation water and generate hydropower from the Nile River. These dams (such as the Sennar Dam) have been implemented since 1925, and still more dams continue to be built. Most of the existing dams are in the Main Nile and Blue Nile sub-basins. The largest dam in the Nile Basin is the Aswan High.

Four dams (Renaissance, Mendya Bekoabo and Karadobi) in the Abbay sub-basin are most likely to be implemented soon. These four potential dams have been considered in the model as an endogenous scenario called “Dam Scenario”. The elevation difference from the lower end (GERD) to upper end (Karadobi) is 405 m. The number of reservoirs to be constructed depends on the available head with the basin that is the maximum or sum of reservoir heads should not be more than this available head. Different combinations of these reservoirs have different impact on the downstream reservoirs on inflow, energy production, loss and other parameters. Reservoirs in the White Nile and Atbara Rivers could not be affected by the reservoirs in the Blue Nile.

The other exogenous scenarios are future irrigation development and expansion in Sudan, south Sudan and Ethiopia. The scenarios are the combination of three stochastic time series flow and irrigation development trajectories which include: current, project anticipated to be implemented before 2025 and long term irrigation development (which can be implemented before 2050).

Table 4-1: Combined exogenous and endogenous scenarios

Endogenous Scenarios (Dam Scenarios) for long term development							
Existing condition	existing + GERD	existing + GERD + Karadobi	existing + GERD + Karadobi + Mendya	existing + GERD + Karadobi + Bekoabo low	existing + GERD + Karadobi + Bekoabo low + Mendya	existing + GERD + Bekoabo high	existing + GERD + Bekoabo high + Mendya

Filling of GERD

Exogenous Scenarios		Endogenous Scenarios (Dam Scenarios)									
		Without GERD					***With GERD***				
		Years					***Years***				
		6	7	8	9	10	6	7	8	9	10
Historical flow scenarios	Normal Flow										
	Dry Flow										
	Wet Flow										
Hypothetical flow scenarios	95% of mean flow										
	90% of mean flow										
	85% of mean flow										
	80% of mean flow										
	105% of mean flow										
	110% of mean flow										
	115% of mean flow										
	120% of mean flow										

GERD Operation

Exogenous Scenarios	***Endogenous Scenarios (Dam Scenarios)***	
	Without GERD	***With GERD***
Mean		
Lower limit		
Upper limit		

	Irrigation trajectories			
Dam	Current	phase I	Phase II	FDL
Current				
after GERD				
GERD and Upper cascades				

FDL =Full Development Level

As shown in above Table 4-1, there are 12 possible conditions for irrigation and dam scenarios combination. Furthermore, these scenarios will combine with three stochastic time series flows (ARMA11, Thomas Ferrying and EN MSIOA) and there are 36 conditions (scenarios) to see the situations of Eastern Nine by considering different stages (phases) of hydropower and irrigation development with different flow series

- Current situations: is reference situation which represent the current level of development or the existing hydropower/ dams and irrigation development.
- Phase I: represent irrigation development projects which are under study and under construction and anticipated to be completed before 2025.
- Phase II: represent all identified Ethiopian irrigation potential advanced either to pre-feasibility or feasibility level and anticipated to be implemented before 2050.
- FDL (Full Development Level): this includes all irrigation potential in Ethiopia, Sudan and south Sudan that is either identified as part of country master plan, and potentially identified under current study.
- after GERD: is after the implementation of GERD
- GERD and upper cascades: is the operation of GERD and reservoirs above GERD (Karadobi, Bekoabo and Mendya) with currently operating reservoirs

Table 4.1 summarizes the endogenous and exogenous scenarios (shaded cells). For full Blue Nile development, there are 8 scenarios. For GERD filling there are 11 exogenous and two dam scenarios with different filling periods for historical dry and wet flows. For GERD operation phase there are three flow conditions and two dam scenarios.

4.3. Validation and Model Performance Analysis

Validation was carried out by comparing the observed flows with outputs of Mike Basin models at selected stations of Kessie, Border Khartoum and Dongola (High Aswan Dam inflow). To facilitate the evaluation, visual as well as statistical comparison has been done. Statistical parameters such as use of Nash-Sutcliffe Efficiency (NSE), Coefficient of determination (R^2), Mean Relative bias (PBAIS) and Root Mean Square error (RSR) were used (Table 4-2).

Table 4-2: General performance ratings for Nash–Sutcliffe Efficiency (NSE) mean relative bias (PBIAS), root mean square error-standard deviation (RSR) and coefficient of determination (R^2) for a monthly time step

Formulae	Value	
$NSE = 1 - \left[\frac{\sum_{i=1}^{n} (X_{obs}(i) - X_{simu}(i))^2}{\sum_{i=1}^{n} (X_{obs}(i) - \overline{X}_{obs}(i))^2} \right]$	• 0.75 < NSE < 1 • 0.65 < NSE < 0.75 • 0.50 <NSE < 0.65 • NSE < 0.50	• Very good • Good • Satisfactory • unsatisfactory
$PBIAS \left[\frac{\sum_{i=1}^{n} (X_{obs}(i) - X_{simu}(i)}{\sum_{i=1}^{n} (X_{obs}(i)} * 100 \right]$	• PBIAS <$\pm$10% • $\pm$10% < PBIAS <$\pm$15% • $\pm$15% <PBIAS <$\pm$25% • PBIAS >$\pm$25%	• Very good • Good • Satisfactory • unsatisfactory
$RSR = \left[\frac{\sqrt{\sum_{i=1}^{n} (X_{obs}(i) - X_{simu}(i))^2}}{\sqrt{\sum_{i=1}^{n} (X_{obs}(i) - \overline{X}_{obs}(i))^2}} \right]$	• 0< RSR <0.50 • 0. 50 <RSR < 0.60 • 0.60 < NSE <0.70 • NSE<0.70	• Very good • Good • Satisfactory • unsatisfactory
$R^2 = \frac{\left[\sum_{i=1}^{n} (X_{obs}(i) - \overline{X}_{obs}((X_{simu}(i) - \overline{X}_{simu}) \right]}{\sum_{i=1}^{n} (X_{obs}(i) - \overline{X}_{obs})^2((X_{simu}(i) - \overline{X}_{simu})^2}$	R^2 >0.5	• Satisfactory

The equations and the interpretation of the values of the statistical functions are given in Table 4-2. The monthly stream flow has been compared against the observed data.

Table 4-3: Model performance statistics for validation periods

Validation								
Location	Observed Mean MCM)	Simulated Mean MCM)	Observed Stdv	Simulated Stdv	NSE	R^2	PBIS	RSR
Kessie	16581	16507	2122	2435.7	0.95	0.97	0.4	0.23
Border	48192	48350	5068	5312.5	0.99	0.99	-0.3	0.09
Khartoum	41300	42899	4759	5436	0.88	0.91	-0.4	0.35
Dongola	72538	72544	5746	7573	0.78	0.89	-0.02	0.47

Table 4-3 indicates that the total simulated monthly stream flow or NSE range 0.75 < NSE <1.00 for all locations which shows very good performance rating. The coefficient of determination for all locations is 0.94 which shows very good performance of the model. (Moriasi et al. 2007). The percentage of bias is within the range of very good performance rating for all selected locations. The model performs very well because 0.00< RSR < 0.50 for validation period of Eastern Nile at Kessie, El-Deim, Khartoum and Dongola. The model performance is satisfactory for the whole Eastern Nile Basin. Good performance of the model in the validation period indicates that the fitted parameters during validation period can be taken as a representative set of parameters for the ENB. The model shows better simulation for the upstream stations than for the downstream stations.

4.3.1. Abbay at Kessie

The simulated flow has been plotted against the observed flow for the validation periods. The result of the flow for the Abbay at Kessie is shown Figure 4-3. There is a good agreement between simulated and observed monthly flows. The low flows are quite well represented and there is good overall agreement in the shape of the hydrograph. In the context of low flow, the observed and simulated flow matched each other well. The model has simulated the behavior of the observed flow during the validation period. The rising and falling limbs have been captured.

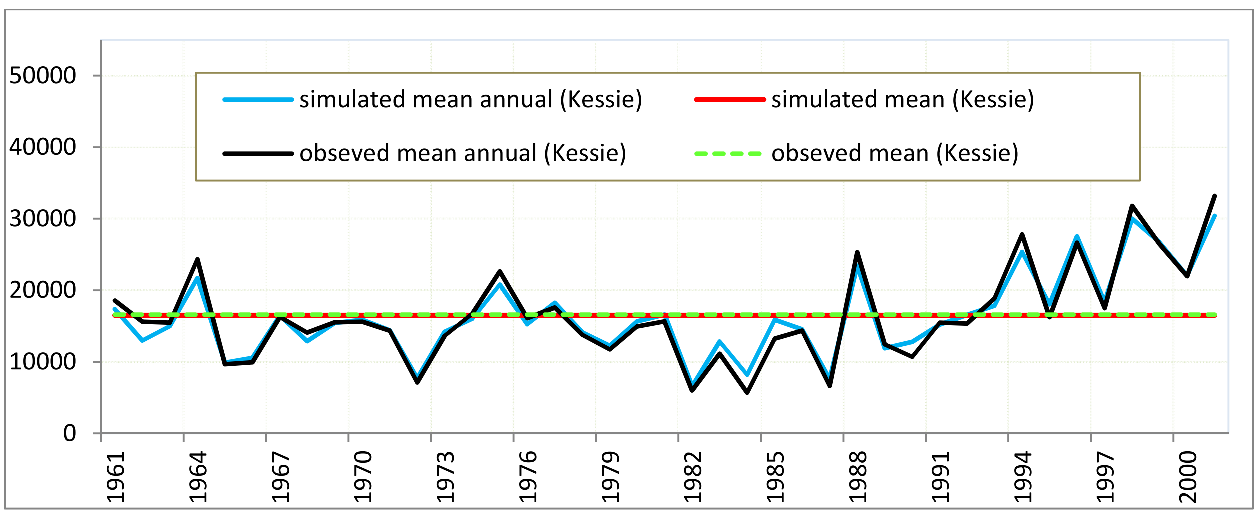

Figure 4-4: Annual flow of simulated and observed at Kessie (MCM)

4.3.2. Abbay at Border

There is a good agreement between simulated and observed monthly flows (Figure 4-4), and only 0.3% difference between simulated and observed annual flows. The seasonal variation shows fairly good agreement between observed and simulated high and low flows. The observed and simulated flow matched each other well for both low and high flow. This station has shown good simulation performance both in dry and wet periods. The rising and falling limbs have been captured.

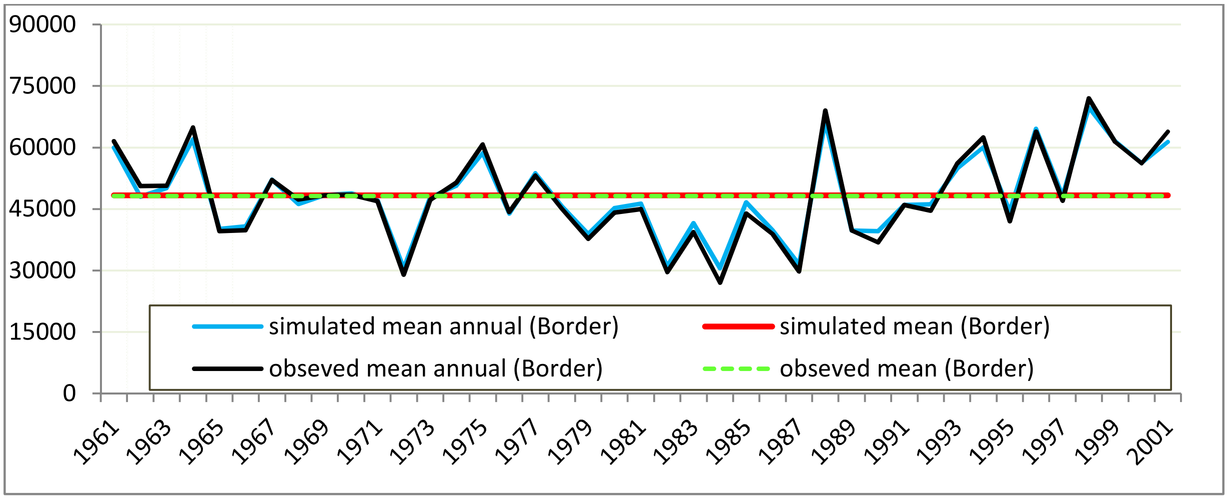

Figure 4-5: Annual flow of simulated and observed at Border (MCM)

4.3.3. Blue Nile at Khartoum

The simulated flow has been plotted against the observed flow for the model performance analysis. The Mike Basin simulated flows in the Blue Nile are presented for the full model simulation period (1961-2002), compared to the observed flows at Khartoum before the confluence with the White Nile. A comparison of the flow statistics is included in Table 4-3. The validation results are presented graphically in Figure 4-5. There is a good agreement between the simulated and the observed flows at Khartoum. The mean annual flows are 4% greater than the observed with an overall R^2 of 91% (Table 4-3).

As shown the visual comparison of simulated flow and observed flow, the model shows good performance in the simulation period. The model slightly under-predicted the high flows (Figure 4-5). In the context of low flow, the observed and simulated flow matched each other relatively well. Overall, this station has shown good simulation performance both in dry and wet periods. The rising and falling limbs have been more or less captured.

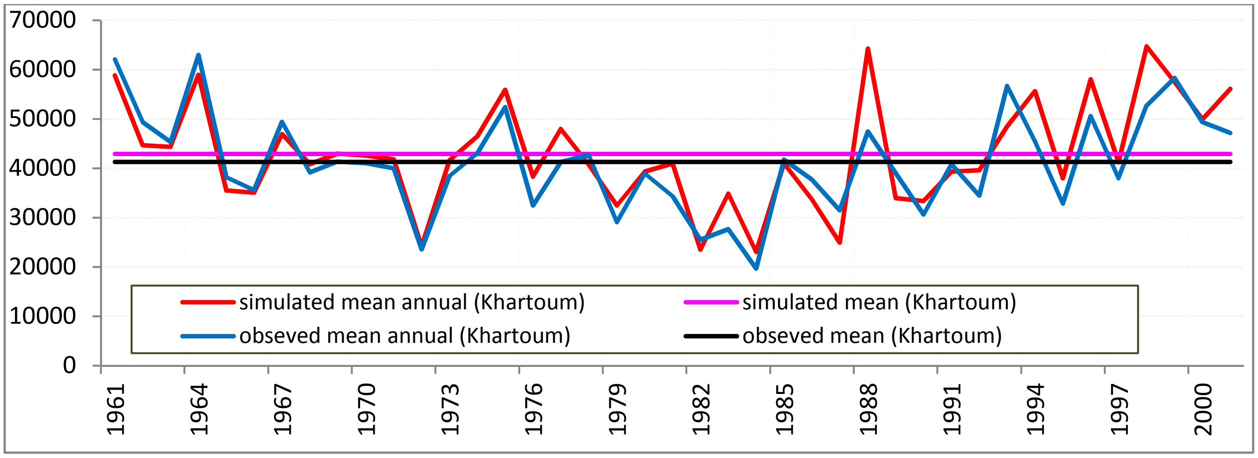

Figure 4-6: Annual flow of simulated and observed at Khartoum (MCM)

4.3.4. Main Nile at Dongola

The simulated flow has been plotted against the observed flow for the model performance. The simulated flows in the main Nile at Dongola following the validation of catchment flows in Mike basin are presented for the full model simulation period (1961-2002. A comparison of the flow statistics is included in Table 4-3. The validation results are presented graphically in Figure 4-6. As compared to the upstream sites, the model performs less in this station, but it is more than satisfactory. Overall, this station has shown good simulation performance both in dry and wet periods. The rising and falling limbs have been captured.

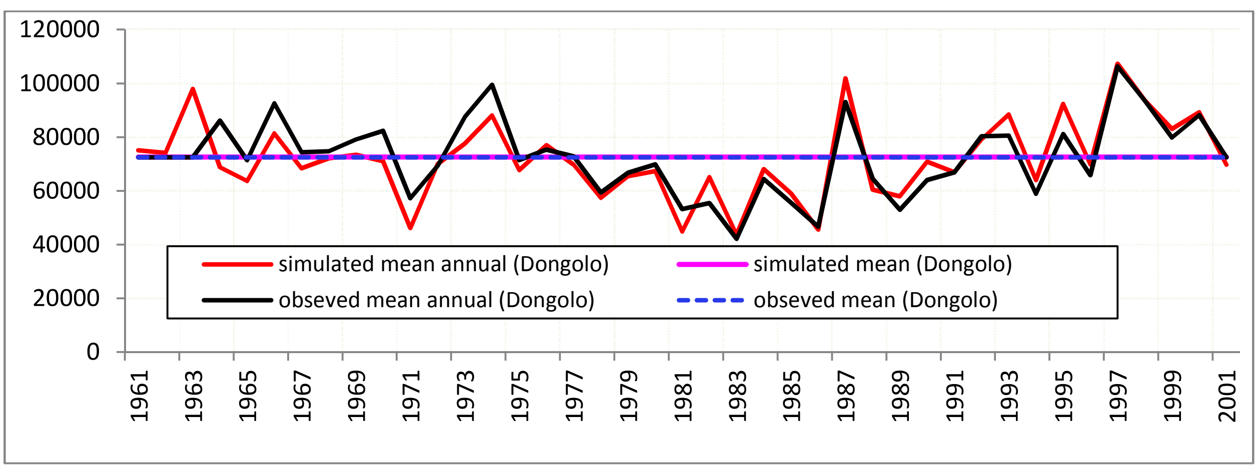

Figure 4-7: Annual flow of simulated and observed at Dongola (MCM)

Chapter Five

Assessment of GERD Impacts on High Aswan Dam (HAD) Reservoir during Impounding Phase

The filling stage of GERD is assessed based on selected historical flow scenarios and hypothetical scenarios as described in Section 4.2.1 and shown in Table 4-1. Three flow conditions are extracted from the historical inflow sequence. These are the normal flow, driest season flow and the wettest flows conditions during the 6 year filling phase of GERD. As described in section 4.2.1, the study further investigated hypothetical flow scenario varying from +/– 5% to +/-20% to understand the extent of GERD influence during the filling phase (section 5.4). The simulation results for each scenario are presented in subsequent sections.

5.1. Simulation under Normal Flow Scenario

Under normal scenario, the 6 years flow sequence average flow at HAD is about 85.5 BCM, which is nearly equivalent to the long term flow at HAD. The 6 year flow sequence which is equivalent to the long term mean flow condition is the historical flow sequence between 1973 and 1978. Corresponding inflow series at GERD and corresponding nodes were abstracted for the same period and used in the simulation.

Table 5-1: Normal flow sequence for HAD Naturalized (MCM)

Year		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1970	**2011**	3085	2890	2697	3070	3011	3356	4378	19009	20744	13836	7218	4931	88225
1971	**2012**	3795	3458	2852	3160	3180	3101	4992	16350	18669	12501	7130	4988	84176
1972	**2013**	3648	3416	2536	2902	3620	3124	5312	12469	12413	8329	4915	3103	65787
1973	**2014**	2328	2119	2082	2423	3289	3275	3969	18217	20362	12981	6342	4110	81497
1974	**2015**	2860	2590	2301	2586	3169	3565	6268	19087	21125	13540	6764	4684	88539
1975	**2016**	3097	2826	2456	2726	2909	4923	12340	22688	15924	9721	6821	5103	91534
1976	**2017**	4369	4056	2808	3064	3355	3498	5138	15720	20944	11634	5762	4363	84711
1977	**2018**	2849	3010	2484	2783	2860	3287	5624	15495	18387	13459	8222	4959	83419
1978	**2019**	3746	3034	2503	2942	3660	3551	5457	14326	17825	14734	7053	4513	83344
Mean (2014-2019)		**3208**	**2939**	**2439**	**2754**	**3207**	**3683**	**6466**	**17589**	**19095**	**12678**	**6827**	**4622**	**85507**

As the filling stage of GERD dictates, GERD impounding stage will not start in 2011 but 2014 and simulation considers filling from 2014. Therefore the 1973-1978 historical inflow series at GERD and at other nodes represents the filling stage of GERD from 2014 to 2019. Table 5-1 through 5-3 present the sequence of average years at HAD (naturalized and Sudanese irrigation deducted) and at GERD on the same period (1973 – 1978).

Table 5-2: Normal flow sequence for downstream Nile (Sudanese irrigation deducted) (MCM)

Year		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1970	**2011**	671	583	494	579	533	302	674	4995	5656	3710	1790	1141	**21128**
1971	**2012**	880	761	560	635	541	249	857	4210	5044	3316	1764	1158	**19975**
1972	**2013**	837	734	462	540	667	324	957	3064	3197	2085	1110	602	**14579**
1973	**2014**	447	379	339	435	510	298	555	4761	5543	3458	1532	899	**19156**
1974	**2015**	605	485	356	448	449	313	1228	5018	5768	3623	1656	1069	**21017**
1975	**2016**	674	539	395	493	470	714	3020	6081	4233	2495	1673	1192	**21979**
1976	**2017**	1050	881	460	546	527	325	897	4024	5715	3060	1360	974	**19817**
1977	**2018**	601	572	395	501	425	269	1041	3957	4960	3599	2087	1150	**19558**
1978	**2019**	866	592	395	517	620	353	992	3612	4794	3975	1742	1018	**19478**
Mean (2014-2020)		**707**	**575**	**390**	**490**	**500**	**379**	**1289**	**4575**	**5169**	**3368**	**1675**	**1050**	**20167**

Table 5-3: Normal flow sequence for Abbay at GERD (MCM)

Year		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Yearly
1970	2011	645	459	553	444	531	1159	7520	19057	11241	5611	2002	1006	50228
1971	2012	692	436	379	341	566	1733	7954	18237	10329	4430	2244	1111	48454
1972	2013	698	432	395	468	617	1328	5628	10340	6186	2681	1389	819	30980
1973	2014	562	359	315	312	798	1735	6609	19551	10920	5207	1975	1053	49396
1974	2015	723	445	455	376	865	1941	10843	18661	10613	4479	1780	1108	52288
1975	2016	619	501	406	348	453	1680	8793	20710	18026	5527	2150	1256	60469
1976	2017	838	522	537	459	751	1521	6787	17923	8963	3320	2233	1105	44961
1977	2018	678	491	481	388	581	1643	11565	17756	11684	5575	3360	1250	55454
1978	2019	702	427	398	369	581	1489	9033	14324	9986	6340	2052	1167	46867
mean (2014_2019)		687	457	432	375	672	1668	8938	18154	11699	5075	2258	1156	51573

5.1.1. GERD Impounding Results of Historical Normal Flow Sequence

Based on the implementation schedule of GERD, simulation indicates GERD water level will reach 560 m.a.s.l in August 2014 and can generate energy starting from this date. GERD will reach its dead storage level (590 m.a.s.l) and normal water level (NWL) of 640 m.a.s.l in September 2015 and at the end of year 2019 respectively (Figure 5-1, Table 5-4).

Table 5-4: GERD impounding stage with average sequence: yearly inflows, losses, outflows and energy generation

Year	Inflow (MCM)	Out Flow (MCM)	Loss (MCM)	Stored Volume (MCM	Energy (GWh)
2014	48814	45139	85	3000	567
2015	50401	32412	423	18846	2738
2016	58562	28920	922	29075	7618
2017	43179	40994	1292	1026	9198
2018	53467	39425	1350	12433	9198
2019	45242	34721	1359	8030	7551
Mean (2014-2019)	49944	36935	905	12068	6145
% of inflow	100	74.0	1.8	24.2	-

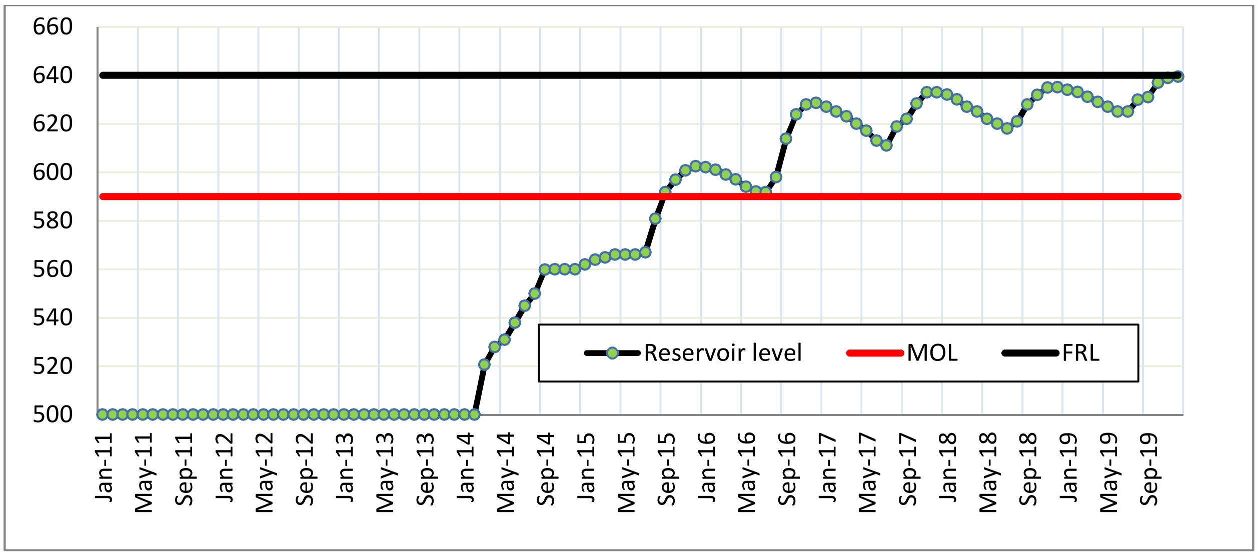

Figure 5-1: GERD water level during impounding with normal flow

During the filling period, the monthly out flow from GERD will generally be more uniform and the dry season outflow to downstream countries is greater than the inflow to GERD (Figure 5-2). The average annual out flow from GERD during the filling period is about 74 % of the mean annual inflow during that period. It means the amount of average inflow storage including evaporation loss is about 26% of the inflow. As shown in Figure 5-2, the outflow distribution is such that it is greater than the inflow during the dry months and less during the wet season providing nearly uniform outflow from GERD as shown by the coefficient of variation. The coefficient of variance of the monthly inflow to and outflow from GERD is 1.22 and 0.8 respectively. Average Annual evaporation loss from GERD is only 0.9 BCM which is 1.8% of the average inflow volume during the filling period. As shown in the Table 5-4, energy generation during the impounding stage, the average annual energy generation will be 6145 GWh.

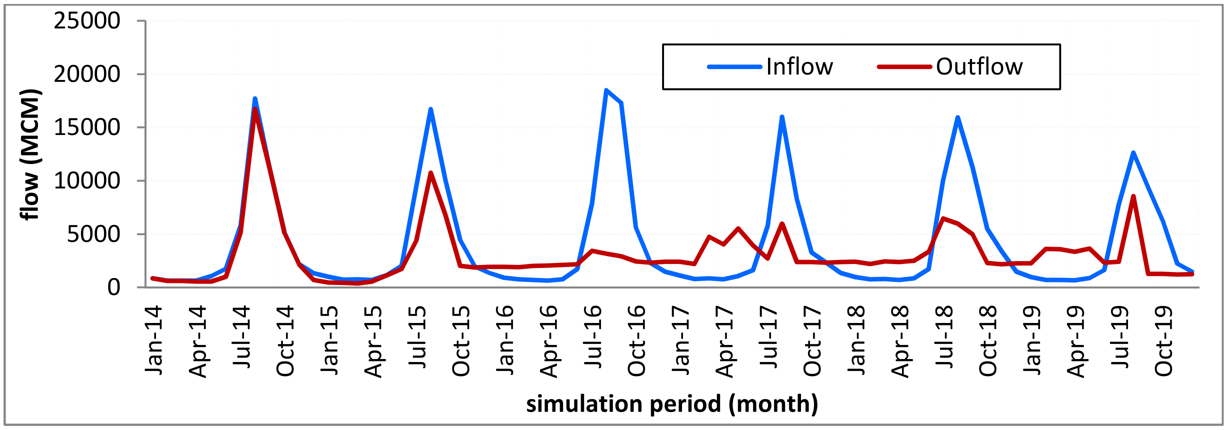

Figure 5-2: Monthly inflow and outflow of GERD during impounding with mean sequence

5.1.2. GERD Impounding and HAD Performance under Historical Normal Flow Sequence

Table 5-5a and 5- 5b presents the hydrological characteristics of HAD before GERD and during the filling period of GERD. The percentage change in Table 5-5b is the difference in the hydrological characteristics of HAD before GERD and during the filling stage of GERD at HAD.

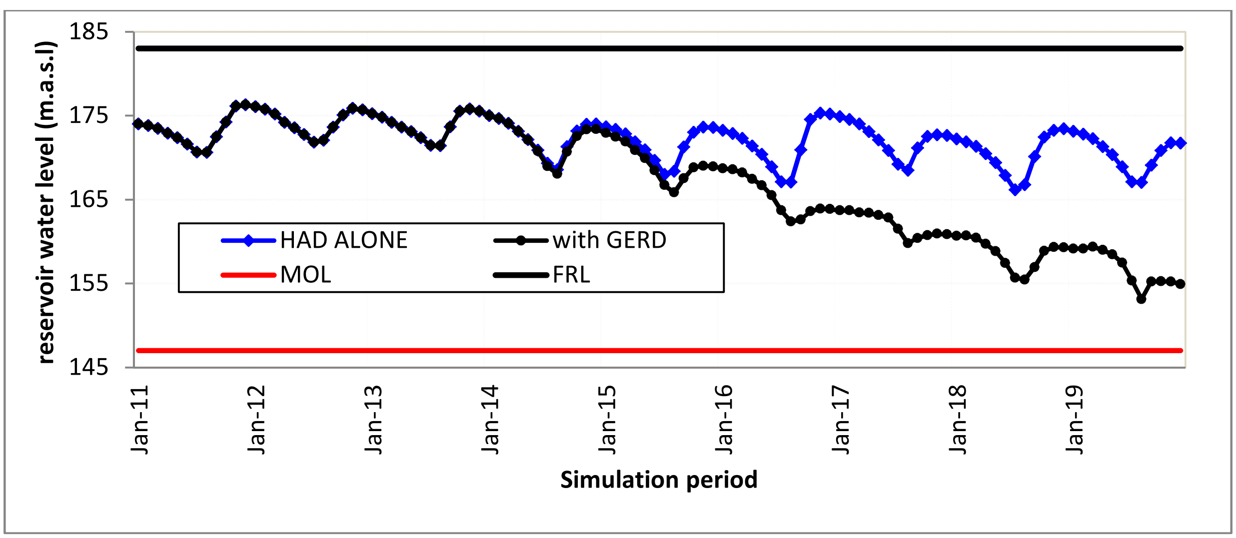

Figure 5-3: HAD water level during impounding with mean flow

The average annual inflow to HAD reservoir decreases by about 19 % or 13 BCM as shown in Table 5-5b. The water level of HAD at the end of the filling period reaches 155 m. however, HAD Minimum Operating Level (147 m) will not be reached during the filling stage (Figure 5-3). Does this reduction have impact on the performance of HAD water uses? This is presented in terms of impact on the agriculture water withdrawal and hydropower generation at HAD

i) *Water withdrawal for Agricultural:* water withdrawal from HAD during the 6 years filling period is not affected in Egypt as shown in Table 5-5b. Despite the inflow reduction by about 19%, and reduced HAD water level, the water requirement from HAD for agriculture is not affected. There is no sign of deficit in any one month during this phase of the project (Table 5-5b). The reduction in storage volume never reached the minimum operation level (147 m.a.s.l) under full withdrawal. This is mainly due to the combined benefit of the large multi-year stored water of HAD as well as water gained from evaporation due to reduced level at HAD.

ii) *Energy production*: Figure 5-4 depicts monthly energy generation of HAD during GERD filling period. Energy production is related to the water level and water discharge amount. Due to the water level lowering at HAD, the mean manual energy production is affected by 13% reduction. HAD annual energy generation may decrease from 0.5% to 24% between 2015 and 2019 (Table 5-5b) over the filling period. According to the simulation results, the energy reduction becomes higher in the last three years of the filling period, underlying the importance of joint reservoir options.

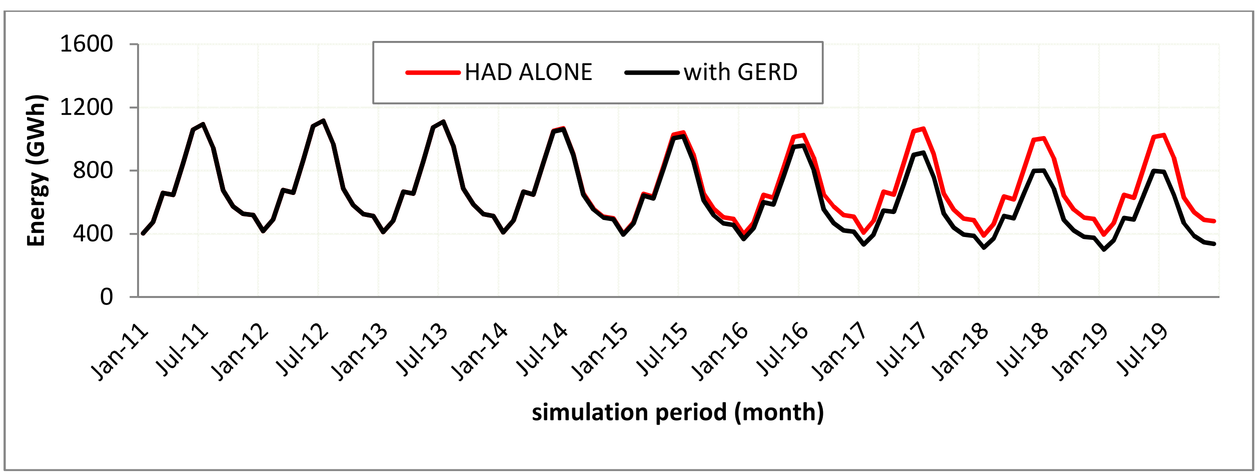

Figure 5-4: Monthly energy production of HAD during filling with mean flow

When viewed from regional perspective, the overall energy benefits from joint operation of GERD and HAD increases tremendously even during the filling phase. The total energy production from the two dams provides about 5112 GWh/year which is 63% incremental of the current cases.

iii) *Water gain from HAD*: Figure 5-5 demonstrates monthly water loss from HAD during filling period. HAD evaporation losses will be reduced during GERD impounding with historical mean flow. The overall 6 years average water loss due to evaporation at HAD has shown a gain of 22% from the past average losses. This means the water gain from lost evaporation over 6 years period reaches to 3.4 BCM (Table-5b). This gained water from the evaporation effectively contributes to maintain HAD to fully withdraw irrigation water without being affected during the infilling phase of the GERD project. It is also a manifestation of how water be gained from Operating HAD at lower level in the future.

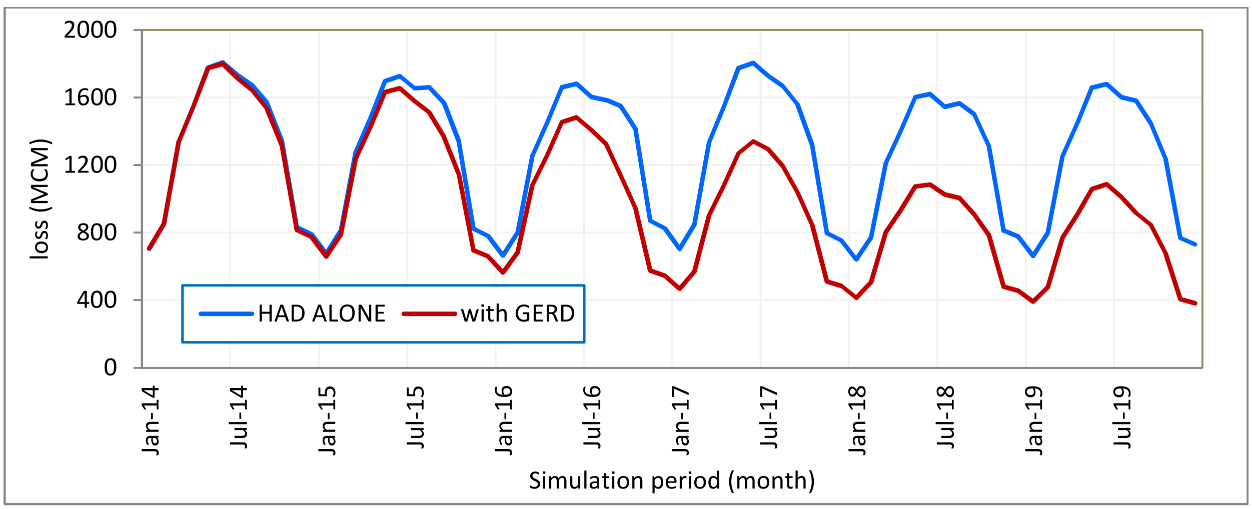

Figure 5-5: HAD annual water loss during impounding with mean flow

Figure 5-6 demonstrates the mean annual water loss from HAD and the cumulative water loss from the two reservoirs. As shown in the figure, annual water loss from HAD will be less as compared to the current situation (baseline scenario). The cumulative loss from the two reservoirs will be less than the baseline scenario. The mean annual loss from both reservoirs will be 12907 MCM which is 16% less than the baseline scenario loss. Overall, there is no impact of filling stage of GERD on agricultural water use from HAD. The only impact will be on energy production due to water level reduction of HAD.

Table 5-5a: HAD yearly inflows, losses, outflows and energy generation for HAD alone during impounding with mean flow

Year	Inflow (MCM)	Loss (MCM)	Outflow (MCM)	Deficit (Number of month)	Energy (GWH)
2014	65998	15972	*56378*	0	8304
2015	69834	15494	*56378*	0	8177
2016	79600	15356	*56378*	0	8136
2017	59633	15830	*56378*	0	8265
2018	75402	14759	*56378*	0	7980
2019	63168	14862	*56378*	0	8015
Mean	*68939*	*15379*	*56378*	*0*	*8146*

Table 5-6b: HAD yearly inflows, losses, outflows and energy generation for HAD influenced by GERD during impounding with mean flow and the difference in percentage from HAD alone

Year	Inflow (MCM)	Inflow Change (%)	Loss (MCM)	Loss Change (%)	Energy (GWh)	Energy change (%)	Outflow (MCM)	Outflow change (%)
2014	62328	*-5.6*	15809	*-1.0*	8262	*-0.5*	56378	*0*
2015	51839	*-25.8*	14354	*-7.4*	7876	*-3.7*	56378	*0*
2016	49962	*-37.2*	12455	*-18.9*	7320	*-10.0*	56378	*0*
2017	57448	*-3.7*	10999	*-30.5*	6852	*-17.1*	56378	*0*
2018	61362	*-18.6*	9470	*-35.8*	6293	*-21.1*	56378	*0*
2019	52649	*-16.7*	8923	*-40.0*	6073	*-24.2*	56378	*0*
Mean	*55931*	*-18.9*	*12002*	*-22.0*	*7113*	*-12.7*	*56378*	*0*

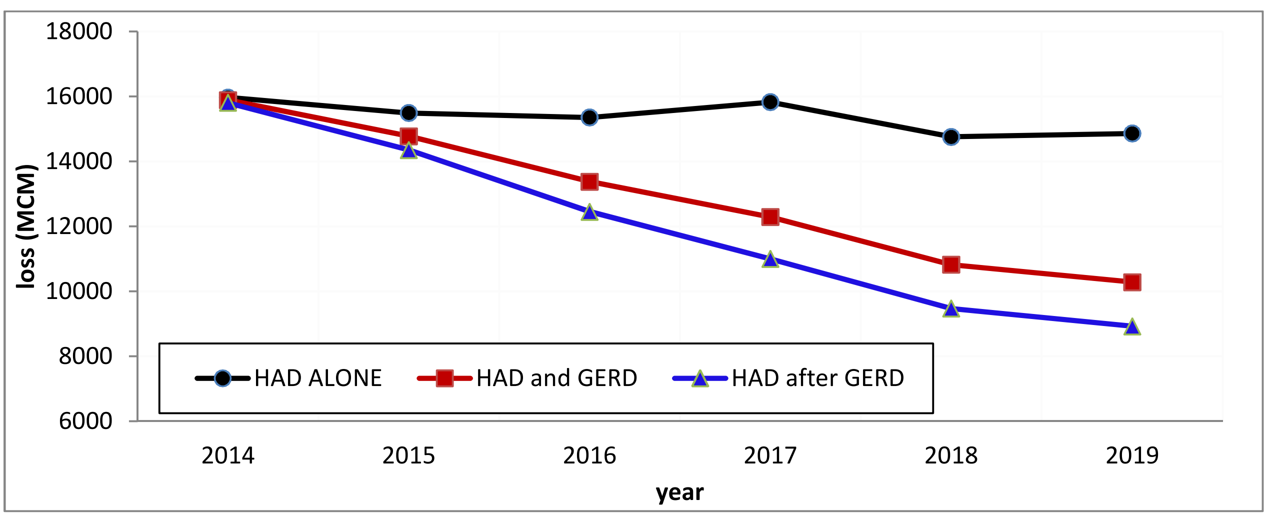

Figure 5-6: HAD annual water loss during impounding with mean flow for HAD alone, HAD after GERD and HAD with GERD + GERD

5.2. Impounding Stage Simulations under Historical Dry Flow Sequences

This is scenario considers the worst hydrological scenario during the filling of GERD. Under this scenario, 7, 8, 9 and 10 years filling period was assessed. Table 5-6 and Table 5-7, shows the selected sequence of dry years which is the period between 1981 and 1987, 1980 to 1987, 1979 to 1987 and 1978 to 1987 for 7, 8, 9 and 10 years respectively. The average value of HAD inflows during these years is the historical minimum average and can be considered one of the rare hydrological occurrences. Statistically, It is a remote possibility to occur but is part of the historical record and we consider its impact during the filling stage of HAD. The average annual flows in this dry period are equal to 71.9, 72.4, 72.5 and 73.6 BCM/year for the 7, 8, 9 and 10 years respectively. Compared to the long term historical average annual flow of 84 BCM, the average dry flow is less by about 15%.

Table 5-7: Mean monthly sequence of historical dry years – HAD naturalized inflows (MCM) (Source GERD report)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1978	3746	3034	2503	2942	3660	3551	5457	14326	17825	14734	7053	4513	**83344**
1979	3676	3308	2823	3089	3744	3564	4279	13530	15206	10318	5849	3721	**73107**
1980	2653	2467	2369	2895	3267	3342	5559	15260	16524	11560	6190	3821	**75907**
1981	2589	2416	2399	2818	3135	3095	4853	14347	17828	12550	6264	4123	**76417**
1982	2675	2393	2385	2689	2789	2617	9420	6080	10362	12439	6527	3339	**63715**
1983	3475	3215	2742	3059	3161	3213	3506	4807	22613	20452	11820	4683	**86746**
1984	3418	3177	2627	2825	3051	3302	4752	7786	12831	9045	5228	3827	**61869**
1985	3376	3187	2661	3096	3510	3436	4833	12931	17724	12805	6610	4374	**78543**
1986	3407	3154	2735	3056	3838	3282	5375	13484	15331	10582	5794	3985	**74023**
1987	3366	3126	2811	3077	3413	3572	4286	6008	12137	10423	5975	4088	**62282**
Mean (7 years)	**3316**	**3076**	**2689**	**2977**	**3279**	**3340**	**5663**	**10480**	**16379**	**13358**	**7300**	**4202**	**71942**
Mean (8 years)	**3120**	**2892**	**2591**	**2939**	**3271**	**3232**	**5323**	**10088**	**15669**	**12482**	**6801**	**4030**	**72438**
Mean (9 years)	**3182**	**2938**	**2617**	**2956**	**3323**	**3269**	**5207**	**10470**	**15617**	**12242**	**6695**	**3996**	**72512**
Mean (10 years)	**3238**	**2948**	**2606**	**2955**	**3357**	**3297**	**5232**	**10856**	**15838**	**12491**	**6731**	**4047**	**73595**

Table 5-8: Mean monthly sequence of historical dry years – GERD inflows (MCM)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1978	928	576	498	413	583	1327	7730	13277	9580	6541	2275	1335	**45063**
1979	900	597	466	397	808	1437	6472	12738	7393	3720	1739	1037	**37704**
1980	686	474	429	482	533	1161	6832	15523	10296	4554	1979	1183	**44132**
1981	750	670	803	475	650	1039	8154	14530	10569	4490	1816	1058	**45002**
1982	753	477	501	428	506	963	3815	7870	6935	4703	1666	956	**29574**
1983	646	423	420	477	688	1088	3576	15110	8988	4923	1968	1049	**39357**
1984	629	416	342	282	456	1687	5839	7851	5976	2027	907	625	**27036**
1985	434	317	301	463	636	1264	5722	15866	12157	4010	1669	1018	**43857**
1986	651	442	461	524	1297	1275	7751	12156	8542	3493	1425	833	**38851**
1987	547	378	571	528	930	1919	3489	9689	5582	3426	1751	919	**29730**
Mean (7 years)	**605**	**416**	**438**	**436**	**699**	**1406**	**6162**	**13287**	**8966**	**4461**	**1765**	**995**	36201
Mean (8 years)	**637**	**450**	**478**	**457**	**712**	**1300**	**5647**	**12324**	**8631**	**3953**	**1648**	**955**	37192
Mean (9 years)	**666**	**466**	**477**	**451**	**723**	**1315**	**5739**	**12370**	**8493**	**3927**	**1658**	**964**	37249
Mean (10 years)	**693**	**477**	**479**	**447**	**709**	**1316**	**5938**	**12461**	**8602**	**4189**	**1720**	**1001**	38031

5.2.1. GERD Impounding Results for Selected Historical Dry Flow Sequences

Figure 5-7, Table 5-8 and Table 5-9 summarize GERD impounding simulation results considering a sequence of dry year periods (7 to 10 years). it's the minimum operating level (590 m.a.s.l) will reach in in years 2015, 2016,2017 and 2018 and the NWL (640 m.a.s.l) will reach at the end of year 2020, 2021, 2022 and 2023 for 7, 8, 9 and 10 years filling period respectively.

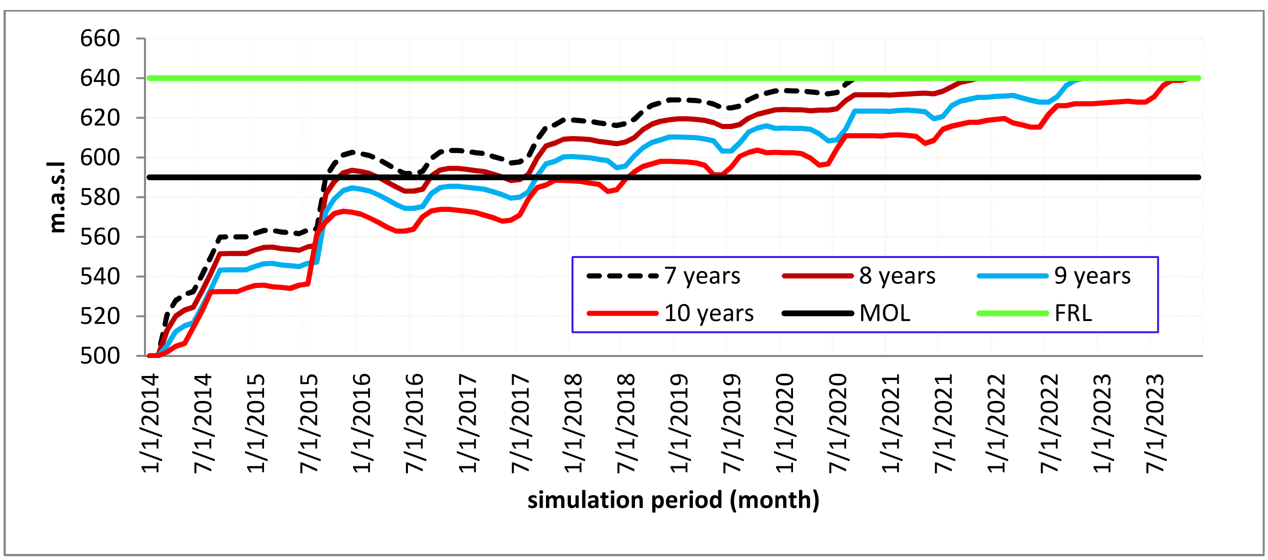

Figure 5-7: Pool level of GERD during filling with historical dry flow for different filling period

Table 5-9: GERD impounding stage with historical dry sequence of 7 years filling period: yearly inflows, losses, outflows and energy generation

Year	Inflow(MCM)	Outflow (MCM)	Loss (MCM)	Stored volume (MCM)	Energy (GWh)
2014	30217	26593	81	3000	567
2015	33230	12911	447	21005	2738
2016	28685	26854	802	877	6062
2017	40399	22615	925	16437	6132
2018	35190	19639	1215	14290	6132
2019	31400	22267	1413	7608	6132
2020	58423	46531	1517	10783	6132
Mean (2014-2020)	36792	25344	914	10571	4842

Yearly GERD outflows during the impounding stage are limited between 13 and 46.5 BCM (Table 5-8). Compared to annual inflow to GERD, the outflow release reaches 40 % to 94 %. Energy generation will be limited, especially in 2014 and 2015 because of GERD water level operates close to the minimum operating level.

Table 5-10: Storage (MCM) during filling with dry flow for two cases for 4 different filling length of period

Year	7 YEARS	8 years	9 years	10 years
2014	3000	2160	1166	222
2015	21005	15178	11075	6918
2016	877	592	466	333
2017	16437	12314	9213	6763
2018	14290	11174	9438	6031
2019	7608	7043	5151	3601
2020	10783	11395	11021	8279
2021		14144	10151	7812
2022			16320	12979
2023				21060
Total	**74000**	**74000**	**74000**	**74000**

5.2.2. GERD Impounding and HAD Performance under Historical Dry Flow Sequence

Figures 5-8, Tables 5-10 and Table 5-11 summarize HAD simulation results during impounding period in historical dry flow scenario. HAD water level will be significantly affected from August 2015 during impounding with dry flow. Before July 2015, stored water in GERD reservoir will not be sufficient to affect HAD operation. From August 2015 to October 2020, HAD water level will decrease significantly as compared to HAD alone scenario. With 7-years dry season filling; HAD water level will reach its minimum operation level for 32 months which cause water demand deficit. While there are small number of months (11 months) with water demand deficit for the HAD alone situation.

Table 5-11a: Number of months with irrigation water demand deficit and demand deficit in MCM at HAD during filling with historical dry flow

	7 YEARS				8 years			
Year	HAD alone		with GERD		HAD alone		with GERD	
	No of month	MCM	No of month	MCM	No of month	MCM	No. month	MCM
2014	0	0	0	0	0	0	0	0
2015	0	0	0	0	0	0	0	0
2016	0	0	5	19775	0	0	0	0
2017	2	1133	5	18794	0	0	3	19831
2018	4	2916	9	28144	0	0	2	5582
2019	3	12615	7	22741	4	600	3	11209
2020	2	15377	6	25245	0	0	5	22692
2021					0	0	6	15851
Total/mean	11	4577	32	16386	4	75	19	9396
% of the required	0.9	0.92	0.6	0.70	0.96	1.00	0.80	0.83

Table 5-12b: Number of months with irrigation water demand deficit and demand deficit in MCM at HAD during filling with historical dry flow

	9 years				10 years			
Year	HAD alone		with GERD		HAD alone		with GERD	
	No of month	MCM			No of month	MCM		
2014	0	0	0	0	0	0	0	0
2015	0	0	0	0	0	0	0	0
2016	0	0	0	0	0	0	0	0
2017	0	0	2	2491	0	0	3	3831
2018	1	3255	4	22002	0	0	3	6086
2019	0	0	6	18458	2	945	4	19780
2020	5	19370	2	5913	1	789	5	9313
2021	0	0	2	10120	4	17712	5	17712
2022	0	0	6	23610	1	567	2	6456
2023					0	0	5	22661
Total/mean	6	2514	22		8	2001	27	8584
% of the required	0.83	0.95	0.80		0.93	0.96	0.83	0.85

Considering GERD impounding upstream, HAD Minimum Operating Level (MOL) will reach for the first time in June 2016. If Egypt water demand reduces to 45 BCM by improving irrigation application method or by selecting crop which demands minimum water, the irrigation water demand deficit will reduce to 7.3 BCM for 7 years filling period. This is 84% performance. HAD water level will also be improved as show in Appendix Figure D-10.

Table 5-13: HAD yearly inflows, losses, outflows and energy generation for HAD influenced by GERD impounding with 7-years historical dry sequence and difference from HAD alone

Year	INFLOW (MCM)	Diff (%)	LOSS (MCM)	Diff (%)	ENERGY (GWH)	Diff (%)	OUTFLOW (MCM	Diff (%)	Irrigation Deficit (Number of month)
2014	42962	-7.8	12595	-1.2	7253	-0.7	56378	0.0	0
2015	26248	-43.6	8960	-10.9	5954	-7.1	56378	0.0	0
2016	45997	-3.8	6248	-19.6	3146	-42.6	53824	-4.5	5
2017	35609	-33.3	6306	-5.7	3244	-20.1	43211	-23.4	5
2018	36637	-29.8	6021	-9.3	2331	-44.8	44444	-21.2	9
2019	38255	-19.3	6046	-6.7	2792	-27.3	38871	-29.5	7
2020	62519	31.9	6415	-6.6	3004	-15.5	46954	3.6	6
Mean	41175	-15.6	7513	-8.2	3961	-20.5	50919	-6.8	5

Due to GERD, energy production will decrease at least by 7% and at most by 44.8 % between 2015 and 2020 because of significant HAD head reduction compared to HAD alone simulations. HAD losses will be reduced in average by 8.2 % (Table 5-11). This has similar trends for 8, 9 and 10 years filling duration with a little modification.

Figure 5-8 shows energy production of HAD for 8 and 9- years filling. Difference in energy production of the two scenarios at HAD will reduce by 12.6 and 11.3% for 8 and 9-years respectively, which have some improvement as compared to 7-years filling which is 20.5% The irrigation water demand deficit will reduce to 19 and 22 months for 8 and 9 years respectively, which was 32 months for 7 years and 27 months for 10 years filling period. This indicates that 8 and 9 years filling duration could be more preferable.

This is because; the ratio of outflow to inflow at GERD will increase as the dry year filling period increases and could again starts to decrease as the number of years increase. Percentage of water released from GERD (outflow to inflow ration) will 69, 74.3 and 77.5% for 7, 8 and 9 years filling periods and HAD could gain more inflow as the filling period increases.

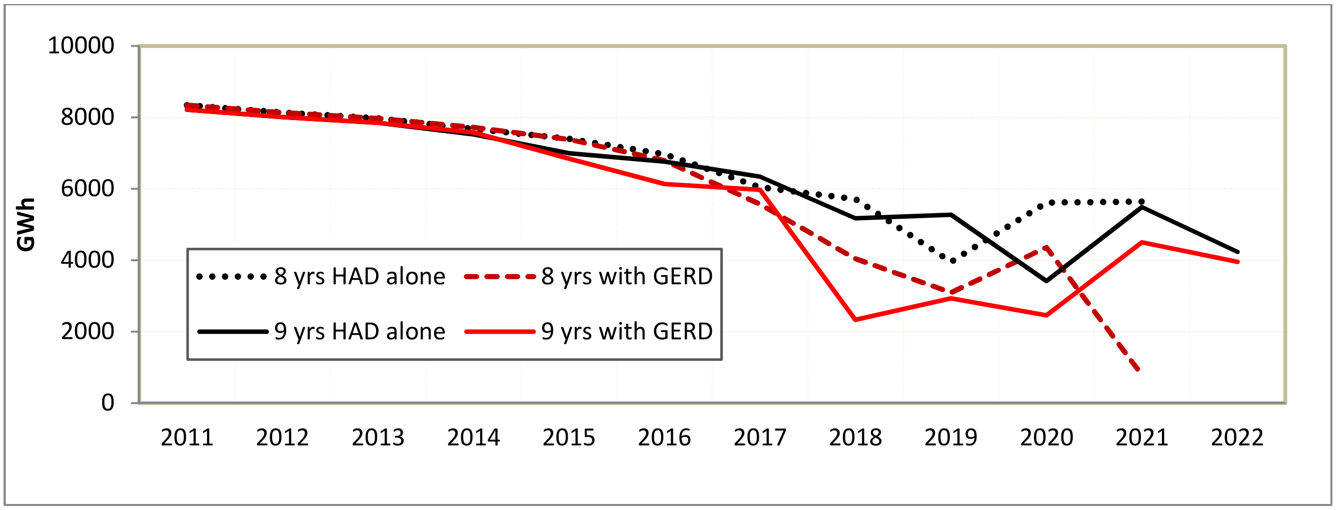

Figure 5-8: HAD annual energy during impounding with 8 and 9-years dry flow

5.3. Impounding Stage Simulations for Historical Wet Flow Sequence

A third case for GERD impounding stage and its downstream impacts on HAD considers a sequence of wet years at HAD, the average of which is above the long term average inflows. In this scenario, 6 years maximum average flow at HAD was considered.

Table 5-12 through Table 5-14 present the selected sequence of wet years which is the period between 1996 and 2001 at HAD. The average value of HAD inflows during these 6 years is equal to 98.0 BCM/year which is 15% more than the mean HAD yearly flow (85.1 BCM/year). The sequence of wet years at GERD on the same period (1996 – 2001) has the average value of 61.8 BCM/year that is 28 % more than the mean GERD yearly inflows (48.2 BCM/year). The sequence of wet years will assume that; 2011 – 2013 flows will be equal to 1993 – 1995 flows from the available time series. During these 3 years, GERD impounding stage will not start yet. 2014 – 2019 flows will be equal to 1996 – 2001 flows from the available time series.

Table 5-14: Sequence of historical wet years – Abbay (MCM)

year		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Yearly
1993	**2011**	**853**	**542**	**450**	**1007**	**1346**	**2890**	**10802**	**16065**	**12679**	**5967**	**2509**	**1306**	**56415**
1994	2012	779	493	451	390	863	2119	12185	24711	13370	3450	1741	956	61507
1995	2013	619	426	478	603	834	1579	7635	18257	9424	3140	1403	977	45376
1996	2014	700	433	571	848	1673	4559	15018	23724	10895	4795	2141	1381	66738
1997	2015	858	469	648	577	1042	3058	11243	14737	6525	4874	3588	1451	49069
1998	2016	812	632	637	675	951	2103	12269	23412	15216	10195	3237	1723	71862
1999	2017	1190	578	613	527	1422	2062	13147	17671	11430	10171	2946	1500	63256
2000	2018	813	635	376	620	878	2221	9970	19285	10209	8082	3214	1422	57727
2001	2019	979	521	798	788	973	2934	16158	19242	11647	4645	2224	1334	62245
mean (2014_2019)		892	545	607	673	1156	2823	12968	19678	10987	7127	2892	1468	61816

Table 5-15: Sequence of historical wet years – Naturalized HAD inflow (MCM)

Year		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Yearly
1993	2011	3670	3331	2824	3640	3780	3408	6939	16081	17193	13994	7887	4947	**87694**
1994	2012	3331	2990	2560	2720	3163	3412	6502	22270	22786	12880	6203	4204	**93021**
1995	2013	3351	3006	2576	2998	3162	3122	4801	15274	17105	10847	5806	3894	**75942**
1996	2014	3333	3123	2783	3302	3865	3600	7804	22214	21763	13497	6849	4778	**96911**
1997	2015	3609	3297	3020	3335	3409	3506	6379	15260	16307	12320	7483	4943	**82868**
1998	2016	4180	3933	3241	3632	4056	3729	7398	23600	27021	20465	10954	6045	**118254**
1999	2017	4294	3883	3248	3437	4018	4256	12942	10675	19724	19720	10059	5527	**101783**
2000	2018	3742	3424	2922	3700	3787	4224	5341	17064	17388	16584	9854	5921	**93951**
2001	2019	3980	3687	3431	3920	4236	5094	9059	9178	19718	16807	9294	5593	**93997**
Mean (2014-2019)		**3856**	**3558**	**3108**	**3554**	**3895**	**4068**	**8154**	**16332**	**20320**	**16566**	**9082**	**5468**	**97961**

Table 5-16: Incremental historical wet seasons follow from GERD to HAD with Sudanese irrigation demand deducted (MCM)

Year		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Yearly
1993	2011	844	692	520	661	555	318	1430	4130	4608	3757	1988	1146	20648
1994	2012	743	599	441	490	465	268	1297	5957	6259	3428	1491	927	22364
1995	2013	749	639	475	527	504	273	802	3892	4582	2828	1373	836	17481
1996	2014	744	680	510	564	555	324	1682	5941	5957	3610	1681	1096	23343
1997	2015	825	657	496	571	507	295	1261	3888	4346	3263	1868	1145	19124
1998	2016	994	845	638	703	689	422	1566	6349	7509	5667	2893	1470	29745
1999	2017	1028	830	595	657	641	517	3198	2535	5355	5447	2629	1318	24749
2000	2018	865	763	580	679	624	507	955	4420	4665	4521	2568	1434	22582
2001	2019	935	772	617	744	664	764	2052	2093	5353	4587	2403	1337	22321
Mean (2014-2019)		**898**	**758**	**573**	**653**	**613**	**472**	**1786**	**4204**	**5531**	**4516**	**2340**	**1300**	**23644**

5.3.1. GERD Impounding Results for Selected Historical Wet Flow Sequences

GERD water level in the reservoir will reach 560 m.a.s.l in August 2014 and can generate energy from this date. GERD will reach its Minimum Operating Level (MOL) (590 m.a.s.l) in September 2015. GERD water level will reach its Normal Water Level (640 m.a.s.l) at the end of year 2019.

Figure 5-9 and Table 5-15 summarize GERD impounding simulation results for sequence of wet years. Yearly GERD outflows during the impounding stage will be comprised between 27 and 62 BCM (Table 5-15). The average outflows between 2014 and 2019 will be equal to 47 BCM/year which is only 22 % less than the mean value of GERD inflows. Energy generation is less, especially in 2014 and 2015 because of GERD water level (lower or close to the MOL) and the fact that hydropower plant will not be fully operational. In 2016, energy generation will be close to 7618 GWh/year. From 2017, GERD will be able to generate more than 9100 GWh/year.

Table 5-17: GERD impounding stage with wet sequence: yearly inflows, losses, outflows and energy Production

Year	Inflow (MCM)	Loss(MCM)	Outflow(MCM)	Stored Volume(MCM)	Energy (GWh)
2014	65638	80	61971	3000	567
2015	47622	436	27354	20794	2738
2016	69821	969	39515	31082	7618
2017	61315	1339	52246	7224	9198
2018	55930	1426	51100	3400	9198
2019	60925	1501	49903	7546	7551
Mean (2014-2019)	60208	958	47015	12174	6145

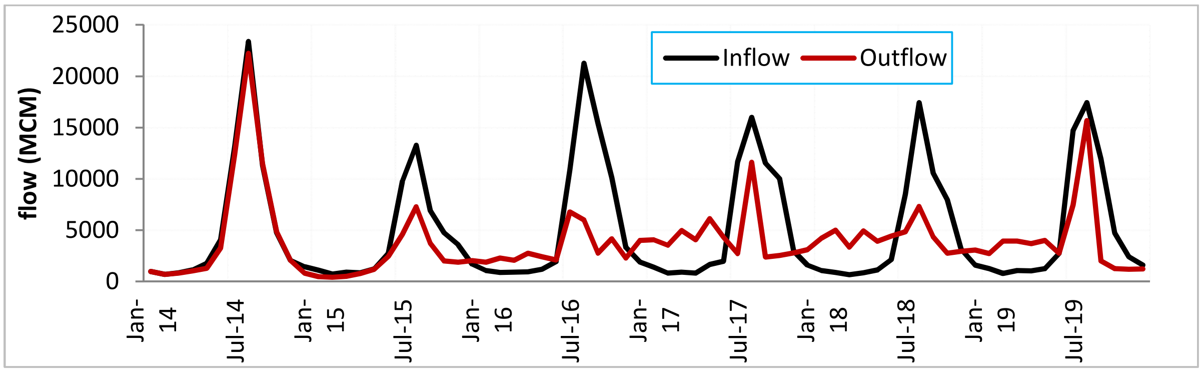

Figure 5-9: Monthly inflow and outflow of GERD during impounding period with wet flow

5.3.2. GERD Influence on HAD during Impounding with Historical Wet Flow Sequence

Figures 5-10, Figure 5-11, Table 5-16 and Table 5-17 summarize HAD simulation results considering GERD upstream during its impounding period with historical wet flow sequence. HAD water level is slightly affected from July 2015.

Table 5-18: HAD yearly inflows, losses, outflows and energy generation for HAD alone with historical wet sequence

Year	Inflow (MCM)	Loss (MCM)	Outflow (MCM)	Irrigation deficit (Number of month)	Energy (GWh)
2014	87285	18121	56378	0	8683
2015	65505	18848	56378	0	8855
2016	97402	18410	56378	0	8754
2017	84730	20736	56378	0	9265
2018	77006	21269	56378	0	9376
2019	82207	21596	56378	0	9440
Mean	82356	19830	56378	0	9062

The average HAD water level will be 179 and 173 m.a.s.l for HAD alone and HAD with GERD respectively. There will be full coverage of HAD downstream irrigation water demand. HAD Minimum Operating Level will never be reached (Figure 5-10).

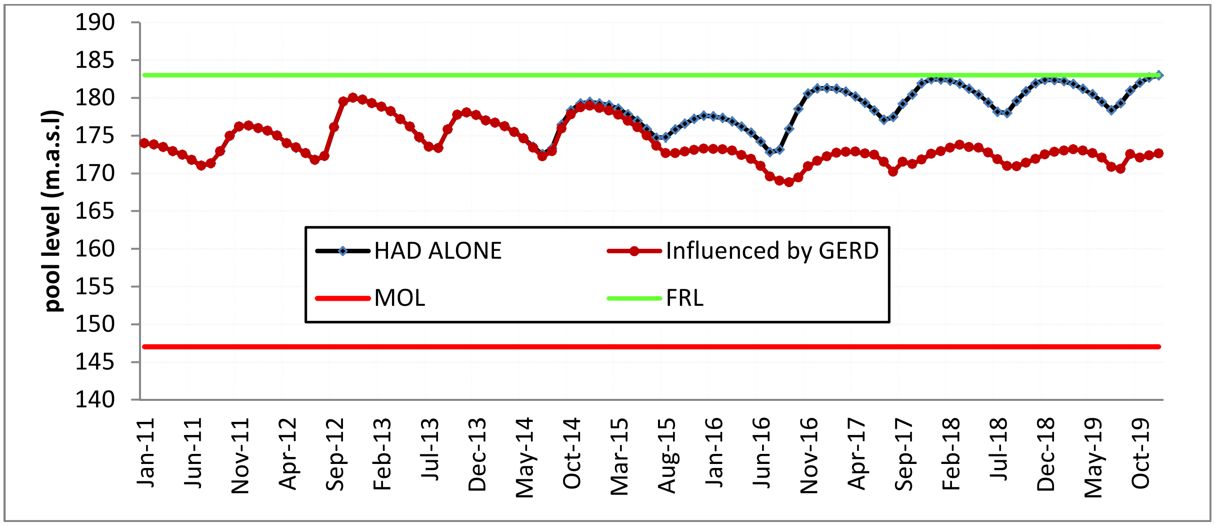

Figure 5-10: HAD reservoir water level during GERD filling period with historical wet flow sequence

At the end of impounding HAD reservoir water level will be 183 and 173 m.a.s.l for HAD alone and HAD with GERD respectively. HAD annual energy generation will decrease by 2.9 % to 13 % between 2015 and 2019 because of HAD head reduction. As shown in Figure 5-11 monthly inflow to HAD with GERD in the dry months is more than that of mean monthly inflow to HAD without GERD.

Table 5-19: HAD yearly inflows, losses, outflows and energy generation for HAD influenced by GERD with historical wet sequence impounding

Year	Inflow (MCM)	Diff (%)	Loss (MCM)	Diff (%)	Energy (GWh)	Diff (%)
2014	83614	*-4.2*	17967	*-0.9*	8649	*-0.4*
2015	45243	*-30.9*	17738	*-5.9*	8601	*-2.9*
2016	67098	*-31.1*	15379	*-16.5*	8037	*-8.2*
2017	75660	*-10.7*	15996	*-22.9*	8187	*-11.6*
2018	72180	*-6.3*	16228	*-23.7*	8245	*-12.1*
2019	71185	*-13.4*	16117	*-25.4*	8212	*-13.0*
Mean	*69163*	*-16.0*	*16571*	*-16.4*	*8322*	*-8.2*

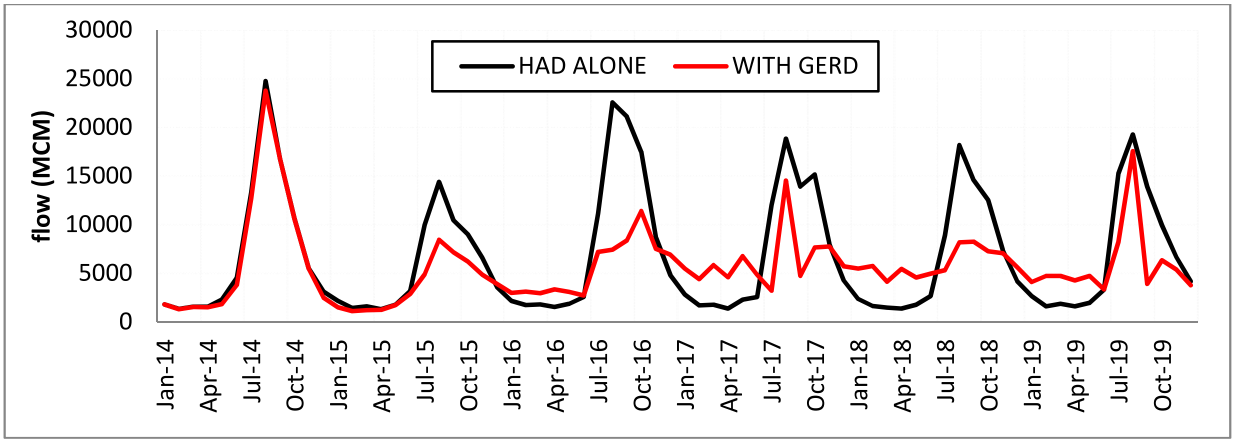

Figure 5-11: Monthly inflow and outflow of HAD during GERD impounding with historical wet flow sequence

5.4. Impounding Stage Simulations for Hypothetical Flow Scenarios

5.4.1. Hypothetical Dry Flow Sequences

Different 6 years hypothetical dry season inflow sequences are generated from the mean sequence by perturbing percentage reductions ranging from the worst (unlikely) to most likely reductions. Simulations for the drier possible sequence scenarios considered inflow reductions to GERD of -20%, -15%, -10% and -5% (Figure 5-12). The reference case is based on a water management simulation modeled with a sequence of observed hydrological years representative of the inter-annual inflows both on HAD and GERD. Over the course of the 42 years between 1961 and 2002, the worst dry sequence reduction was about 18% over the drought period between 1982 and 1987. This indicates the possibility of extreme drier flow conditions and hence this attempts to consider the drier condition from unlikely to likely.

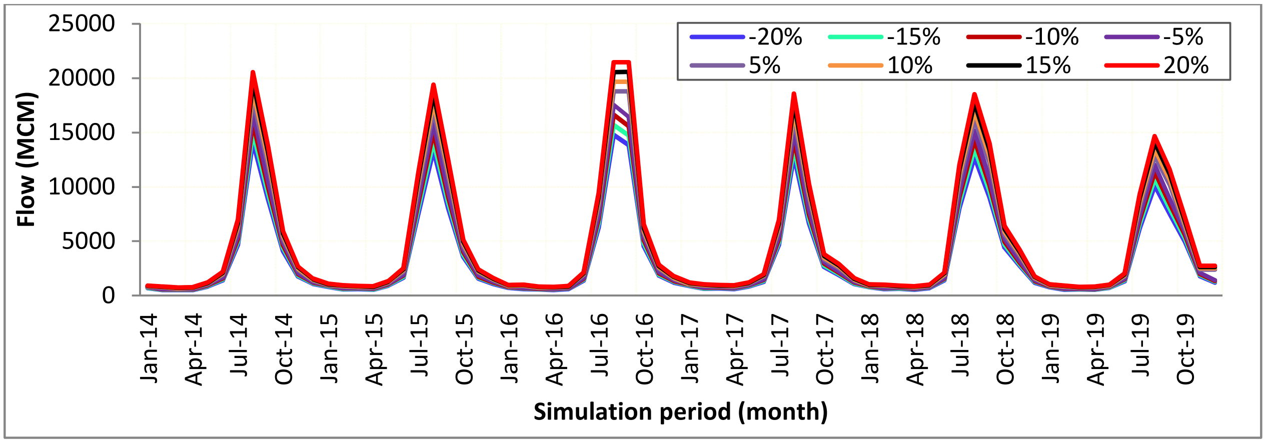

Figure 5-12: Hypothetical dry and wet flow at Border for impounding of GERD

5.4.1.1. GERD Impounding Results for Hypothetical Dry Flow Sequences

The filling strategy is similar with the mean (normal) flow scenario. GERD will reach its dead storage Level (590 m.a.s.l) in October 2015 and will reach its Normal Water Level of 640 m.a.s.l at the end of year 2019 (Figure 5-1). Yearly GERD outflows during the impounding stage will be as lower as 12 BCM/year for -20% flow reduction filling scenario (Table 5-18).

Table 5-20: GERD inflow and outflow (MCM), and percentage released from GERD during filling with hypothetical dry flows

Year	-20%			-15%			-10%			-5%		
	Inflow	outflow	Released (%)	Inflow	outflow	Released (%)	Inflow	outflow	Released (%)	Inflow	outflow	Released (%)
2014	39051	35370	91	41492	37811	91	43933	40251	92	46373	42692	92
2015	40321	20082	50	42841	22602	53	45361	25121	55	47882	27642	58
2016	46850	23013	49	49778	24606	49	52706	26199	50	55634	27791	50
2017	34543	12270	36	36703	15744	43	38862	19216	49	41020	22685	55
2018	42774	48796	114	45448	51395	113	48121	53994	112	50793	56592	111
2019	36193	27220	75	38456	29558	77	40717	31893	78	42980	34230	80
Mean	39955	27792	70	42453	30286	71	44950	32779	73	47447	35272	74

Table 5-19 shows the inflow and out flow from GERD during filling with different flow percentage reduction. There will be at least 70% release from GERD during filling period, that is only 30% of the inflow will be impound in the reservoir. This is for the worst case (20% flow reduction). But other flow reduction the average percentage release would be 74, 73, 71% for 5, 10, 15% flow reductions respectively. There could be flow regulation. In the dry moths (February to June) the percentage released from GERD is more than 100%.

Table 5-21: GERD loss (MCM), Energy (GWh) and stored water (MCM) during filling with hypothetical dry flows

Year	-20%		-15%		-10%		-5%		Stored volume (for all flow)
	Loss	Energy	Loss	Energy	Loss	Energy	Loss	Energy	
2014	77	4460	78	4765	78	5069	78	5373	3000
2015	420	3609	420	4078	420	4548	420	5018	18500
2016	894	5600	893	5987	891	6374	889	6761	20332
2017	1279	4048	1271	5180	1262	6305	1253	7432	7834
2018	1360	15900	1360	16740	1357	17579	1354	18419	13786
2019	908	9100	983	9881	1058	10661	1133	11442	10044
Mean	823	7474	834	8133	844	8793	855	9456	73495 (cumulative)

5.4.1.2. GERD Influence on HAD During Impounding with the hypothetical Dry Flow Sequences

Figure 5-13 through Figure 5-16 and Table 5-20 to Table 5-23 summarize HAD simulation results considering GERD upstream during its impounding period with different hypothetical dry flow scenarios. Between January 2011 and January 2014, water storage is not started and it has no effects on HAD water level.

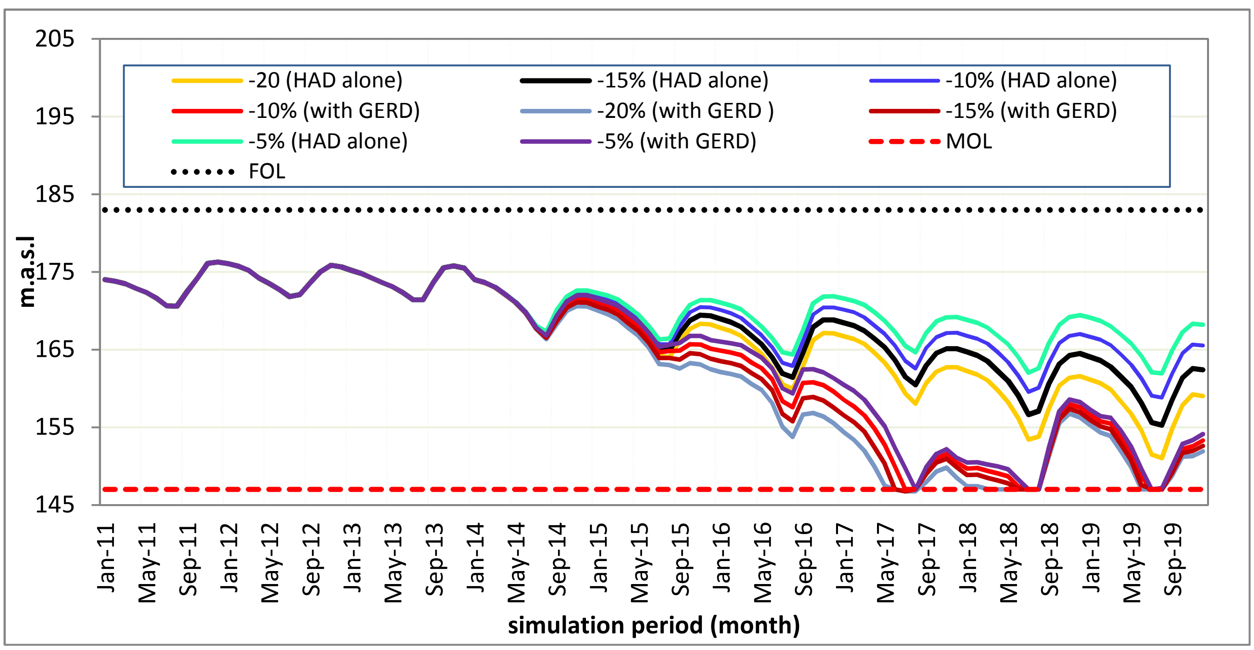

Figure 5-13: HAD reservoir water level during fillings with hypothetical dry flows

From January 2014 to June 2015, HAD water level will be slightly affected because some amount of water is started to be stored in GERD. From July 2015 to December 2019, HAD water level will decrease significantly. HAD Minimum Operating Level (147 m) will be reached after

May 2017 and there will be irrigation water demand deficit. The deficit generally occurs towards the end of the dry years and beginning of the wet season of the year 2017 and 2019.

Figure 5-14 shows the inflow hydrographs of HAD during the impounding period of GERD. As previous cases these is flow regulation effects of GERD. That is why the monthly inflow graph of HAD during dry months is above that of HAD alone situation and HAD will gain relatively more uniform flow for its operation.

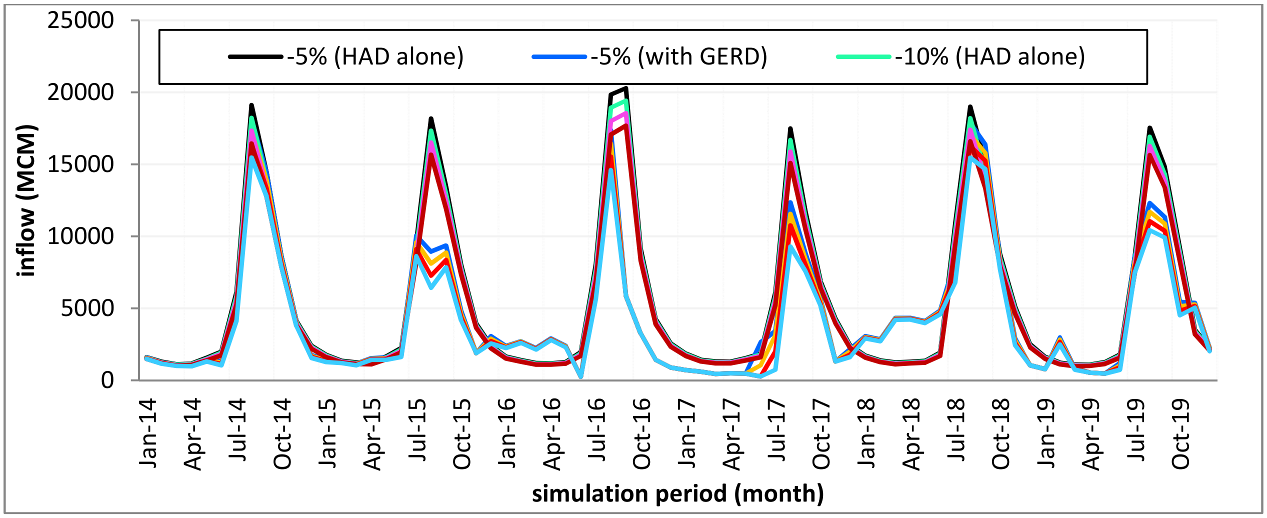

Figure 5-14: Monthly inflow to HAD during filling with hypothetical dry flow sequences

Table 5-22: Mean annual inflow to HAD (MCM) during filling with hypothetical dry flows

Year	-20%			-15%			-10%			-5%		
	HAD alone	with GERD	Diff (%0	HAD alone	with GERD	Diff (%0	HAD alone	with GERD	Diff (%0	HAD alone	with GERD	Diff (%0
2014	56234	52553	-7	58675	54993	-6	61115	57434	-6	63556	59875	-6
2015	57504	39516	-31	60024	42036	-30	62543	44555	-29	65064	47076	-28
2016	64032	44051	-31	66961	45644	-32	69889	47236	-32	72817	48829	-33
2017	51726	28720	-44	53885	32193	-40	56045	35665	-36	58203	39135	-33
2018	62208	70731	14	64882	73330	13	67555	75928	12	70228	78526	12
2019	57230	45145	-21	59494	47482	-20	61755	49817	-19	64017	52154	-19
Mean	58156	46786	-20	60653	49280	-19	63150	51773	-18	65647	54266	-17

Table 5-20 shows the inflow to HAD during filling period of GERD. Maximum average reduction in inflow is 20% for the worst flow reduction (20%). There could be 19, 18 and 17% inflow reduction to HAD due to filling of GERD for 15, 10 and 5% flow reduction respectively.

i. *Water withdrawal for Agriculture:* water withdrawal form HAD will be affected significantly if specifically the worst scenario of 6 years continuous inflow reduction by -20% occurs. The water withdrawal from HAD will be affected starting from December 2017 until the reservoir recovers in the wet season which starts in June 2018. After the reservoir recovery, the next deficit occurs in April 2019. Therefore, two critical water deficit periods spanning for 7 months (in 2018) and 4 month (2019) may occur under such worst occurrence of -20 % reductions in inflows (Figure 5-15).

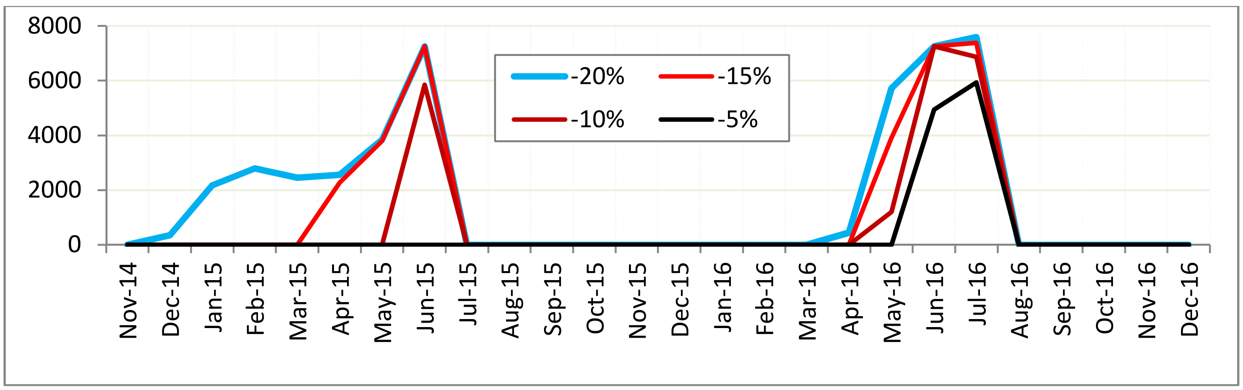

Figure 5-15: Monthly HAD irrigation water demand deficit (MCM) during impounding with hypothetical dry flow sequences

For 15, 10 and 5% inflow reduction to GERD, the corresponding water deficit during the filling period improves significantly as shown in Table 5-22. On average, there could be 10, 6 and 3% deficit for -15, -10 and -5% inflow reduction respectively. Such circumstances invite series consideration of joint dynamic operation of all the reservoirs in the system including the relatively small dams in Sudan. Furthermore, improving water management efficiency (irrigation system efficiency) and water allocation efficiency (temporarily shifting to less water consuming crops) saves water from the system. Drier scenarios must initiate joint planning and cooperation among the three countries during the construction of GERD.

Table 5-23: Irrigation water demand deficit of HAD during filling for hypothetical dry flow scenarios (MCM)

		-20%			-15%			-10%			-5%		
	Demand	Used	Deficit		Used	Deficit		Used	Deficit		Used	Deficit	
year	(MCM)	(MCM)	(MCM)	(%)	(MCM)	(MCM)	(%)	(MCM)	(MCM)	(%)	(MCM)	(MCM)	(%)
2014	55500	55500	0	0	55500	0	0	55500	0	0	55500	0	0
2015	55500	55500	0	0	55500	0	0	55500	0	0	55500	0	0
2016	55500	55500	0	0	55500	0	0	55500	0	0	55500	0	0
2017	55500	55155	345	1	55500	0	0	55500	0	0	55500	0	0
2018	55500	34437	21063	38	42176	13324	24	49644	5856	11	55500	0	0
2019	55500	34480	21020	38	36959	18541	33	40170	15330	28	44627	10873	20
Mean	55500	48429	7071	13	50189	5311	10	51969	3531	6	53688	1812	3

ii) *Energy production*: Energy production is related to the water level and water discharge amount. Due to the water level lowering at HAD, the energy output will be reduced from 25 % (for -20% flow reduction) to 16% (for -5% flow reduction) as compared to HAD alone situation (Table 5-22 and Figure 5-16). It may reach over 52% output reduction under the -20% flow reduction scenario by 2017. When viewed from regional perspective, the overall energy benefits from joint operation of GERD and HAD is not remarkable during the filling period under drier condition.

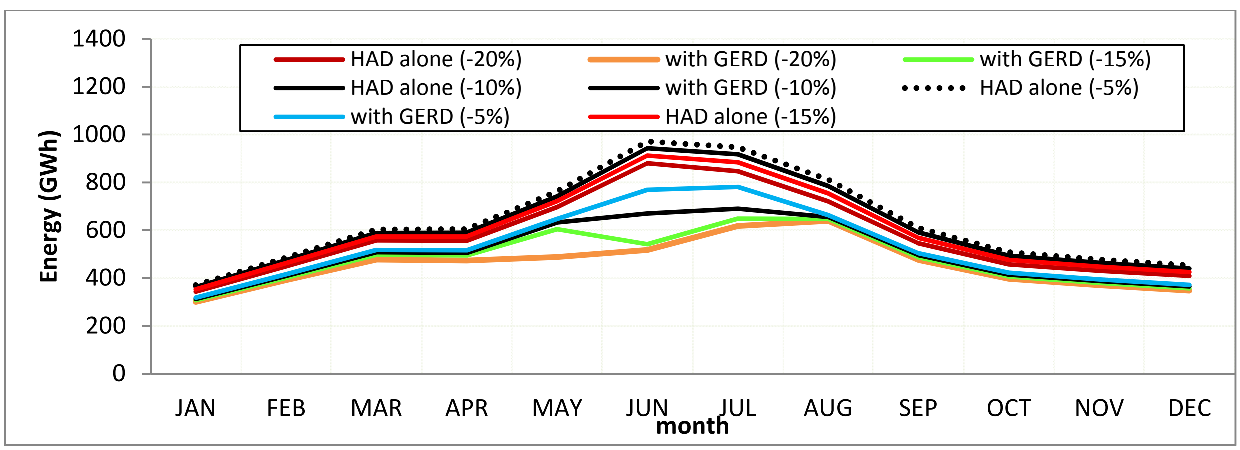

Figure 5-16: Mean monthly HAD energy during fillings with hypothetical dry flow

Table 5-24: HAD yearly Energy (GWH) during impounding with hypothetical dry flow sequences and different percentage from the current situation

Year	-20%			-15%			-10%			-5%		
	HAD alone	with GERD	Diff (%)	HAD alone	with GERD	Diff (%)	HAD alone	with GERD	Diff (%)	HAD alone	with GERD	Diff (%)
2014	7950	7911	0	7972	7933	0	7993	7954	0	8015	8028	0
2015	7487	7212	-4	7598	7331	-4	7701	7447	-3	7801	7688	-1
2016	7054	6150	-13	7254	6396	-12	7448	6628	-11	7630	6966	-9
2017	6786	3233	-52	7088	3896	-45	7366	4647	-37	7627	5718	-25
2018	6181	4201	-32	6593	4541	-31	6964	4793	-31	7299	4889	-33
2019	5906	4281	-28	6415	4546	-29	6863	4813	-30	7263	5191	-29
Mean	6894	5498	-20	7153	5774	-19	7389	6047	-18	7606	6413	-16

iii) *Water gain from HAD:* The overall 6 years average water loss due to evaporation at HAD will show gain under the drier scenarios. The water gain varies between 25% and 19 % under the driest scenario to dry scenario (-5%) (Table 5-23). The volumetric water gain varies between 2.1 to 3.5 BCM for the driest (-20%) to dry condition (-5%). Even though the evaporative gain is quite large it is inadequate to offset the combined effect of the dry flow scenario and the GERD filling during the 6 years period.

Table 5-25: HAD yearly evaporative loss during impounding period with hypothetical dry flow with and without GERD

Year	-20%			-15%			-10%			-5%		
	HAD alone	with GERD	Diff (%)	HAD alone	with GERD	Diff (%)	HAD alone	with GERD	Diff (%)	HAD alone	with GERD	Diff (%)
2014	15073	14922	-1	15157	15006	-1	15241	15090	-1	15325	15175	-1
2015	13390	12478	-7	13770	12863	-7	14146	13247	-6	14521	13624	-6
2016	11965	9383	-22	12616	10039	-20	13263	10688	-19	13905	11331	-19
2017	11141	6458	-42	12067	6831	-43	12977	7246	-44	13879	7735	-44
2018	9464	6592	-30	10586	6752	-36	11689	6897	-41	12771	7057	-45
2019	8762	6806	-22	10081	6961	-31	11375	7130	-37	12643	7317	-42
Mean	11632	9440	-19	12379	9742	-21	13115	10050	-23	13841	10373	-25

5.4.2. Hypothetical Wet Flow Sequences

The optimistic case for GERD impounding stage and its downstream impacts on HAD considers a sequence of hypothetical wet years flow regarding HAD inflows which includes 6 years flow sequence with 20, 15, 10 and 5% flow increment from the normal flow condition.

5.4.2.1. GERD Impounding Results for Hypothetical Wet Flow Sequence

The filling strategy is similar with the other flow conditions (mean and hypothetical dry flows condition). Under this scenario, GERD water level in the reservoir will reach 560 m.a.s.l in August 2014 and can generate energy from this date. The minimum yearly GERD outflow is around 34.3 BCM which is 65% of the inflow for the impounding with 5% incremental flow (Table 5-25).

Table 5-26: Inflow (MCM), out flow (MCM) and percentage released water from GERD during filling with hypothetical wet flows

Year	20%			15%			10%			5%		
	Inflow	outflow	Released (%)	Inflow	outflow	Released (%)	Inflow	outflow	Released (%)	Inflow	outflow	Released (%)
2014	58238	55499	95	55811	53058	95	53385	50617	95	50958	48177	95
2015	60152	41561	69	57646	39041	68	55139	36521	66	52633	34001	65
2016	70156	46685	67	67233	44227	66	64310	41768	65	61386	39310	64
2017	51487	42060	82	49342	39440	80	47197	37530	80	45051	35671	79
2018	63937	51651	81	61273	48977	80	58609	45599	78	55945	42170	75
2019	53658	42716	80	51481	40528	79	49305	38341	78	47128	36152	77
Mean	59605	46695	78	57131	44212	77	54657	41729	76	52184	39247	75

Table 5-27: GERD Energy (GWh), loss (MCM) and stored water during the filling period of hypothetical wet flows

Year	20%			15%			10%			5%		
	Loss	Stored volume	Energy	Loss	Stored volume	Energy	Loss	Stored volume	Energy	Loss	Stored volume	Energy
2014	77	3000	6259	77	3000	5984	77	3000	5710	77	3000	5436
2015	419	21500	7417	419	21500	6952	419	21500	6488	418	21500	6023
2016	886	43237	10671	884	43705	10107	880	43237	9543	873	41832	8980
2017	1235	51942	12134	1225	52650	11357	1212	51942	10793	1189	49665	10250
2018	1346	63800	15784	1341	63800	14963	1332	63800	13911	1321	63451	12845
2019	1506	73719	14441	1504	73794	13702	1500	73719	12962	1494	73495	12223
Mean	911	42866	11117	909	43075	10511	903	42866	9901	895	42157	9293

GERD can be used to balance the flow in highly managed systems; taking in water during high flows and releasing it again during low flows. If there is storm water will overfill the reservoir, water is slowly let out of the reservoir prior to, and during the storm. If done with sufficient lead time, the major storm will not fill the reservoir and areas downstream will not experience damaging flows. As shown in Table 5-25 the minimum percentage release from GERD during filling period will be 64% and the maximum could be up to 95% of the inflow to GERD. The mean release from GERD is 75 to 78 % of the inflow. Mean annual losses from GERD will not exceed 1 BCM for all flow conditions. And there could be up to 11100 GWh energy productions on average.

5.4.2.2. GERD Impounding Influence on HAD during Impounding with Wet Flows

Figure 5-17, Figure 5-18 and Table 5-27 to Table 5-29 summarize HAD simulation results considering GERD upstream during its impounding period with different hypothetical wet flow scenarios. Between January 2011 and January 2014, water storage is not started and HAD water level will not be affected. From January 2014 to June 2015, HAD water level will be slightly affected because some amount of water is started to be stored in GERD. From July 2015 to December 2019, HAD water level will decrease because of GERD impounding.

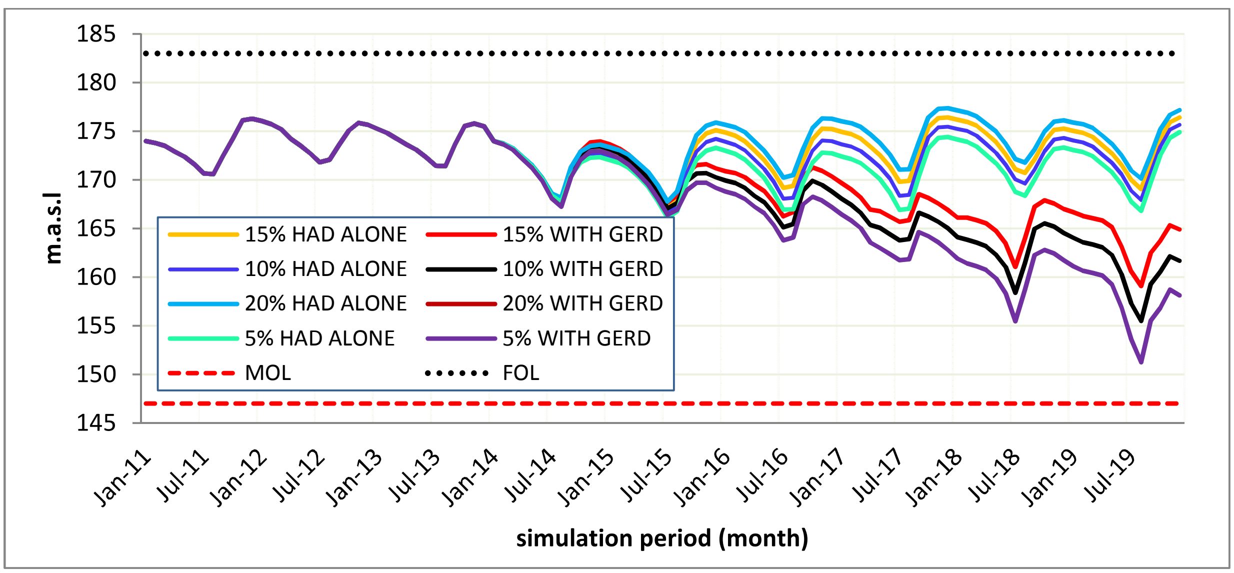

Figure 5-17: HAD reservoir water level during filling with hypothetical wet flow

There will not be agricultural water deficit from HAD. The minimum operating level will never be reached (Figure 5-17). The anticipated energy reduction from HAD will be contained between 7 to 11 % on average because of HAD head reduction (Table 5-27).

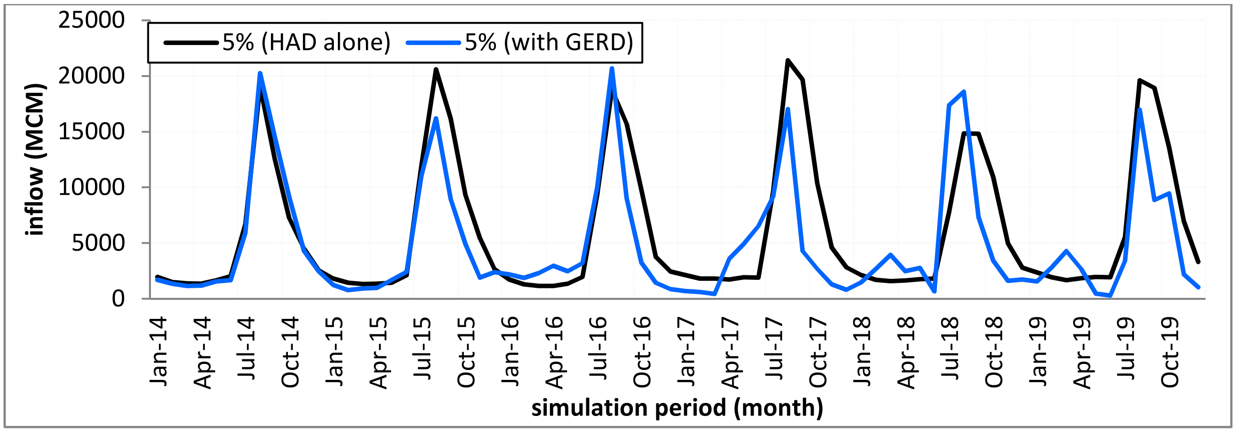

Figure 5-18: Mean monthly inflow to HAD during filling with 5% incremental flow

Figure 5-18 demonstrates the inflow to HAD during filling period of GERD with hypothetically 5% flow reduction from the normal flow. The other flow scenarios (10, 15 and 20%) have similar trend of inflow to HAD.

Table 5-28: Annual inflow (MCM) to HAD during filling with hypothetical wet flows

Year	20%			15%			10%			5%		
	HAD alone	with GERD	Diff (%0	HAD alone	with GERD	Diff (%0	HAD alone	with GERD	Diff (%0	HAD alone	with GERD	Diff (%0
2014	68998	72682	5	66839	70241	5	64680	67800	5	62521	65360	5
2015	83596	60996	-27	80922	58476	-28	78248	55955	-28	75575	53435	-29
2016	75328	67723	-10	73066	65264	-11	70804	62806	-11	68541	60348	-12
2017	79829	58510	-27	79829	55890	-30	79829	53980	-32	79829	52121	-35
2018	66777	73586	10	66777	70912	6	66777	67534	1	66777	64104	-4
2019	79643	60640	-24	79643	58452	-27	79643	56265	-29	79643	54077	-32
Mean	75695	65689	-13	74513	63206	-15	73330	60723	-17	72148	58241	-19

Table 5-29: HAD yearly energy during impounding with hypothetically 20%, 15%, 10% and 5% incremental flow

Year	20%			15%			10%			5%		
	HAD alone	with GERD	Diff (%0	HAD alone	with GERD	Diff (%0	HAD alone	with GERD	Diff (%0	HAD alone	with GERD	Diff (%0
2014	8096	8088	0	8076	8067	0	8057	8046	0	8037	8026	0
2015	8103	8070	0	8018	7974	-1	7930	7878	-1	7841	7777	-1
2016	8365	7919	-5	8220	7753	-6	8068	7579	-6	7912	7391	-7
2017	8475	7738	-9	8307	7491	-10	8129	7234	-11	7943	6953	-12
2018	8542	7504	-12	8397	7184	-14	8247	6839	-17	8086	6459	-20
2019	8415	7362	-13	8282	6974	-16	8142	6536	-20	7999	6044	-24
Mean	8333	7780	-7	8217	7574	-8	8095	7352	-9	7970	7108	-11

Table 5-30: HAD yearly losses during impounding with hypothetically 20%, 15%, 10% and 5% incremental flow

Year	20%			15%			10%			5%		
	HAD alone	with GERD	Diff (%0	HAD alone	with GERD	Diff (%0	HAD alone	with GERD	Diff (%0	HAD alone	with GERD	Diff (%0
2014	15657	15623	0	15576	15539	0	15496	15119	-2	15416	15203	-1
2015	15703	15557	-1	15366	15183	-1	15026	13306	-11	14685	13684	-7
2016	16738	14990	-10	16144	14360	-11	15543	11138	-28	14939	11797	-21
2017	17206	14282	-17	16501	13410	-19	15787	8897	-44	15068	9827	-35
2018	17473	13502	-23	16852	12428	-26	16225	7236	-55	15591	7976	-49
2019	16930	12974	-23	16375	11711	-28	15818	6774	-57	15260	7080	-54
Mean	16618	14488	-13	16136	13772	-15	15649	10412	-33	15160	10928	-28

5.5. Conclusive Remarks

Simulations were undertaken to assess the impacts of GERD on downstream cascades during impounding. All results shown changes in the hydrology of the Eastern Nile system due to GERD is inevitable during the filling phase. Six years filling period is considered sufficient for filling the GERD reservoir if normal or above normal flow conditions prevails during the filling period. If the worst drought historical flow scenario occurs for the consecutive 6 years during the impounding period of the reservoir, it requires extending the filling period of GERD beyond the 6 years period. Investigations for 7 to 10 years filling under such scenario indicate potential improvements of filling. Based on hypothetical scenario, it was indicated that reduction of flow sequence below -10 % may be undesirable for irrigation and requires modification of filling and irrigation scheduling. To avoid such negative impacts, regionally coordinated mitigation strategies should be in place.

Chapter Six

Assessments of Long Term Impact/Benefit of GERD

This chapter assesses the long term interaction of GERD with the existing water storage facilities. It is intended to assess the long term impacts and benefits on the socio-economic sectors of the Eastern Nile countries over the period of 2020 to 2060. The inflow time series data used was the historical (from 1960 to 2002) flow series with the assumption that the historical flow series will be one of the future realization of the possible future flow sequences. In order to capture ranges of possible future flow sequences, realizations within 95% confidence interval was considered. In this case, three flow conditions of upper limit, the mean (historical) and lower limits of the possible realizations are considered. The distribution is normal distribution so, statistically the upper and lower limits are found by using the student t test value for 95% confidence interval and 42 years data length (Figure 6-1).

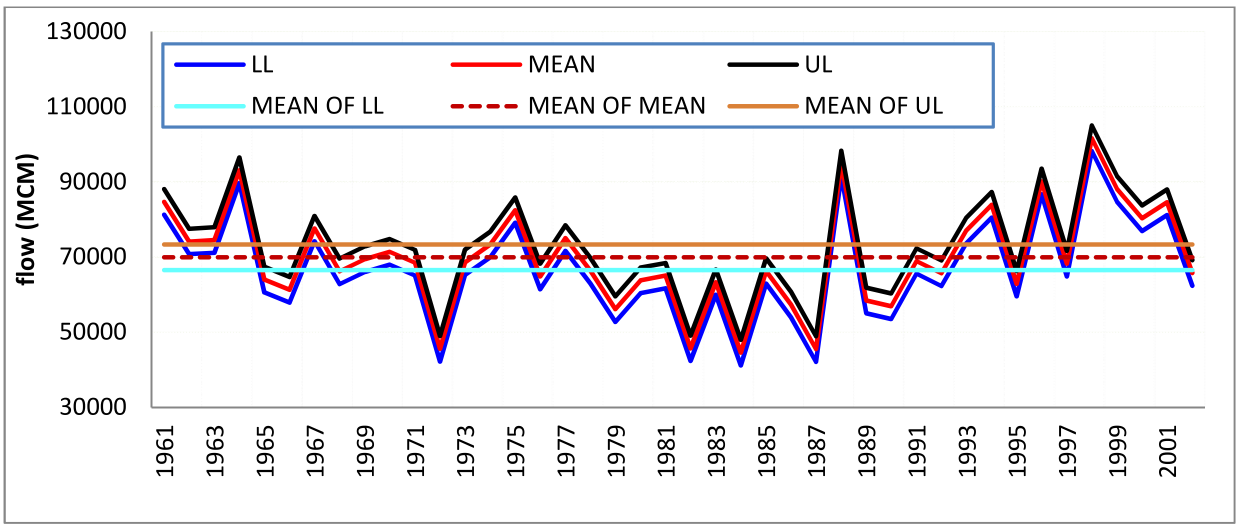

Figure 6-1: Mean annual flow of Nile for upper limit, mean and lower limit

The mean annual for upper, normal and lower flows are found by using equation 1 and the results are shown in Figure 6-1.

$$UCL / LCL = \overline{X_n} \pm t_{\alpha/2} * \frac{s}{\sqrt{n}} \quad 1$$

Where:

$t_{\alpha/2}$ = student t-value (1.684)

UCL = Upper Confident Limit (+ sign is used)

LCL = Lower Confident Limit (- sign is used)

s = standard deviation

n = number of data

6.1. Long Term Simulations Results at GERD

The long term simulation starts after the filling of the GERD reservoir in December 2019. From the results of the filling, the GERD water level is around 636 m.a.s.l and water volume stored in GERD reservoir is equal to 72 BCM at the end of December. The long term simulation indicates that, on the average, the reservoir water levels will rich its lowest level in June and the maximum water level will be in October and November. Mean GERD water levels during the operation simulation period are equal to 632, 631, and 630 m.a.s.l for upper, mean and lower flow respectively. The minimum value (622 m.a.s.l) mostly occurs in the months from April to July and the maximum water level (640 m.a.s.l) will occur from September to November.

Mean annual energy generation is 16605, 15673 and 14766 GWh for upper, mean and lower flow. Minimum energy production is in months from April to June when the reservoir level is also at lower level. As compared to the target power, there are 39, 57 and 87 months of energy deficit throughout the simulation period for upper, mean and low flow respectively. This is anticipated due to the existence of worst dry flow periods in the historical flow sequences. As shown in Table 6-1, the maximum energy deficit is in May and June which is the end of dry season, whereas from July to November there is no energy deficit. Therefore, dry flow sequences of historical nature may persist in the future as one of the realization and proper operation of GERD reservoir during such dryers of flow periods using seasonal flow forecasting models provides advance reschedule power outputs and downstream water release.

Table 6-1: Number of months with energy deficit at GERD

Month	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	Total
UPPER Limit	3	3	4	8	8	10	3	0	0	0	0	0	39
MEAN	4	4	8	9	12	16	3	0	0	0	0	1	57
LOWER Limit	4	7	10	13	22	24	3	0	0	0	0	4	87

6.2. HAD Operation Simulations Results

HAD initial conditions at the end of GERD impounding stage in based on average filling condition is considered for simulation. Water levels for HAD alone and HAD with GERD conditions were 171 and 156 m.a.s.l. respectively on December 2019 (the end of GERD filling). Operation simulation was started with these water level for both the HAD alone and with GERD situations.

Table 6-2: Mean monthly reservoir water level (m.a.s.l) of HAD

	HAD alone			With GERD			Difference (%)		
Month	Upper Limit	Mean	Lower Limit	Upper Limit	Mean	Lower Limit	Upper Limit	Mean	Lower Limit
Jan	169	166	163	165	161	158	-3	-3	-3
Feb	169	165	162	165	161	158	-2	-2	-3
Mar	168	164	161	165	161	158	-2	-2	-2
Apr	167	163	160	165	161	158	-1	-2	-2
May	166	162	159	164	160	157	-1	-1	-1
Jun	165	161	157	164	159	156	-1	-1	-1
Jul	163	159	155	162	158	154	-1	-1	-1
Aug	163	159	156	161	157	153	-1	-1	-2
Sep	167	163	160	162	157	154	-3	-4	-4
Oct	169	165	163	163	159	155	-3	-4	-4
Nov	170	166	164	164	160	157	-3	-4	-4
Dec	170	166	163	165	161	158	-3	-3	-4
Yearly	167	163	160	164	160	156	-2.1	-2.3	-2.5

As shown in the Table 6-2, there is slight difference in reservoir level for all situations. On average there is 3, 3 and 4 m reservoir water level reduction for upper mean and lower flow respectively as compared to the HAD alone case. At the end of simulation period the reservoir levels will increase and will be 180 and 170 m.a.s.l for HAD alone upper limit flow and with GERD lower limit flow respectively. For the other conditions HAD water level at the end of simulation period will be within this ranges. As shown in Table 6-2, reservoir water level difference between HAD alone and with GERD conditions in the dry months (from April to June) is less (1% reduction). The fluctuation of water level is reduced compared to HAD alone simulation results. This is a consequence of the seasonal inflows regime regulation: more constant flows arrive at HAD all over the year.

Figure 6-2 shows that HAD inflows will increase from November to June, and decrease from July to October, and will be more regular. The inflow to HAD is more uniform due to the presence of GERD. As shown in Table 6-4, the dry months' inflow to HAD with GERD is more than the inflow to HAD without GERD. The mean annual inflow difference to HAD with and without GERD is 2% reduction.

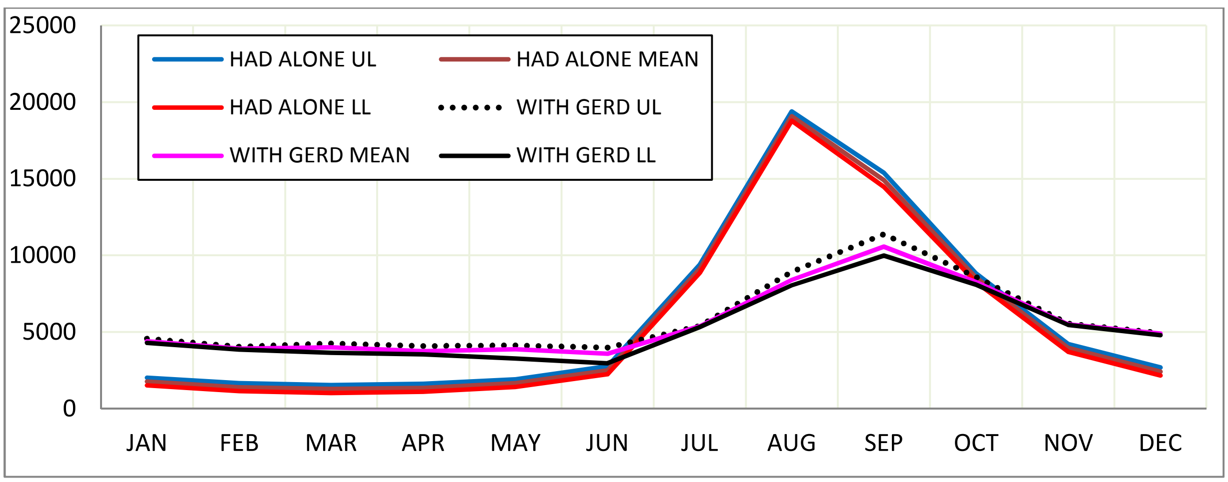

Figure 6-2: Mean monthly inflow to HAD during operation (MCM)

There are months with the water level reaches its minimum operation level (147m.a.s.l) and the amount of outflow is less. In these months there is also water demand deficit. Table 6-3 shows the number of months in water demand deficit at HAD. The maximum deficit (22 months) will occur with GERD and lower limit flow condition and less number of months with water demand deficit will occur HAD alone and upper limit flow condition which is 8 months. Therefore regardless of the presence or absence of GERD, there will likely be water deficit for irrigation downstream of HAD due to the occurrence of the dry flows that resembles the historical flows which occurred starting from 1978. The impacts of GERD during the long term operation are minimal but the occurrences of the dry flows that resemble the dry flow sequences in the historical flows are critical for both GERD and HAD operations. Therefore, joint operation of GERD and HAD should be facilitated using seasonal forecasting models, and management of agricultural water such as using low water use crops during dry flow years.

Table 6-3: Number of months in water demand deficit

*Year	HAD alone UL	HAD alone Mean	HAD alone LL	With GERD UL	with GERD Mean	with GERD LL
1973	0	0	3	0	0	3
1974	0	0	0	0	0	1
1980	0	0	3	0	0	3
1981	0	0	1	0	0	2
1982	0	0	2	0	0	3
1983	0	4	5	0	4	6
1984	0	1	2	0	2	3
1985	3	6	6	2	5	6
1986	0	0	1	0	0	2
1987	2	3	4	2	3	4
1988	3	4	4	4	4	5
1989	0	0	0	0	0	0
1990	0	0	0	0	0	0
1991	0	0	1	0	0	2
1992	0	0	2	0	0	2
1993	0	0	0	0	0	1
Total	8	13	18	8	18	22

**the other years have no water demand deficit*

Table 6-4: HAD Inflow difference between the two scenarios (with GERD and without GERD) (%)

	HAD alone			With GERD			Difference (%)		
Month	Upper Limit	Mean	Lower Limit	Upper Limit	Mean	Lower Limit	Upper Limit	Mean	Lower Limit
Jan	2035	1779	1524	4571	4401	4295	125	147	182
Feb	1665	1410	1154	4049	3927	3851	143	178	234
Mar	1548	1290	1032	4248	3999	3658	174	210	254
Apr	1625	1367	1110	4091	3761	3544	152	175	219
May	1929	1672	1412	4136	3890	3277	114	133	132
Jun	2768	2512	2251	3976	3597	2957	44	43	31
Jul	9397	9135	8862	5411	5382	5328	-42	-41	-40
Aug	19398	19084	18773	8934	8410	8056	-54	-56	-57
Sep	15379	14908	14459	11387	10569	9994	-26	-29	-31
Oct	8829	8539	8268	8593	8248	8093	-3	-3	-2
No	4216	3960	3704	5550	5512	5470	32	39	48
Dec	2683	2428	2172	4953	4909	4791	85	102	121
Yearly	71471	68084	64723	69899	66605	63313	-2	-2	-2

Table 6-5: Energy production of HAD (GWh)

	HAD alone			With GERD			Difference (%)		
Month	Upper Limit	Mean	Lower Limit	Upper Limit	Mean	Lower Limit	Upper Limit	Mean	Lower Limit
Jan	375	349	330	344	316	295	-8	-10	-11
Feb	441	409	382	410	377	352	-7	-8	-8
Mar	606	552	507	570	522	477	-6	-5	-6
Apr	586	525	480	559	502	457	-5	-4	-5
May	747	670	596	718	645	575	-4	-4	-4
Jun	910	808	679	887	784	679	-3	-3	0
Jul	932	834	751	905	806	691	-3	-3	-8
Aug	813	738	679	773	688	625	-5	-7	-8
Sep	599	553	518	539	487	446	-10	-12	-14
Oct	519	484	457	464	422	389	-11	-13	-15
Nov	472	441	417	425	388	360	-10	-12	-14
Dec	462	432	408	422	386	359	-9	-11	-12
Yearly	7460	6797	6203	7016	6323	5703	-6	-7	-8

Figure 6-3 show monthly water loss at HAD and total loss from the two reservoirs. There is water loss reduction due to GERD by at least 11% on average. The maximum mean annual loss of HAD will be HAD alone with upper limit flow condition which is 13550 MCM and the minimum loss will be with GERD and lower limit flow condition which is about 8866 MCM. The cumulative mean annual loss from the two reservoirs is nearly equal (Figure 6-3)

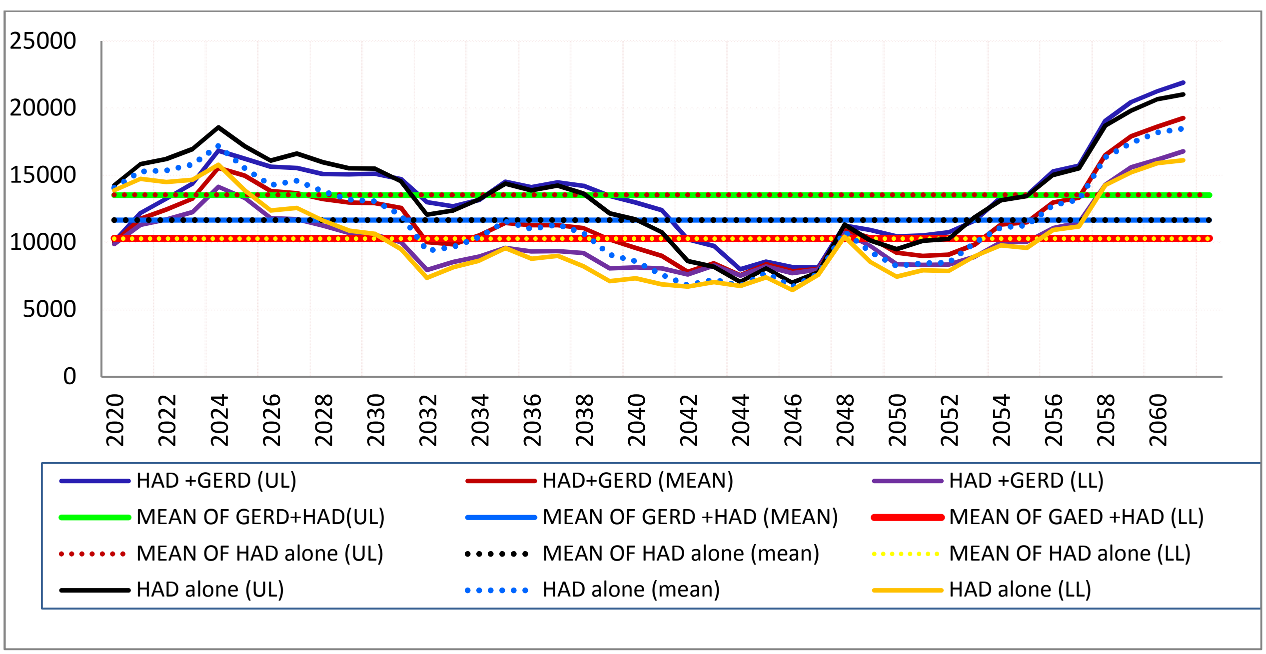

Figure 6-3: Mean annual loss with GERD, HAD alone and GERD+HAD (MCM)

6.3. Performance Analysis of the Reservoirs during Operation

It is useful to have an understanding of the uncertainties associated with the flow situations in the basin. Reservoir planning is concerned with determining the storage required in a reservoir for meeting a given yield with an acceptable level of performance. Performance measures often considered include reliability, resilience, vulnerability, and sustainability (Loucks 1997).

Therefore evaluating the satisfaction of irrigation at HAD been undertaken by considering the three flow conditions for both HAD alone and with GERD scenarios. Reliability can be described as the probability that a reservoir will be able to meet, within the simulation period, the target demand in any given interval of time. Time-based reliability considers the proportion of intervals during the simulation period that reservoir can meet the target demand. A general expression for estimating the time based reliability is using equation 2:

$$R_t = \frac{N_s}{N}; \quad 0 < R_t \leq 1 \qquad (2)$$

Where,

- R_t = time based reliability.
- N_s = the numbers of interval that the target demand is fully meet.
- N = the total number of intervals covering the simulation analysis period, which is equal to 504 for this study.

Volumetric reliability is defined as the volume of water supplied to the demand center divides by the total target demand during the entire simulation period, i.e.

$$R_v = 1 - \frac{\sum_{i=1}^{N}(D_i - D'_i)}{\sum_{i=1}^{N} D_i} = 1 - \frac{Total\ shortfall}{Total\ t\arg et\ demand}; 0 < R_v \leq 1 \qquad (3)$$

Where:

- R_v = Volumetric reliability
- D_i = the target demand during the i^{th} period
- D'_i = the volume of water actually supplied or available in the reservoir during the i^{th} period
- N = the number of time interval in simulation period

Resilience is a metric defining how quickly a reservoir will recover from a failure. The method used in this study is the widely used definition of Hashimoto et al. (1982). According to Hashimoto et al. (1982) the resilience is the probability of a year of success following a year of failure and expressed by equation 4.

$$\varphi = \frac{f_s}{f_d},\ f_d \neq 0 \qquad 4$$

Where,

φ= is the resilience

fs = is the number of individual continuous sequences of failure periods and

fd = the total duration of the failure

Vulnerability measures the average volumetric severity of failure during a period and vulnerability by volume is defined by Hashimoto et al. (1982) as follows;

$$\eta' = \frac{\sum_{j=1}^{j=f_s} \max(s_j)}{f_s} \qquad 5$$

- η' = Vulnerability
- s_j = the volumetric shortfall during the j^{th} continuous failure sequence
- f_s = the number of continuous sequence of failure

Because equation 4 averages out the maximum shortfall over all the continuous failure periods, then a reduction in *fs* will cause η ' to increase when the numerator in equation 5, remains unchanged. Another point to note about equation 5 is that η ' is in volumetric units; a more useful expression of vulnerability is its dimensionless form (Thomas and Rosbjerg, 2004) given by:

$$\eta = \frac{\eta'}{D_f} \quad 0 < \eta \leq 1 \qquad 6$$

Where:

η = dimensionless Vulnerability

D_f = is the constant or average of all demand

6.3.1. Performance Analysis of HAD Irrigation Demand

The three system of assessment i.e. reliability, resilience and vulnerability could ensure a consistent assessment of reservoir system performance (Thomas et al. 2004). The values of the Performance Indices of the HAD reservoir in meeting various irrigation demands for the simulated period are shown in the Table 6-6. It may be seen from the index volumetric reliability (Rv) that the percentages of success of the reservoir in meeting the irrigation requirement at HAD are almost the same with and without GERD as shown in Table 6-6.

The percentages of success in terms of metric reliability (Rt) are also above 96% for all conditions. The recovery of the reservoir (resilience) is less in lower limit flow conditions as compared to others which is 0.90 and 0.95 for HAD alone and with GERD respectively. HAD alone scenario is relatively vulnerable as compared to with GERD scenario (Table 6-6). The results indicate that the system is capable of meeting the demands in all flow conditions.

Table 6-6: Performance analysis for HAD irrigation demand

Performance indices		HAD alone			With GERD		
		UL	**Mean**	**LL**	**UL**	**Mean**	**LL**
Volumetric Reliability	total shortfall (MCM)	28642	64613	124158	27610	65839	131193
	total target demand (MCM)	2331000	2331000	2331000	2331000	2331000	2331000
	Rv	**0.99**	**0.97**	**0.95**	**0.99**	**0.97**	**0.94**
Metric Reliability	Ns	496	491	486	496	486	461
	N	504	504	504	504	504	504
	Rt	**0.98**	**0.97**	**0.96**	**0.98**	**0.96**	**0.91**
Resilience	fs	8	17	28	8	18	41
	fd	8	18	31	8	18	43
	φ	**1.00**	**0.94**	**0.90**	**1.00**	**1.00**	**0.95**
Vulnerability	sum sj	14803	23656	47522	13544	24510	55073
	fs	8	17	28	8	18	41
	η′	1850	1392	1697	1693	1362	1343
	Df	4625	4625	4625	4625	4625	4625
	η	**0.40**	**0.30**	**0.37**	**0.37**	**0.29**	**0.29**

6.3.2. Performance Analysis of GERD Energy Production

The values of the performance indices of the GERD reservoir in meeting target hydropower demands for the simulated period are shown in the Table 6-7. From the index volumetric reliability (Rv) that the percentages of success of the reservoir in meeting the requirement are 97%, 95% and 92% for upper, mean and lower limits of flow respectively. The percentages of success in terms of metric reliability (Rt) are 92%, 89% and 83% for upper, mean and lower limits of flow respectively. The vulnerability and recovery of the reservoir (resilience) is more or less similar for all flow conditions. The results indicate that the system is capable of satisfying the target hydropower demands in all flow conditions.

Table 6-7: Performance analysis for GERD hydropower generation

Performance indices		Upper limit	Mean	Lower limit
	total deficit (GWh)	28262	46681	72561
	total target demand (GWh)	898128	898128	898128
Volumetric Reliability	**Rv**	**0.97**	**0.95**	**0.92**
	Ns	465	444	414
	N	504	504	504
Metric Reliability	**Rt**	**0.92**	**0.89**	**0.83**
	fs	37	52	81
	fd	39	57	87
Resilience	**φ**	**0.95**	**0.91**	**0.93**
	sum sj	9287	15316	25548
	fs	37	52	81
	η'	251	295	315
	Df	1782	1782	1782
Vulnerability	**η**	**0.14**	**0.17**	**0.18**

6.4. Impacts and Benefits of GERD on HAD

Simulations were undertaken to assess the impacts of GERD on HAD during operation periods. Impacts and benefits are assessed based on performances of the reservoir (HAD) in meeting irrigation water demand for the three (upper limit, mean and lower limit) flows. The impacts and benefits of GERD on HAD will be seen by comparing the changes on the water resource and water demand at HAD with and with no GERD. The parameters to compared are inflow to HAD, outflow from HAD, water demand (irrigation) deficit of Egypt, energy generations and losses at HAD.

6.4.1. Impacts

The computed results of the sensitive analysis related to irrigation water demand coverage and Hydropower are synthesized and shown in Tables 6-6 and 6-7. There are slight reductions in water level, inflow and energy generation because of GERD. As shown in Table 6-2, reservoir water level will decrease on average by 3 m (2.5%) due to GERD in operation. Mean annual inflow to HAD will decrease by 2% for all flow conditions. As shown in Table 6-3 the number of months with water demands deficit will increase by 4 months for low flows, but for the mean and upper flow limit there is no changes. Reduction in reservoir water level (head) will cause energy reduction of HAD by 6 to 8% because of GERD (Table 6-5).

6.4.2. Benefits

Benefits of GERD on HAD is also assessed based on the parameters indicated above (flows, water demand, energy, loss etc.). With its 6000 MW installed power generation capacity; GERD will increase Ethiopian Hydroelectric power generation.

The energy reduction at HAD due to GERD implementation represents only 7 % of the present HAD energy generation, but it will be largely compensated by the additional energy produced by GERD. Energy reduction at HAD is unavoidable but, at the same time, GERD will considerably increase the present production capacity of the whole Eastern Nile Basin.

If the two reservoirs are considered as single unit, energy will increase by 217% % (from 7460 to 23620 GWH/year for upper flow limit. For mean energy production will increase by 224% (from 6797 to 22000 GWh/year) and lower flow energy in the Eastern Nile will increase by at least 230%, which is from 6200 to 20470 GWh/year.

There is regulated flows arriving at HAD due to the presence of GERD and evaporation loss from HAD will reduce. From the performance analysis of the two reservoirs, there is insignificant differences on the indices between HAD alone and with GERD scenarios. The performances are acceptable in both cases.

6.5. Sudanese Reservoirs' Operation Simulation Results Considering GERD Upstream

Simulations are realized at downstream structures in future conditions (with GERD) based on historical monthly flows from January 1961 to December 2002. The irrigation demands have been simulated for the current irrigation demands. Current irrigation water demand results on the period 1961 – 2002 are taken as possible future hydrologic pattern. The fluctuation of water level is reduced compared to without GERD simulation results. This is a consequence of the seasonal inflows regime regulation; more constant flows arrive at Sudanese reservoirs (Roseires, Sennar and Merowe) all over the year. Sudanese irrigation water demand is always satisfied during the simulated period with more than 96% performance (Table 6-9). This result highlights the benefit of GERD construction compared to present situation. GERD has no negative impacts on either of the Sudanese cascades, instead in all reservoirs the inflow is more uniform and the energy production increases.

There is a significant increase in power generation from Sudanese reservoirs. This benefit is the result of maintaining a higher level of consistency in the pool elevations of the Roseires, Sennar and Merowe reservoirs and reducing the inflows during the flooding period and hence reducing the probability of spills from the reservoirs. The higher reservoir water level will have larger surface area and maximum water loss (Figure 6-4). There could be some improvement in satisfying irrigation water demand in Sudanese reservoirs (Table 6-9).

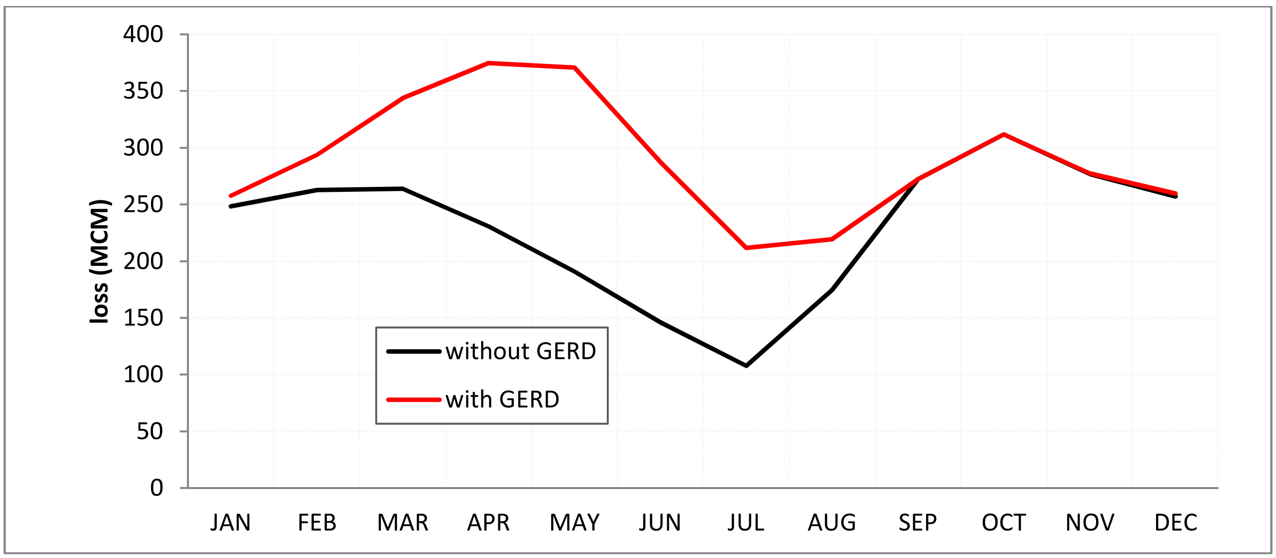

Figure 6-4: Cumulative water loss from Sudanese reservoirs

The GERD operation rules which will be applied in the future water management system will consider that the objective of GERD is energy generation. Energy will be generated satisfying the monthly demand as long as GERD water level is above the MOL. If GERD water level becomes higher than 640 m.a.s.l. water volumes will be spilled downstream or possibly turbine (with-in the capacity of the installed power). Thus, to satisfy this objective of firm energy generation, GERD will turbine water at a quite regular rate all over the year. In the Sudan, as it will be necessary to withdraw water downstream GERD, there will be no change in yearly water volume arriving in the 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 (Figure 6-5).

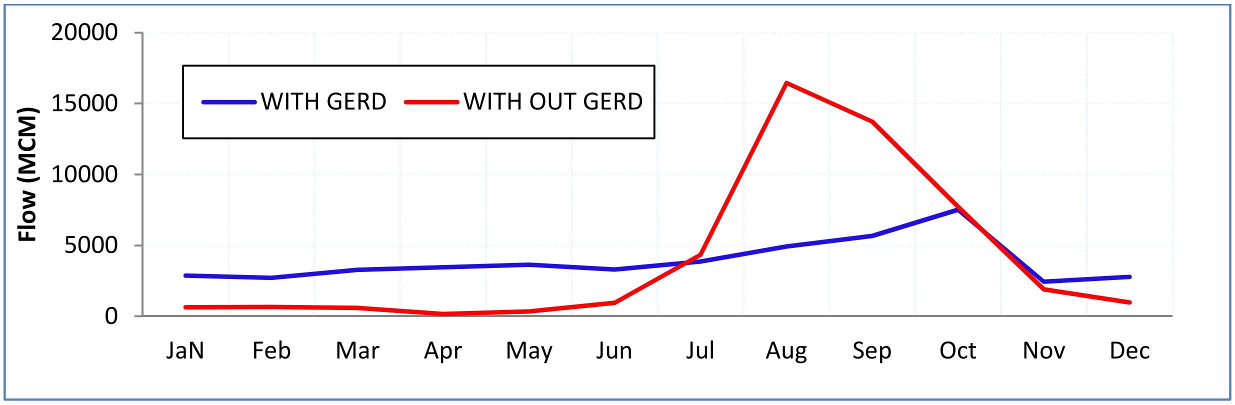

Figure 6-5: GERD impact on mean monthly inflow Khartoum in wet seasons

Table 6-8: Mean monthly energy production of Sudanese reservoirs (GWh/month) with and without GERD

Month	Rosaries			Sennar			Merowe			Cumulative (Sudanese total)		
	With out	with GERD	Diff (%)	With out	with GERD	Diff (%)	With out	with GERD	Diff (%)	With out	with GERD	Diff (%)
Jan	144	299	107	11	11	2	484	707	46	639	1017	59
Feb	131	289	120	10	11	4	468	599	28	609	899	48
Mar	66	282	329	7	11	53	453	604	33	526	897	71
April	34	266	685	7	10	38	408	589	44	449	865	93
May	51	237	367	10	11	5	313	581	86	374	829	122
June	128	246	93	11	11	0	292	582	99	431	839	95
July	296	290	-2	11	11	0	492	687	40	799	988	24
Aug	305	305	0	11	11	0	736	732	-1	1052	1048	0
Sept	303	306	1	11	11	0	732	738	1	1046	1055	1
Oct	302	305	1	11	11	0	727	735	1	1040	1051	1
Nov	257	303	18	11	11	0	622	729	17	890	1043	17
Dec	157	301	91	11	11	1	517	725	40	685	1037	51
Annual	**2174**	**3430**	**58**	**123**	**131**	**6**	**6244**	**8007**	**28**	8541	11568	35

Table 6-9: Irrigation performances of Sudanese project

Irrigation site	Number of month with deficit		water deficit (MCM)		NS coefficient	
	With GERD	with out	With GERD	with out	Without GERD	With GERD
D/ Sennar	3	16	74	235	0.97	0.99
Gizira	2	20	370	2690	0.96	1

6.6. Conclusive Remarks

Benefits and impacts of GERD in the long term perspective are assessed based on satisfaction of irrigation water demand, hydropower generation, water loss and hydrological perspectives of the Eastern Nile.

- The energy gain from GERD and Sudanese reservoirs due to storage capacity of the Blue Nile will increase the Eastern Nile energy by at least 18200 GWh/year while slightly energy reduction at HAD (average 7%) due to water level reduction.
- Egyptian and Sudan agricultural water demands are always satisfied with more than 96% reliability.
- As a consequence of upstream flow regulation the downstream reservoirs' water level has less fluctuation and this reduces the future risk due to hydrological variability with sequences of dry and wet years for downstream water use sectors.
- The routing capacity (flood storage capacity) of the Nile River will be increased and there will be better flood control in the Blue Nile.

Table 6-10: Country wise gain and losses

	Energy (GWH/YEAR)				Water (MCM)	
Country	Current	Future	Gain	Loss	Gain	Loss
Ethiopia	-	15673	15673	_	_	1475
Sudan	8541	11568	3027	_	_	737
Egypt	6797	6323	-	474	1495	-
Over all	15338	33564	18226	-		717

Chapter Seven

Strategic Perspective and Options Assessment of Upper Blue Nile (Abbay-Blue Nile) River Basin Cascades Development

7.1. Introduction

There is huge hydro power development potential in the Eastern Nile Basin (Waterbury and Whittington, 1998; Waterbury, 2002; Swain, 2002). The greatest development potential, about 58 % of the total in the Nile Basin, is located in Ethiopia; this is because of the great differences in altitude (Ethiopia, 2000).

There are a number of water resource development projects in Ethiopia (Abbay-Blue Nile River Basin).The projects are at different level, some are in operational stage, some are under construction and the other are in the studying and design phases. Due to the high variability in annual rainfall, conservation of water and irrigated agriculture are seen as a way to mitigate the effects of drought.

According to the master plan of Abbay river basin (BCEOM, 1999), the total potential for hydropower generation in the basin is about 13,000 MW; this is many times as much as the existing installed capacity. Abbay basin master plan in Ethiopia and other regional projects, for instance Joint multipurpose projects (JMP) has identified three hydropower dams upstream of GERD. The realization of the long run may be a necessary to Ethiopia or regional power requirement.

The objectives of this section is to provide quantitative analysis of water resources management for the Eastern Nile region by considering the current water use situation and proposed reservoirs in the Abbay-Blue Nile River basin upstream of GERD. This analysis is then used for estimation of impacts and benefits of upper cascades on downstream structures and basin wide benefits and impacts in the Eastern Nile region during their filling and full operation phases. Furthermore, the study tests the utility of hydropower development on the Abbay-Blue Nile River by testing different development or dam scenarios shown in Table 4-1.

7.2. Development Scenarios

During this study, an investigation has been conducted to assess the future probable changes of hydrological process which may have impacts on the spatial and temporal distribution of water availability in the basin. There are three proposed dams (Karadobi, Bekoabo high/low and Mendya) in the Abbay basin. There are two options for Bekoabo (Bekoabo high and Bekoabo low). It is not possible to combine Bekoabo high and Karadobi because of the minimum available elevation difference between them.

The construction and fillings of each cascades is based on five year intervals from the top to downstream, i.e., Karadobi, Bekoabo and Mendya will be constructed and fill in order. To get the best combination of the reservoirs operating simultaneously, the following scenarios have been considered and summarized in the Table 7-1.

Table 7-1: Hydropower dams development scenarios in the Eastern Nile basin with their implementation intervals in years

Starting Year	Before 2020	2020	2025	2030	2035
Scenario 1	Currently operating reservoirs in the Eastern Nile Basin				
Scenario 2		GERD			
Scenario 3		GERD	Karadobi		
Scenario 4		GERD	Karadobi	Mendya	
Scenario 5		GERD	Karadobi	Bekoabo low	
Scenario 6		GERD	Karadobi	Bekoabo low	Mendya
Scenario 7		GERD	Bekoabo high		
Scenario 8		GERD	Bekoabo high	Mendya	

- Baseline scenario (Scenario 1): the reference scenario or current condition.
- GERD only (Scenario 2): the combination of GERD and currently operating reservoirs.
- Karadobi and GERD (Scenario 3): the second scenario with Karadobi.
- Karadobi, GERD, and Mendya (Scenario 4): this one is the combination of Karadobi, GERD and Mendya with the currently scenario.
- Karadobi, GERD and Bekoabo low (Scenario 5): this is scenario 4, but Bekoabo low instead of Mendya.
- Karadobi, GERD, Mendya and Bekoabo low (Scenario 6): here four reservoirs are considered with current condition.

- ➢ Bekoabo high and GERD (Scenario 7): this similar with scenario 3 but Bekoabo high instead of Karadobi.
- ➢ Bekoabo high, GERD and Mendya (Scenario 8): Mendya with scenario 7.

7.3. Inflow to Reservoirs

The flow regime of the downstream dam is governed by the operations of the upstream hydroelectric power schemes and runoff from the catchments (the incremental flow) between the two dams. Reservoirs in the upstream have effects on the downstream reservoirs inflow. During filling period of new constructed reservoir, the amount of water released will be reduced and more regulated. For instance, there is slight inflow reduction to GERD during the impounding of upper cascades in the Abbay-Blue Nile River (Figure 7-1 and Figure 7-2). During full operation phase, the reservoirs in the downstream will gain maximum flow in the dry months and the flood will decrease in wet months as a result of regulating effects of upstream cascades.

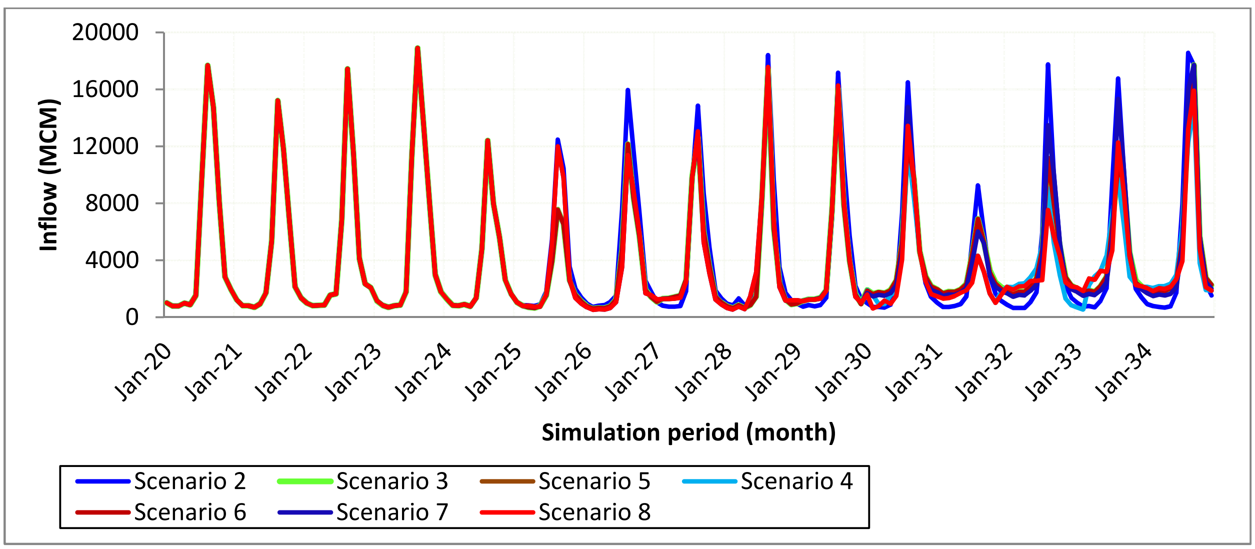

Figure 7-1: Monthly Inflows to GERD during fillings of upper reservoirs based on scenario 1 to 8

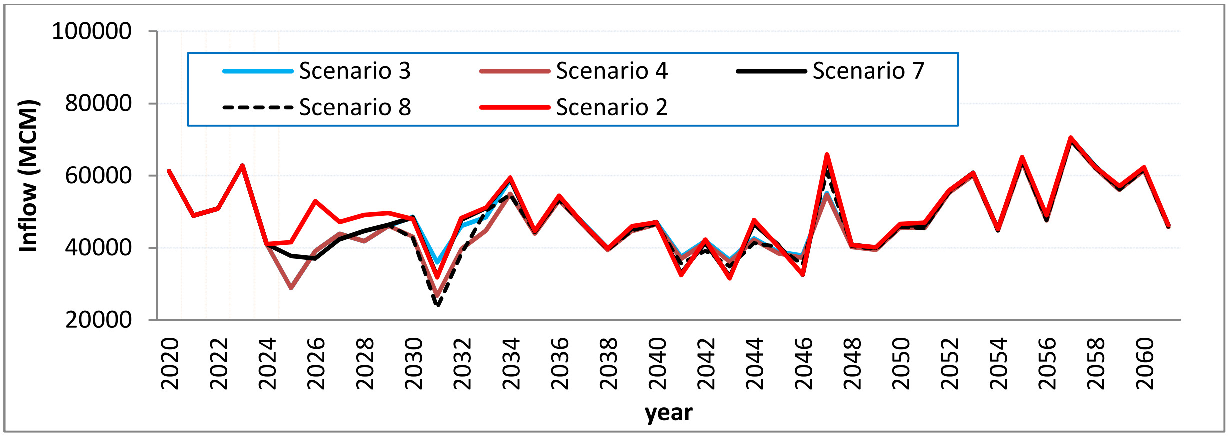

Figure 7-2: Annual Inflow Series to GERD including the filling periods of each scenario.

Releases from Karadobi, Bekoabo and Mendya dam constitute the major inflow into GERD dam, This means that the more the release from upper reservoir the faster the downstream reservoir fill up and excess will be discharged. The operation of GERD and other upstream dams dictate operation pattern in downstream dam, excess releases at GERD will force the reservoir manager at Rosaries dam to release so as to accommodate releases from GERD and thereby causing flooding at the downstream area.

Because of its storage capacity, GERD has significant effect on the inflow of the Sudanese reservoirs. Rosaries and Sennar dam receive more regulated flow due to GERD implementation. The monthly reservoirs inflow coefficient of variance is maximum in baseline scenario as compared to the other scenarios. The mean monthly inflow to downstream reservoirs will also be improved, for instance the mean monthly coefficient of variance for Rosaries is 1.2 and 0.2 for baseline and other scenarios respectively. For Sennar it is 1.3 for baseline scenario and 0.16 for the other scenarios. The same is true for HAD inflow, the coefficient of variance of inflow to HAD decreases from 1 (for baseline scenario) to 0.5 (for other scenarios).

There are changes in other flow statistics. The mean, maximum and minimum monthly flow to downstream reservoirs will be changed due to the implementation of upper cascades. For instance, the maximum inflow to HAD in dry month (May) is 3.4 BMC for base line scenario but for the scenarios 1 to 8, it is 4.6 BCM that is 35% incremental. But for the wet month (August) it is 32.6 BCM and 19 BCM for baseline and for scenario 1 to 8 respectively that is 42% reduction.

The inflow to HAD in the dry months (March, April, May and June) of selected dry year periods (from 1982 to 1988) will increase by 133% (from 1272 MCM to 2967 MCM) due to the implementation of upper cascades. This shows water availability at HAD could be safe even drought occurs.

For the selected wettest years (from 1996 to 2001) and wet months (July, August, September and October), flow to Khartoum will decrease by 100% (from 10113 MCM to 5084 MCM). That is, if flow which cause flood occurs in the highlands of Ethiopia, it will be controlled by the upstream reservoirs and will be released in regulated manner.

The impact of the upstream cascades on the mean annual flow to reservoirs in the downstream is insignificant. For instance the difference between maximum (65294 MCM, with current scenario) and the minimum (62438 MCM, for the scenario 4) mean annual inflow to HAD is 4.4%. For Merowe the difference between maximum and minimum mean annual inflow is 3.3%.

7.4. Reservoir Water Level

Filling period for Karadobi is assumed to be 5 years and after that it start operating with full capacity. Bekoabo low will start filling when Karadobi reaches its full level and then Mendya filling will start. The construction and filling of Mendya lags by 5 years of Karadobi or Bekoabo high filling, but for the three reservoirs combination (Karadobi + Bekoabo low + Mendya), the filling will be after 10 years of Karadobi filling.

There is no reservoir upstream of Karadobi which affects its operation. From Figure7-3 through Figure 7-11 show the reservoirs' pool level during filling and operation phases of the upstream reservoirs. As shown in Figure 7-3 and Figure 7-4, there are slight impacts of upstream cascades filling on the GERD pool level. There could be up to 7 meters monthly water level reduction of GERD during filling periods of the upper cascades. After filling of all upstream reservoirs, the maximum GERD mean monthly reservoir water level difference, which is between scenario 2 and scenario 4, is 3 meters.

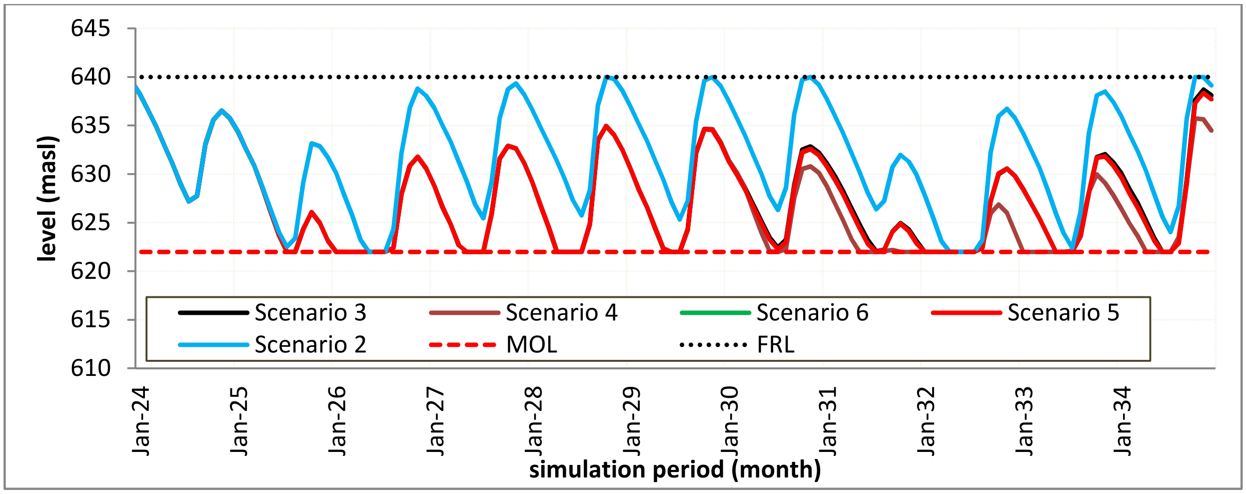

Figure 7-3: GERD pool level during impounding of upper cascades

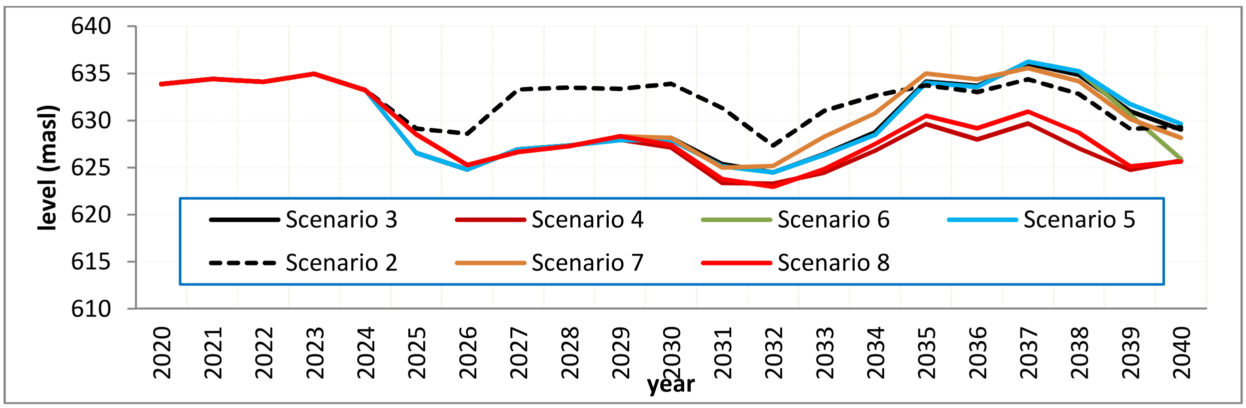

Figure 7-4: Mean annual GERD water level during filling of upper cascades

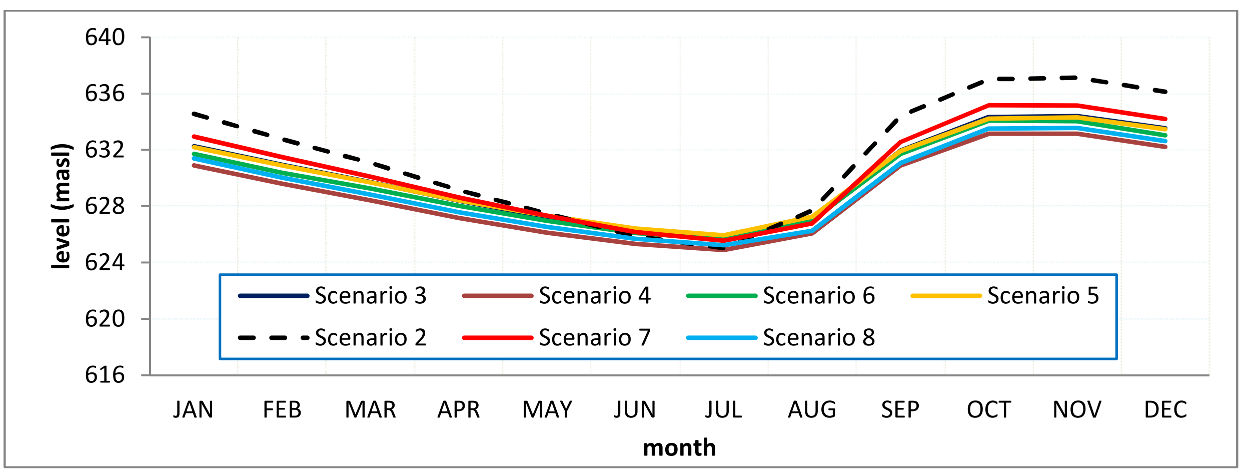

Figure 7-5: Mean monthly GERD water level during full operation phase

Figure 7-6 through Figure 7-9 show Sudanese reservoir water levels for different scenarios. As shown in the figures, all Sudanese reservoirs water level will increase due to upper cascades implementation. Their pool level never be below baseline scenario's level in both filling and operation phases. The maximum pool level for all Sudanese reservoirs is scenario 2. Though it is not below baseline scenario level, there could be up to 11 meters water level reduction of Rosaries during the filling of Karadobi, Media and Bekoabo (scenario 4) as compared to scenario 2 (Figure 7-6).

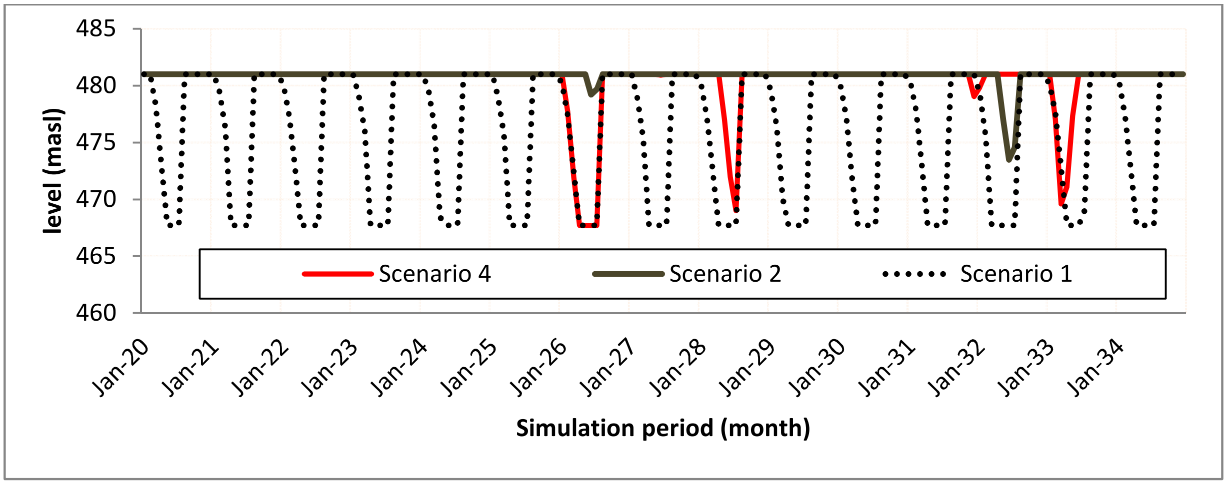

Figure 7-6 Rosaries pool level during impounding of upper cascades

As shown from Figure 7-8, Sennar water level will not be affected by reservoirs in Abbay-Blue Nile river basin in both filling and operation phases. Because of its storage capacity there is water level reduction in the dry months for the baseline scenario but this could be mitigated by implementing reservoirs in the upstream as shown in the Figure 7-7.

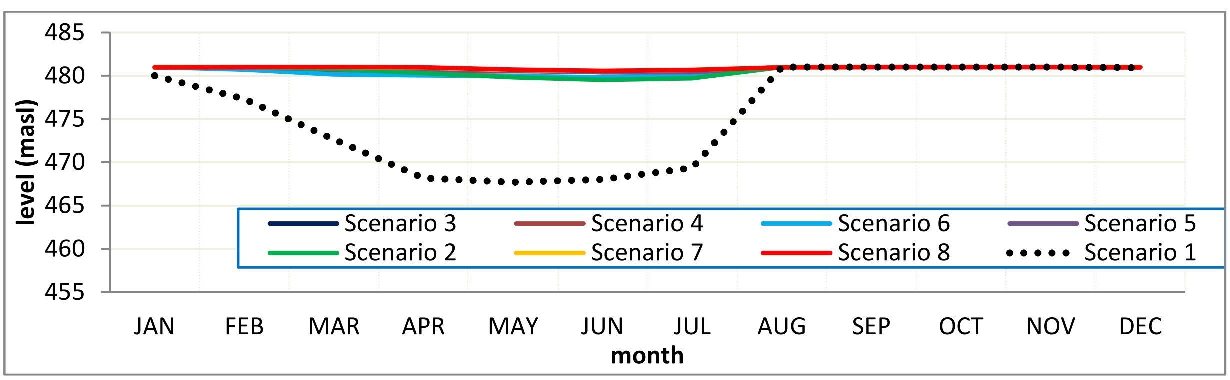

Figure 7-7: Mean monthly Rosaries water level during full operation phase

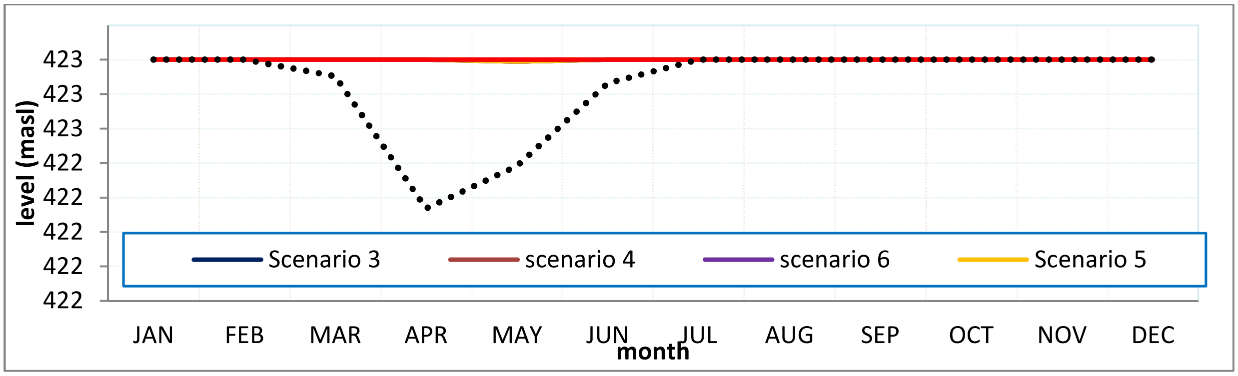

Figure 7-8: Mean monthly Sennar water level during full operation phase

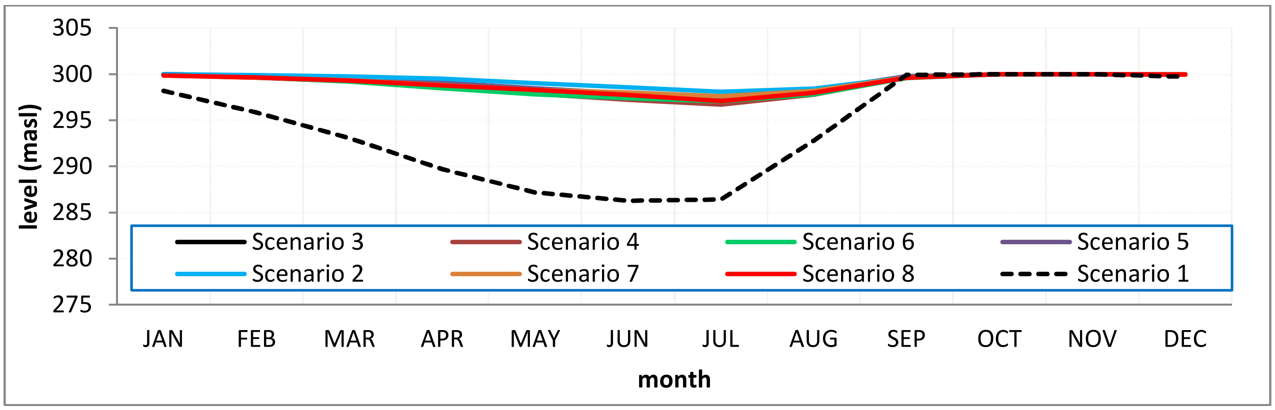

Figure 7-9: Mean monthly reservoir water level of Merowe during filling and operation of upper cascades (m.a.s.l)

Figure 7-9 and Appendix Figure F-18 show Merowe mean monthly and annual reservoir water level for different scenarios respectively. There is slight impact of upper cascades filling on Merowe reservoir as compared to scenario1 and scenario2. There could be up to 5 meters water level reduction of Merowe reservoir due to upper cascades filling as compared to scenario 2, but it will never reach below water level of baseline scenario.

At the end of impounding of all reservoirs HAD reservoir water level decreases up to 14 meters (Figure 7-10). The maximum reservoir water level reduction will be if all proposed reservoirs in Abbay River are implemented. As shown in Figure 7-11, HAD reservoir water level will have less fluctuation when there are more reservoirs in upstream. Reservoir water level range is 36 m in the simulation period of baseline scenario, but for the other scenarios it is around 31meters.

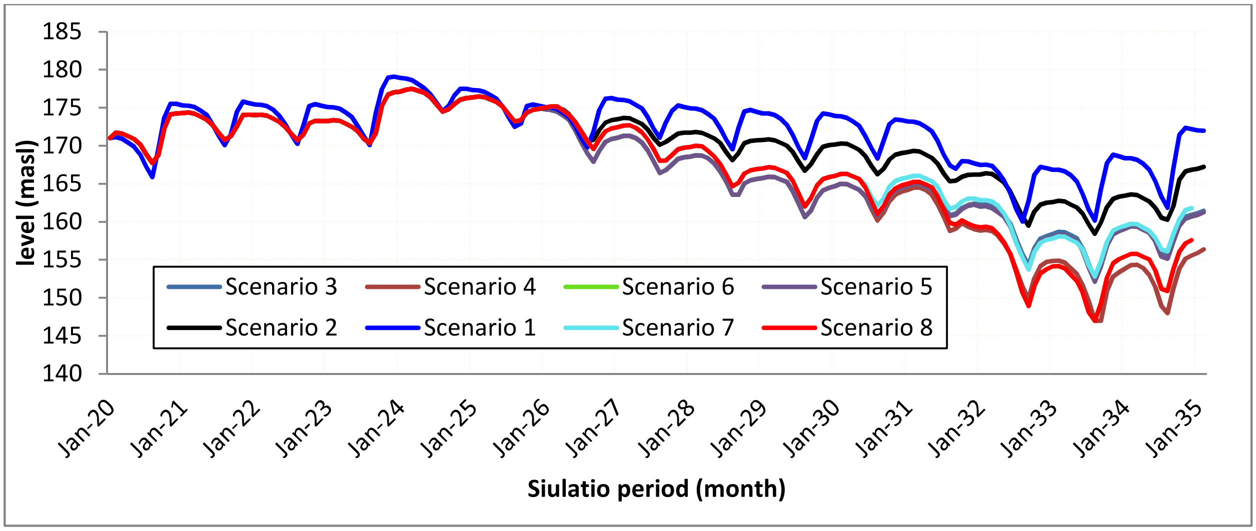

Figure 7-10: HAD pool level during impounding of upper cascades

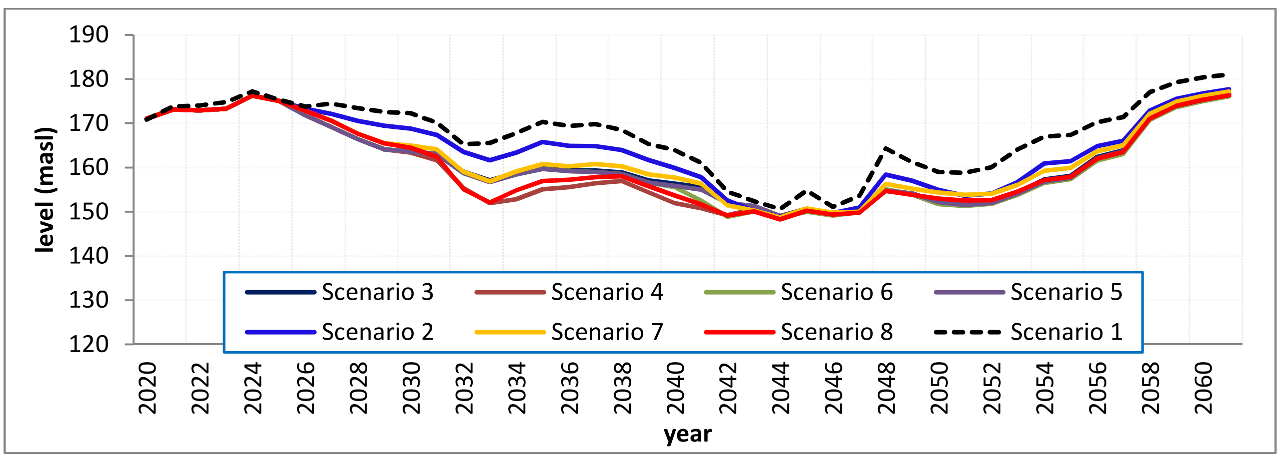

Figure 7-11: HAD reservoir water level during filling and operation of upper cascades (m.a.s.l)

7.5. The Impacts and Benefits of Upper Cascades on Energy Production of Eastern Nile

To discuss the impact and benefits of combinations of Upper cascades, it is necessary to consider each reservoir separately and the Eastern Nile basin as a system. This section discusses the production of energy in the Eastern Nile region by considering scenarios shown in Table 7-1. Regional and each Eastern Nile country's' hydropower production will be discussed in the following sub-sections.

7.5.1. Energy Production in Abbay-Blue Nile River (Ethiopia)

The energy production impact of upstream cascade development in the Abbay-Blue Nile River basin is similar with their impacts on the reservoir water level. The simulation results of energy production for the different scenarios are provided in Table 7-2 and Table 7-3. As shown in the Figure 7-12 and Figure 7-13 and in the Tables 7-2 and 7-3, the energy generation at GERD will be slightly affected due to the implementation of upper cascades. Because of their maximum capacity, Karadobi and Bekoabo high have significant impacts on the energy production of GERD during their filling phase. During Karadobi filling period, the energy production of GERD will reach minimum level (9163 GWh) which is 68% of scenario 2 (Figure 7-12). Bekoabo high filling will reduce the GERD energy to 10883 GWh which is 2546 GWh less than that of scenario 2.

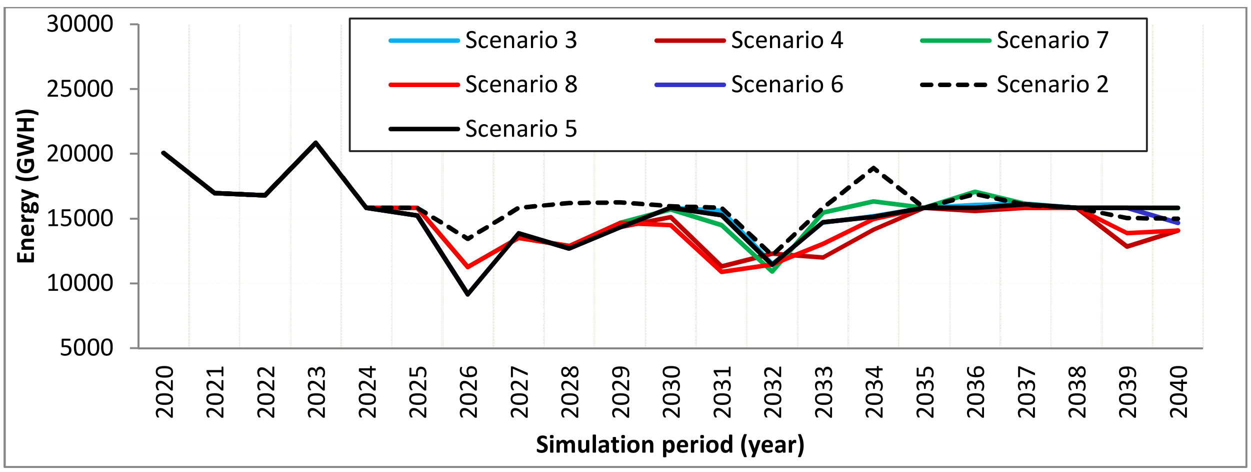

Figure 7-12: GERD energy production during filling periods of upper cascades

Figure 7-13 demonstrates the energy generation at GERD during full operation of all reservoirs. As show in the figure, there is slight fluctuation of energy production when only GERD is in operation (scenario 2). For instance, the coefficient of variance of the energy within the simulation period for GERD is 0.4 for scenario 2, while it is 0.35 for the other scenarios.

At full development level, maximum GERD energy (16256 GWH) could be generated when there is no cascade upstream of GERD. When there are more reservoirs in operation above GERD, there could be slight energy production of GERD (Table 7-3). The different between the maximum and the minimum is 463 GWH that is 3% reduction from scenario 2.

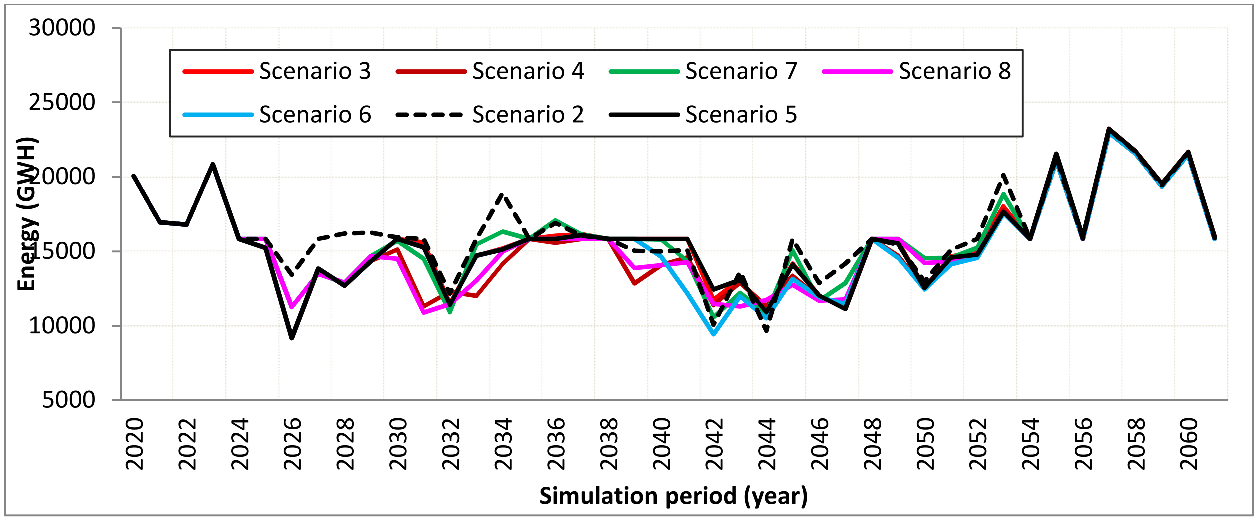

Figure 7-13: Annual energy generation of GERD during filling phases of all reservoirs in Abbay river basin (GWH)

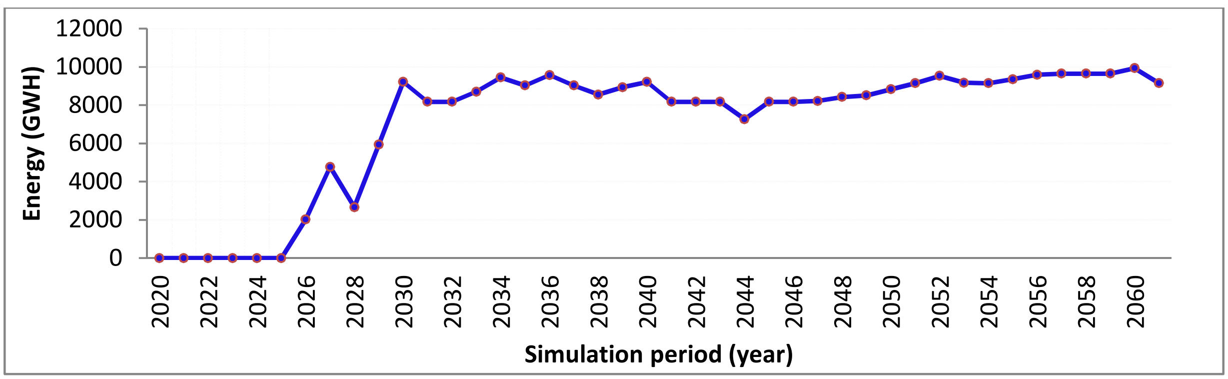

Figure 7-14: Karadobi energy production during impounding and operation phases

Figure 7-14 presents energy production of Karadobi during filling and operation periods. The energy production at Karadobi will not be changed because there are no reservoirs above it. The mean annual energy at Karadobi is 8864 GWH during its full operation phase. There are three scenarios for Mendya that is Mendya with Bekoabo high, Mendya with Karadobi and Mendya with Karadobi and Bekoabo low. Maximum energy production at Mendya (8775 GWH) is when Karadobi and Bekoabo low are in operation upstream of it. If Bekoabo high and Karadobi are in operation above Mendya, energy production has no significant difference that is Mendya energy will be 8612 and 8607 GWH for Bekoabo high and Karadobi respectively (Table 7-3).

Figure 7-15 shows energy production of Mendya during filling and operation phases for the combination of Mendya with; Karadobi, Karadobi + Bekoabo low and Bekoabo high. The impounding period is assumed to 5 years and maximum energy production will be after the filling of the reservoir to its full reservoir level (808 m.a.s.l).

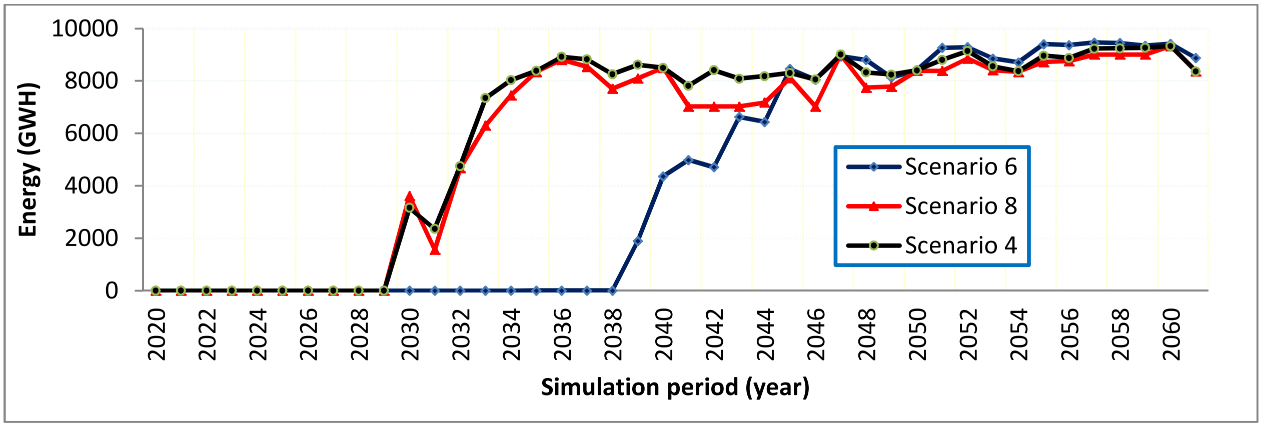

Figure 7-15: Mendya energy production during impounding and operation phases when combined with different combination of the upper cascades

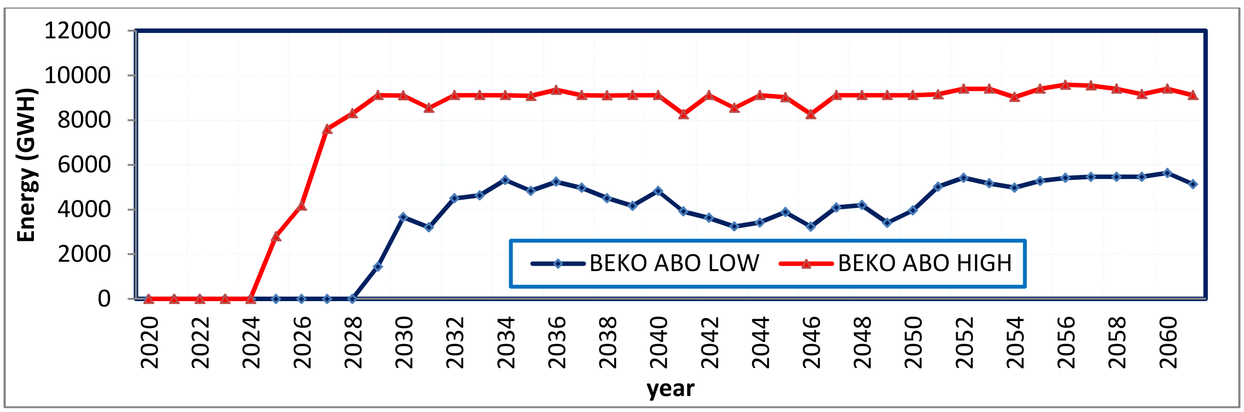

Figure 7-16: Bekoabo (Bekoabo low and Bekoabo high) energy production during impounding and operation phases

Figure 7-16 show energy production of Bekoabo low and Bekoabo high during filling and full operation phases respectively. There are two options for Bekoabo that is Bekoabo high and Bekoabo low with Karadobi. As the name indicates, there is difference between Bekoabo high and Bekoabo low in storage capacity and normal water level. Therefore, there is big mean annual energy production difference between Bekoabo High and Bekoabo low (12093 and 4744 GWH respectively). The construction and filling of Bekoabo low is after the implementation of Karadobi.

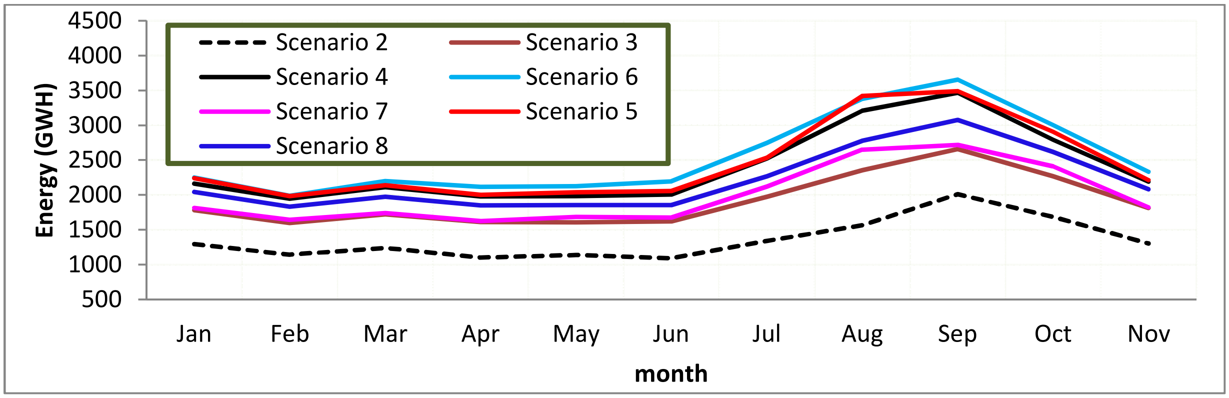

Figure 7-17: Cumulative mean monthly energy generation in Abbay River (Ethiopia) during full operation phases of all reservoirs (GWH)

Figure 7-17 and figure 7-19 demonstrate the cumulative (total) energy production in Abbay-Blue Nile River (Ethiopia) after filling phases of all reservoirs are completed. As shown in Figures and Table 7-2 and Table 7-4, the overall energy production in Ethiopia will increase significantly due to the construction of the upper cascades. As shown in Table 7-4, the maximum mean annual energy production (38200 GWH) is scenario 6 which combines four reservoirs (GERD, Karadobi, Bekoabo low and Mendya) in Abbay-Blue Nile River basin. The next maximum mean annual energy production (36525 GWH) is scenario 8 which combines GERD, Bekoabo high and Mendya. The minimum mean annual energy production (16256 GWH) is in scenario 2.

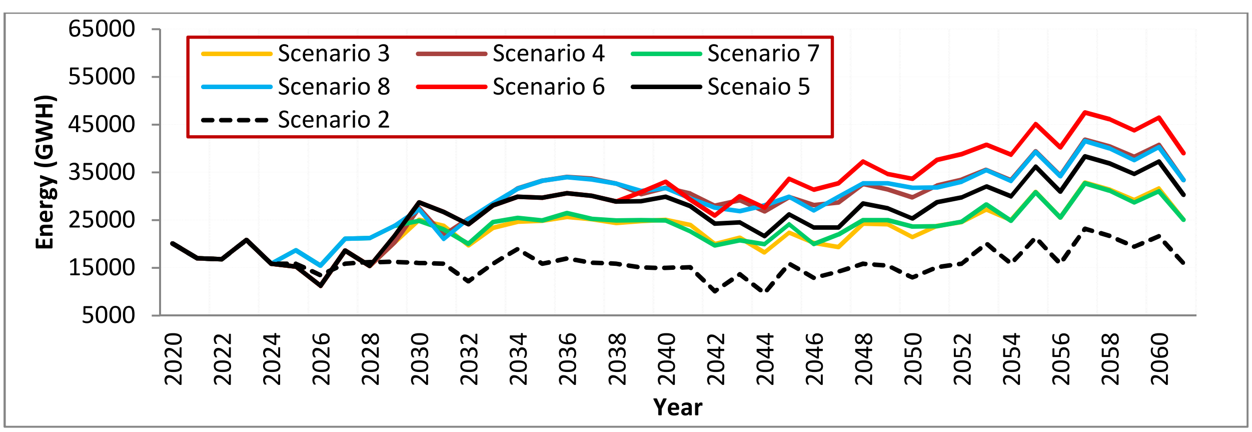

Figure 7-18: Total annual energy generation in upper Abbay River (Ethiopia) during impounding and operation phases of the upper cascades (GWH)

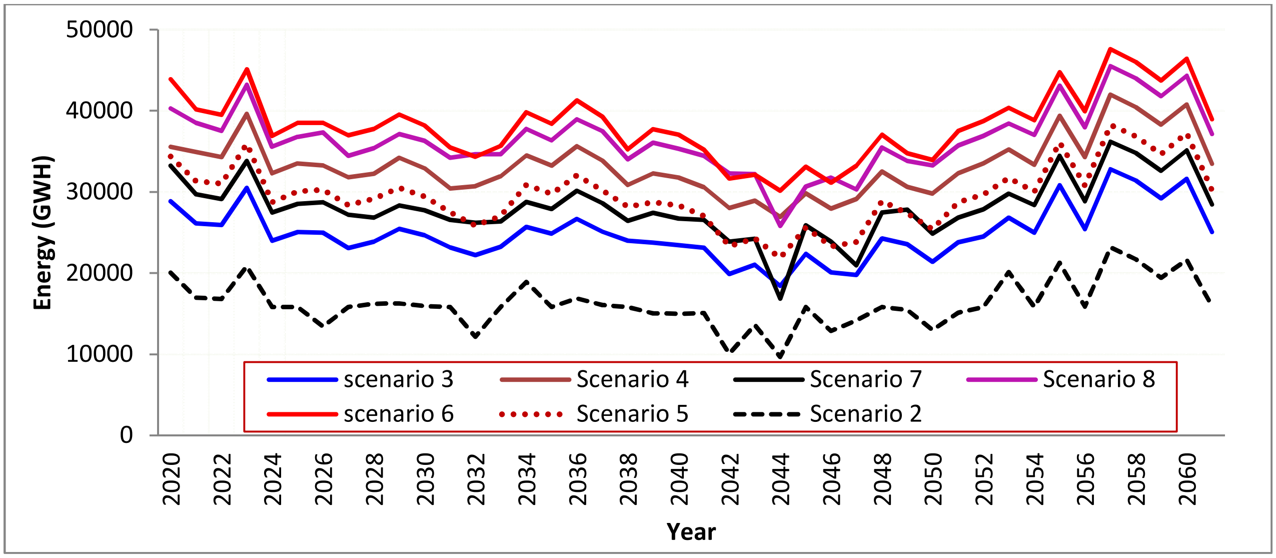

Figure 7-19: Total annual energy generation in Abbay River (Ethiopia) during full operation phases of the upper cascades (GWH)

7.5.2. Energy Production in Sudan

Energy production in Sudan is from Rosaries, Sennar and Merowe dams. Sudan would also benefit from the upstream infrastructures: reduced spillage makes more water available for hydropower generation. Figure 7-21 and Figure 7-22 present the monthly average energy generated by the major hydropower plants (Rosaries and Merowe) for all development scenarios. As shown in Figure 7-20, there is slight reduction of energy at Roseires during the filling periods of cascades in Abbay-Blue Nile River as compared to scenario 2. But energy generation of Rosaries is always more than that of scenario 1. Even though there is a slight effect of upstream cascades filling on Merowe energy production as compared to the scenario 2, there is significant incremental of energy as compared to scenario 1 (Figure 7-21). For instance there is around 900 GWh more energy production during Bekoabo high filling as compared to scenario 1. Generally there are positive impacts of upper cascade development for energy production in Sudan. Due to their less storage capacity, the energy production in the dry months is less but the upper cascade development can mitigate this problem.

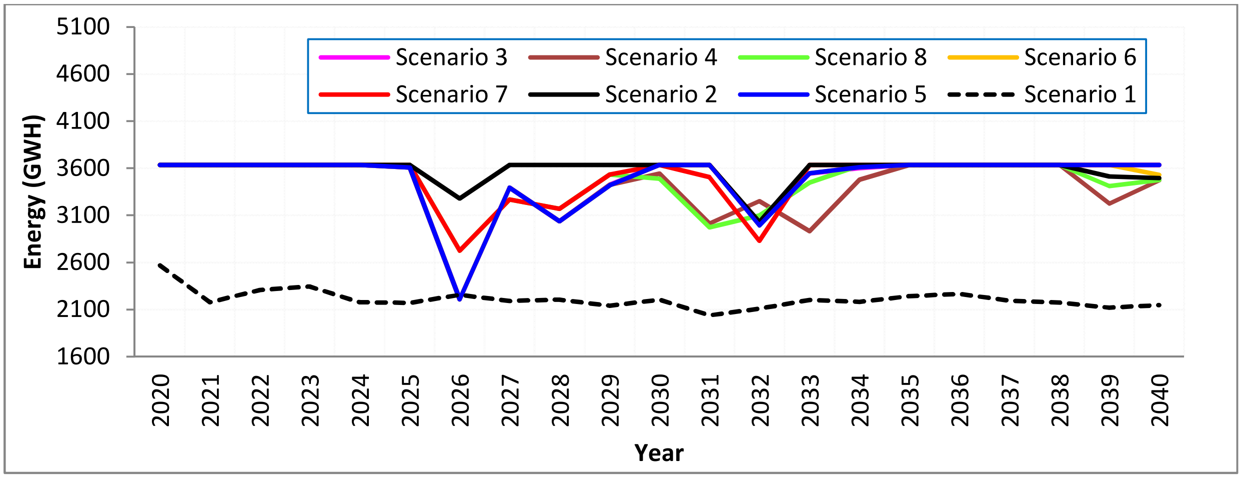

Figure 7-20: Annual energy generation of Rosaries during filling phases of upper cascades (GWH)

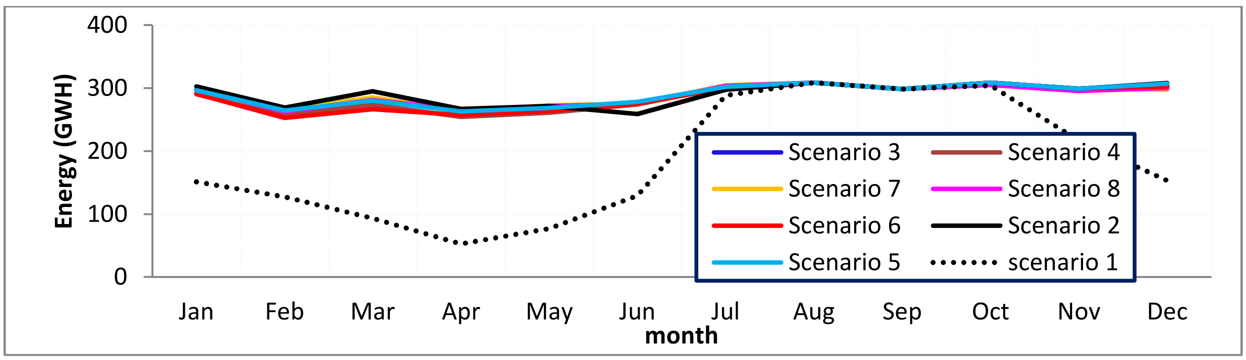

Figure 7-21: Mean monthly energy generation at Rosaries during full operation of all reservoirs (GWH)

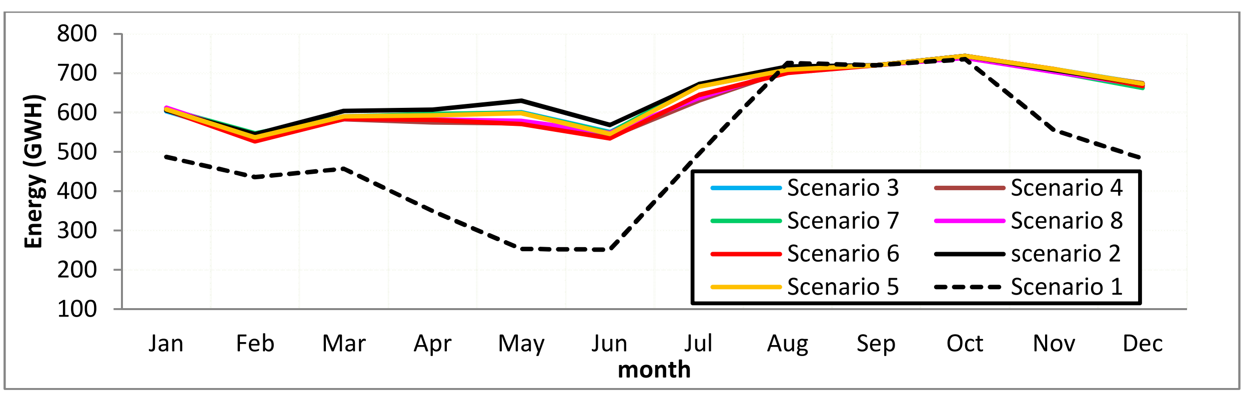

Figure 7-22: Mean monthly energy generation at Merowe during full operation of all reservoirs (GWH)

From Figure 7-23 and Figure 7-24 show, the cumulative energy production of reservoirs located in Sudan during filling and full operation phases. Due to the upper cascades, there will be flow regulation and reservoirs in Sudan will get uniform flows and the energy production will increase due to the upper cascades. The minimum energy production in Sudanese reservoirs is in the current situation (when there are no cascades in operation in the upper Blue Nile). But if there is a reservoir in upper Blue Nile, cumulative energy production in Sudan will increase by at least 35% (Table 7-2).

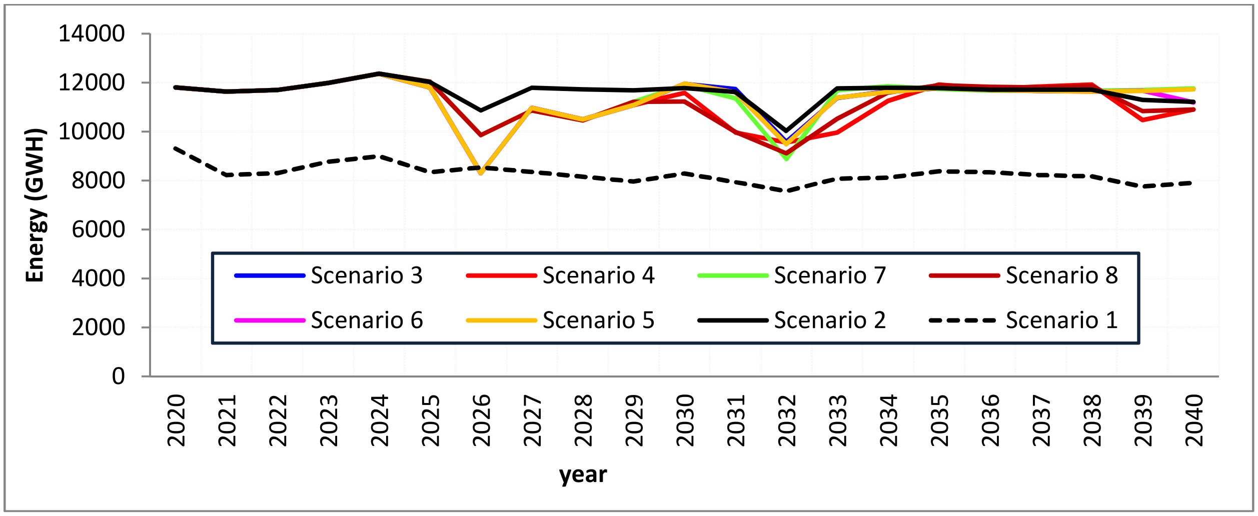

Figure 7-23: Annual energy generations in Sudan during filling phases of the upper reservoirs (GWH)

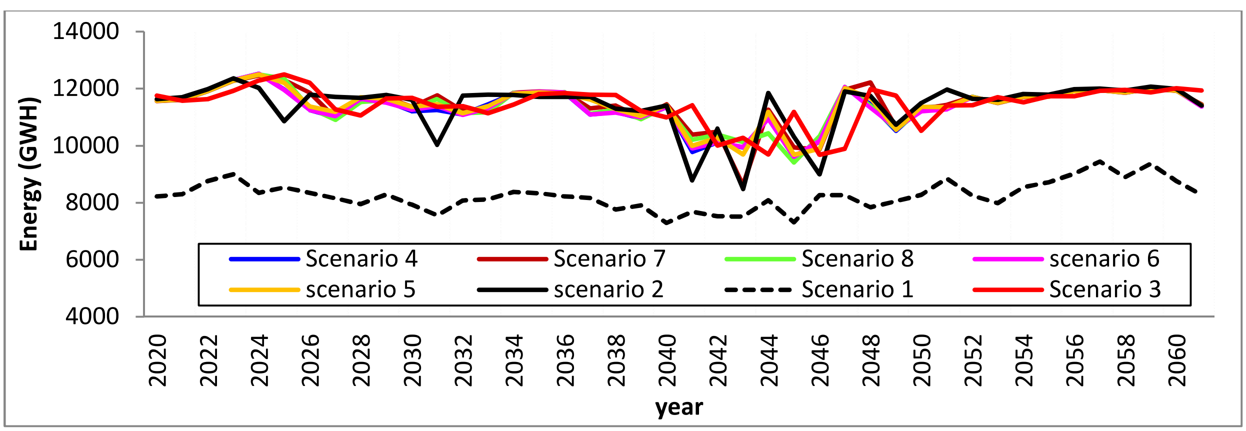

Figure 7-24: Annual energy generation in Sudan during full operations of the upper cascades

7.5.3. Energy Generation at HAD

Energy production at HAD will decrease due to the upper cascades. The production of hydroelectricity from HAD in Egypt would be reduced on average by 8.43% as compared to baseline scenario. Figure 7-25 depicts the energy production of HAD during filling and operation phases of upper cascades. Karadobi or Bekoabo high filling will reduce the HAD mean annual energy to 5039 GWh which is 33% less than the baseline scenario (Figure 7-25). The overall impacts of the upper cascades filling are insignificant (Table 7-2). Maximum energy reduction at HAD will be 14% of the baseline scenario. During full operation phases, the maximum energy (7462 GWH) is the baseline situation (Table 7-4). Maximum energy reduction as compared to the baseline scenario is 9% (Table 7-4) during the full operation phases.

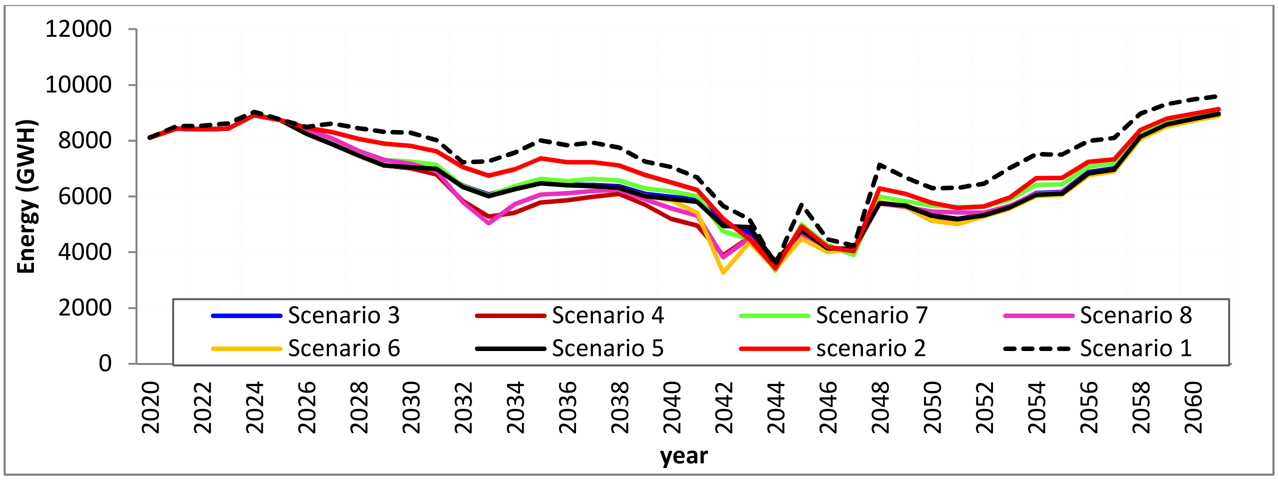

Figure 7-25: Annual energy generation at HAD during filling and operations of the upper cascades (GWH)

7.5.4. Energy production in Eastern Nile

At the basin scale, the annual production of hydroelectricity is boosted by at least 34645 GWH amongst which 3130 GWh is from Sudanese reservoir due to the regulation capacity of Ethiopian reservoirs. Positive impacts are also observed for Sudan where less spillage occurs. As shown in Figure 7-26, Figure 7-27, Table 7-3 and Table 7-4, the energy production in the whole Eastern Nile system will increase significantly when all reservoirs are at their full operation level.

During their filling phase there is slight reduction of energy generation as compared to scenario 2 (Figure 7-26). The column 'Diff' in Table 7-3 and Table 7-4 indicates the difference in energy production of Eastern Nile between the current situation (without GERD) and other scenarios. During the full operation phase, Eastern Nile energy will increase at least by 120% and it will reach up to 258% incremental. If each reservoir is considered as shown in Table 7-3, energy productions in Sudanese will increase due to the upper cascades but in HAD energy production will slightly decrease because of head reduction. The maximum energy in the Eastern Nile could be 56396 GWH for scenario 6 which combines GERD, Mendya, Bekoabo low, and Karadobi with the baseline scenario.

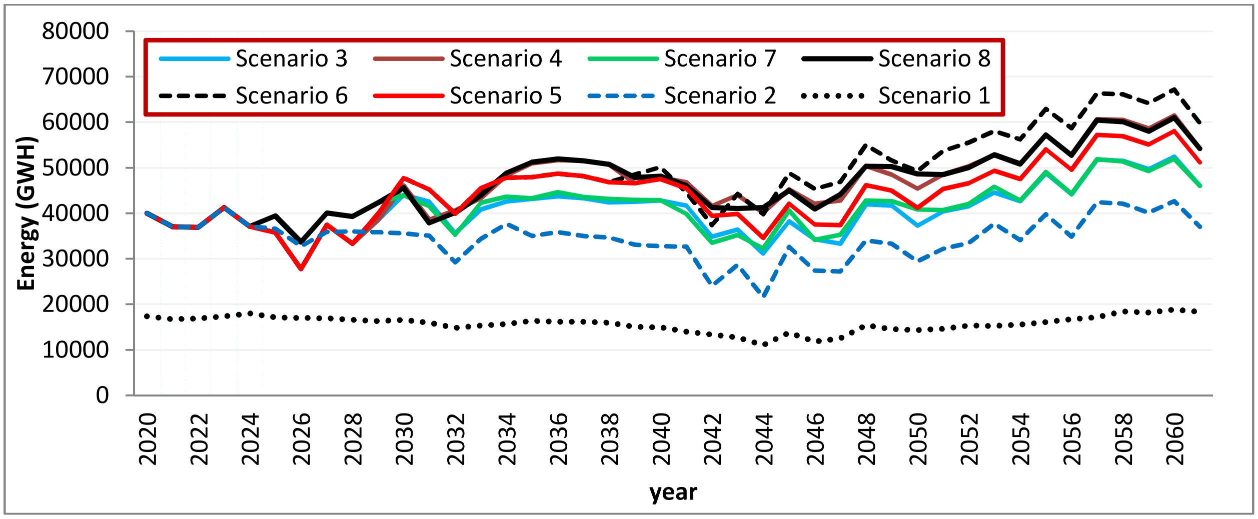

Figure 7-26: Energy generation of eastern Nile with upper cascades in Abbay River during filling and operation phases of upper reservoirs (GWH)

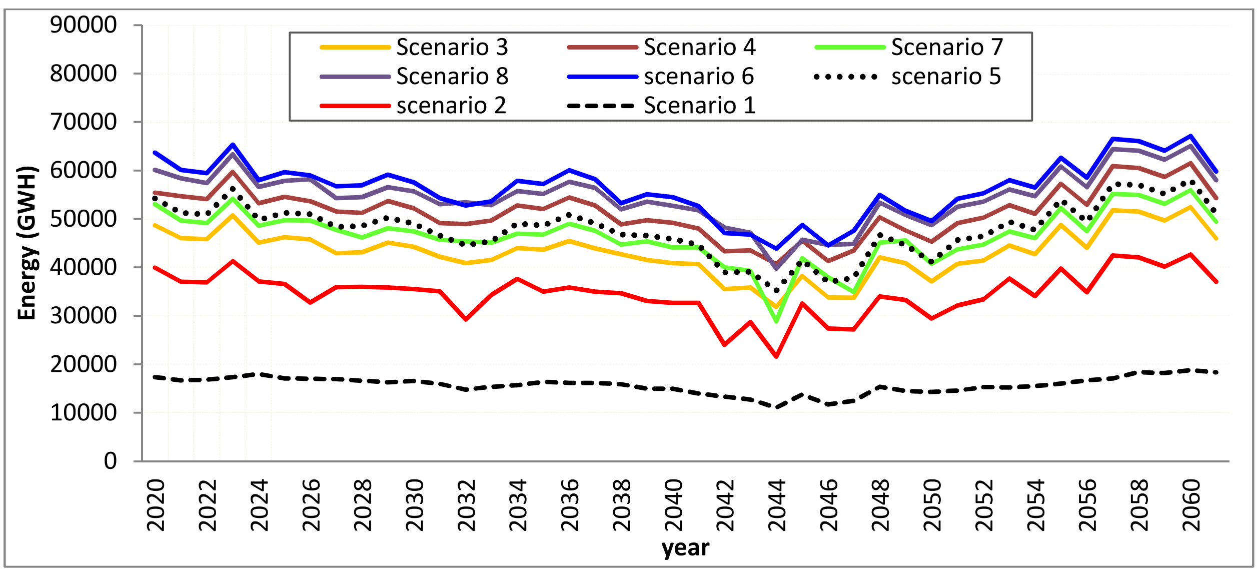

Figure 7-27: Annual Energy generation of eastern Nile with upper cascades in Abbay River full operation phase (GWH)

Table 7-2: Energy production (GWH) in each country from different combinations of the reservoirs during filling and operation phase

Scenarios	Energy in Ethiopia(GWH)	Difference		Energy in Sudan(GWH)	Difference		Energy at HAD (GWH	Difference	
		GWH	(%)		GWH	(%)		GWH	(%)
Scenario 1				8277	0	0	7462	0	0
Scenario 2	16256	0	0	11406	3129	38	6982	-480	-6
Scenario 3	22849	6593	41	11603	3326	40	6628	-834	-11
Scenario 4	28548	12292	76	11144	2867	35	6411	-1051	-14
Scenario 5	26329	10073	62	11298	3021	36	6608	-856	-11
Scenario 6	30322	14066	87	11143	2866	35	6508	-954	-13
Scenario 7	23547	7291	45	11303	3026	37	6736	-726	-10
Scenario 8	28953	12697	78	11211	2934	35	6493	-969	-13

Table 7-3: Mean annual Energy generation (GWH) of each reservoir for different scenarios during filling and operation phases of upper reservoirs

	Mean Annual Energy (GWH)									
scenarios	GERD	Roseires	Sennar	Merowe	Had	Mendia	Bekoabo Low/High	Karadobi	EN	Diff (%)
Scenario 1		2200	131	5946	7462				15739	
Scenario 2	16256	3485	131	7790	6982				34644	120
Scenario 3	15717	3774	131	7698	6628			7132	41080	161
Scenario 4	15269	3426	131	7587	6411	6147		7132	46103	193
Scenario 5	15699	3476	131	7691	6608		3498	7132	44235	181
Scenario 6	15376	3425	131	7587	6508	4316	3498	7132	47973	205
Scenario 7	15848	3474	131	7698	6736		7699		41586	164
Scenario 8	15394	3465	131	7615	6493	5860	7699		46657	196

Table 7-4: Country wise and Basin wide (Eastern Nile) energy generation full operation phases of all reservoirs in the Eastern Nile

countries	Ethiopia			HAD (Egypt)			Sudan			Eastern Nile		
	GWh	Diff		GWh	Diff		GWh	Diff (%)		GWh	Diff	
scenarios		GWh	%		GWh	%		GWh	%		GWh	%
Scenario 1				7462			8277			15742		
Scenario 2	16256			6982	-482	-6	11407	3130	38	34645	18904	120
Scenario 3	24876	8620	53	6893	-571	-8	11428	3151	38	43197	27456	174
Scenario 4	33264	17008	105	6791	-674	-9	11382	3104	38	51436	35695	227
Scenario 5	29594	13338	82	6891	-573	-8	11429	3152	38	47914	32173	204
Scenario 6	38200	21944	135	6816	-648	-9	11380	3103	37	56396	40654	258
Scenario 7	28133	11877	73	6926	-539	-7	11450	3172	38	46508	30767	195
Scenario 8	36525	20269	125	6820	-644	-9	11396	3119	38	54742	39000	248

7.6. Water Loss from Reservoirs

Water loss is due to evaporation from the water surfaces of the reservoirs. As the water level increase there will be more free water surface area and the evaporation loss will be increased. The column 'Diff' in Table 7-5 indicates the difference in water loss from the reservoirs of Eastern Nile between the current situation (scenario 1) and other scenarios. Evaporation loss (mm/day) in upstream of the basin is less as compared to the downstream. Meanwhile as a dam is constructed in the upstream, there will be additional free water surface area and more evaporation loss. The loss in Ethiopia will increase from nil up to 2024 MCM because of the reservoirs.

There is more regulated and constant flow of water to the Sudanese reservoir and the reservoir level is maintained at higher level and there is water surface area incremental. Due to that the loss in Sudanese reservoirs increases by at least 35% during full development stages of all upper reservoirs. Water loss at HAD slight decrease as the water level also slightly decreases with addition of reservoir in the upper basin. The maximum HAD loss (11673 MCM) is in baseline scenario and the minimum loss (10190 MCM) is in scenario 2.

Table **7**-5: Mean annual losses (MCM) from each reservoir for deferent scenarios during filling and operation phases of all reservoirs

					Mean Annual Loss (MCM)							
Scenarios	**GERD**	**Rosaries**	**Sennar**	**Merowe**	**HAD**	**Mendya**	**Bekoabo Low**	**Karadobi**	**EN**	**Diff (%)**	**Eth loss**	**Sudan loss**
Scenario 1		241	198	1647	11673				13759	0		2086
Scenario 2	1459	419	200	2251	10190				14519	6	1459	2870
Scenario 3	1446	424	210	2224	11153			245	15702	14	1691	2858
Scenario 4	1416	422	210	2191	10714	363		245	15561	13	2024	2823
Scenario 5	1445	424	210	2226	11099		21	245	15670	14	1711	2860
Scenario 6	1435	416	210	2196	10988	247	21	245	15758	15	1948	2822
Scenario 7	1460	428	210	2221	11490		174		15983	16	1634	2859
Scenario 8	1426	428	210	2207	10929	360	174		15734	14	1960	2845

7.7. Irrigation Water Demand Deficit

Irrigated agriculture in Sudan will be benefited from upstream storage in Ethiopia since the Sudanese annual withdrawals are lower in all scenarios. Those allocation decisions illustrate that once water has passed through the Ethiopian hydropower plants, irrigated agriculture starts competing with hydropower generation and irrigation withdrawals become more economically sound.

Table 7-6 illustrates the benefits and impacts of storage in Ethiopia on the irrigated agriculture sector. The regulation capacity of the reservoirs located in Ethiopia would increase irrigation water availability in Sudan. No significant impacts are observed for Egypt.

The filling impact on water demand is insignificant that is there only two events of irrigation water demand deficit at HAD due to the filling of the reservoirs. The irrigation water demand deficit has been seen in the downstream projects, especially in HAD in all scenarios during full operation phase. The difference between scenarios to scenario is the extents of demand deficit within the simulation period. The performance analysis is made by using equation shown below. As shown in Table 7-6, the water demand deficit is not significant. That is the performance is nearly 100% in irrigation projects in Sudan and more than 92% for HAD irrigation water demand.

$$Event-based\ reliability = \frac{Total\ number\ of\ non-failure\ months}{Total\ number\ of\ months} * 100$$

Table 7-6: Water demand deficit (number of months with water demand deficit, amount of deficit water in million cubic meters (MCM) and Sutcliff Nash coefficient) for full operation phase

	HAD			Gizira		
Scenarios	No of Month	MCM	NS	No of Month	MCM	NS
Scenario 1	25	93368	0.95	2	10.9	1.00
Scenario 2	34	113245	0.93	1	72.4	1.00
Scenario 3	35	113951	0.93	0	0	1.00
Scenario 4	36	114876	0.93	0	0	1.00
Scenario 5	40	126205	0.92	0	0	1.00
Scenario 6	42	125497	0.92	0	0	1.00
Scenario 7	34	111750	0.93	0	0	1.00
Scenario 8	40	123486	0.92	0	0	1.00

7.8. Conclusive Remarks

The scenarios were evaluated based on economic benefits for the whole Eastern Nile (basin wide) and on the project site or based on the three countries' benefit. The economic benefits which are considered are energy production and irrigation water demand satisfaction. From the simulation results the following conclusions are presented:

- There could be maximum energy production in Ethiopia and in the whole Eastern Nile Basin in the scenario 6. The maximum cumulative mean annual energy will be 38200 and 56396 GWh for Ethiopia and Eastern Nile basin respectively. The next maximum energy could be when Bekoabo high, Mendya and GERD are combined (scenario 8).
- Energy in eastern Nile will increase at least by 120% for scenario 2 and could increase by 258% for scenario 6.
- The energy production in Sudan will increase by 38% due to the construction of a single reservoir in the Abbay River.
- There could be slight energy reduction (up to 10%) at HAD due to the reduced reservoir water level.
- The construction of new reservoirs in the Abbay-Blue Nil will made the basin with more free water surface area and the eastern Nile water loss will increase as compared to the baseline scenario. The maximum water loss incremental in the Eastern Nile could be 16% as compared to the baseline scenario
- Water loss at HAD slight decrease as the water level also slightly decreases.
- The maximum loss (11673 MCM) is in the current situation and the minimum loss (10714 MCM) at HAD is in scenario 4.
- The amount of water flowing to reservoirs will be more regulated and constant due to the cascades in upstream.
- Reservoirs in Sudan are small in storage capacity and they cannot store enough water for dry seasons and there are fluctuations in energy production and reservoir water level. But the presence of the upper cascades will enable them to take advantage from the regulation and mitigate energy production fluctuation.
- There will be reduction of the risk due to hydrological variability with sequences of dry and wet years.
- With cascade development, the total storage capacity along the Nile River will significantly increase in the long term.

- The water demand deficit is insignificant in all scenarios, that is, the performance is more than 92% in all cases. It means coordinated and efficient water management may offset the deficits.
- Since the implementation of cascades in Abbay- Blue Nile has little significant effects and the impacts are similar for all scenarios, scenario 6 which combines four reservoirs is the best option for Abbay-Blue cascade development to get maximum energy.

Chapter Eight

Water Availability for Future Irrigation and Hydropower Development Using Stochastic Time Series Flows Simulation

8.1. Introduction

In this chapter, an investigation has been conducted to assess the future probable changes of hydrological process which may have impacts on the availability of water and spatial and temporal distributions of water resource in the basin due to the implementation and expansion of irrigation projects in Eastern Nile.

When defining the investment strategy and action plan it will be important to be in alignment with national and regional policies and development strategies. This analysis is not only aimed at defining national or local development paths. It is important the action plan proposed in the final step of the study present actions that are of regional significance whether this is from the point of view of the impacts or the benefits. Projects which are trans boundary in terms of their implementation can also be assumed to be of regional significance. Issues such as the impact on water resources in each of the sub-basins and on those of the overall Eastern Nile region will come out of application water resource simulation model but it will be important to decide what are acceptable limits in terms of utilization of this trans boundary resource.

The construction and fillings of each cascades is based on as described in chapter four and seven. The dam scenario which has maximum energy production in the Eastern Nile (scenario 6 in chapter seven) is selected as future hydropower implementation scenario. The simulation starts from 2020 and ends 2119. The simulation also encompasses the sequential fillings of each reservoir. Given the large cumulative volume of the planned reservoirs in Ethiopia, the reservoirs filling should be planned and managed in such a way that, adverse downstream impacts are minimized. The question of how much more large-scale irrigation is possible in the Eastern Nile has been examined.

Mike Hydro; a physical and conceptual model system for catchments, rivers and floodplains developed without dependencies on ArcGIS is used for modeling and simulation in this chapter.

To ensure consistency with the data sets used in previous chapters, other flow data (stochastic time series flow data) are used for further irrigation developments in the Eastern Nile basin. The data for irrigation demands and stochastic flow sequences are discussed in chapter 3.

In this chapter the impacts and benefits of filling and long term stage of GERD and future cascade and irrigation developments of Ethiopia and Sudan are assessed based on generated stochastic time series flows (ARMA11, EN MSIOA and Thomas ferrying). The irrigation development considers two stages of implementation. The first one considers the projects which are under construction and anticipated to be fully implemented before 2025. The second stage considers irrigation projects which are under different level of study and anticipated to be completed before 2050.

8.2. Development Scenarios

Scenarios are used to investigate complex systems that are inherently unpredictable or insufficiently understood to enable precise predictions. In this instance, although there is reasonable (but not total) knowledge of current water demand, there is considerable uncertainty about how future water resources development will proceed. Consequently, a scenario approach was adopted.

For many potential schemes there is currently considerable uncertainty about the dates when they will be completed. In the current study it was assumed that, for Ethiopian schemes, if prefeasibility studies have been undertaken then the scheme will be completed in the medium term. For all other planned schemes it was assumed that they will be completed in the long term. However, clearly the two scenarios reflect only an approximate timeline for water resources development in the basin. In reality, development is dependent on many external factors and so it is impossible to predict exactly when many planned schemes will actually be implemented, or indeed the exact sequencing of schemes. As they stand the medium-term and long-term future scenarios represent a plausible development trajectory, but it is unlikely that it will actually come to pass in exactly the way envisaged.

The model was set up to simulate four irrigation scenarios with three development stages (phases) and three dam scenarios. Table 8-1 represents possible future irrigation and hydropower trajectories of the Eastern Nile. Table 8-2 shows the scenarios which results from the combination of irrigation, stochastic time series flow and hydropower/ dam scenarios as described in section 4-2. As shown in Table 8-2, 30 possible conditions were analyzed and discussed in this chapter.

Table 8-1: Hydropower and irrigation development stages

<table>
<tr><th></th><th>2020-2025</th><th>2026-2030</th><th>2031-2035</th><th>2036-2040</th><th>After 2040</th><th>After 2050</th></tr>
<tr><td rowspan="4">Reservoirs</td><td rowspan="4">GERD filling</td><td colspan="5">GERD operation</td></tr>
<tr><td rowspan="3">Karadobi filling</td><td colspan="4">Karadobi operation</td></tr>
<tr><td rowspan="2">Bekoabo filling</td><td colspan="3">Bekoabo operation</td></tr>
<tr><td>Mendya filling</td><td colspan="2">Mendya operation</td></tr>
<tr><td rowspan="2">Irrigation</td><td rowspan="2">Current situation</td><td colspan="4" rowspan="2">Phase I (from 2025 to 2050)</td><td>Phase II (after 2050)</td></tr>
<tr><td>FDL (after 2050)</td></tr>
</table>

Table 8-2: Combined scenarios of stochastic time series flows, future dam/hydropower and irrigation development trajectories

		Irrigation trajectories			
Dam	Flow	Current	phase I	Phase II	FDL
current	EN MSIOA	**1**	**10**	**19**	
	TF	**2**	**11**	**20**	
	ARMA11	**3**	**12**	**21**	
after GERD	EN MSIOA	**4**	**13**	**22**	
	TF	**5**	**14**	**23**	
	ARMA11	**6**	**15**	**24**	
GERD and Upper cascades	EN MSIOA	**7**	**16**	**25**	**28**
	TF	**8**	**17**	**26**	**29**
	ARMA11	**9**	**18**	**27**	**30**

8.3. Results and Discussion

The results presented in this chapter are based on many assumptions. There are lack of data on flow and water demand and use. However, where it has been possible to verify them the model results appear to be reasonably accurate. For example, in the current scenario, simulated flows closely match the observed flows at key locations on the main stem of the river. Consequently, though the results should be treated with caution, they are believed to be broadly indicative of the likely impacts arising from the development currently being considered in Ethiopia, south Sudan and Sudan. By illustrating what may occur the scenarios provide information that is useful for resource planning, and the results provide a basis for discussion.

As in the past, future water resources development in the Blue Nile will be driven predominantly by the need of water for agriculture and hydropower, and hence the need for large volumes of stored water. Irrigation will remain the largest user of water and the future scenarios indicate significantly increased water withdrawals as a consequence of increasing irrigation, predominantly in Sudan, and also increasingly in Ethiopia. The construction of the dams particularly the very large hydropower dams proposed by Ethiopia, though not consuming large amounts of water will significantly alter the flow regime of the river, resulting in lower wet season flows and much greater dry season flows. The results of this are likely to be beneficial for Sudan. The frequency of flooding, which occurs every few years in the flat areas of the country and is particularly devastating in and around Khartoum, may be reduced. Higher dry season flows mean greater availability of water at a time when it is naturally scarce and hence increased opportunities for withdrawals for irrigation and other uses. Thus increased water storage in Ethiopia has the potential to provide benefits for Sudan too. The other significant benefits of storing water in the Ethiopian Highlands, rather than in the lower, more arid, regions of Sudan and Egypt are significantly reduced evaporation losses.

For all scenarios, the model was run as a single system, by giving the same priority for upstream and downstream demands and water was released from reservoirs in Ethiopia to meet downstream demand. This assumes a much higher level of cooperation between the four states, in relation to both the planning and management of water resources, than at present.

8.3.1. Flows

Increased water storage in dams and greater withdrawals will inevitably alter the now regime of the river and its main tributaries. The planned water resources development in the basin will cause reductions in flows. The impact of water resource development on flows at key locations in the basin is summarized in Table 8-3 to 8-5. The model results indicate that, through provision of water for hydropower and irrigation, increased water storage behind large dams is likely to contribute to economic development in the medium-to-long term with only marginal impacts on flow in Sudan. Comparison of the mean monthly flows in Sudan (at Khartoum, Jebel Aulia and El Girba) and HAD for the simulated natural condition, current situation, between 2025 to 2050 and the situation after 2050 indicates how the mean annual runoff is progressively reduced as a consequence of greater upstream abstractions.

Table 8-3: Flows at selected sites of Eastern Nile (Blue and Main Nile) during different stages of hydropower and irrigation development

Irrigation	Current			phase II			FDL		
Flow	ARMA11								
Site	HAD	Khartoum	Border	HAD	Khartoum	Border	HAD	Khartoum	Border
2020-2119	71068	39822	46546	59077	32974	45859	42571	24100	45859
Before20 25	79721	45530	51988	62317	31716	51336	60290	30369	51336
2025-2050	70573	39630	46319	61310	32438	42386	50616	26310	42386
after 2050	70714	39581	46332	58450	33222	46338	39781	23282	46338
Flow	TF								
2020-2119	63553	41793	51521	59077	37934	45014	42776	25486	45014
Before20 25	76194	48749	48593	62317	34780	48916	48578	26627	48916
2025-2050	67210	41956	51347	61310	36586	42068	48598	28208	42068
after 2050	62053	41404	51833	58450	38482	45475	41193	24878	45475
Flow	EN MSIOA								
2020-2119	77430	42270	50196	69756	36085	45014	46003	23661	45014
Before20 25	74717	42560	51047	62124	30149	48916	58760	28867	48916
2025-2050	76628	41766	49800	69710	35420	42068	54852	26387	42068
after 2050	77857	42437	50319	70310	36654	45475	43355	22799	45475

Table 8-3 and 8-4 show the mean annual flows at the selected locations. Table 8-5 demonstrates the flow difference between the current scenario and the future development conditions. These results indicate there is decline in the flow at different location due to the irrigation development. There are significant declines of flow at all locations in full development level (FDL). The inflow to HAD is reduced more significantly than at the other locations because of the diversion of water to the Sudanese irrigation projects. The impact of Ethiopian irrigation development on HAD in flow is less as compared to the Sudanese irrigation expansion. The maximum reduction is 17% at full development level of Ethiopian irrigation but it will reach up to 44% due to Sudanese irrigation expansion.

Table 8-4: Flows at selected sites of Eastern Nile (White Nile and TAS) during different stages of hydropower and irrigation development

Irrigation	Current		phase II		FDL	
Flow	ARMA11					
Site	Girba	Jebel Aluia	Girba	Jabil aula	Girba	Jebel Aluia
2020-2119	11415	26424	9709	16786	8990	14516
Before20 25	12790	29608	11167	24868	12572	15040
2025-2050	11294	26144	9180	23282	8802	14080
after 2050	11375	26332	9753	14888	8828	14608
Flow	TF					
2020-2119	12859	27383	10786	16619	9799	13964
Before20 25	11906	25736	11637	19341	11637	17339
2025-2050	12622	27284	11644	20407	10440	16864
after 2050	12993	27559	10574	15678	9570	13169
Flow	EN MSIOA					
2020-2119	11045	29343	11652	28752	11085	18257
Before20 25	11868	25932	13119	25998	13119	23974
2025-2050	10877	29251	11807	29289	11139	24676
after 2050	11053	29580	11553	28814	10971	16528

At the Ethiopia-Sudan border the current situation is almost identical to the natural condition. If full development occurs, the total flow at the Ethiopia-Sudan border is predicted to decrease from the current 49 BCM (near natural) to 42 BCM and at Khartoum from the current 42 BCM to 23 BCM. However, although there is a significant reduction in wet season flow at both locations, dry season flow will actually increase because of the greater upstream flow regulation. Under current conditions of the three stochastic flow time series, 80 to 83 per cent of the river flow occurs in the wet season months (July-October). In the long-term scenarios this is reduced to 46 to 53 per cent.

By increasing water availability in the dry season and reducing in the wet season this increased regulation promises significant benefits for Sudan. Maximum flow reduction at Border and Khartoum is in period between 2020 and 2040 for all flow conditions. This period (2020 to 2040) is the filling period of upper cascades. There is a slight inflow improvement at Khartoum after the impounding of all reservoirs. In the full dam development scenario flows are significantly less variable than in the other scenarios, and in the latter part of the century the periods of lowest flow are reduced slightly as a consequence of upstream storage.

Table 8-5: Flow difference (%) between current scenario and different level of future hydropower and irrigation development in the Eastern Nile

Irrigation	Phase II			FDL		Phase II		FDL	
Site	HAD	Khartoum	Border	HAD	Khartoum	Girba	Jebel Aluia	Girba	Jebel Aluia
Flow	ARMA11								
b/n 2020 & 2119	-17	-17	-1	-40	-39	-15	-36	-21	-45
b/n 2020 & 2025	-22	-30	-1	-24	-33	-13	-16	-2	-49
b/n 2025 &2050	-13	-18	-8	-28	-34	-19	-11	-22	-46
after 2050	-17	-16	0	-44	-41	-14	-43	-22	-45
Flow	TF								
b/n 2020 & 2119	-7	-9	-13	-33	-39	-16	-39	-24	-49
b/n 2020 & 2025	-18	-29	1	-36	-45	-2	-25	-2	-33
b/n 2025 &2050	-9	-13	-18	-28	-33	-8	-25	-17	-38
after 2050	-6	-7	-12	-34	-40	-19	-43	-26	-52
Flow	EN MSIOA								
b/n 2020 & 2119	-10	-15	-10	-41	-44	-5	-2	-5	-38
b/n 2020 & 2025	-17	-29	-4	-21	-32	-10	0	0	-8
b/n 2025 &2050	-9	-15	-16	-28	-37	-8	0	-6	-16
after 2050	-10	-14	-10	-44	-46	-4	-3	-5	-44

The situation after 2025 (after filling of GERD) illustrates the benefit for Sudan of increased upstream regulation in Ethiopia. This is highlighted by the simulated water-levels in the Roseires Reservoir which show that it is possible to fill and empty the reservoir in all years. This contrasts with the current situation when in some years there is insufficient flow to fill the reservoir and is despite the fact that raising the dam will substantially increase the reservoir storage and irrigation demands will also have increased greatly.

8.3.2. Reservoirs Level

Based on the implementation schedule shown in the Table 8-1, the impacts of GERD and other reservoirs above GERD were assessed for the three flow conditions. If all planned dams are constructed the total reservoir storage in Ethiopia is estimated to increase to 74 and 160 BCM which is 1.5 and 3.2 times the mean annual flow at the border for the mid-term and long term development levels respectively.

Figure 8-1 shows the pool level of GERD during the filling periods of all reservoirs for the three flow time series. The filling period of GERD is considered to be 6 years. The graph shows, the three stochastic time series flows have no significant difference and the impacts of upper cascades filling have insignificant impacts on GERD water level. There could be up to 7 meters water level reduction of GERD due to Karadobi and Bekoabo filling. Mendya filling has insignificant impacts (less than 3 meters). Figure 8-2 shows the filling periods of Karadobi, Bekoabo and Mendya.

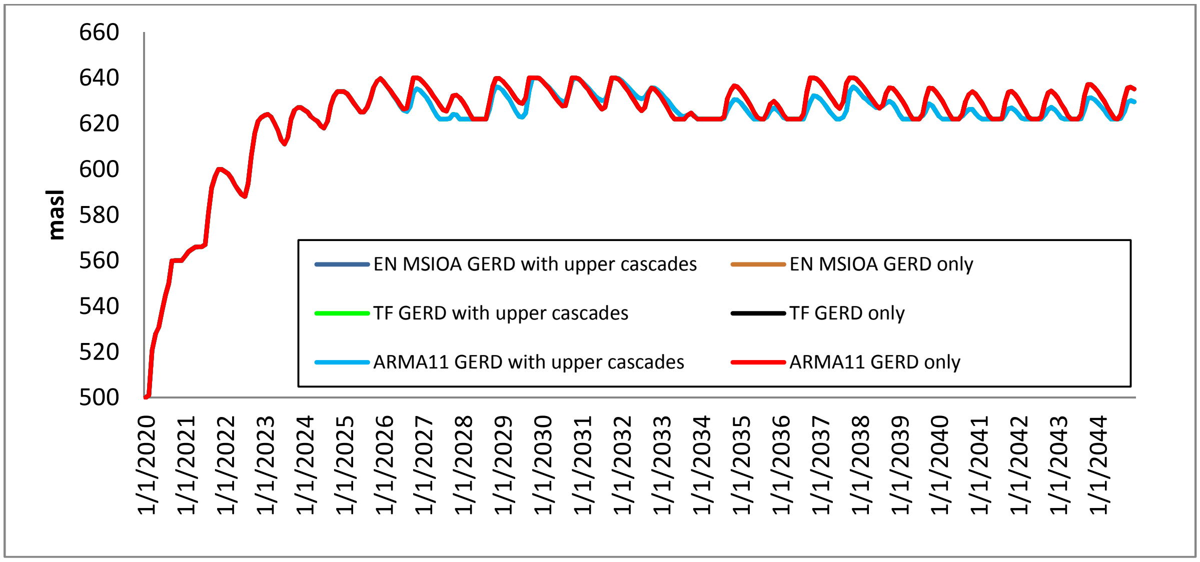

Figure 8-1: GERD impounding stage water level and impacts of upper cascades filling

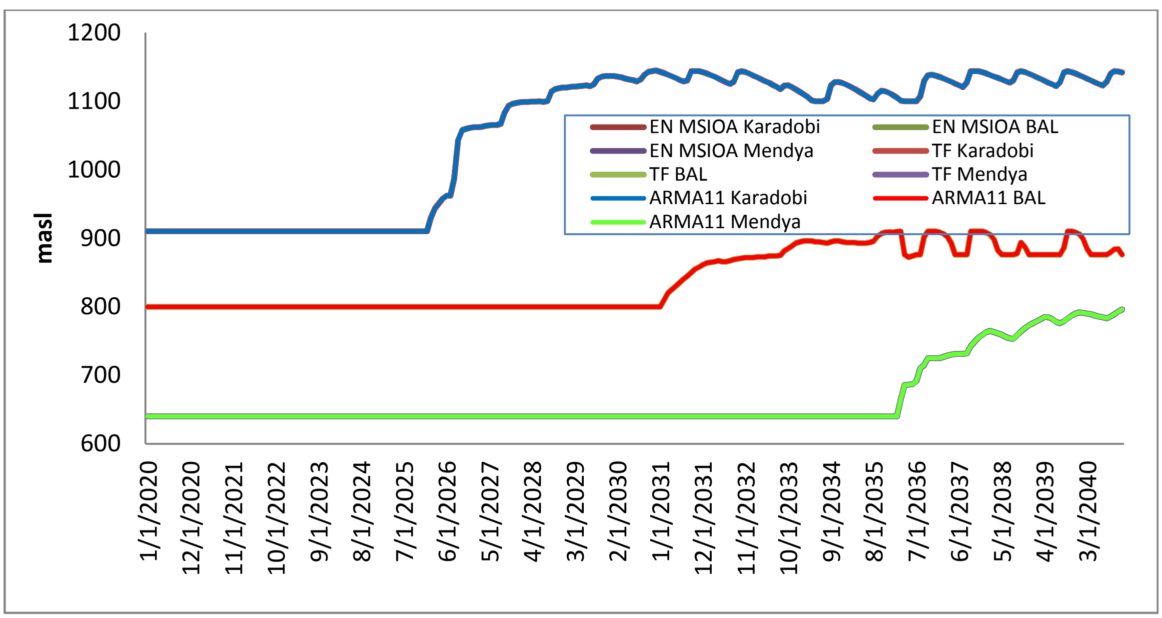

Figure 8-2: Impounding periods of Karadobi, Bekoabo and Mendya

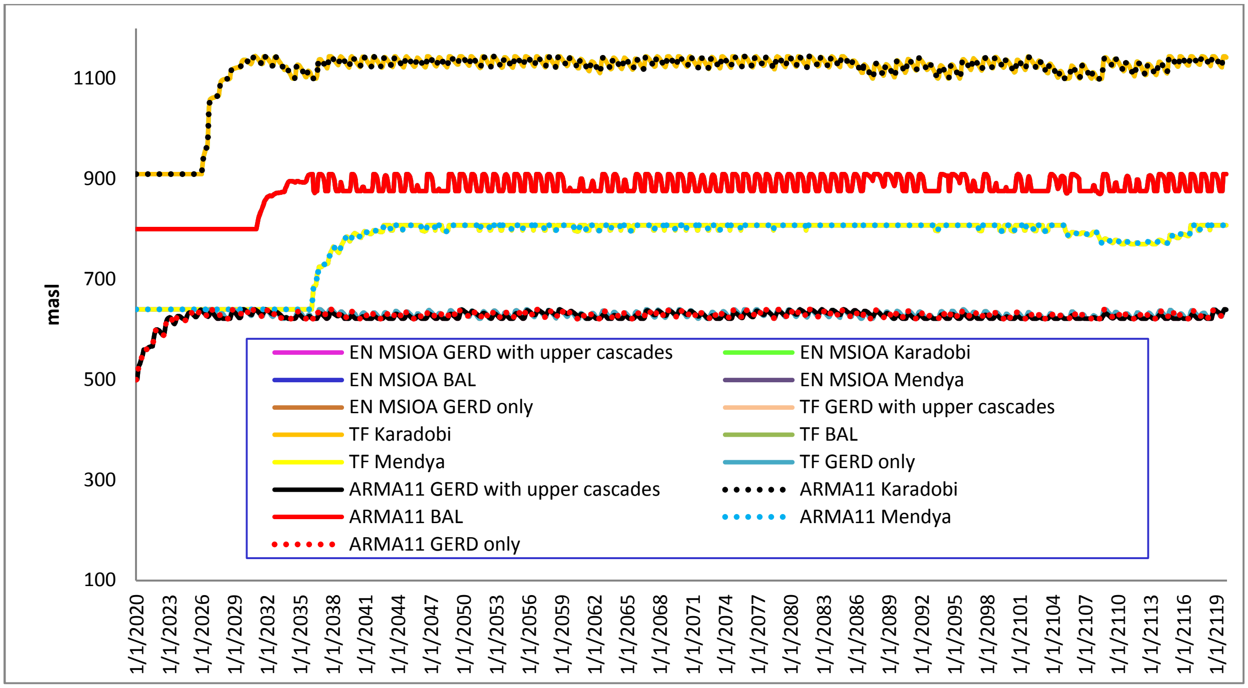

Figure 8-3: Reservoirs' water level of Abbay River during their impounding and operation phase

Figure 8-3 shows the reservoirs' water level of GERD and upper cascades during their filling and long term development stages. The figure depicts, the impacts of future Ethiopian irrigation development has insignificant impacts on the reservoir pool level.

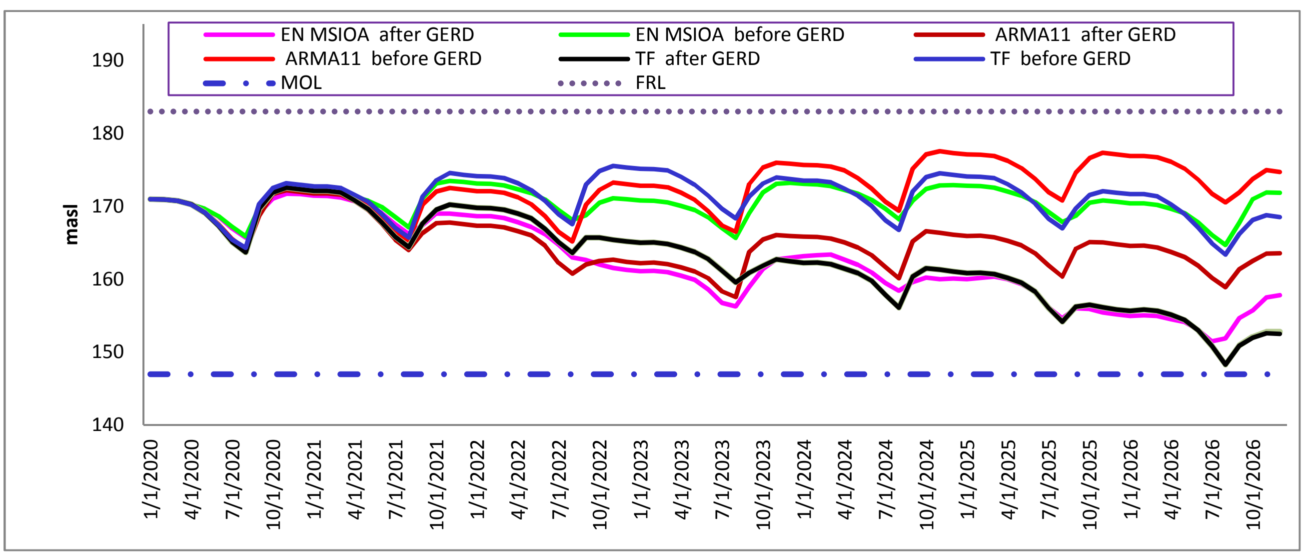

Figure 8-4: the impacts of GERD filling on HAD with EN MSIOA, ARMA11 and TF flow sequences

Figure 8-4 shows the pool level of HAD during GERD filling. At the end of GERD filling HAD water level will reduce by 14, 16 and 11 meters for EN MSIOA, TF and ARMA11flow sequences respectively. HAD water level is always above its minimum operation level (147 m.a.s.l). Upper cascades fillings have insignificant impacts on HAD pool level. However the long term irrigation developments will have significant impacts on the water level of HAD.

8.3.3. Irrigation Water

Currently, irrigation water withdrawals in Sudan greatly exceed those in Ethiopia because of the differences in irrigated area. The total irrigation demand in Sudan is estimated to average 13.67 BCM/ year. This compares with an average of just 0.367 BCM/ year in Ethiopia. With the planned irrigation development, demand is estimated to increase to 18.5 BCM/ year and 4.83 BCM/ year in the medium-term scenarios, and to 32.2 BCM/ year and 14.4 BCM/ year in the long-term scenarios in Sudan and Ethiopia, respectively (Table 8-6).

Both Ethiopia and Sudan have plans to unilaterally develop the water resources of the Blue Nile for hydropower and irrigation. The extent to which this plan will actually be implemented is unclear. However, if both countries totally fulfill their stated objectives the following are estimated to occur: large-scale irrigation withdrawals in Sudan will increase from the current 13.67 to 32.2 BCM/year; large-scale irrigation withdrawals in Ethiopia will increase from the current 0.367 to 14.47 BCM, and south Sudan will demand 3.2 BCM/year which is currently nil. The long term Eastern Nile total irrigation water demand will be more than 105 BCM which is much more than the naturalized flow (around 90 BCM).

Table 8-6 show irrigation water demands, used water and irrigation water demand deficit of the four countries (Ethiopia, Sudan, South Sudan and Egypt). In first column, scenarios 1 to 3 are the current irrigation water uses and currently reservoir operation for the three flow scenarios (EN MSIOA, TF and ARMA11). In these scenarios there is no water demand deficit on Egyptian and Sudanese irrigation schemes. Scenarios from 19 to 27 consider the Ethiopian irrigation development with the implementation of four dams (GERD, Karadobi, Bekoabo and Mendya).

Currently, shortfalls (i.e. failure in any given month to supply the full amount of water needed for irrigation withdrawals needs) in Ethiopia are negligible. However, in the medium-term scenario shortfalls increase to 0.4 to 0.6 BCM/year (Table 8-6). All the medium- and long-term irrigation schemes of Ethiopia are not on the main river. They are located in the tributaries (Dedesa, Anger, Fincha, inflow to lake Tana, Raha, Dinder, Baro-Akobo and Tekeze rivers). There is irrigation water demand deficit in Ethiopia especially in the Lake Tana and Tekeze demands. There is at least 1.65 BCM/year deficit in the long term irrigation development of Ethiopia.

Because of water abstraction from the main river which is regulated by big upstream reservoirs, there is little or no irrigation water demand deficit in Sudan due to Ethiopian irrigation development. Because of the improved flow regulation there are no shortfalls in irrigation in Sudan in either the medium (between 2025 and 2050) or the long-term (after 2050) Ethiopian irrigation development scenarios. These results reflect the fact that, if irrigation development is considered, the four dams located in Ethiopia give more advantage to the Sudanese schemes than that of Ethiopian.

The changes in water abstraction in Sudan and Ethiopia will have significant impacts on irrigation demands of Egypt. Because of Ethiopian irrigation development, there could be up to 6.3 BCM irrigation water demand deficit in Egypt. The irrigation expansion of Sudan will increase the irrigation water demand deficit of both Sudan and Egypt consequently the cumulative Eastern Nile agricultural water demand. Scenarios 28 to 30 represent the full irrigation development (both Ethiopia and Sudan) for the EN MSIOA, TF and ARMA11flow sequences respectively. As shown in Table 8-6 Egypt irrigation water demand deficit will be 20, 22 and 23.8 BCM for EN MSIOA, TF and ARMA11flow sequences respectively. If Egypt plan or implement 5.5 BCM additional water demand, the irrigation water demand deficit will increase to 25.8, 27.6 and 29.6 BCM for EN MSIOA, TF and ARMA11flow sequences respectively. The Sudanese irrigation demand deficit will also be 2.1, 1.3 and 1.4 BCM for EN MSIOA, TF and ARMA11flow sequences respectively.

Table 8-6: Irrigation water demand trajectory, used water and water demand deficits in the Eastern Nile countries (MCM)

	Ethiopia			Sudan			South Sudan			Egypt		
Scenario	Demand	Used	Deficit	Demand	Used	Deficit	Demand	Used	Deficit	Demand	Used	Deficit
1	367	367	0	13670	13670	0	0	0	0	55500	55500	0
2	367	367	0	13670	13670	0	0	0	0	55500	55500	0
3	367	367	0	13670	13670	0	0	0	0	55500	55500	0
4	367	367	0	13670	13670	0	0	0	0	55500	55500	0
5	367	367	0	13670	13670	0	0	0	0	55500	55500	0
6	367	367	0	13670	13670	0	0	0	0	55500	55500	0
7	367	367	0	13670	13670	0	0	0	0	55500	55500	0
8	367	367	0	13670	13670	0	0	0	0	55500	55500	0
9	367	367	0	13670	13670	0	0	0	0	55500	55500	0
10	4827	4233	594	13670	13670	0	0	0	0	55500	55500	0
11	4827	4443	384	13670	13670	0	0	0	0	55500	55500	0
12	4827	4441	386	13670	13670	0	0	0	0	55500	55500	0
13	4827	4233	594	13670	13670	0	0	0	0	55500	55500	0
14	4827	4443	384	13670	13670	0	0	0	0	55500	55133	367
15	4827	4441	386	13670	13670	0	0	0	0	55500	55460	40
16	4827	4233	594	13670	13670	0	0	0	0	55500	55500	0
17	4827	4443	384	13670	13670	0	0	0	0	55500	53107	2393
18	4827	4441	386	13670	13670	0	0	0	0	55500	54313	1187
19	4827	4233	594	18500	18300	200	0	0	0	55500	54088	1412
20	4827	4443	384	18500	18460	40	0	0	0	55500	51954	3546
21	4827	4441	386	18500	18462	38	0	0	0	55500	51071	4429
22	4827	4233	594	18500	18485	15	0	0	0	55500	53299	2201
23	4827	4443	384	18500	18500	0	0	0	0	55500	50684	4816
24	4827	4441	386	18500	18494	6	0	0	0	55500	49799	5701
25	14447	12788	1659	18500	18500	0	0	0	0	55500	53136	2364
26	14447	11775	2172	18500	18500	0	0	0	0	55500	50057	5443
27	14447	12058	2389	18500	18500	0	0	0	0	55500	49197	6303
28	14447	12788	1659	32190	30056	2134	3210	3195	15	55500	35455	20045
29	14447	11775	2172	32190	30935	1255	3210	3210	0	55500	33625	21875
30	14447	12058	2389	32190	30764	1426	3210	3210	0	55500	31715	23785

In the table the color indicates the hydropower development level as:

Before GERD
After GERD
GERD and upper cascades

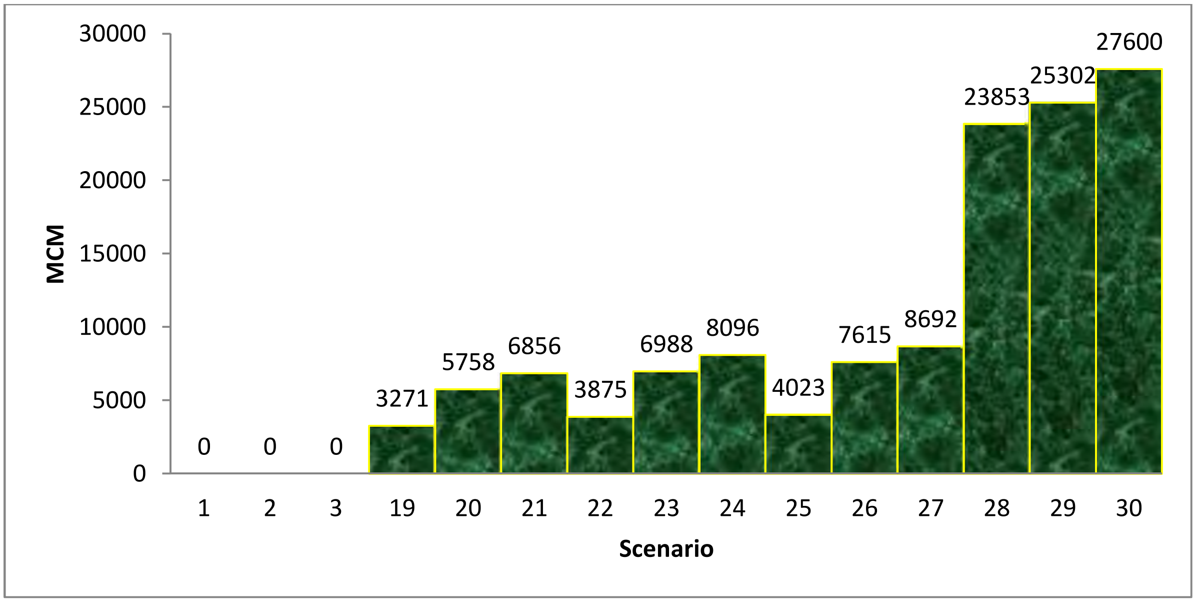

Figure 8-5: Mean annual Eastern Nile irrigation water demand deficit due to future Ethiopian and Sudan hydropower and irrigation development

As shown in the Figure 8-5, the long-term cumulative Eastern Nile agricultural water demand deficit will reach 24, 25.3 and 27.6 BCM for EN MSIOA, TF and ARMA11flow sequences respectively. The water use will be 81.5, 79.5 and 77.7 BCM for EN MSIOA, TF and ARMA11flow sequences respectively. As compared to the naturalized flow at HAD (94.6, 93.2 and 90.5 for EN MSIOA, TF and ARMA11flow sequences respectively), there will be 13, 13.7 and 12.8 BCM water loss for EN MSIOA, TF and ARMA11flow sequences respectively. Additional scenarios: scenario 31, 32 and 33 for EN MSIOA, TF and ARMA11flow sequences respectively was considered for additional 5.5.BCM Egyptian irrigation water demand. As shown in Appendix Figure G-7, the Eastern Nile irrigation water demand deficit will reach 29.6, 31 and 33.4 BCM for EN MSIOA, TF and ARMA11flow sequences respectively.

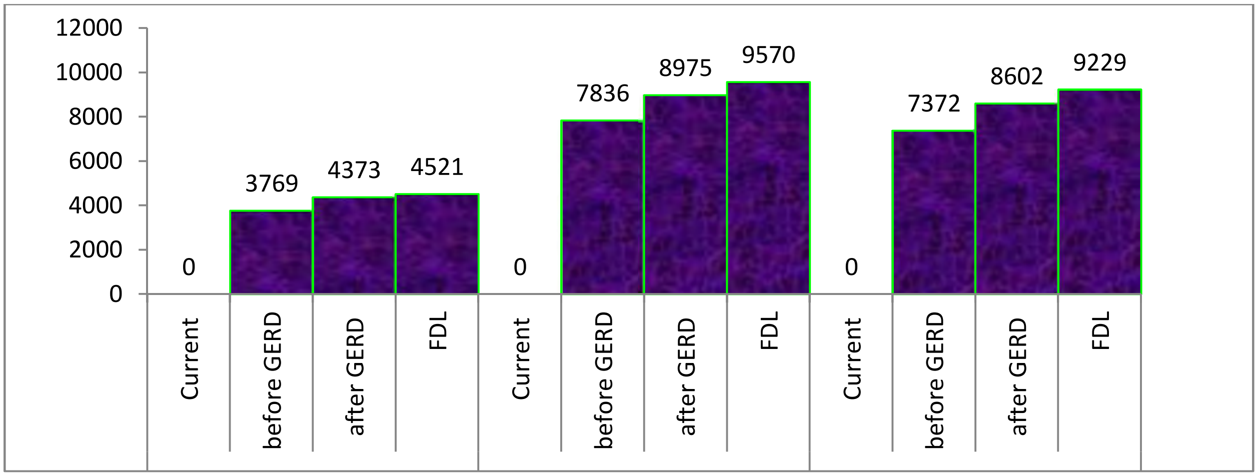

Figure 8-6: Mean annual Eastern Nile irrigation water demand deficit due to future Ethiopian hydropower and irrigation development (MCM)

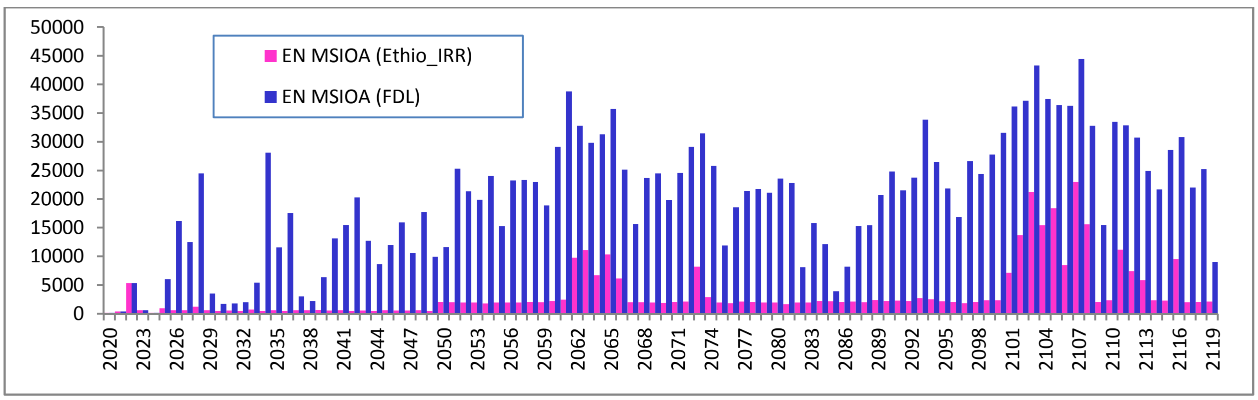

Figure 8-7: Annual Eastern Nile irrigation water demand deficit due to future Ethiopian and Sudan hydropower and irrigation development for EN MSIOA flow

8.3.4. Energy Production

Hydropower generated in Ethiopia, from the Tana Beles transfer, is currently estimated to be 3000 GWh/year. With the construction of GERD, Karadobi, Bekoabo and Mendya dam, the energy generation is estimated to increase to 28000 GWh/year in the medium term, the period from filling of GERD to full operation of the other reservoirs. In the long term, at full operation level of GERD, Karadobi, Bekoabo and Mendya hydropower stations, Ethiopian electricity production could increase to 36500 GWh/year. There could be up to 1Billion US$ annual income in the long term hydropower development (Appendix Table G-1).

Figure 8-8 depicts annual energy generation of Tana Beles transfer from the Thomas Fiering stochastic flow simulation. As shown in the figure; irrigation development around Lake Tana will affect the energy production of Tana-Beles. The mean annual energy will reduce by 18%.

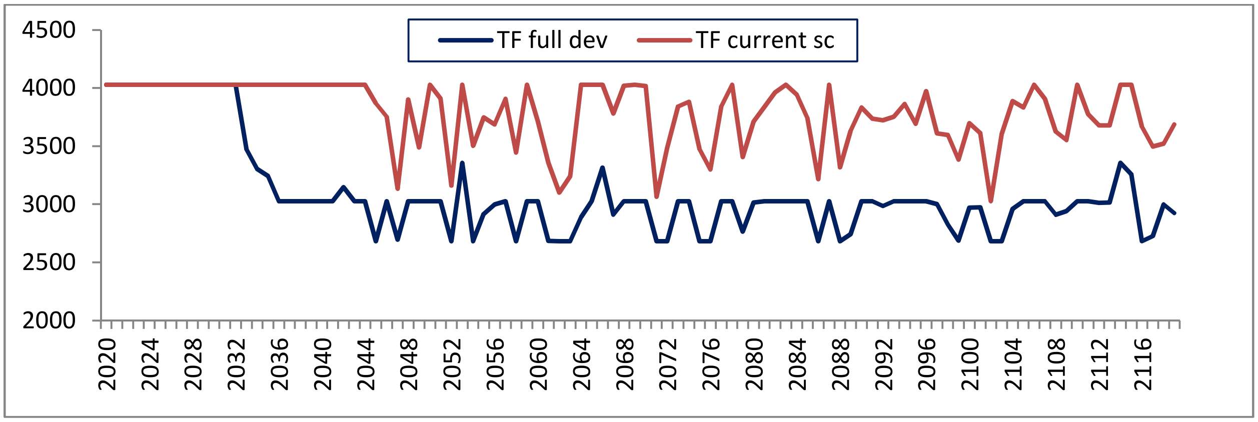

Figure 8-8: Tana Beles energy production for current and future Ethiopian irrigation development in the Lake Tana basin

Table 8-7: Impacts of future irrigation development on eastern Nile energy production after the implementation of GERD

Flow	EN MSIOA			ARMA11			TF		
Irrigation	Current	Future	Diff. (%)	Current	Future	Diff. (%)	Current	Future	Diff. (%)
Ethiopia	19046	18180	-5	18955	16952	-11	18785	18062	-4
Sudan	7576	7531	-1	7577	7366	-3	7564	7560	0
Egypt	8503	6750	-21	8061	5447	-32	7850	5460	-30
EN	35125	32461	-8	34593	29765	-14	34199	31081	-9

Table 8-7 shows the impacts of future Ethiopia and Sudan irrigation development on the mean annual energy generation of the Eastern Nile after the completion of GERD. The scenarios in the table are GERD and currently operating hydropower plants with current and future irrigation development. The Ethiopian mean annual energy production from GERD and Tana Beles will reduce by 5 to 11% (724 to 2002 GWh) due to the future irrigation development in the Abbay river basin. As shown in the table future irrigation development has insignificant impacts on Sudan hydropower. However, the Egypt energy will be affected significantly (up to 32% reduction). The overall eastern Nile energy will be affected by 8 to 14%.

Figure 8-9 depicts annual energy projection of Abbay River (in Ethiopia) from the EN MSIOA flow simulation. Before 2035 all reservoirs are not at their full energy production capacity because they are at their impounding stages. As shown in the figure, before 2035 the energy production has increasing trends and it will reach its maximum level after 2035 (long term development). Table 8-7, Table 8-8 and Table 8-9 show future energy productions of the three countries and cumulative Eastern Nile energy for current, future Ethiopian and Sudanese irrigation development respectively. Diff. I (%) in the tables represent energy production difference between current scenario and other scenarios (future energy production for three irrigation conditions: current, phase II or future Ethiopian irrigation and FDL or future Ethiopian and Sudanese irrigation development). This is to show the impacts of future development as compared to the current situation. Diff. II (%) represents the difference in energy production for the situations between mid-term hydropower for current irrigation and other hydropower development scenarios. This is to show the impacts of irrigation development on the potential energy production.

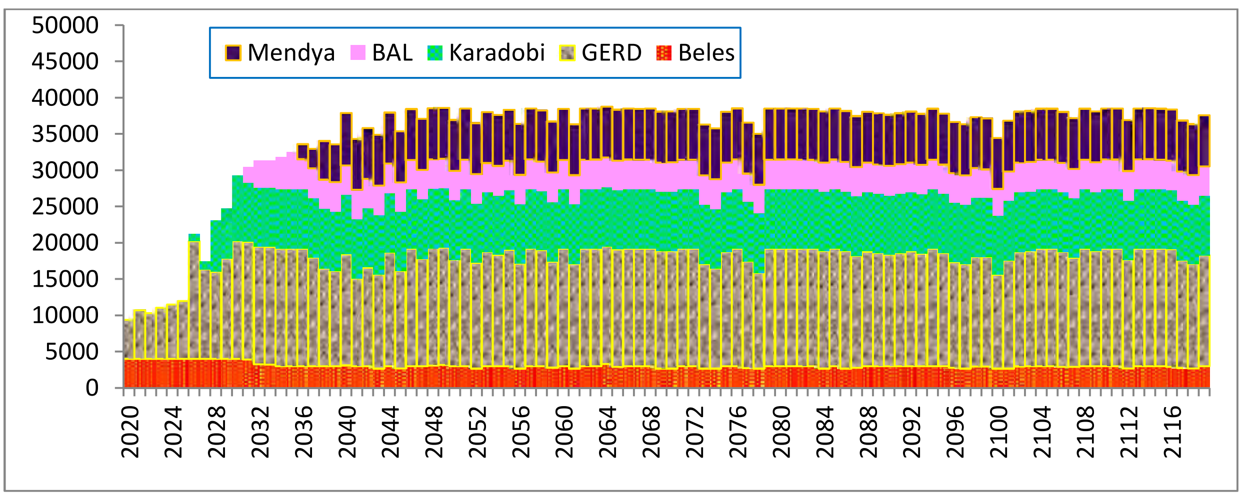

Figure 8-9: Ethiopian energy (GWh) from five reservoirs during filling and operation phases for EN MSIOA flow and future irrigation development

As shown in Table 8-7, the cumulative Ethiopian energy will reach more than 36900 GWh/year. By considering Tana Beles hydropower as a current Ethiopian energy, there will be 645 to 1088% incremental of energy. The irrigation development in the Abbay river basin has insignificant impacts on Ethiopian energy (Table 8-8 and Figure 8-9).

Average hydropower production of the three flows in Sudan is currently estimated to be over 6500 GWh/year. Because of the additional head and increased storage the Sudanese energy will increase to 7330 GWh/year in the medium term but it will reduce to 6600 GWh/year due to the irrigation expansion of Sudan. In hydropower development trajectory, the situation before 2035 is the filling periods of reservoirs in Abbay River. As shown in the table the Sudanese hydropower is not affected during the impounding and operation phases of upstream cascades. The Sudanese energy will increase at least by 2% and it could increase by 23% as compared to the current scenario and Sudan can gain up to 20 million UD$ per year (Appendix Table G-1).

Energy production is related to the water level and water discharge amount. Irrigation development in Sudan and Ethiopia will affect the energy production of Egypt. Due to the water level lowering and inflow reduction at HAD, the mean manual energy production will reduce by 21 to 64%. However, the hydropower development in Abbay river basin has less impact as compared to irrigation development. During the filling periods of reservoirs in Abbay river basin, HAD energy will be reduced by 17 to 23% and the impact reduce to 5 to 11% after filling or during operation phases of the reservoirs.

Table 8-8: Mean annual Eastern Nile energy (GWh) for current irrigation and upper cascades development; and difference (%) from the current energy production

		EN MSIOA flow			
Irrigation		**Current**			
Hydropower	**Current**	**before 2035**		**after 2035**	
	GWH	**GWH**	**Diff. I (%)**	**GWH**	**Diff. I (%)**
Sudan	7319	7466	2	7577	4
HAD	9709	7497	-23	8678	-11
Ethiopia	3645	28857	692	38272	950
EN	20673	43820	112	54526	164
		TF flow			
Sudan	6066	7309	20	7572	25
HAD	8639	6852	-21	8036	-7
Ethiopia	3790	28332	648	37965	902
EN	18495	42494	130	53073	187
		ARMA11 flow			
Sudan	6180	7547	22	7577	23
HAD	8701	7242	-17	8235	-5
Ethiopia	3075	29320	853	38304	1146
EN	17956	44108	146	54116	201

Table 8-9: Mean annual Eastern Nile energy (GWh) for Ethiopian irrigation and upper cascades development; and difference (%) from the current energy production and from mid-term energy (before 2035) and current irrigation

Irrigation	Ethiopia Irrigation					
Hydropower	before 2035			after 2035		
	GWH	Diff. I (%)	Diff. II (%)	GWH	Diff. I (%)	Diff. II (%)
EN MSIOA Flow						
Sudan	7451	2	0	7525	3	-1
HAD	7415	-21	-1	6517	-33	-25
Ethiopia	27622	658	-4	36910	913	-4
EN	42488	107	-3	50952	146	-7
TF Flow						
Sudan	7370	21	1	7568	25	0
HAD	6376	-26	-7	5324	-38	-34
Ethiopia	28235	645	0	37686	894	-1
EN	41980	127	-1	50577	173	-5
ARMA11 flow						
Sudan	7179	16	-5	7386	20	-3
HAD	6739	-23	-7	5297	-39	-36
Ethiopia	28172	816	-4	36531	1088	-5
EN	42089	134	-5	49214	174	-9

Table 8-10: Mean annual Eastern Nile energy (GWh) for full level irrigation development and upper cascades development; and difference (%) from the current energy production and from the current irrigation but mid-term energy

Irrigation	FDL					
Hydropower	before 2035			after 2035		
	GWH	Diff. I (%)	Diff. II (%)	GWH	Diff. I (%)	Diff. II (%)
EN MSIOA Flow						
Sudan	7263	-1	-3	6764	-8	-11
HAD	5366	-45	-28	3560	-63	-59
Ethiopia	27622	658	-4	36910	913	-4
EN	40251	95	-8	47234	128	-13
TF Flow						
Sudan	6700	10	-8	6237	3	-18
HAD	4583	-47	-33	3346	-61	-58
Ethiopia	28235	645	0	37686	894	-1
EN	39518	114	-7	47269	156	-11
ARMA11 Flow						
Sudan	7521	22	0	6847	11	-10
HAD	5048	-42	-30	3098	-64	-62
Ethiopia	28172	816	-4	36531	1088	-5
EN	40741	127	-8	46476	159	-14

Table 8-11: Cumulative mean annual Eastern Nile energy (GWh) at different development stages; and energy difference (%) from the current hydropower (Diff. I) and upper cascades development with current irrigation (Diff. II)

	EN MSIOA Flow												
Irrigation	**Current**			**Ethiopia Irrigation**							**FDL**		
Dam	**Current**	**FDL**		**before GERD**		**after GERD**		**FDL**					
Development stages	**GWH**	**GWH**	**Diff. I (%)**	**GWH**	**Diff. I (%)**	**GWH**	**Diff. I (%)**	**GWH**	**Diff. I (%)**	**Diff. II (%)**	**GWH**	**Diff. I (%)**	**Diff. II (%)**
b/n 2020 & 2119	20673	51221	148	18153	-12	32588	58	48388	134	-6	45052	118	-12
b/n 2020 &2025	20255	27558	36	20231	0	27558	36	27558	36	0	27558	36	0
b/n 2025 & 2050	20899	46699	123	20150	-4	34163	63	45373	117	-3	42440	103	-9
after 2050	20622	54526	164	17292	-16	32385	57	50952	147	-7	47234	129	-13
	ARMA11 Flow												
b/n 2020 & 2119	17956	50993	184	15081	-16	30382	69	47052	162	-8	44725	149	-12
b/n 2020 &2025	19149	27920	46	19095	0	27920	46	27920	46	0	27920	46	0
b/n 2025 & 2050	18473	46863	154	17304	-6	32336	75	44826	143	-4	43182	134	-8
after 2050	17685	54116	206	14000	-21	29860	69	49214	178	-9	46476	163	-14
	TF Flow												
b/n 2020 & 2119	18495	49880	170	14940	-19	31845	72	47957	159	-4	45050	144	-10
b/n 2020 &2025	19150	27028	41	18107	-5	27028	41	27028	41	0	27028	41	0
b/n 2025 & 2050	18558	45512	145	16405	-12	32846	77	44806	141	-2	42444	129	-7
after 2050	18426	53073	188	14190	-23	31831	73	50577	174	-5	47269	157	-11

Annual energy generation of the Eastern Nile for different hydropower and irrigation development scenarios are shown in the Figures 8-10, Appendix Figure G-6 and G-7 for EN MSIOA, ARMA11 and TF flow respectively.

In the figure:

- No IRR before GERD: represent the current irrigation and dam/hydropower situation
- Current IRR_GERD & Upper cascades: is the current irrigation scenario with full dam/hydropower development level
- Ethio. IRR before GERD represent: the current dam/hydropower scenario with future Ethiopian irrigation development.
- Ethio. IRR after GERD represent: the implementation of GERD with future Ethiopian irrigation development.
- Ethio. IRR GERD and upper cascades represent: the implementation of four dams (GERD, Karadobi, Bekoabo and Mendya) with Ethiopian future irrigation development.

➢ FDL GERD & upper cascades represent: the implementation of four dams (GERD, Karadobi, Bekoabo and Mendya) with Ethiopian and Sudanese irrigation.

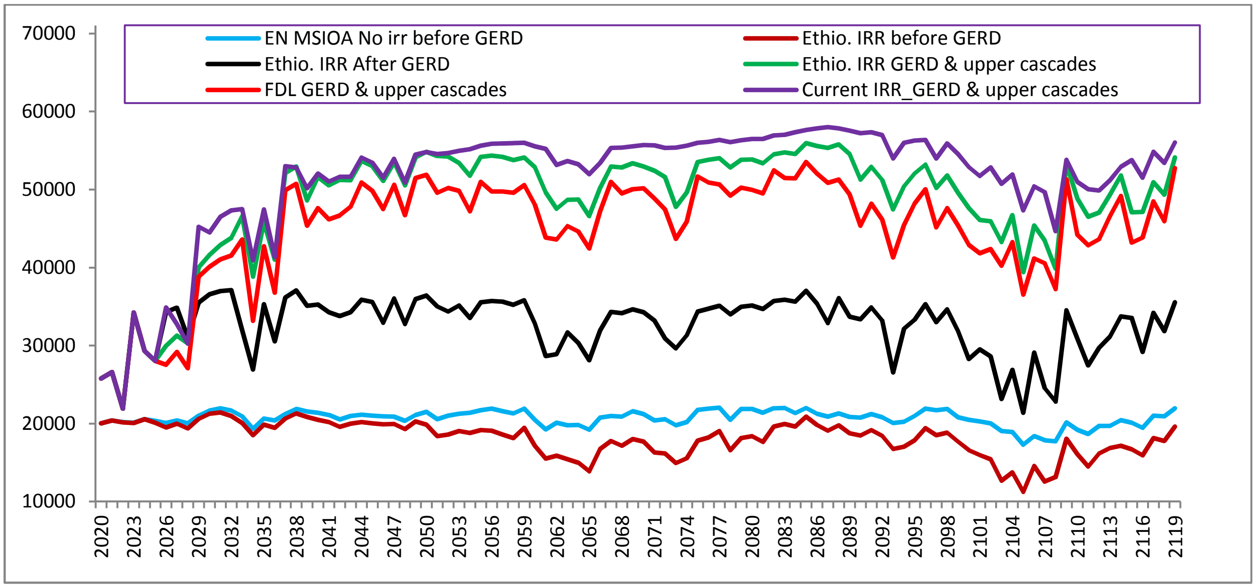

Figure 8-10: Cumulative Eastern Nile energy (GWh) for different dams and irrigation development scenarios EN MSIOA flow

After 2035 all reservoirs in Abbay river basin will generate energy at their full level and there will be maximum cumulative energy eastern Nile. As shown in the Table 8-10 and figures above, the long term energy generation in Eastern Nile will increase from the current around 19000 to around 54000 GWh/ year. This is 164, 187 and 201% incremental of energy for EN MSIOA, ARMA11 and TF flows respectively (Table 8-7). However the irrigation development in Sudan will decrease the energy production by at list 3000 GWh. That is the incremental will reduce to 129, 163 and 157% for EN MSIOA, ARMA11 and TF flows respectively (Table 8-10). Ethiopian future irrigation development also decreases the Eastern Nile energy by 5 to 9% from its potential. There could be up to 200 million US$ loss per year from the energy sector because of irrigation expansion in the Eastern Nile (Appendix Table G-1).

8.4. Conclusive Remarks

Future planned irrigation expansion in Sudan and Ethiopia was considered based on planned irrigation development in both countries. Results indicate that irrigation development in the

Eastern Nile Basin may complicate water use situation for hydropower and agriculture. Results of simulation based on medium and long term planned irrigation development in the Eastern Nile are summarized;

1. Based on the medium irrigation development plan 0.344 million ha in Ethiopia and 2.02 million ha in;
   - There may be irrigation water deficit of up to 5.7 BCM and additional loss of 4056. GWh/year of power production may be observed in Egypt.
   - The Ethiopian planned energy production will reduce by up to 1148 GWh (4%) due to future irrigation development in Abbay-Blue Nile river basin.
   - The regional hydropower potential output decreases by 7 to 8 %.
2. The long term irrigation development scenario of 1.44 million ha in Ethiopia and 3.28 million ha in Sudan may result in;
   - Irrigation water deficit of up to 23.8 BCM and additional loss of 5603 GWh/year of power production may be observed in Egypt.
   - The Ethiopian planned energy production will reduce by up to 1773 GWh (5%) due to future irrigation development in Abbay river basin.
   - The planned irrigation development reduces planned regional hydropower potential output by 11 to 14%.

So irrigation expansion under medium or long term plan has consequences on the existing hydropower and irrigation water uses in the basin. There may be greater possibilities of increased irrigation development in the Eastern Nile basin under regional cooperation but individual planning shows consequence of irrigation development in the basin. The greater possibilities of expansion of irrigation come from regional cooperative water supply and demand management, and trade-offs of development.

Chapter Nine

Summary, Conclusions and Recommendations

9.1. Summery

Water resources model is developed for comprehensive assessment of the impacts and benefits of Eastern Nile River basin development under current and future planned development scenarios. The following four major case studies are evaluated for several input scenario;

1. Evaluation of the impacts and benefits of the on-going construction of Grand Ethiopian Renaissance Dan (GERD) during the filling stage of the GERD reservoir.
2. Evaluation of the long term impacts and benefits of the GERD after filling of the reservoir and full operation started.
3. Evaluation of the futures planned hydropower development in the Abbay-Blue Nile Basin in Ethiopia upstream of the GERD
4. Evaluation of the impacts of future irrigation development in Ethiopia and Sudan.

Mike Basin and Mike Hydro simulation models were used for the evaluation. The schematization of the river basin for the available water at major control structures and major water extraction points (users) is sufficiently represented in the model. Model performance was tested using statistical and graphical procedures at four selected sites in the river system.

1. For the GERD filling Scenario, three historical 6 years inflow scenario and additional hypothetical inflow scenario of +/-20 % were evaluated. Results of the filling stage of GERD indicate;
   - Under normal and wet flow scenarios of the 6 years period, GERD has no significant impact on downstream water uses. The agricultural water requirement from HAD which is a concern in Egypt is not affected under these scenarios. The reduction in the storage volume of HAD never reached its' minimum operation level.
   - While the regional energy increases by about 63% due to early start of energy production at GERD, the annual energy production from HAD may be reduced by 12.7% due to the reduction in the head available at the Dam in Egypt. The reduction in head compensates

through reduction in the evaporation loss by 3.4 BMC which is 22% of the current evaporation baseline condition.

- If the worst scenario of 6 years consecutive drought of the 1980s magnitude (18 % of the longer term mean) occur, or the flow is reduced by 10% or more from the long term mean annual flow, the planned 6 years filling of GERD was found insufficient to fill the reservoir without affecting the downstream water uses. Under such extended dry scenario, agricultural water use will be stressed. For instance, even if the reservoir filling is extended for 8 to 10 years period in this dry scenario, the agricultural water use from HAD will be stressed for 19 to 27 months. Though, the statistical chance of occurrence of the 1980s driest flows is remote, the assessment provides the retrospective understanding of worst conditions and implement precautionary measures. It is recommended to implement flow forecasting and coordinated reservoir operations under any eventualities.
- Further analysis of the filling of GERD using stochastic generated flows of ARMA11, ENMSIOA and Thomas-Feiring has no shown little or change from the above summaries. In all stochastic flows, there is no impact on agricultural use, and the HAD water level will not reach its minimum operation level.

3. Long term impacts and benefits of GERD is simulated by considering a 95% confidence interval of 42 years monthly inflow time series as a possible realization of the future series. Results of the long term simulation indicate;

- The overall regional annual energy production increase by 119% (to 33564 GWh). The GERD annual energy generation will increase within the range of 14766 and 16605 GWh boasting the total Ethiopian energy by 300%. Sudan gain about 3000 GWh of energy due to implementation of GERD without additional investment. However, the mean annual energy production at HAD may decrease by 6 to 8 % due to the average reservoir water level reduction of HAD.
- In the long term sense, there no significant decrease in agricultural water use to the downstream water use. Sustainability indicators show that, the percentage of success in terms of reliability is above 96% for all conditions. In fact, the recovery of HAD reservoir (resilience) from low flow conditions is greater after implementation of GERD

(95 %) than without GERD (83%). That means HAD alone scenario is more vulnerable to drought as compared to with GERD scenario in the long term sense.

- Sudanese irrigation water demand is always satisfied during the simulated period with more than 96% performance. GERD has no negative impacts on any one of the Sudanese reservoir. Instead, in all reservoirs the inflow is more uniform and the energy production increases.

4. In the case of implementing additional cascades of hydropower dams upstream of GERD dam in the Abbay-Blue Nile, which includes the optimal dam combinations of Karadobi, Bekoabo low, Mendya and GERD, the results indicate;

   - The total annual Energy production in Ethiopia will increase to about 38182 GWh from all flow scenarios boasting the regional energy pool of the Eastern Nile by 258%.
   - The energy production in Sudan increases by 38% (more than 3000 GWh/year) without additional investment and energy production from HAD is 6816 GWh.
   - Due to future cascade hydropower production upstream of GERD in Ethiopia, agricultural water use in Sudan and Egypt will not be affected.
   - The upper cascades have no significant negative impacts on the performance of downstream reservoirs either in filling or after filling phases. There is the added value of the regulation capacity of the proposed reservoirs located in Ethiopia.
   - Under such complex implementation of multiple storage reservoirs in Eastern Nile, Robust seasonal and annual flow forecasting model has to be put in place. Furthermore, it is important to consider regionally coordinated dynamical reservoir operation and management.

5. Based on the medium irrigation development plan of 0.344 million ha in Ethiopia and 2.02 million ha in Sudan;
   - There may be irrigation water deficit of up to 5.7 BCM and additional loss of 4056 GWh/year of power production may be observed in Egypt.
   - The Ethiopian potential energy production will reduce by up to 1148 GWh (4%) due to medium level irrigation development in Abbay-Blue Nile river basin.
   - The regional hydropower potential output decreases by 7 to 8 %.

6. The long term irrigation development scenario of 1.44 million ha in Ethiopia and 3.28 million ha in Sudan may result in;

- Irrigation water deficit of up to 23.8 BCM and additional loss of up to 5603 GWh/year of power production may be observed in Egypt.
- The Ethiopian planned potential energy production will reduce by up to 1773 GWh (5%) due to future irrigation development in Abbay river basin.
- The planned irrigation development reduces planned regional hydropower potential output by 11 to 14%.

9.2. Conclusion

On the basis of the four case studies conducted in the basin, the following can be concluded.

- ❖ The planned 6 years filling period is mostly sufficient to fill the GERD reservoir with no or little impact on the current irrigation water use of Egypt and Sudan without additional management investment. However, if a rare scenario of 6 years dry consecutive sequence of flow that was observed in the historical sequence of the 1980s occurs, the filling strategy need to be revised.
- ❖ Analysis of the hypothetical scenarios within -/+ 20 flow variation from the long term mean indicates, the 6 years filling sequence below the normal (mean) flow by about 10% will be in the tolerable range of filling. However, joint operation of reservoirs is required to reduce any unforeseen impacts downstream of the dam.
- ❖ In terms of long term, GERD has no impact on the agricultural water use downstream of the dam in Sudan and Egypt. The annual energy production from HAD may decrease by 6 to 8% in Egypt but regional power pool increased by 119%. In the long term perspective, the presence of GERD in the Eastern Nile System renders more regional benefit than before.
- ❖ The cumulative long term average energy gain in Eastern Nile basin will be 258 % for historical flow and 164 to 206% incremental for stochastic time series flows. The incremental will reduce to 134 to 178% and 126 to 163% because of future Ethiopian and Sudanese irrigation development respectively. The upstream country Ethiopia can generate as much as 38200 GWh/year of Energy while the energy production in Sudan increases by 38%.

- ❖ Assessment of the strategic development option that include cascaded dams above GERD indicate maximum of 56396 GWh/year of energy could be generated from Eastern Nile system after all the proposed additional cascaded dams are filled and operated without significant impact on regional agricultural water uses. Therefore, there is enormous hydropower potential that can be tapped in the highlands of Ethiopian Nile basin if carefully planned and executed.
- ❖ Iirrigation expansion under medium or long term development plan has consequences on the existing hydropower and irrigation water uses in the basin. There may be greater possibilities of increased irrigation development in the Eastern Nile basin under regional cooperation but individual planning shows consequence of irrigation development in the basin. The greater possibilities of expansion of irrigation come from regional cooperative water supply and demand management, and trade-offs of development.

9.3. Recommendation

The following recommendations are stated based on the problems which face to conduct this study and based on future insights of the Eastern Nile water resource development/management and research works:

- ➢ Valid and reliable data of stream flow of every catchment of Eastern Nile basin especially for Abbay river basin with their spatial and temporal distributions is crucial.
- ➢ Detail information of under operation and future plan infrastructure development; data for metrology and climate change are essential for further research works
- ➢ Future research work should integrate impacts of climate change and uncertainties in the Eastern Nile basin water resource development.
- ➢ Optimization study is essential by considering different water use sectors
- ➢ Further works are required to develop mitigation plan under deficit scenarios
- ➢ Regional operation plan that integrate hydrological forecast model, dynamic operation rules common strategy is required.
- ➢ Further and updated evaluations may be necessary after detail and final design and studies stages of Abbay River cascades.

- Further or detail study could also be necessary by considering all proposed and implemented small and medium irrigation and water abstraction projects in Abbay-Blue Nile River basin.
- Future research is needed to reform the model by considering improved estimates of irrigation water demand; improved estimates of the dates on which schemes will become operational and more realistic dam operating rules.
- Future research works for the way to improve irrigation methods and water use efficiency are crucial to minimize the agricultural water deficit.
- Manage water resources in a way that brings benefits to all with the frame work of Nile Basin Initiative (NBI) that aims to develop the river in a shared-vision and cooperative way. To take full advantage of the water resources of the basin it is necessary that they are managed as a single system which requires the establishment of much more effective institutional arrangements than those currently existing. It is to be hoped that such arrangements will be devised through the protracted negotiations currently under way.

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Appendices

A. Stream flow data

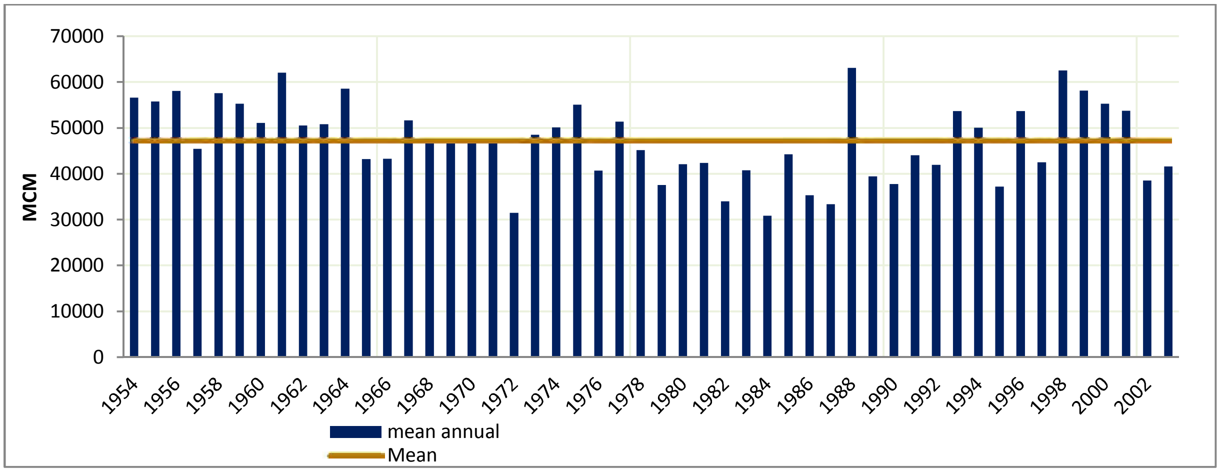

Figure A-1: Annual flow at Rosaries from 1954 – 2003

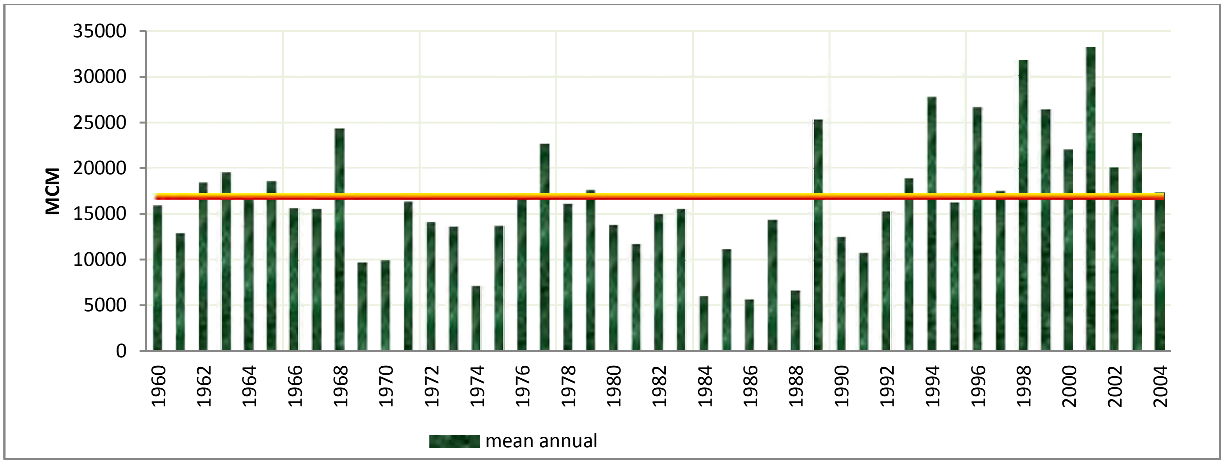

Figure A-2: Annual flow at Abbay at Kessie from 1960 – 2004

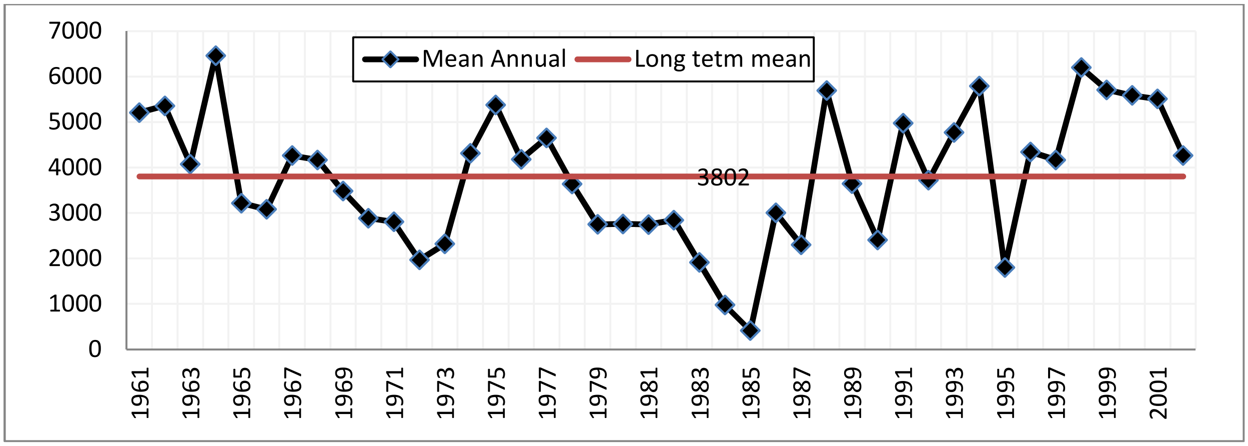

Figure A-3: Annual runoff Series of Abbay at Bahir Dar (1961-2002) (MCM)

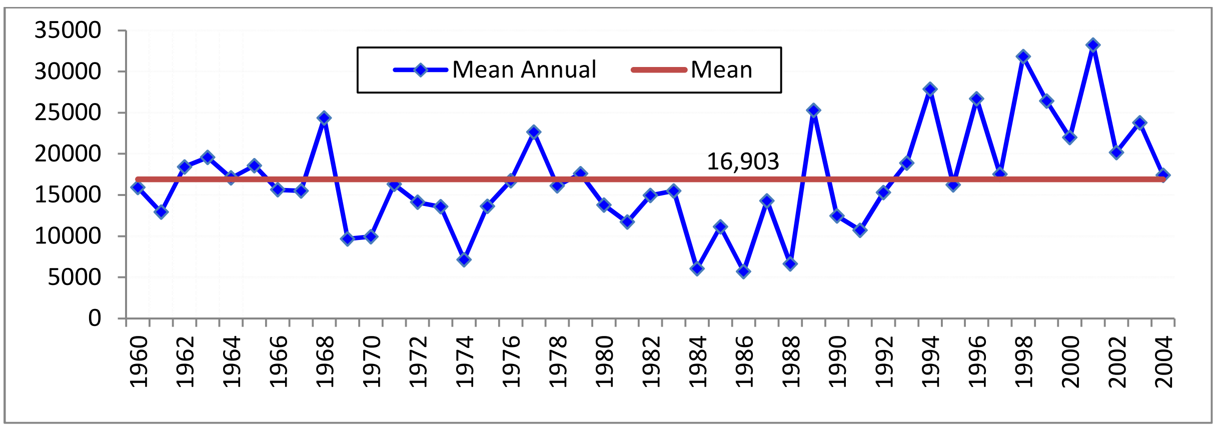

Figure A-4: Annual runoff Series of Kessie (1960-2004) (MCM)

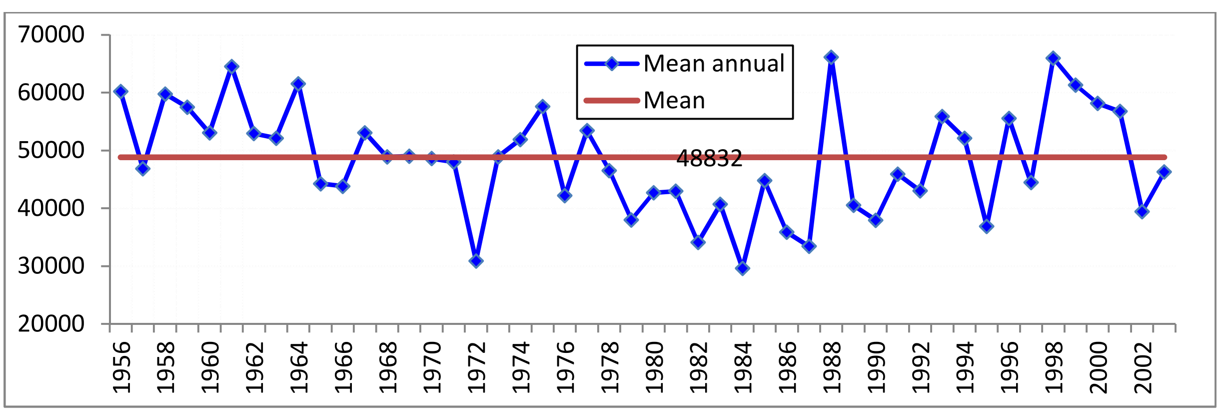

Figure A-5: Annual runoff Series of Border (1956-2003) (MCM)

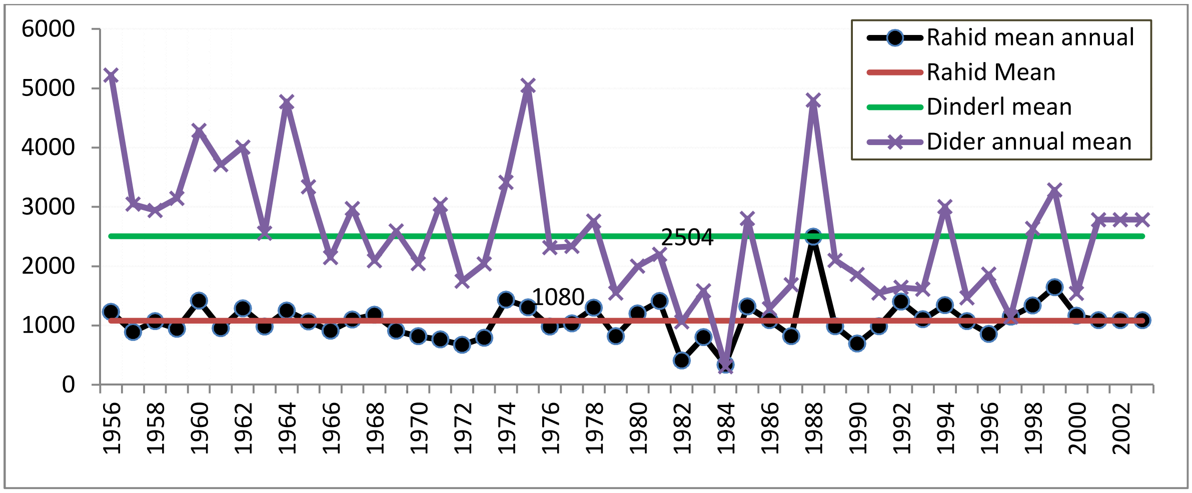

Figure A-6: Annual runoff series of Rahid and Dinder rivers (1956-2003) (MCM)

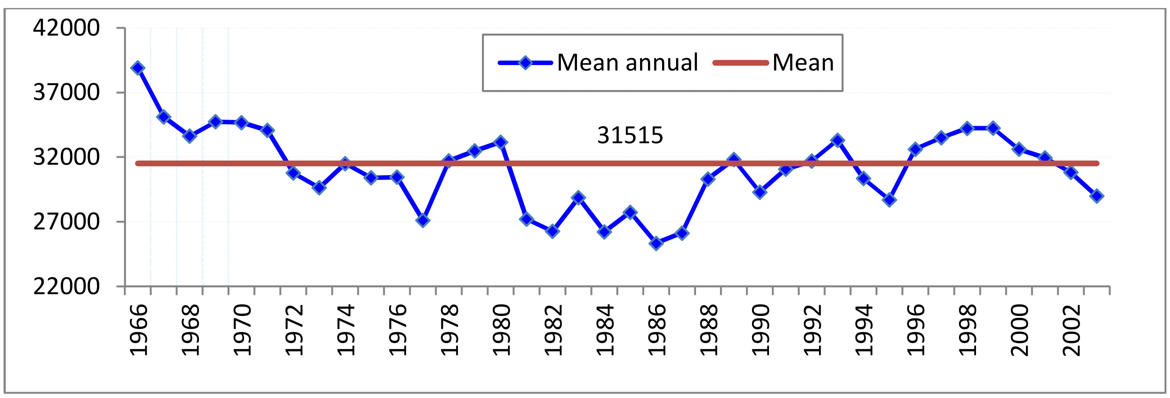

Figure A-7: Mean annual inflows entering the White Nile River at Malakal (1965-2003) (MCM)

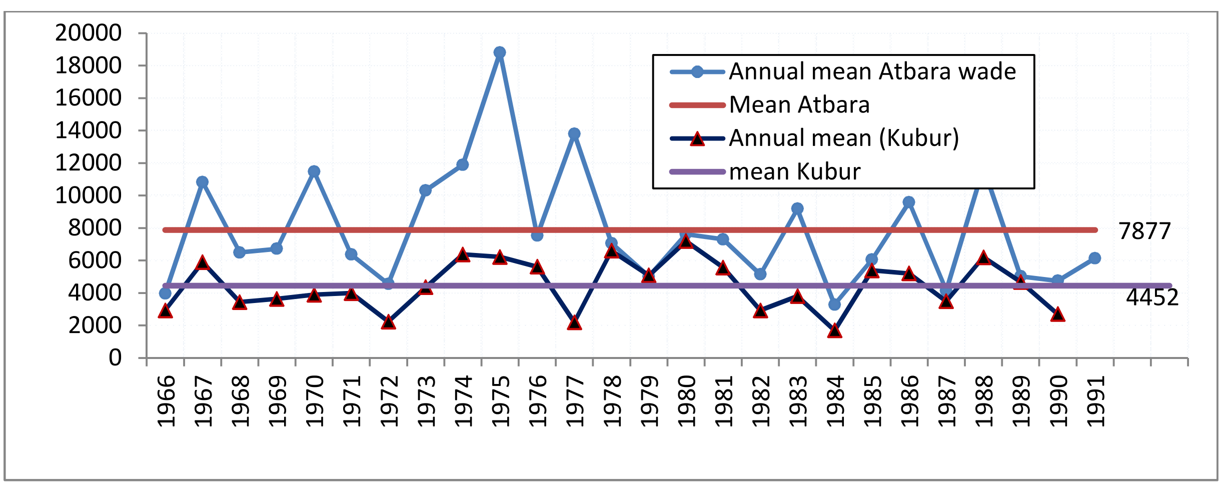

Figure A-8: Annual flow time series for Atbara and Kubur (1966-1991) (MCM)

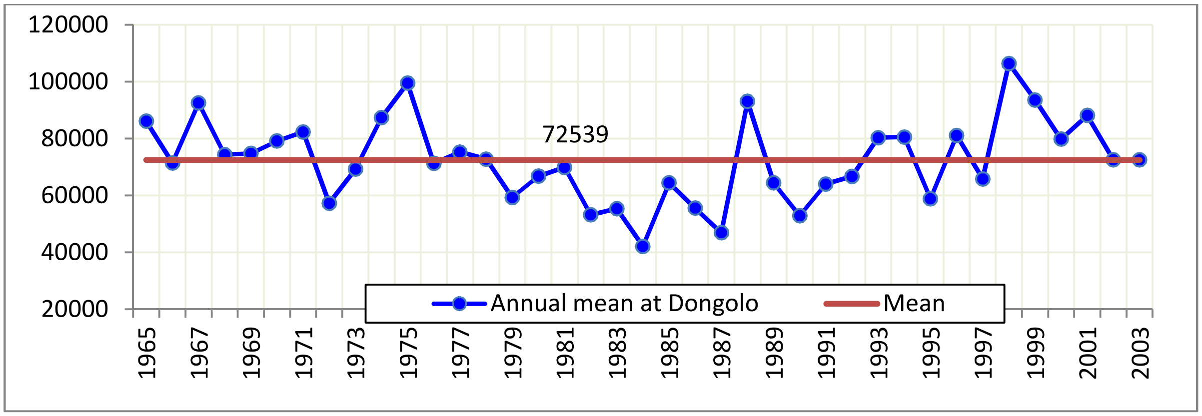

Figure A-9: Mean annual inflow at Dongola station (1965-2003)

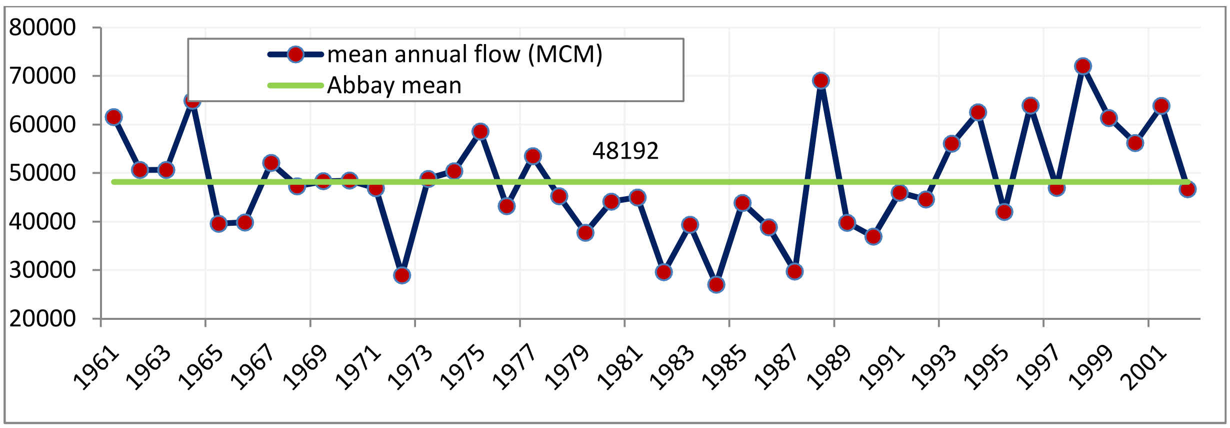

Figure A-10: Mean annual Stream flow data of Abbay River at Border

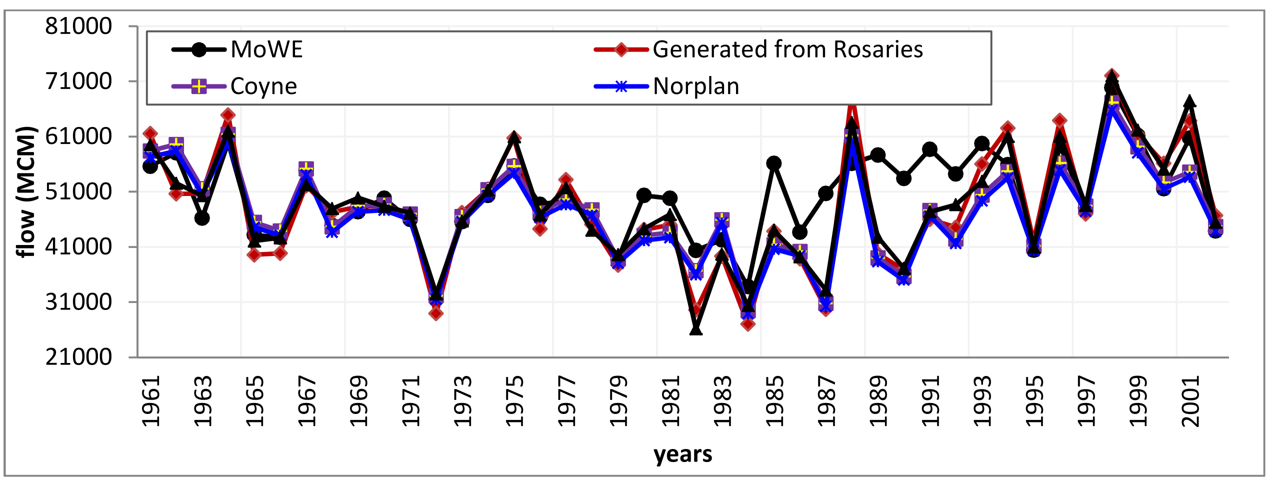

Figure A-11 Stream flow data of Abbay River studied by different organizations

Table A-1: Selected hydrological gauging stations (Below Kessie)

below station kessie						Above station kessie				
S. number	River	Drainage area			Installation	River	drainage area			Installation
		Gauged	Un gauged	Total			Gauged	Un gaged	Total	
1	Abbay	65784	0	65784	1951	Azuari	209	1188	1397	1980
2	Dabus	10139	4623	14762	1963	Sede	209	247	456	1987
3	Dedesa	9981	6415	16396	1959	Aleltu	447	1790	2237	1983
4	M/Beles	3431	9390	12821	1962	R/Jida	762	123	885	1983
5	Debena	3281	347	3628	1961	R/Gume	787	62	849	1983
6	Mugger	489	6986	7475	1958	Andasa	573	30	603	1959
7	Guder	524	3838	4362	1959	Sedie		1548	1757	1987
8	Anger	4674	2453	7127	1961	Muga	375	917	1292	1980
9	Missi	16	2111	2127	1988	Suha	359	361	720	1985
10	Chem	364	1098	1462	1960	Weleka	-	5802	5802	-
11	Jedeb	305	701	1006	1959	Wonchit	4090.6	15.4	4106	
12	Dura	758	1315	2073	1983	Jema	5412	2896	8308	1986
13	Fetem	757	300	1057	1986	Beshilo	-	13319	13319	-
14	Lah	288	1204	1492	1959	Un	-	2044	2044	-
15	Birr	978	769	1747	1985	M/Abbay	-	6774	6774	-
16	G/Bel	675	620	1295	1980	Garno	94	316	410	1987
17	Nesh	322	44	366	1963	Koga	244	0	244	1959
18	Uke	202	488	690	1976	G/Abbay	1664	2792	4456	1959
19	Amerti	252	680	932	1963	Gemero	174	410	584	1984
20	Fincha	1391	691	2082	1959	Magic	462	538	1000	1959
21	Debis	799	58	857	1997	Gumara	1394	736	2130	1959
22	Duber	-	1994	1994	1997	Un-gauged		1233	1233	
23	Aleltu	29	236	265	1981					
24	Temcha	406	948	1354	1960					
25	Yeda	125	583	708	1988					
26	Bogena	166	670	836	1996					
27	Teme	156	300	456	1985					
28	M/Abbay	-	16252	16252	-					

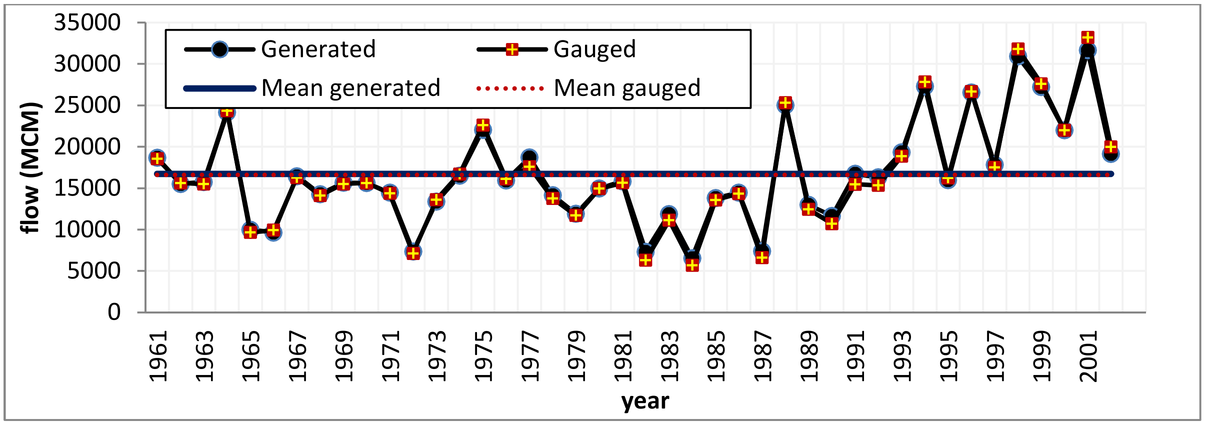

Figure A-12: Generated and gauged mean annual flow of Abbay at Kessie

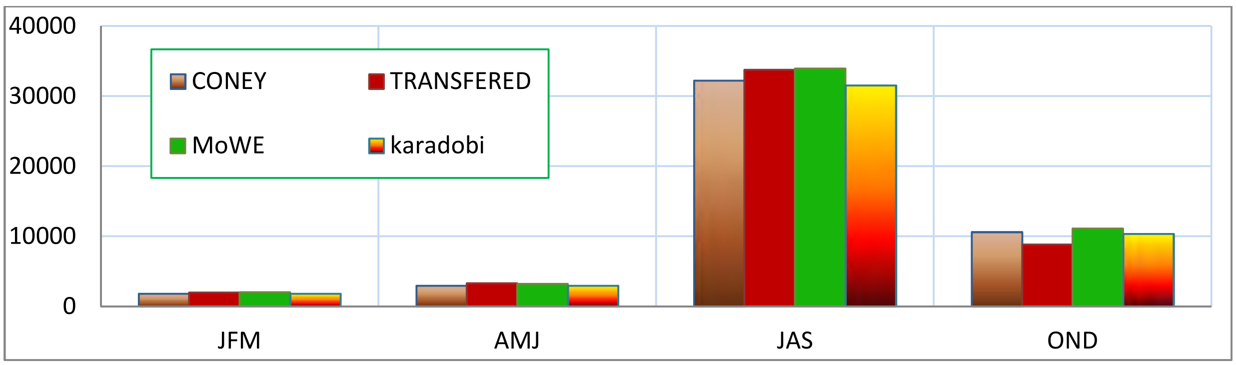

Figure A-13: Mean seasonal Stream flow data of Abbay River studied by different organizations

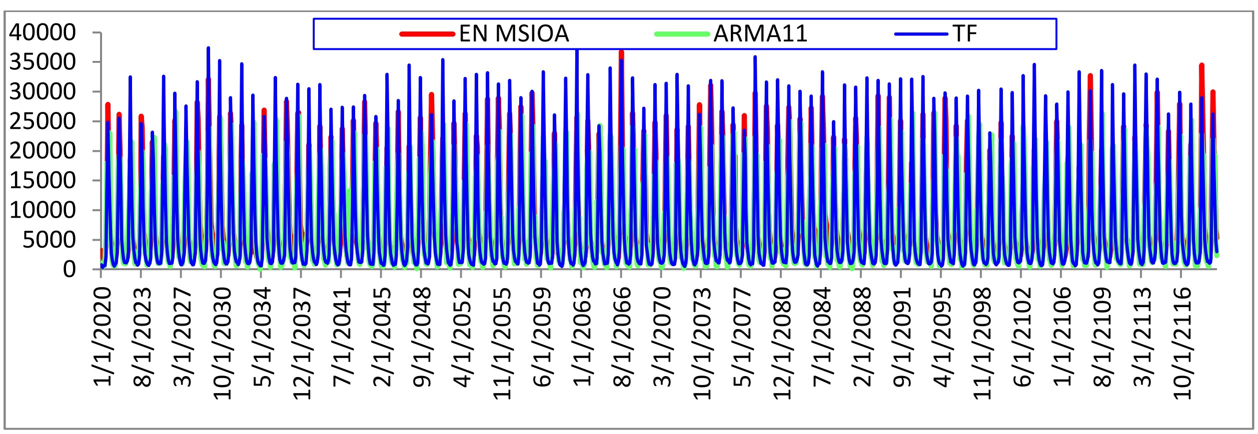

Figure A-14: Stochastic tie series flow data (MCM)

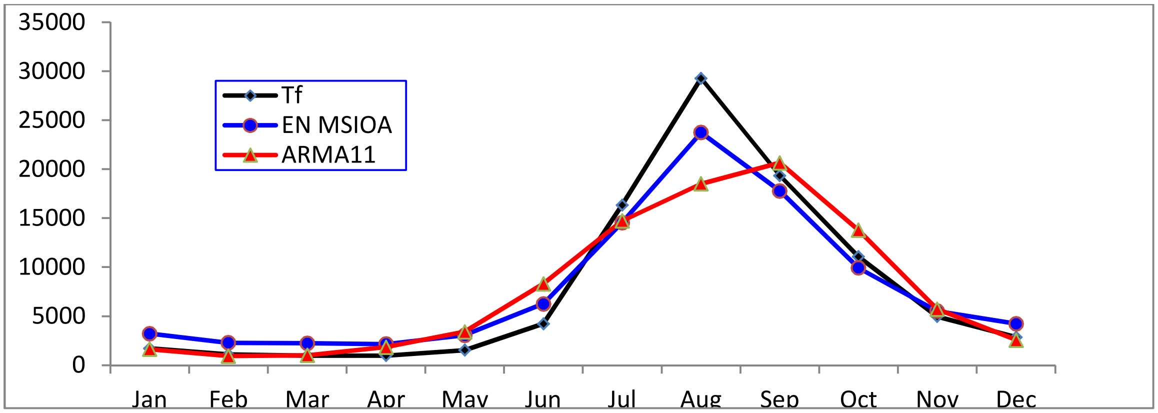

Figure A-15: Mean monhly flows of stochastic time series data

Table A-2: Mean annual flows of stochastic flows

	EN MSIOA	ARMA11	TF
Tana inflow	5444	5230	5382
Dedesa	8469	8303	8153
Bahir Dar to Kessie	12258	12877	12177
Kessie to Karadobi	4130	4015	4215
Karadobi to BA	3253	3380	3150
Bekoabo to Mendya	2278	2315	2512
Mendya to border	9701	10102	11085
Beles	5008	4804	4314
Melakal	29390	26574	27574
Tekeze	7386	7945	7945
Kubur	3761	4831	4679
Rahad	1080	1072	1185
Dinder	2802	2400	2287
Total	**94960**	**93847**	**94658**

Appendix B: Reservoirs Characteristics

The followings are major reservoirs in the eastern Nile river basin

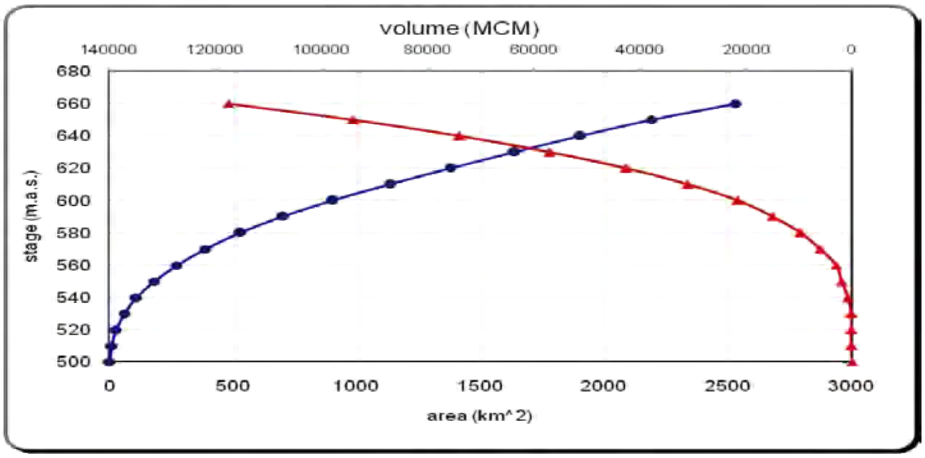

Figure B-1: Elevation area volume relations of GERD

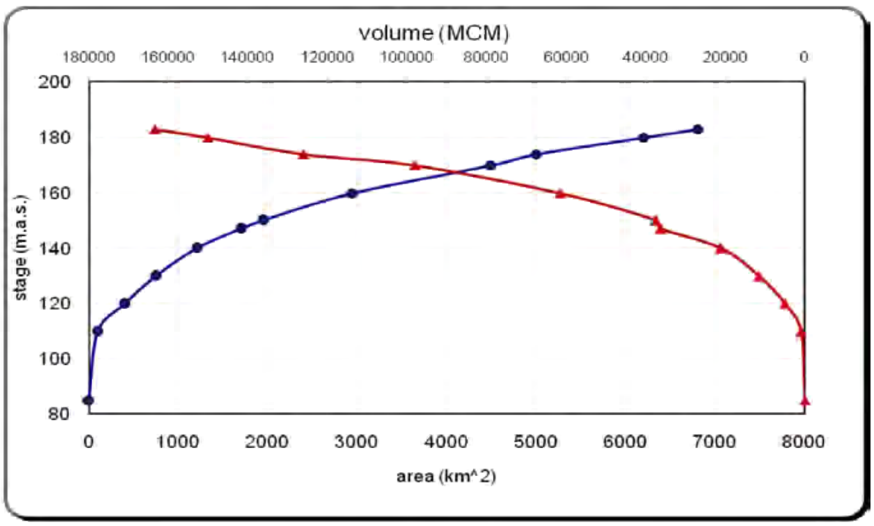

Figure B-2: Elevation area volume relations of HAD

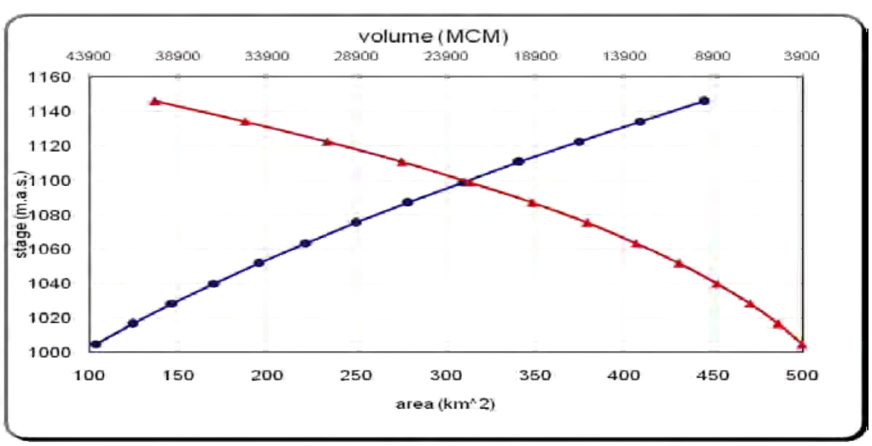

Figure B-3: Elevation area volume relations of Karadobi

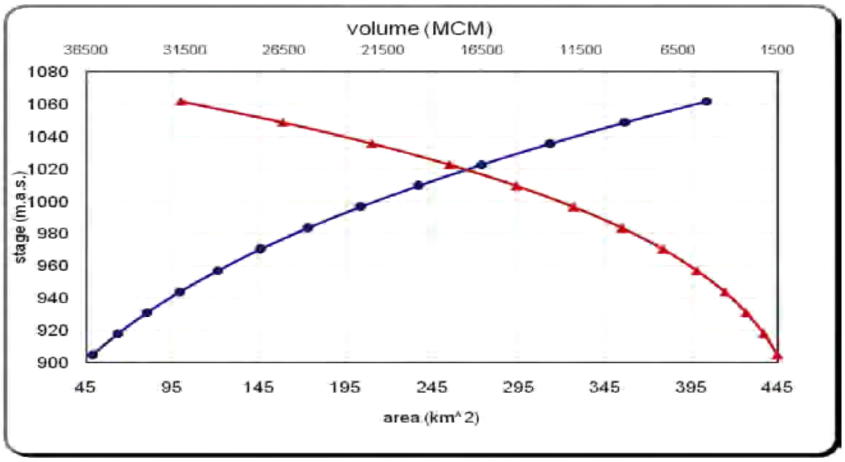

Figure B-4: Elevation area volume relations of Bekoabo

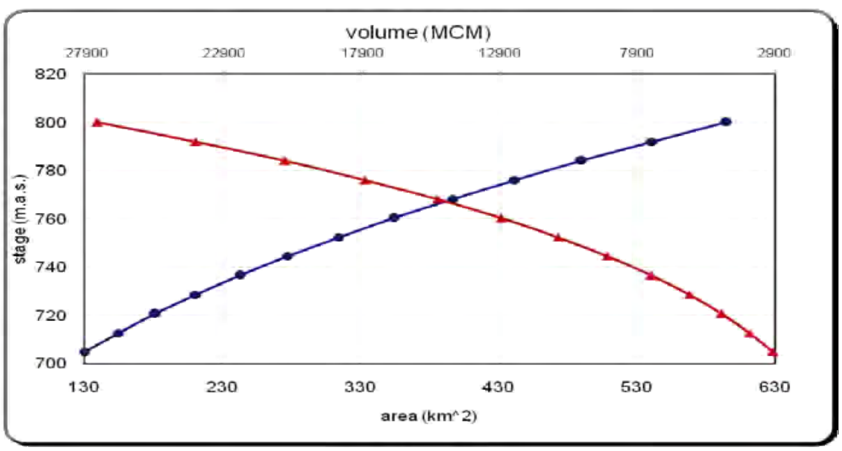

Figure B-5: Elevation area volume relations of Mendya

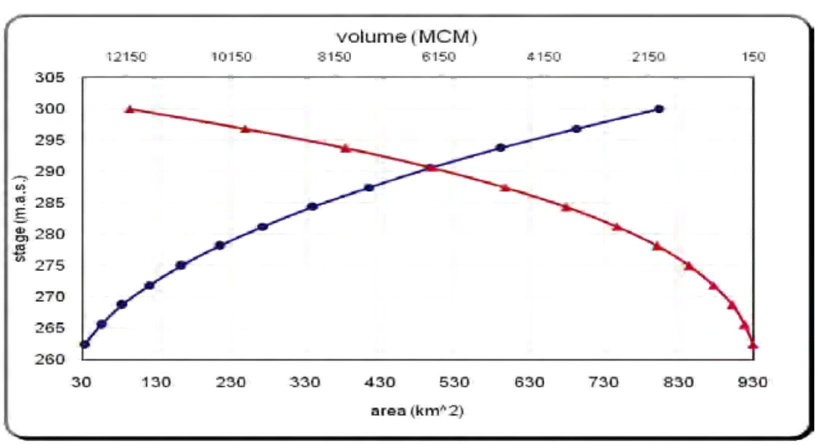

Figure B-6: Elevation area volume relations of Merowe

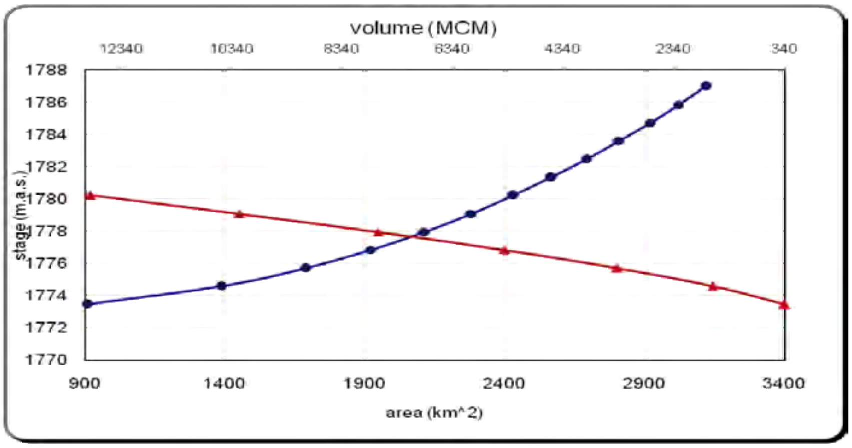

Figure B-7: Elevation area volume relations of Lake Tana

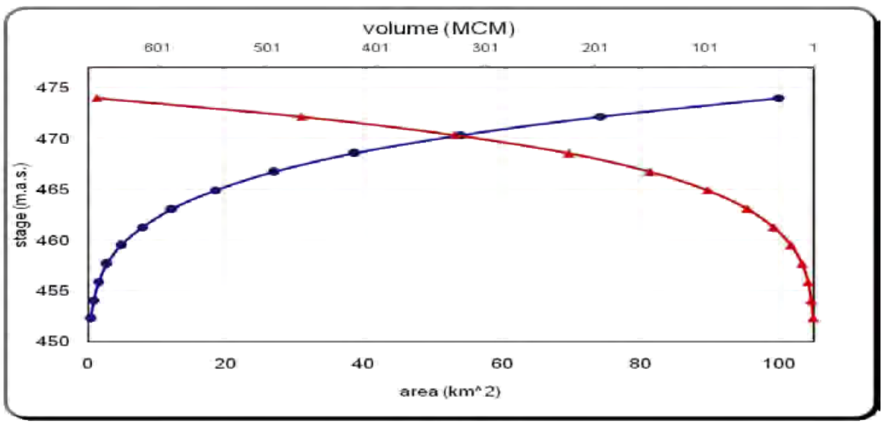

Figure B-8: Elevation area volume relations of Roseires

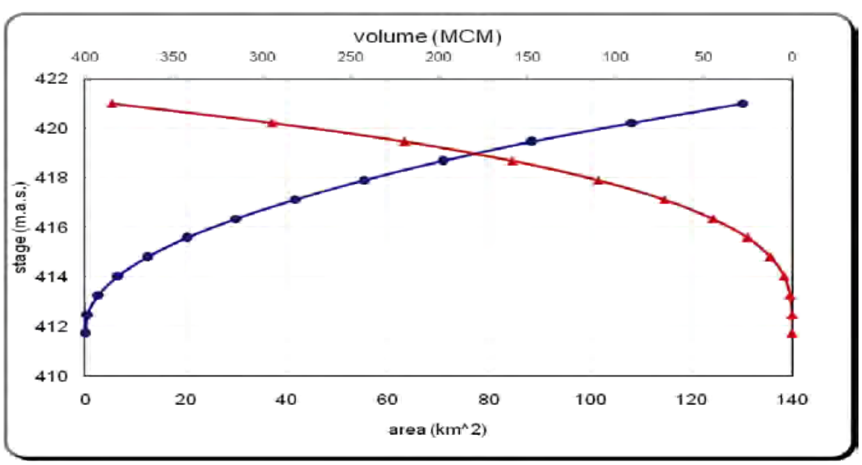

Figure B-9: Elevation area volume relations of Sennar

Appendix C: Future irrigation development data

Table C-1: Monthly irrigation water demand of Abbay river basin (cms)

Site	Beles		Anger-Dedesa		Lake Tana		Fincha-Nesh		Lake Tana to Karadobi	
Scenario	MTD	FTD	MTD	FTD	MTD	FTD	MTD	FTD	MTD	FTD
Jan	86.8	92.1	37.7	51.4	48.7	73.4	7.0	7.0	0.0	34.8
Feb	111.8	119.3	47.6	65.0	53.9	83.7	7.7	7.7	0.0	50.5
Mar	93.0	99.6	25.3	34.7	53.8	82.7	5.1	5.1	0.0	36.1
Apr	63.5	66.5	3.4	5.1	32.4	49.4	4.0	4.0	0.0	9.4
May	10.6	10.6	0.0	0.0	3.2	4.5	0.4	0.4	0.0	0.0
Jun	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Jul	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Aug	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Sep	0.0	0.0	0.0	0.0	0.0	0.0	1.2	1.2	0.0	0.0
Oct	0.0	0.0	0.0	0.0	5.5	7.2	5.3	5.3	0.0	0.0
Nov	78.3	0.0	23.7	0.0	35.1	52.1	8.9	1.2	0.0	0.0
Dec	86.1	90.6	33.2	44.5	33.5	51.9	8.8	8.8	0.0	33.0
Area (1000 HA)	138.7	147.2	75.4	101.4	80.5	125.1	15.7	15.7	0.0	76.5

Table C-2: Monthly irrigation water demand of Tekeze, Dinder and Rahad river basins in Ethiopia (cms)

	Metema		Angereb		Humera		Tekeze		Dinder		Rahad	
Scenario	MTD	FTD	MTD	FTD	MTD	FTD	MTD	FTD	MTD	FTD	MTD	FTD
Jan	0.0	6.2	0.0	8.9	22.9	22.9	8.9	69.3	0.0	38.8	0.0	36.6
Feb	0.0	11.4	0.0	16.4	45.4	45.4	16.4	117.4	0.0	54.3	0.0	51.2
Mar	0.0	6.7	0.0	9.6	28.1	28.1	9.6	74.2	0.0	49.6	0.0	46.9
Apr	0.0	4.9	0.0	6.9	19.5	19.5	6.9	52.4	0.0	23.8	0.0	22.6
May	0.0	7.4	0.0	10.6	35.8	35.8	10.6	82.0	0.0	2.8	0.0	2.6
Jun	0.0	2.5	0.0	3.5	22.0	22.0	3.5	26.8	0.0	0.0	0.0	0.0
Jul	0.0	0.0	0.0	0.0	9.3	9.3	0.0	0.0	0.0	0.0	0.0	0.0
Aug	0.0	0.0	0.0	0.0	9.3	9.3	0.0	0.0	0.0	6.0	0.0	5.4
Sep	0.0	4.4	0.0	6.2	30.3	30.3	6.2	46.9	0.0	3.3	0.0	2.8
Oct	0.0	7.0	0.0	10.0	31.6	31.6	10.0	78.0	0.0	0.0	0.0	0.0
Nov	0.0	4.4	0.0	6.2	24.4	30.3	7.7	46.9	0.0	3.3	0.0	2.8
Dec	0.0	4.0	0.0	5.7	17.4	17.4	5.7	44.1	0.0	31.8	0.0	30.0
Area (1000 HA)	0.0	11.6	0.0	16.5	43.0	43.0	40.0	141.0	0.0	58.5	0.0	55.0

Table C-3: Monthly irrigation water demand of Baro-Akobo river basin (cms)

	U/s Alwero		Awaro left bank		Gilo 1		Gilo 2		Itang		Baro	
Scenario	MTD	FTD	MTD	FTD	MTD	FTD	MTD	FTD	MTD	FTD	MTD	FTD
Jan	0.0	28.4	4.6	4.6	0.0	35.8	0.0	41.9	0.0	90.9	0.0	86.5
Feb	0.0	52.2	8.4	8.4	0.0	65.8	0.0	77.0	0.0	166.9	0.0	158.8
Mar	0.0	30.4	4.9	4.9	0.0	38.4	0.0	44.9	0.0	97.3	0.0	92.6
Apr	0.0	22.1	3.6	3.6	0.0	27.9	0.0	32.6	0.0	70.7	0.0	67.3
May	0.0	33.7	5.4	5.4	0.0	42.4	0.0	49.7	0.0	107.6	0.0	102.4
Jun	0.0	11.3	1.8	1.8	0.0	14.3	0.0	16.7	0.0	36.1	0.0	34.4
Jul	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Aug	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Sep	0.0	19.8	3.2	3.2	0.0	24.9	0.0	29.2	0.0	63.3	0.0	60.2
Oct	0.0	32.0	5.2	5.2	0.0	40.3	0.0	47.2	0.0	102.3	0.0	97.3
Nov	0.0	19.8	3.2	3.2	0.0	24.9	0.0	29.2	0.0	63.3	0.0	60.2
Dec	0.0	18.1	2.9	2.9	0.0	22.8	0.0	26.7	0.0	57.8	0.0	55.0
Area (1000 HA)	0.0	64.5	10.4	10.4	0.0	81.4	0.0	95.2	0.0	206.3	0.0	196.3

Table C-4: Monthly irrigation water demand of Atbara and Main Nile river basin in Sudan (cms)

	Atbara			Elgibra			sobolka			dongola		
Scenario	Current	MDL	FDL	Current	MDL	FDL	Current	MDL	FDL	Current	MDL	FDL
Jan	0.0	108.6	109.4	37.7	37.7	37.7	18.9	31.2	31.2	13.4	58.0	61.9
Feb	0.0	85.3	93.3	27.5	27.5	27.5	12.9	33.6	33.6	10.8	45.0	49.3
Mar	0.0	42.0	63.8	16.4	16.4	16.4	5.3	33.2	33.2	20.4	30.8	34.4
Apr	0.0	34.7	58.3	17.4	17.4	17.4	4.6	31.1	31.1	25.1	30.5	32.9
May	0.0	17.2	40.3	31.7	31.7	31.7	7.2	22.8	22.8	25.9	25.2	25.2
Jun	0.0	26.1	41.2	71.0	71.0	71.0	14.8	18.1	18.1	23.3	20.0	20.0
Jul	0.0	27.5	33.4	68.7	68.7	68.7	13.4	11.9	11.9	18.9	12.4	12.8
Aug	0.0	42.2	39.9	56.4	56.4	56.4	10.8	8.9	8.9	12.9	9.6	9.7
Sep	0.0	94.7	85.9	84.1	84.1	84.1	20.4	22.9	22.9	5.3	22.0	24.0
Oct	0.0	115.0	108.3	85.9	85.9	85.9	25.1	32.7	32.7	4.6	29.4	33.5
Nov	0.0	96.6	100.0	69.4	69.4	69.4	25.9	34.8	34.8	7.2	46.4	50.6
Dec	0.0	100.8	102.5	47.0	47.0	47.0	23.3	30.8	30.8	14.8	52.2	56.1
Area (1000 HA)	0.0	168.0	168.0	146.0	146.0	146.0	51.7	51.7	51.7	89.9	89.9	89.9

Table C-5: Monthly irrigation water demand of White Nile and Blue Nile (Sudan) river basin (cms)

	South Sudan			White Nile			Gezira and Raha-Dinder			D/S Sennar		
Scenario	Current	MDL	FDL	Current	MDL	FDL	Current	MDL	FDL	Current	MDL	FDL
Jan	0.0	104.5	163.2	77.4	119.1	129.2	297.6	552.5	738.8	7.5	435.5	463.3
Feb	0.0	107.7	168.4	79.1	115.4	126.5	279.5	412.6	568.9	8.1	334.0	368.9
Mar	0.0	101.0	153.9	54.0	99.9	111.6	166.3	186.8	288.6	10.4	120.8	194.4
Apr	0.0	11.5	47.5	52.4	91.1	103.7	68.4	155.7	260.8	11.7	110.6	186.6
May	0.0	0.0	12.9	43.0	63.7	76.1	80.7	81.5	178.0	12.4	80.4	149.5
Jun	0.0	0.0	10.1	37.9	58.3	69.1	268.9	120.0	216.6	12.5	110.7	167.6
Jul	0.0	6.3	21.7	31.7	44.8	51.6	381.2	126.9	197.8	9.0	123.0	149.2
Aug	0.0	23.1	58.9	38.4	44.3	50.3	385.5	191.6	272.3	7.2	205.9	199.9
Sep	0.0	47.6	126.6	80.2	88.7	97.7	535.2	410.4	554.9	10.3	428.8	398.9
Oct	0.0	55.0	152.2	106.6	122.4	134.3	538.5	499.9	670.4	11.4	497.3	469.8
Nov	0.0	98.7	159.5	95.9	116.5	127.7	422.2	458.8	620.8	10.1	413.7	425.1
Dec	0.0	94.1	151.0	79.9	114.5	124.7	295.8	505.1	680.5	7.3	411.4	434.0
Area (1000 HA)	0.0	105.0	210.0	218.8	245.2	247.8	258.5	613.4	1190.9	651.0	701.8	1176.4

Appendix D: Additional Information on GERD Filling Assessments

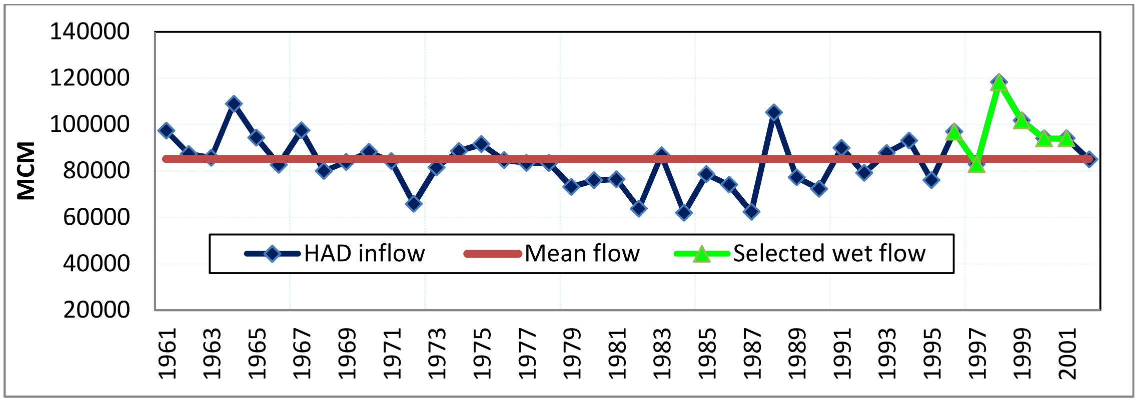

Figure D-1: Selected wet sequence of Naturalized HAD inflow

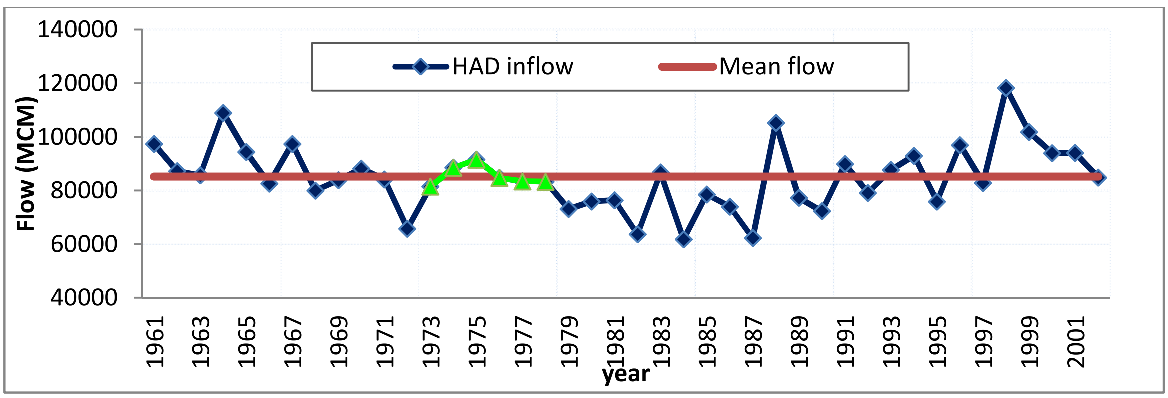

Figure D-2: Selected mean annual flow of HAD Naturalized

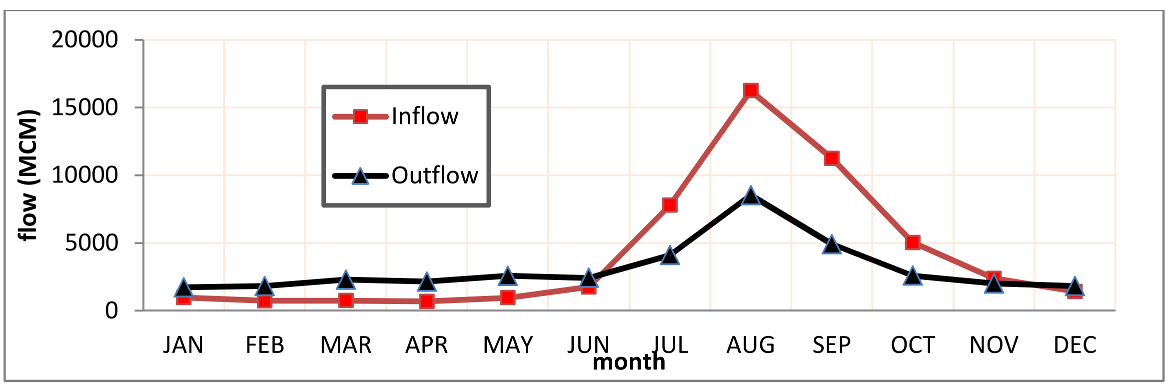

Figure D-3: Mean Monthly inflow and outflow of GERD during impounding with mean sequence (MCM

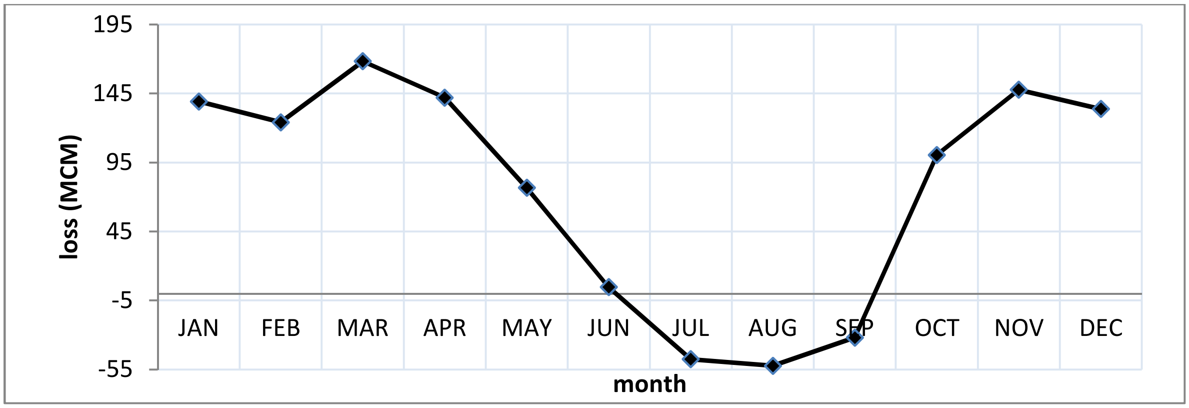

Figure D-4: Mean monthly loss from GERD during filling with mean flow

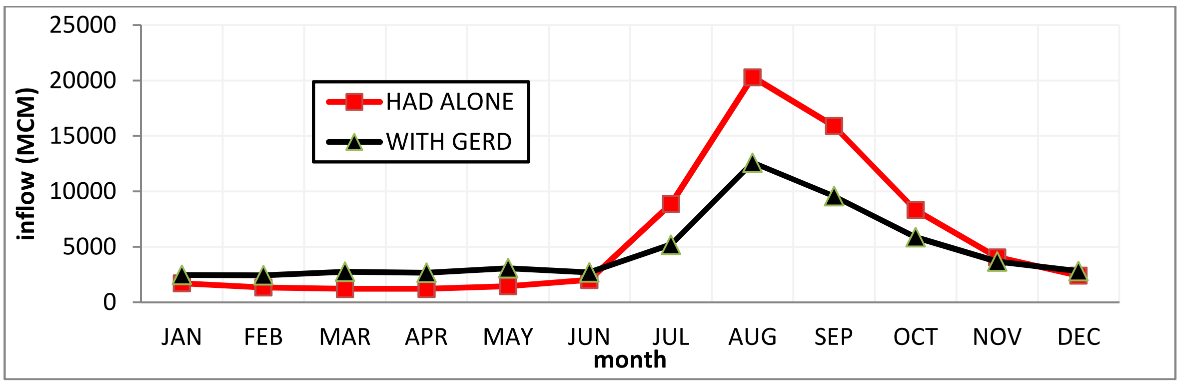

Figure D-5: Mean Monthly inflow to HAD during impounding with mean flow (MCM)

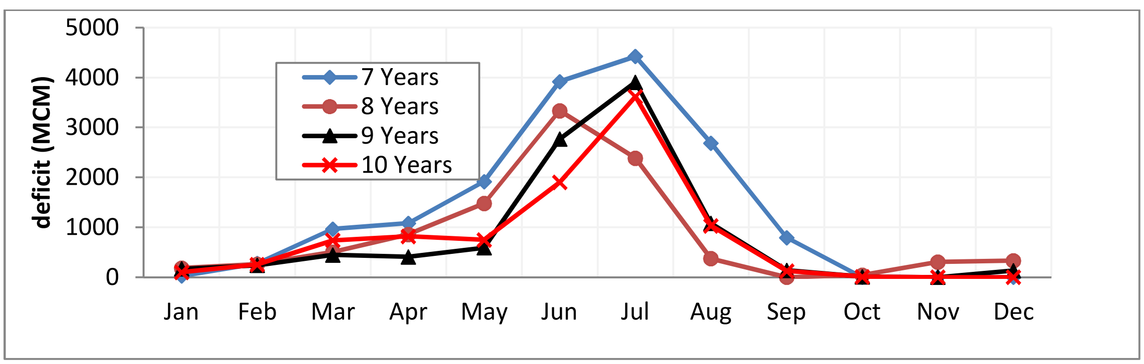

Figure D-6: Monthly deficit at HAD during GERD filling with dry flow

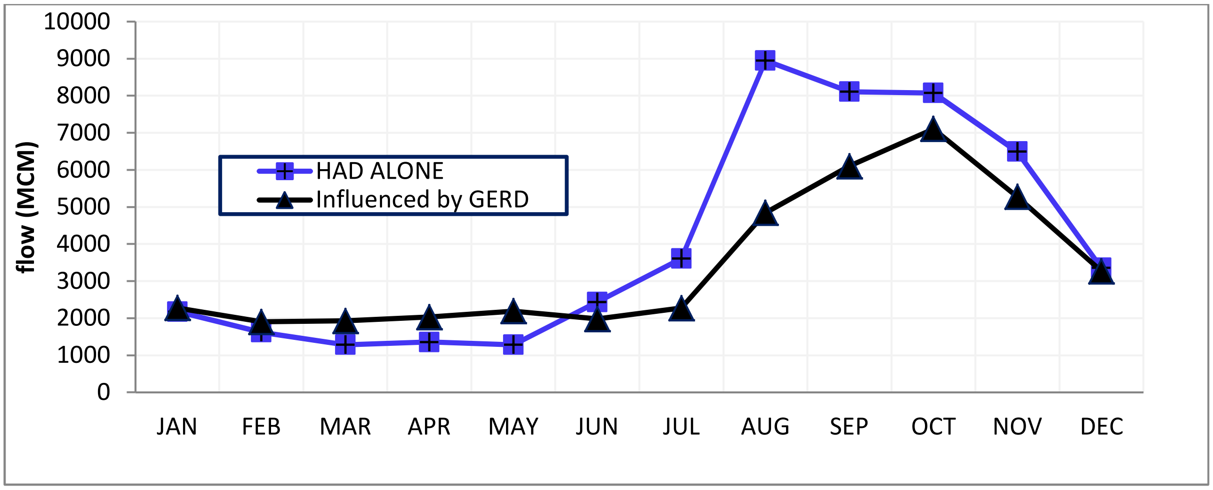

Figure D-7: Mean monthly inflow to HAD during impounding with 7 years dry flow (MCM)

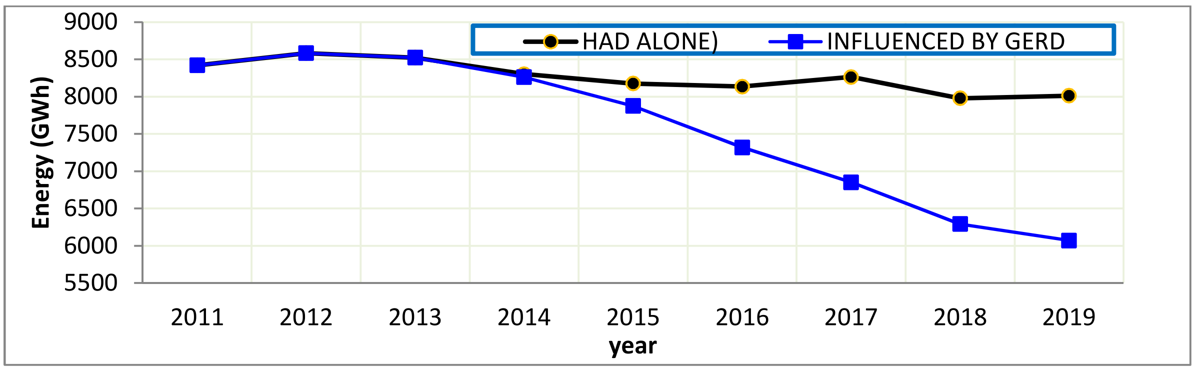

Figure D-8: Annual energy production of HAD during filling with mean flow

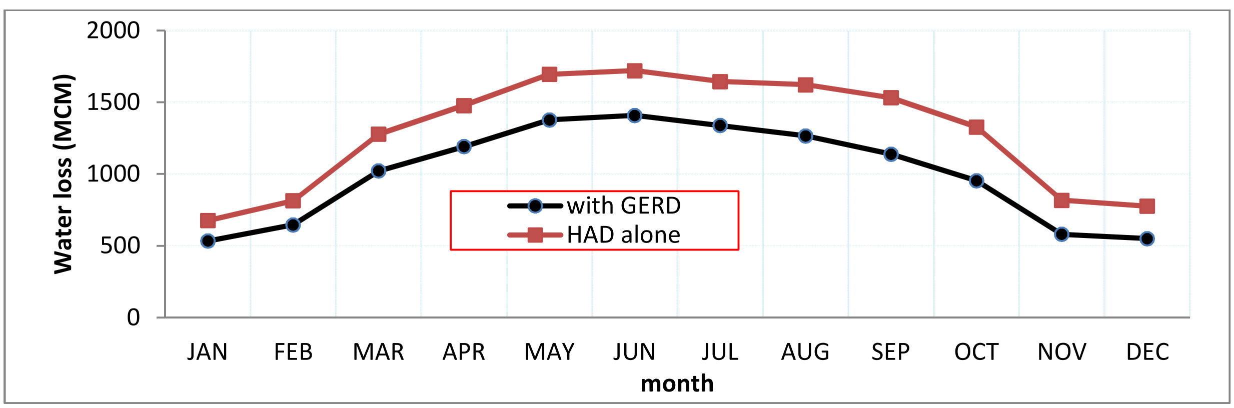

Figure D-9: Mean monthly loss from HAD during impounding with mean sequence (MCM)

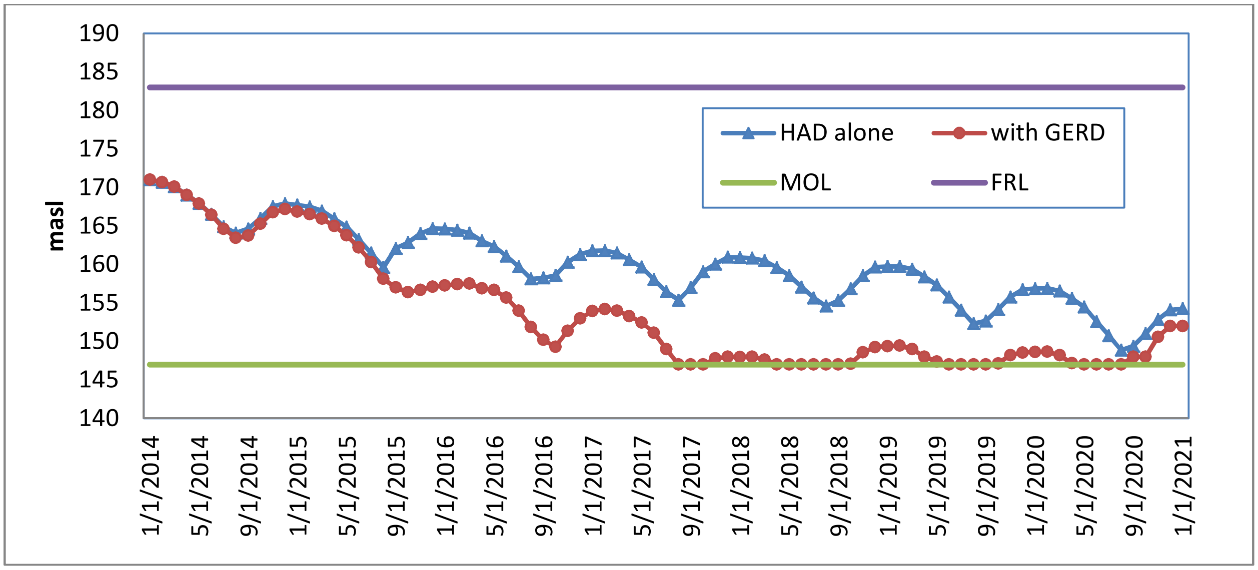

Figure D-10: HAD water level for dry flow and 45BCM irrigation demand

Table D-1: Energy generation of Sudanese reservoirs and cumulative energy in Sudan (GWh)

	ROSERIES			SENNAR			MEREWE			Sudanese Energy		
YEAR	**WITH**	**NO**	**DIF (%)**	**WITH**	**NO**	**DIF (%)**	**WITH**	**NO**	**DIF (%)**	**WITH**	**NO**	**DIF (%)**
2011	2270	2270	0.0	131	131	0.0	6495	6495	0.0	8897	8897	0.0
2012	2304	2304	0.0	131	131	0.0	7672	7672	0.0	10107	10107	0.0
2013	2286	2286	0.0	131	131	0.0	6947	6947	0.0	9364	9364	0.0
2014	2040	2250	-9.3	131	92	42.4	6582	6778	-2.9	8753	9120	-4.0
2015	1577	2177	-27.6	131	117	12.4	6183	6604	-6.4	7891	8898	-11.3
2016	2441	2142	14.0	131	114	15.6	6946	6492	7.0	9519	8748	8.8
2017	3155	2099	50.3	119	131	-9.3	7360	6493	13.4	10635	8724	21.9
2018	2839	2126	33.5	114	131	-13.3	7128	6549	8.8	10080	8806	14.5
2019	2546	2060	23.6	114	131	-13.6	6727	6180	8.8	9387	8372	12.1
MEAN (2014-2019)	**2433**	**2142**	**13.6**	**123**	**119**	**3.3**	**6821**	**6516**	**4.7**	**9377**	**8778**	**6.8**

Table D-2: Irrigation water demand deficit of Sudanese projects during GERD impounding with mean flow

	Number of month		water deficit (MCM)		NS coefficient	
Irrigation site	with	with out	with	with out	With	with out
D/ Sennar	2	0	0.53	0	1	1
Gizira	5	2	16	1.15	0.99	1

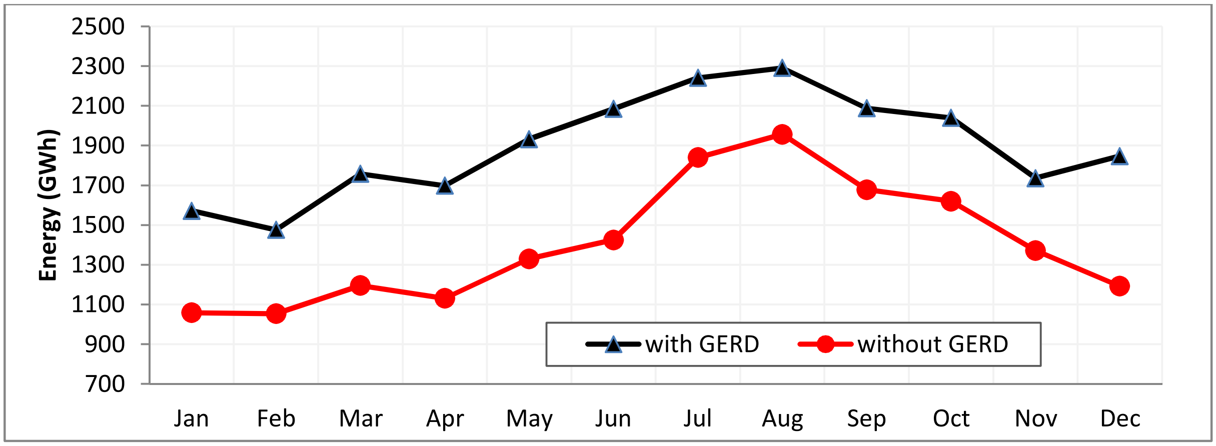

Figure D-11: Mean monthly cumulative Eastern Nile energy during impounding (GWH)

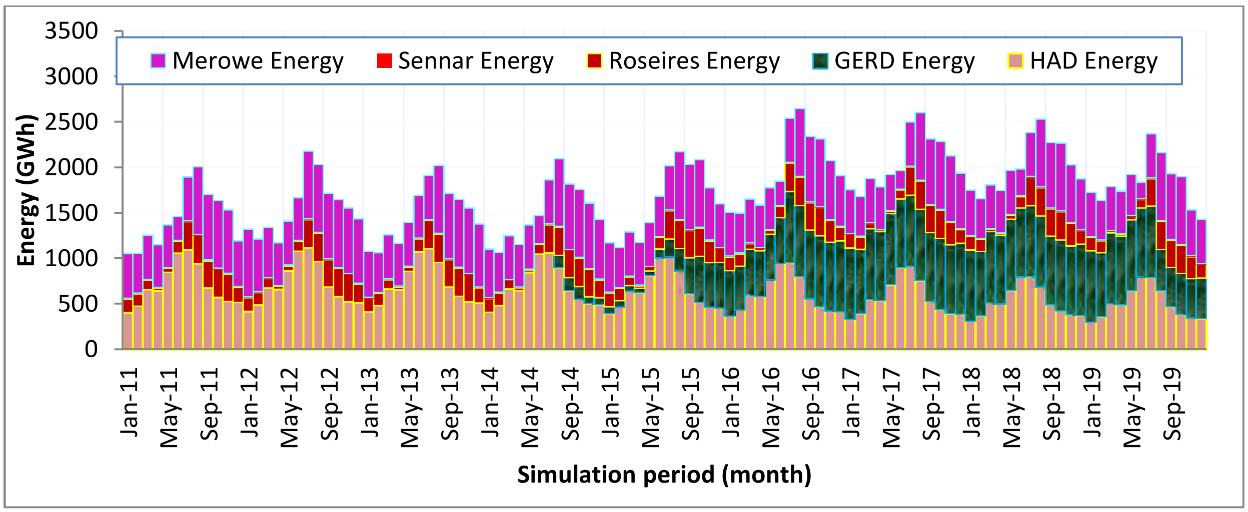

Figure D-12: Monthly energy generation in the Eastern Nile during GERD filling (GWH)

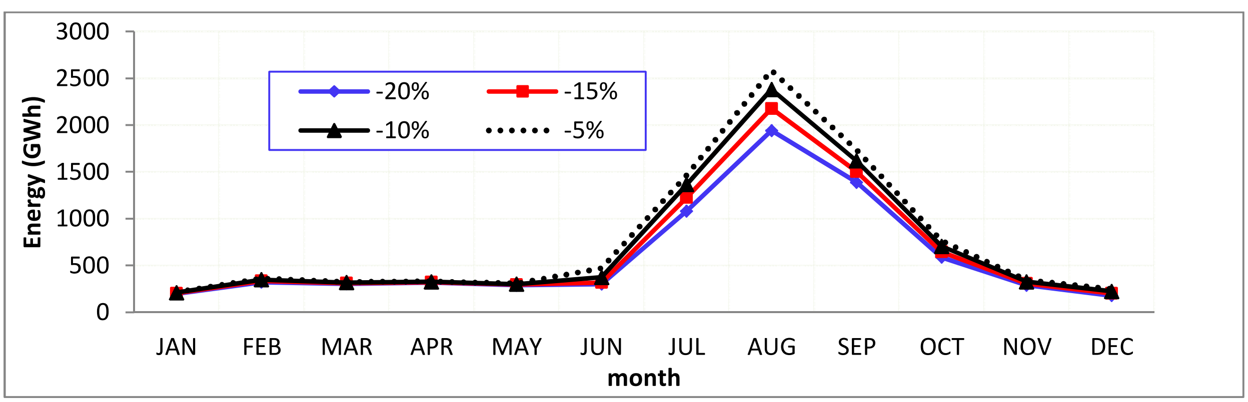

Figure D-13: GERD Energy during fillings with hypothetical dry flows

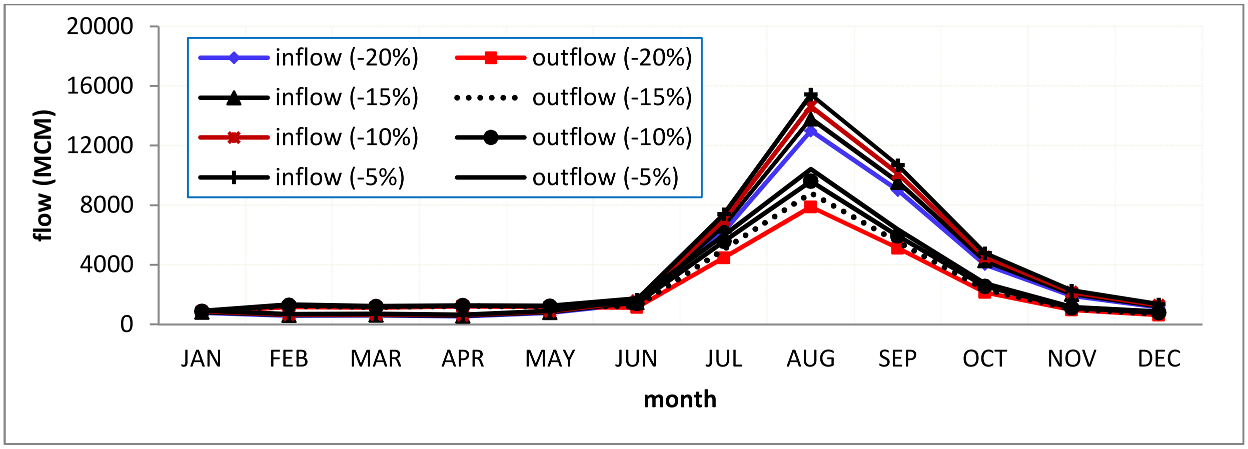

Figure D-14: Inflow and outflow from GERD during impounding with hypothetical dry flows

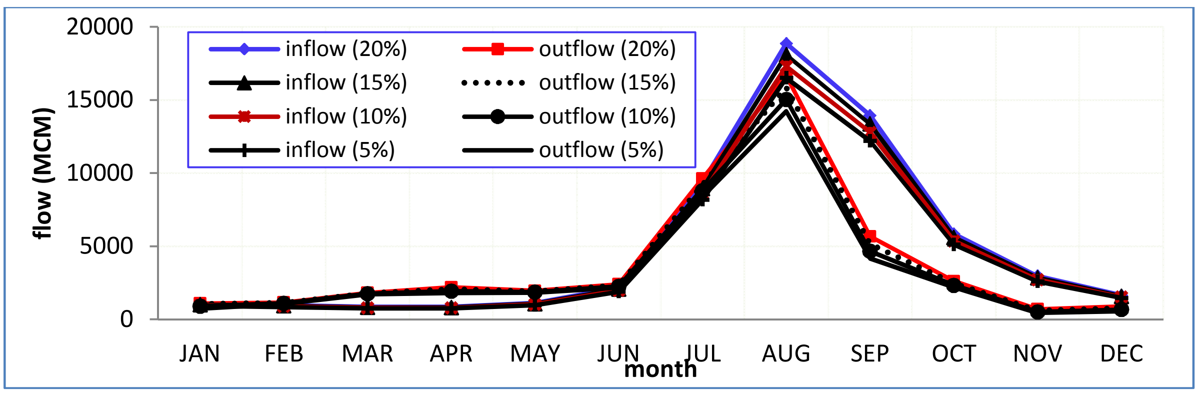

Figure D-15: Mean monthly inflow and outflow from GERD during filling with hypothetical wet flows

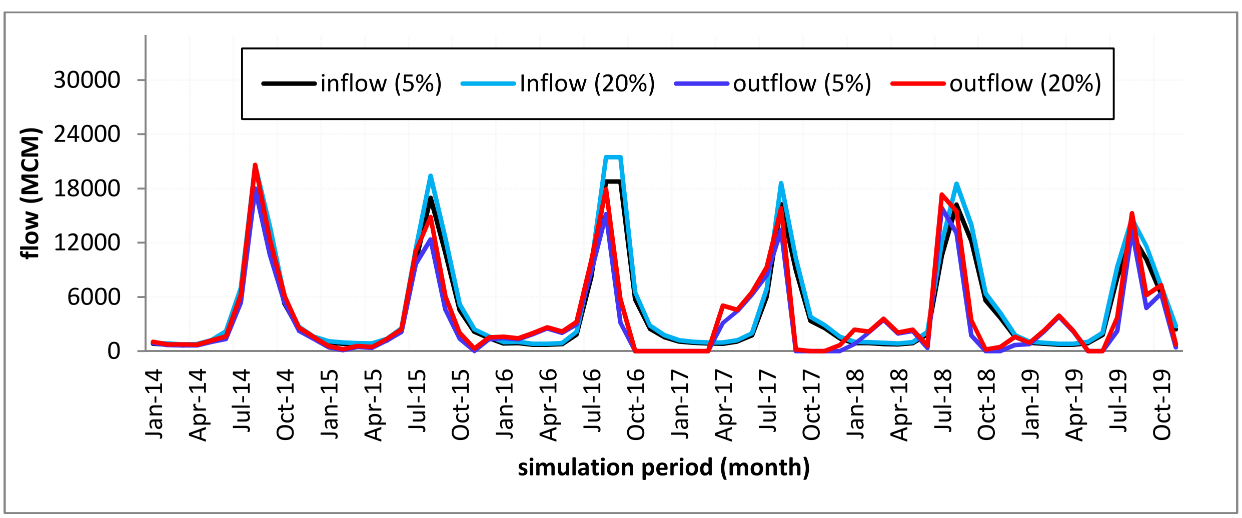

Figure D-16: Monthly inflow and outflow at GERD during filling with 5 and 20% flow incremental

Appendix E: Additional Figure on GERD Operation Simulations

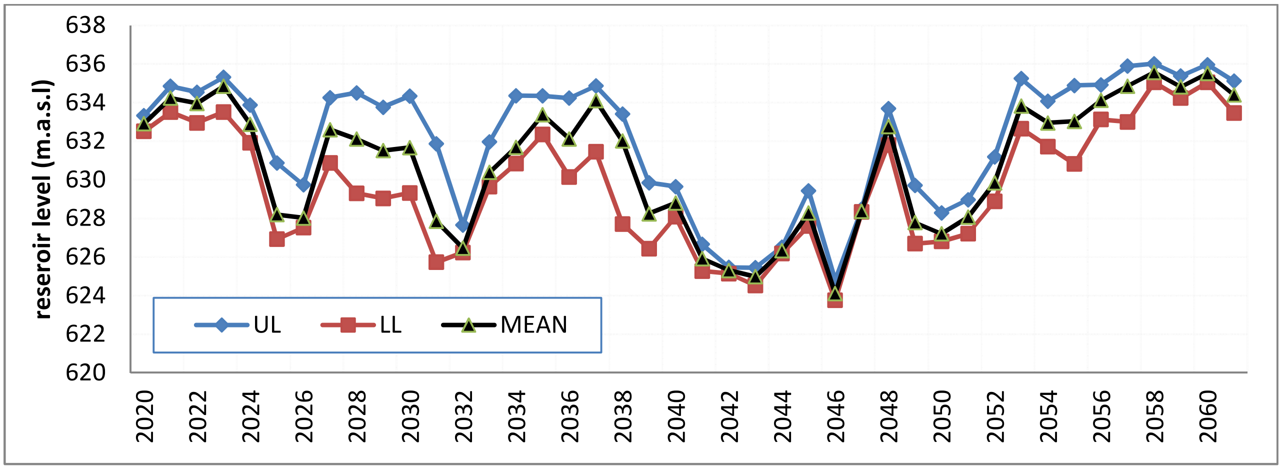

Figure E-1: GERD water level during operation phase

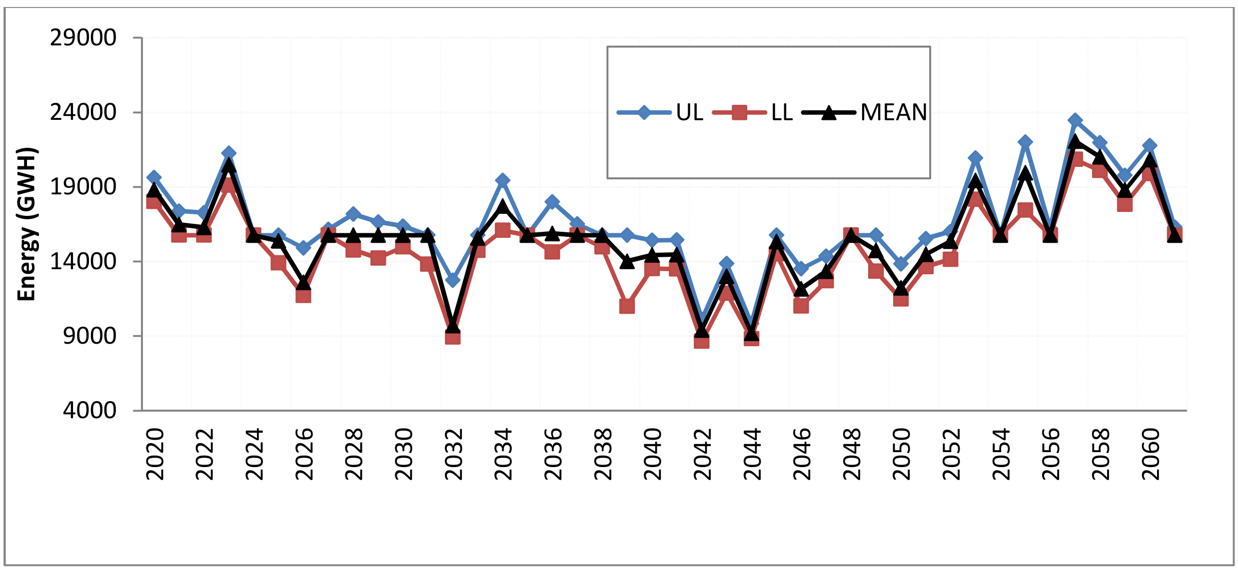

Figure E-2: GERD energy during operation phase

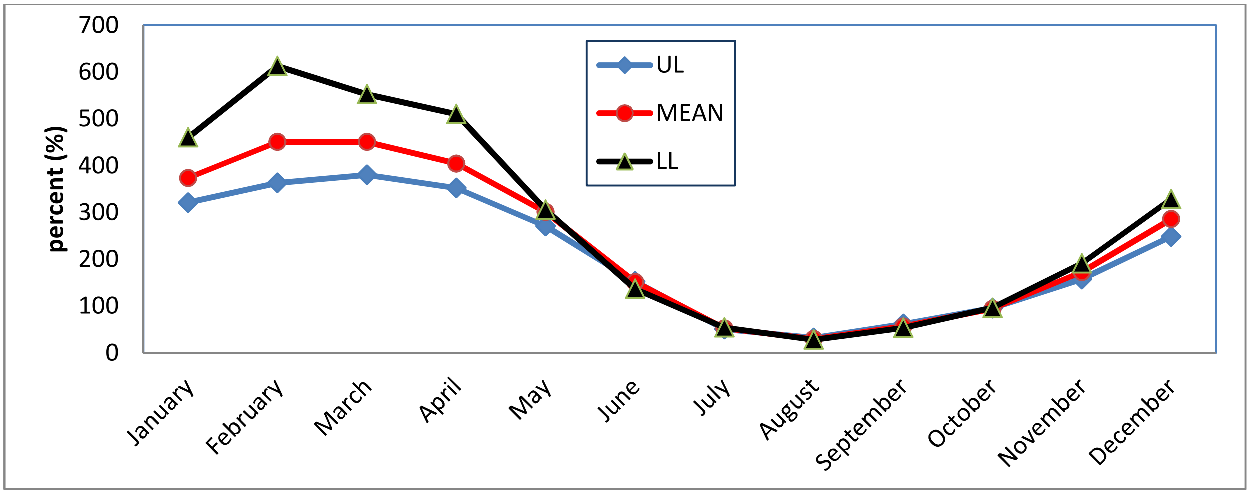

Figure E-3: Monthly percentage of water released from GERD

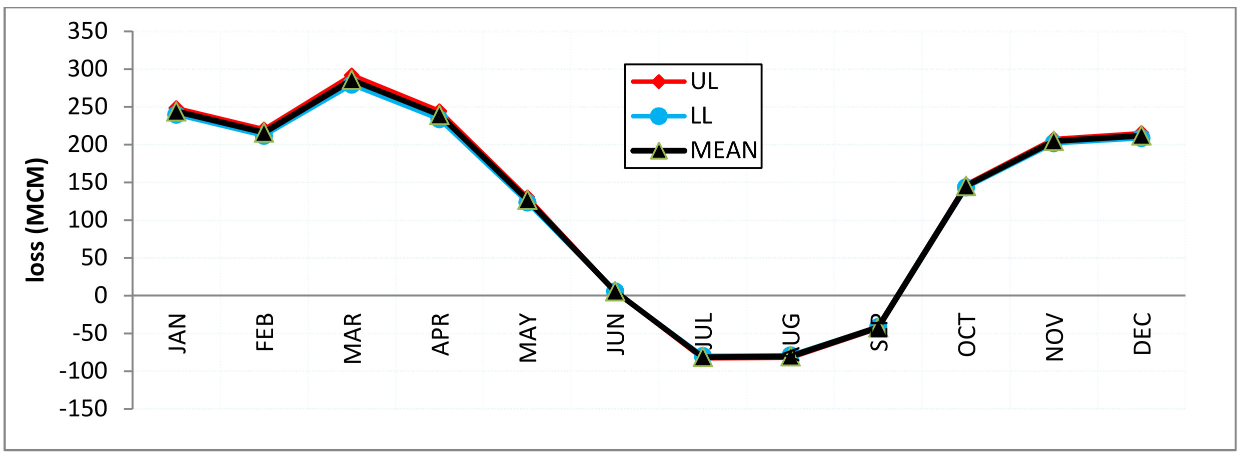

Figure E-4: Mean monthly loss at GERD during operation (MCM)

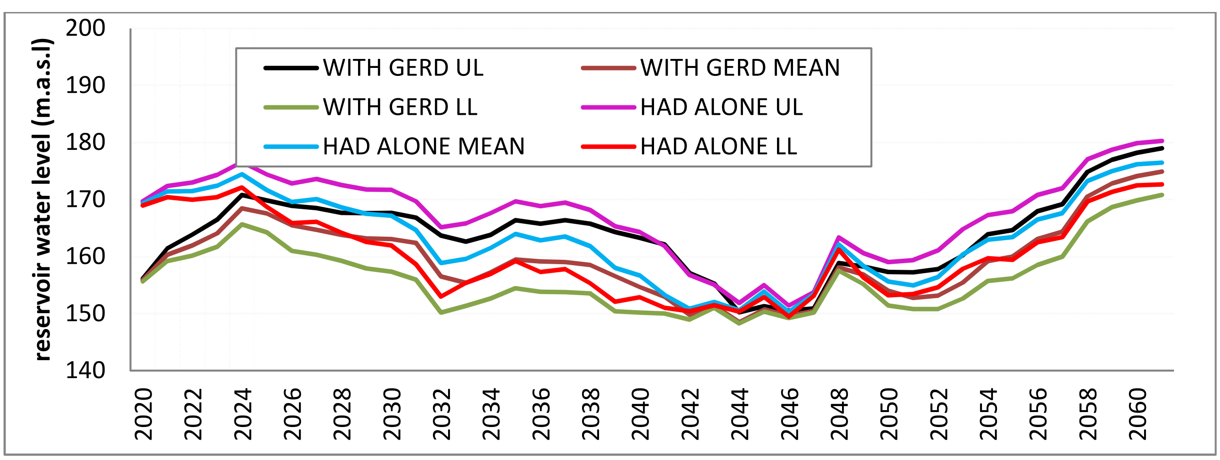

Figure E-5: Annual HAD reservoir water level during GERD operation

Appendix F: additional figure on Upper cascades simulations for historical flows

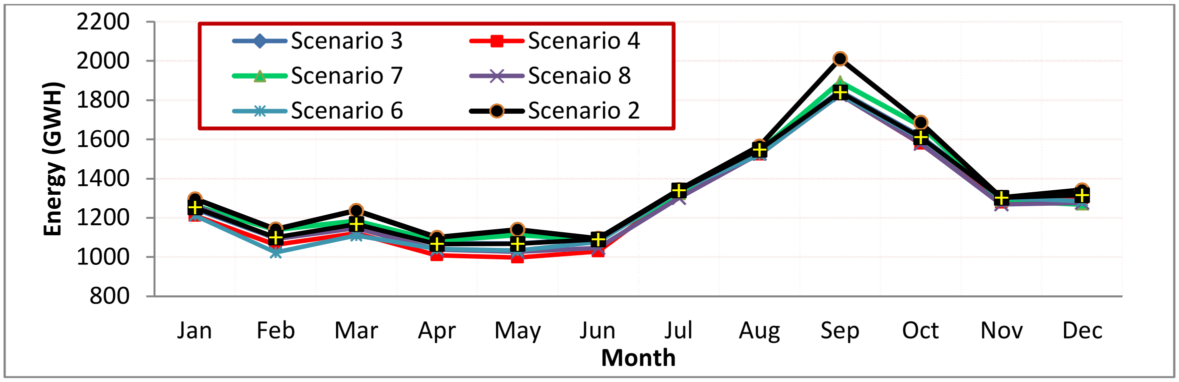

Figure F-1: Mean monthly Energy production of GERD during filling and operation phases of all Reservoirs

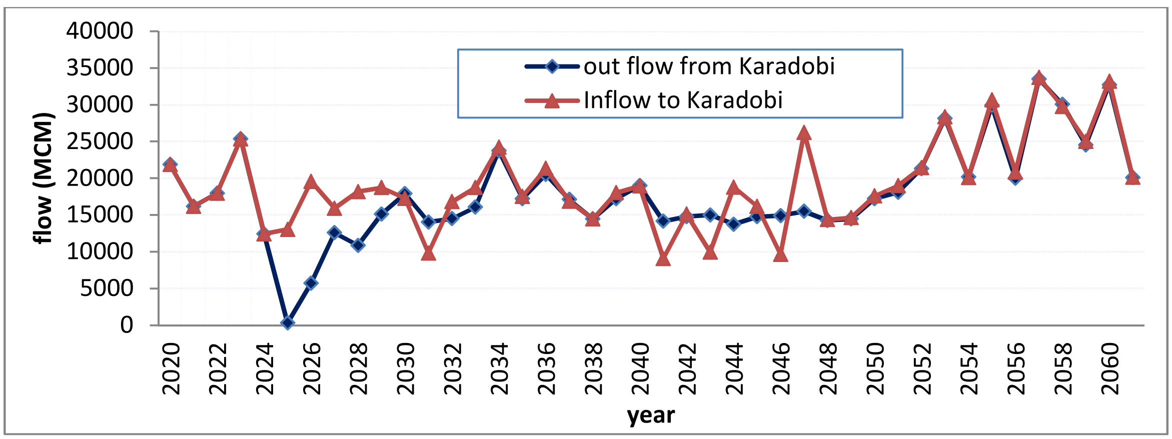

Figure F-2: Inflow and out flow at Karadobi during filling and operation

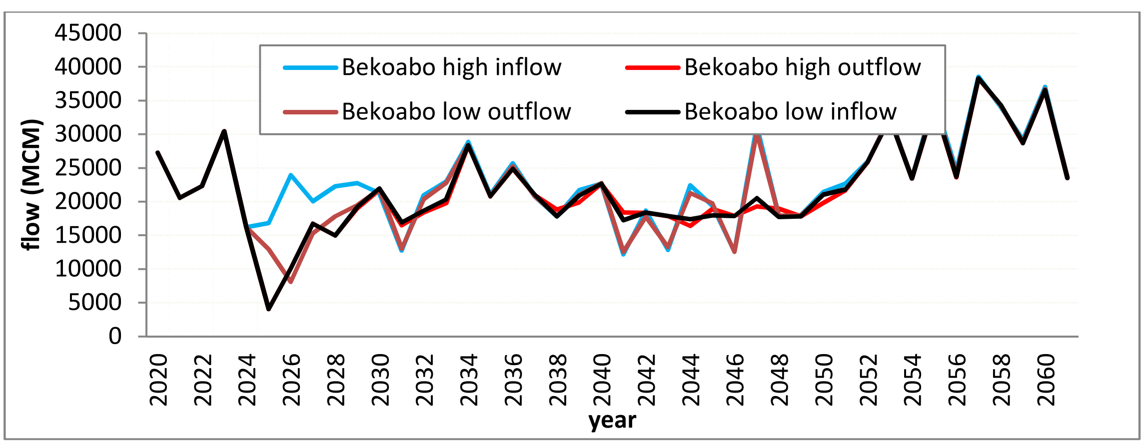

Figure F-3: Inflow and out flow at Bekoabo during filling and operation

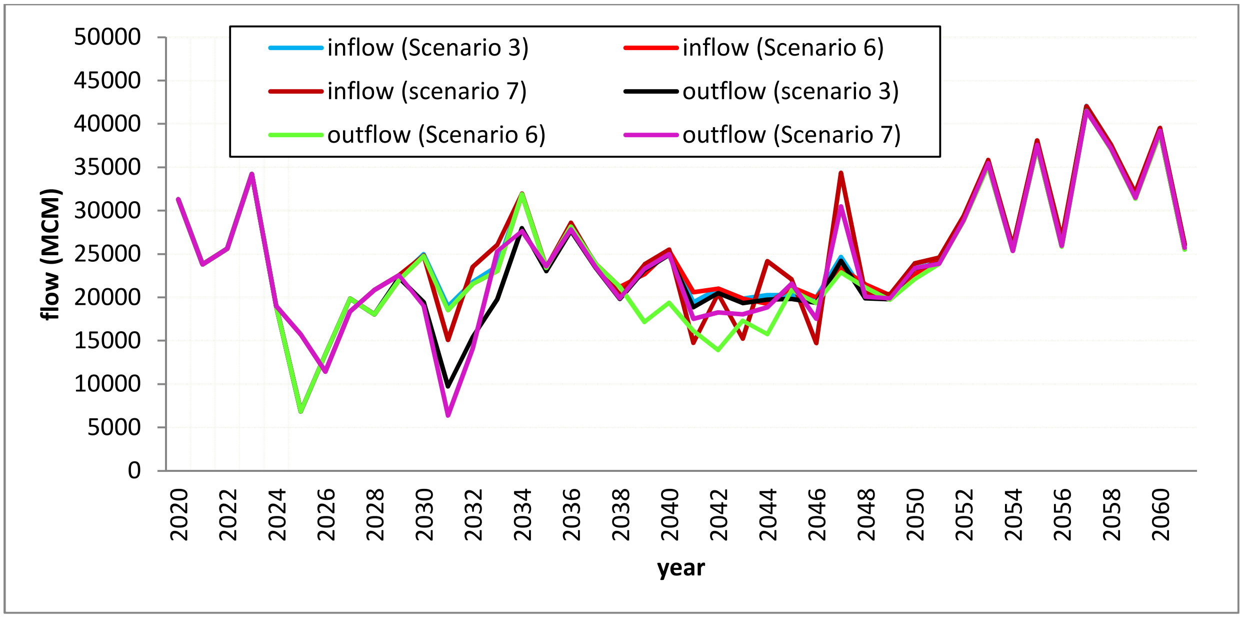

Figure F-4: Annual inflow and outflow of Mendya during filling and operation phases

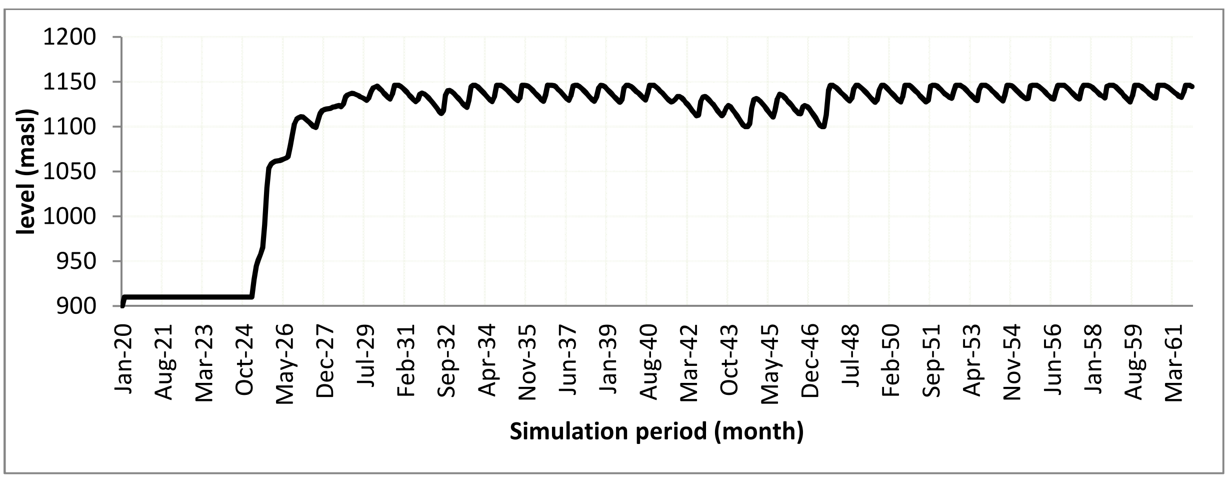

Figure F-5: Karadobi reservoir water level during filling and operation

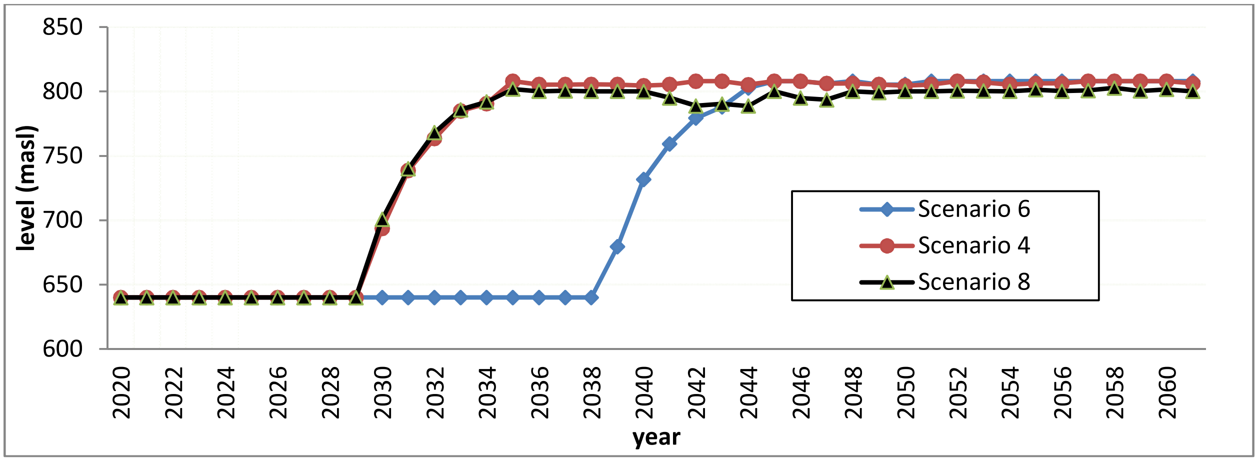

Figure F-6: Mendya reservoir water level during filling and operation

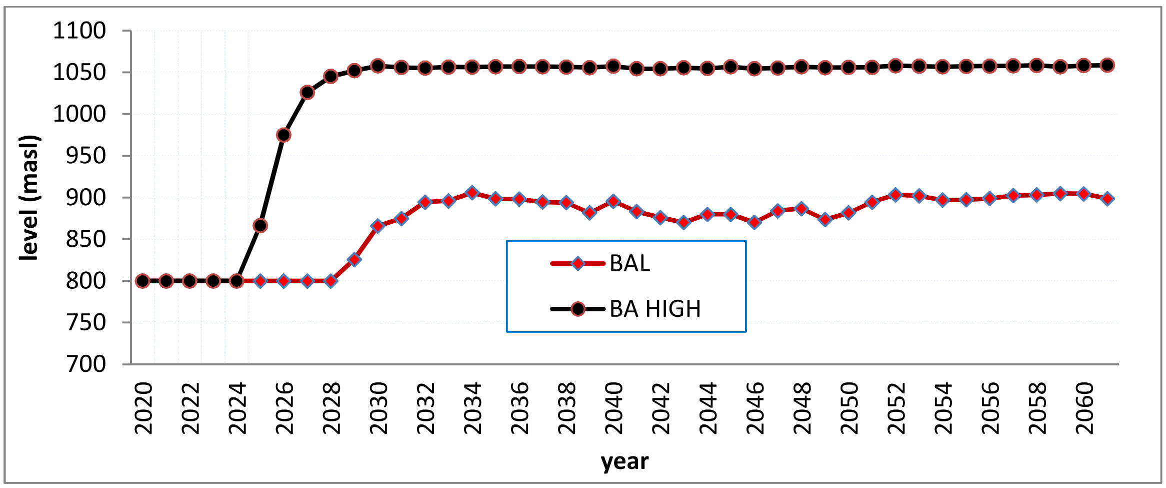

Figure F-7: Bekoabo reservoir water level during filling and operation

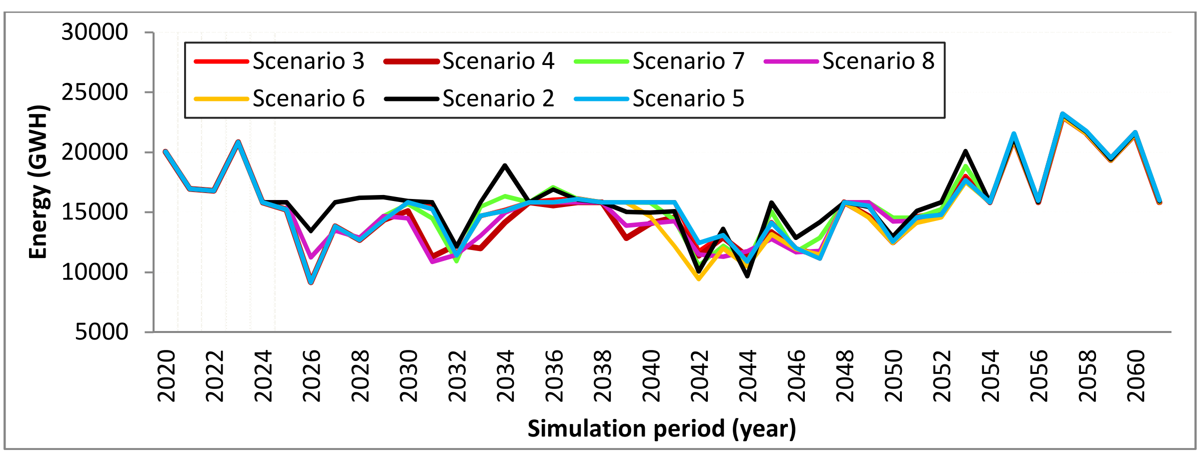

Figure F-8: GERD energy production during fillings and operation of upper cascades

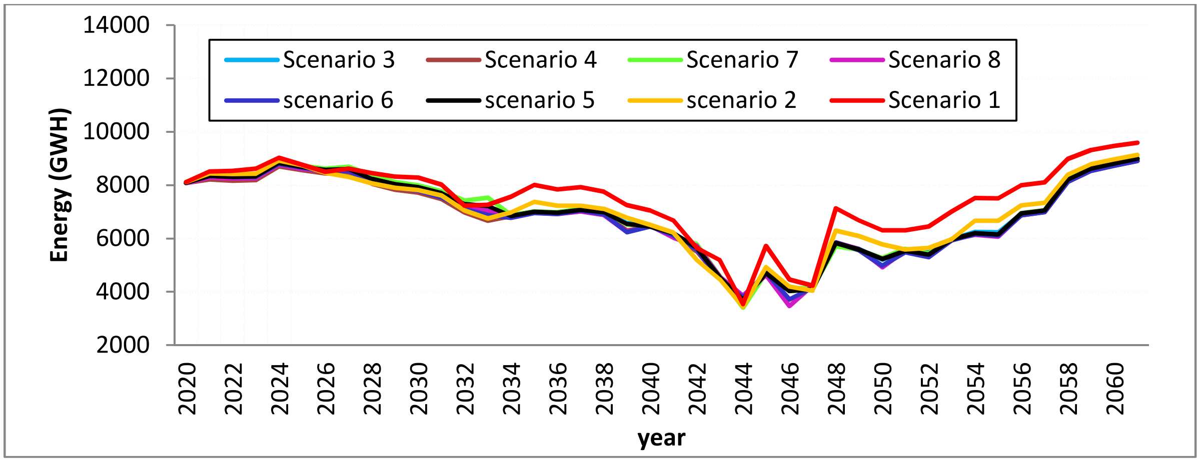

Figure F-9: HAD energy production during full operation phases of upper reservoirs in Blue Nile.

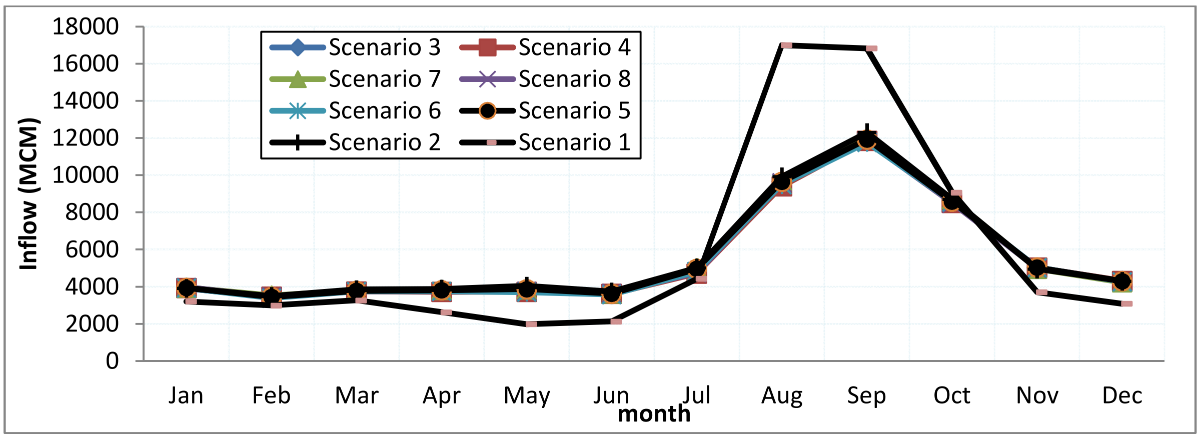

Figure F-10: Mean monthly inflow to HAD during operation phases of all reservoirs (CMC)

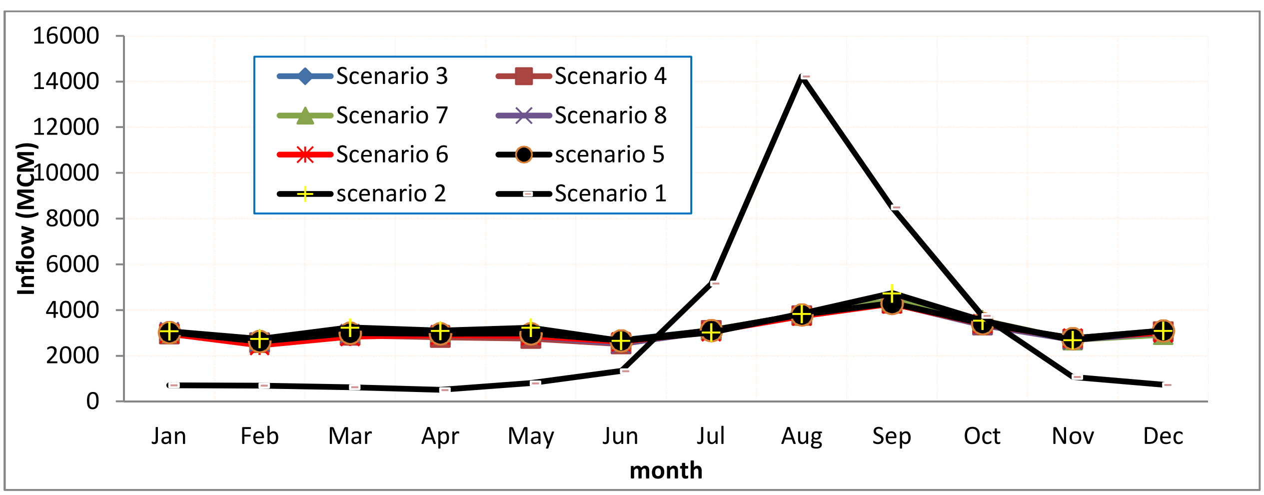

Figure F-11: Mean monthly inflow to Sennar during operation phases of all reservoirs (MCM)

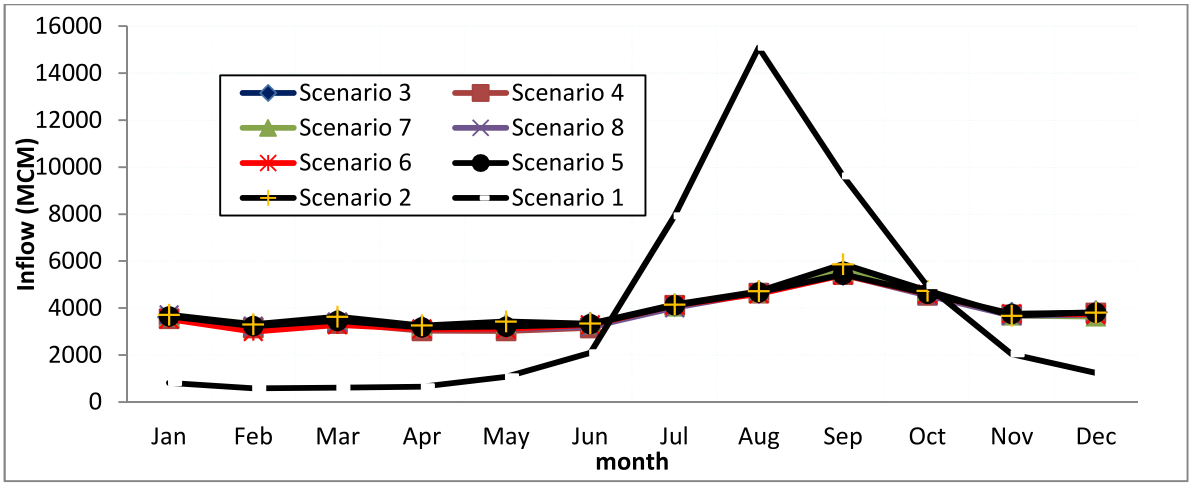

Figure F-12: Mean monthly inflow to Rosaries during operation phases of all reservoirs (MCM)

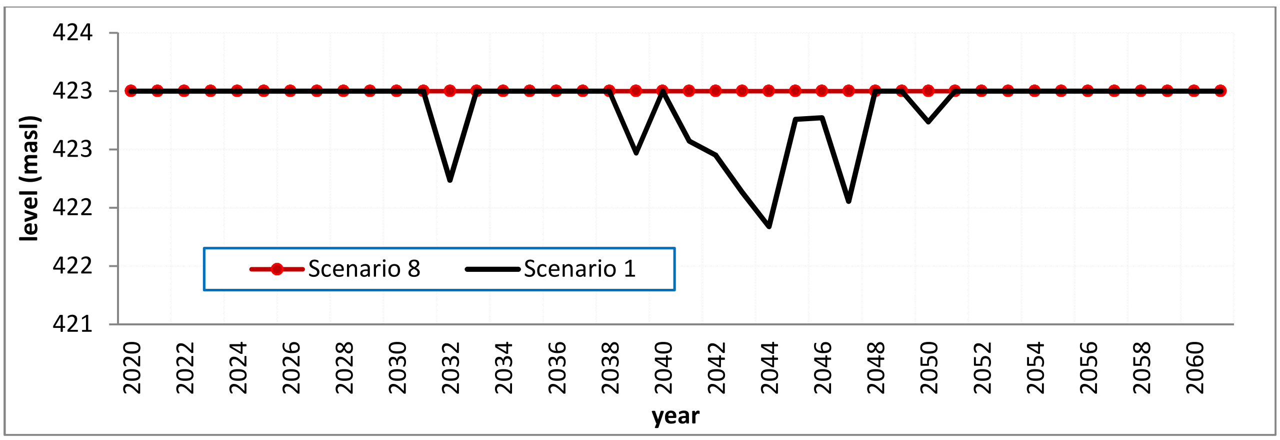

Figure F-13: Annual reservoir water level of Sennar during filling and operation of upper cascades

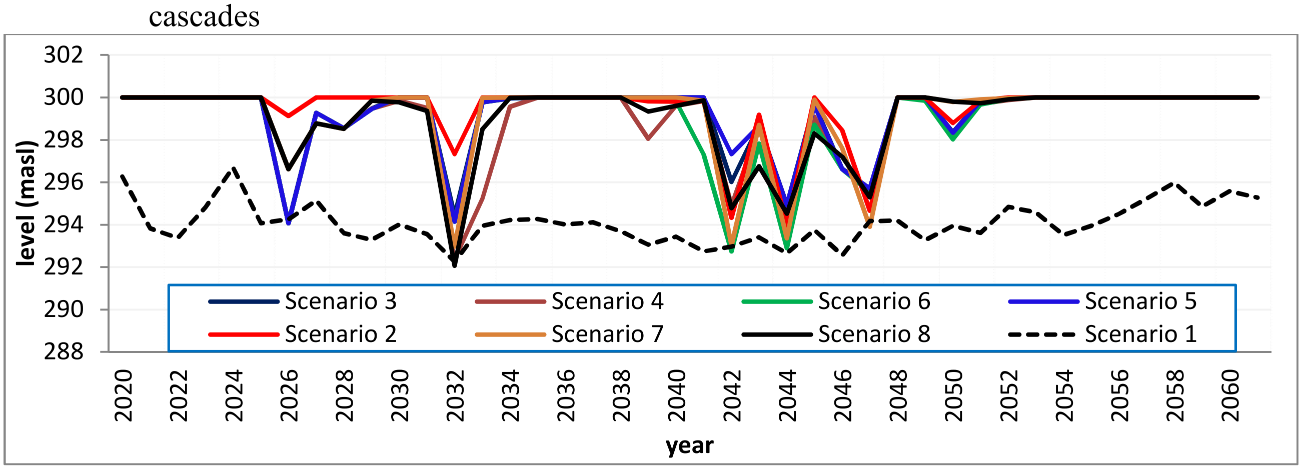

Figure F-14: Annual reservoir water level of Merowe during filling and operation of upper cascades (m.a.s.l)

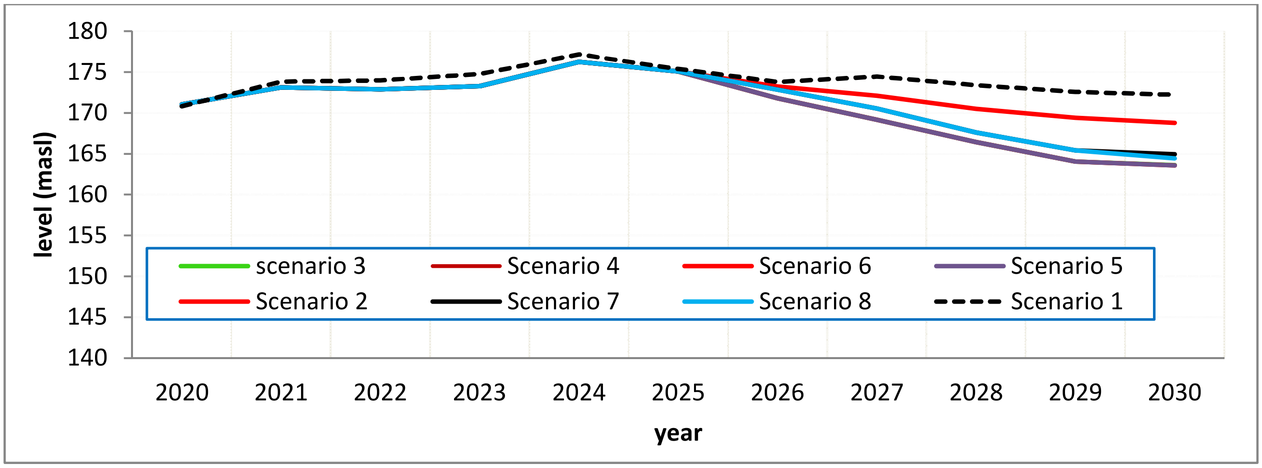

Figure F-15: Mean annual HAD reservoir level during filling and operation of upper cascades (m.a.s.l)

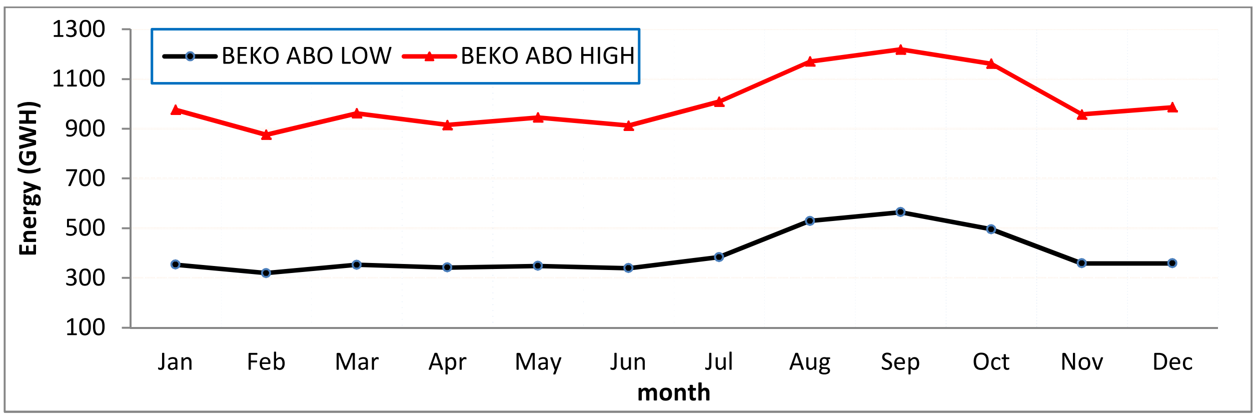

Figure F-16: Mean monthly energy at Bekoabo (Bekoabo low and Bekoabo high) during operation phase (GWH)

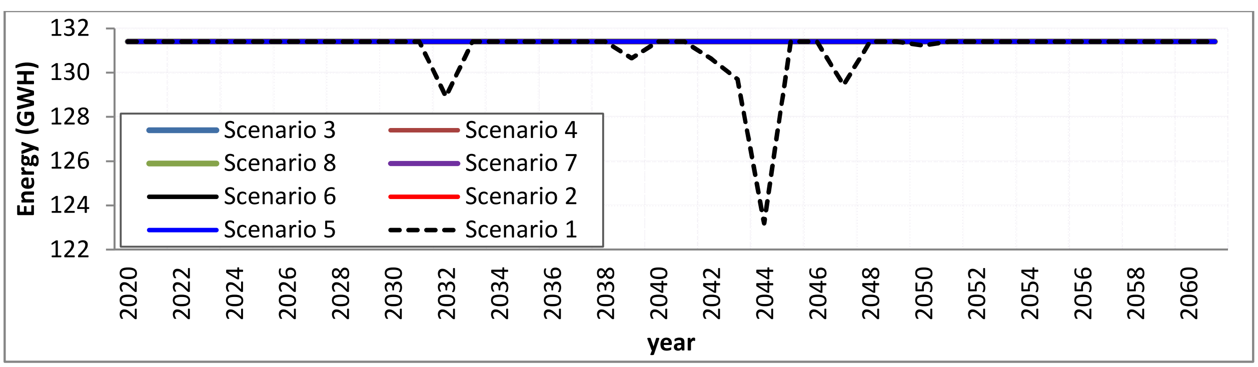

Figure F-17: Annual energy generation at Sennar during full operation of all reservoirs (GWH)

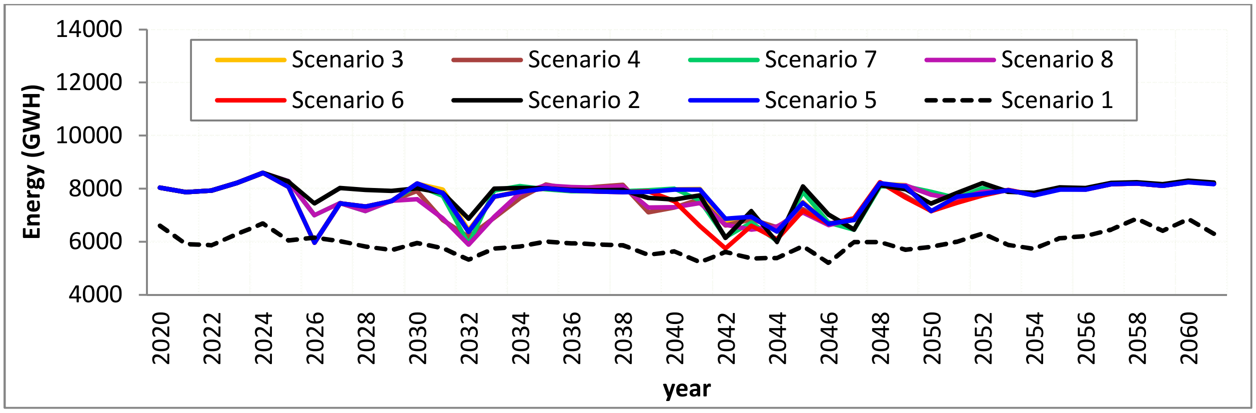

Figure F-18: Annual energy generation at Merowe during full operation of all reservoirs (GWH)

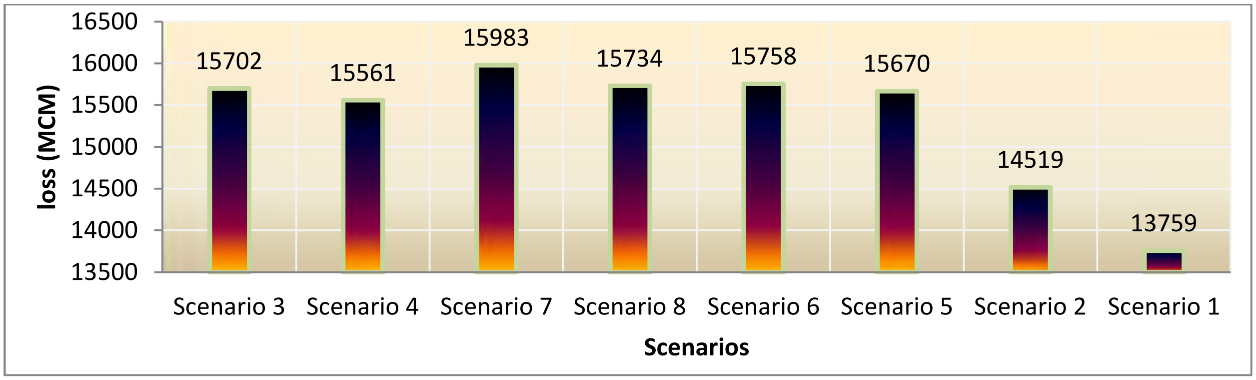

Figure F-19: Mean annual loss from eastern Nile full operations of Abbay reservoirs (MCM)

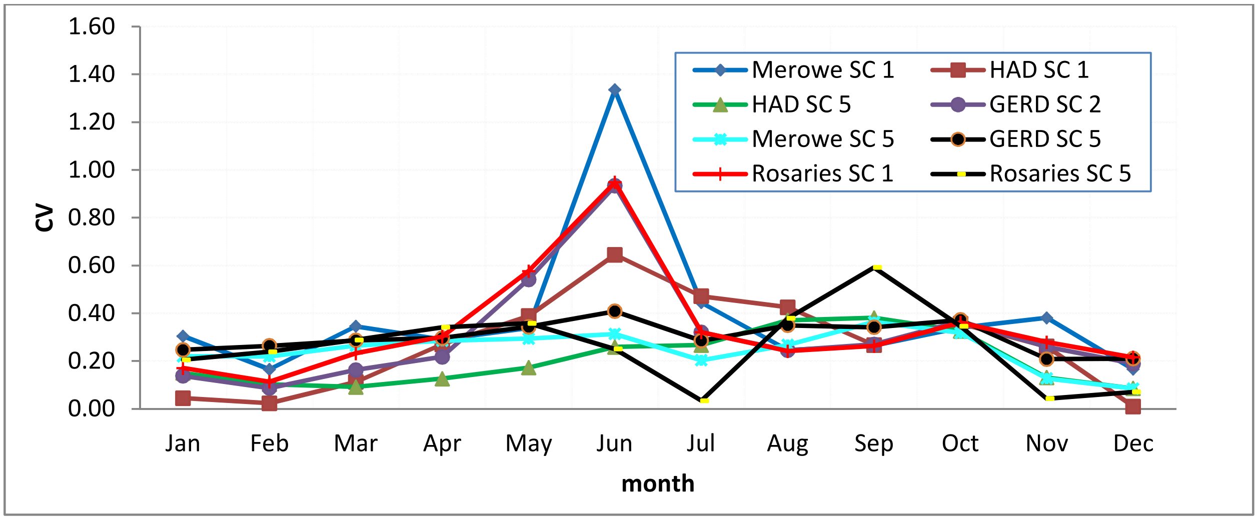

Figure F-20: Mean month reservoirs inflow Coefficient of variation

Appendix G: Addition results for future irrigation and stochastic flow simulations

- Before GERD: before the implementation of GERD
- After GERD: after the implementation of GERD
- No irr: when there is no any irrigation schemes in the eastern Nile
- Current: currently existing irrigation
- Ethio. IRR: Ethiopian irrigation development
- FDL: full level irrigation development in the Eastern Nile
- FDL HP: full level hydropower development

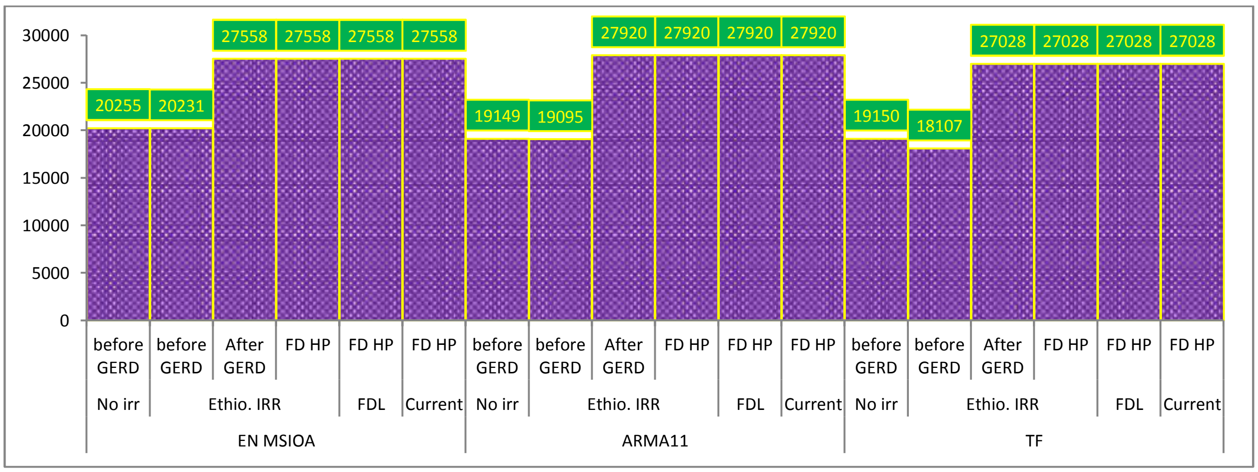

Figure G-1: Energy production in Eastern Nile before 2025

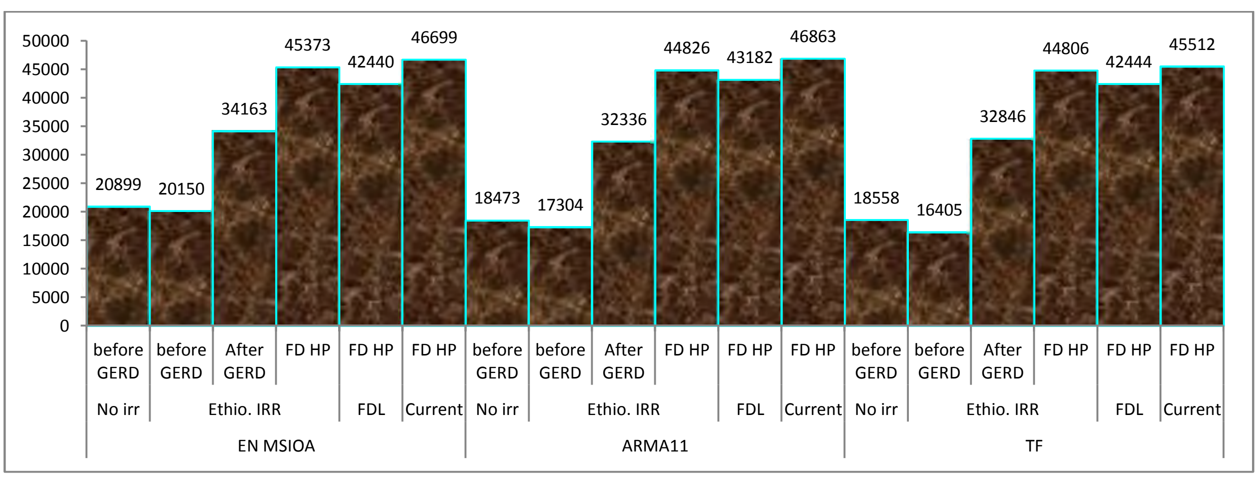

Figure G-2: Energy production in Eastern Nile between 2025 and 2050 (mid-term development stage)

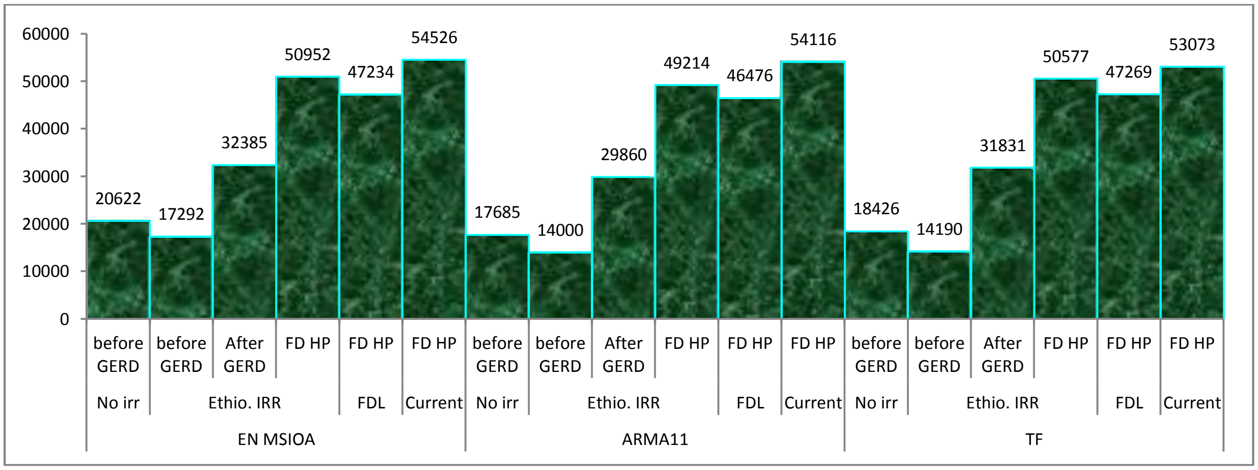

Figure G-3: Energy production in Eastern Nile after 2050 (long term development level)

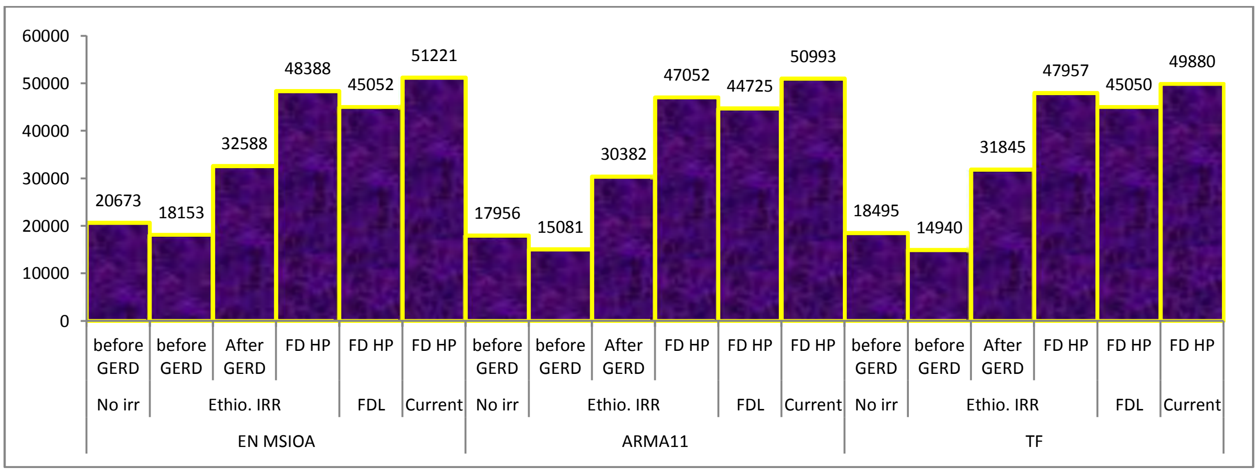

Figure G-4: Energy production in Eastern Nile between 2020 and 2119 (full simulation period)

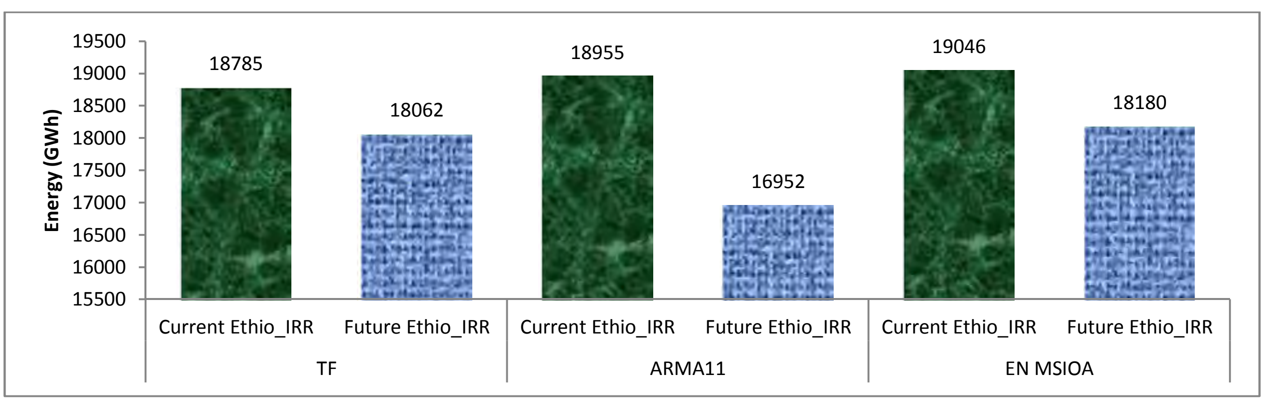

Figure G-5: The impacts of Future Ethiopian irrigation development on GERD and Tana Beles energy production

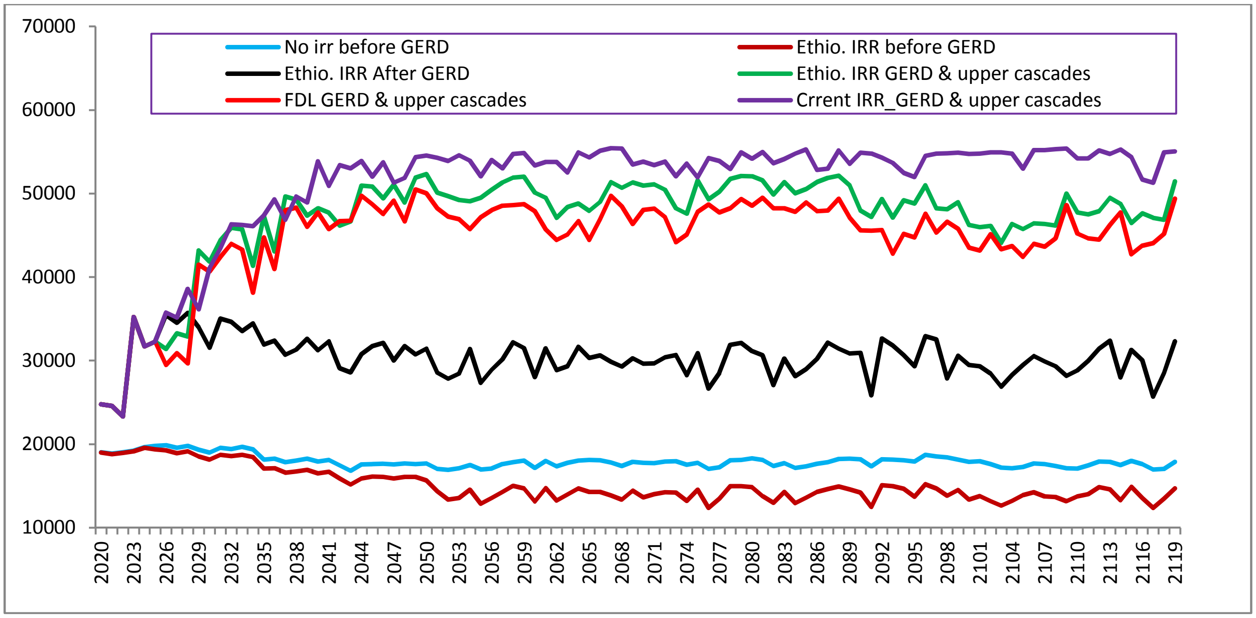

Figure G-6: Cumulative Eastern Nile energy (GWh) for different dams and irrigation development scenarios for ARMA11 flow

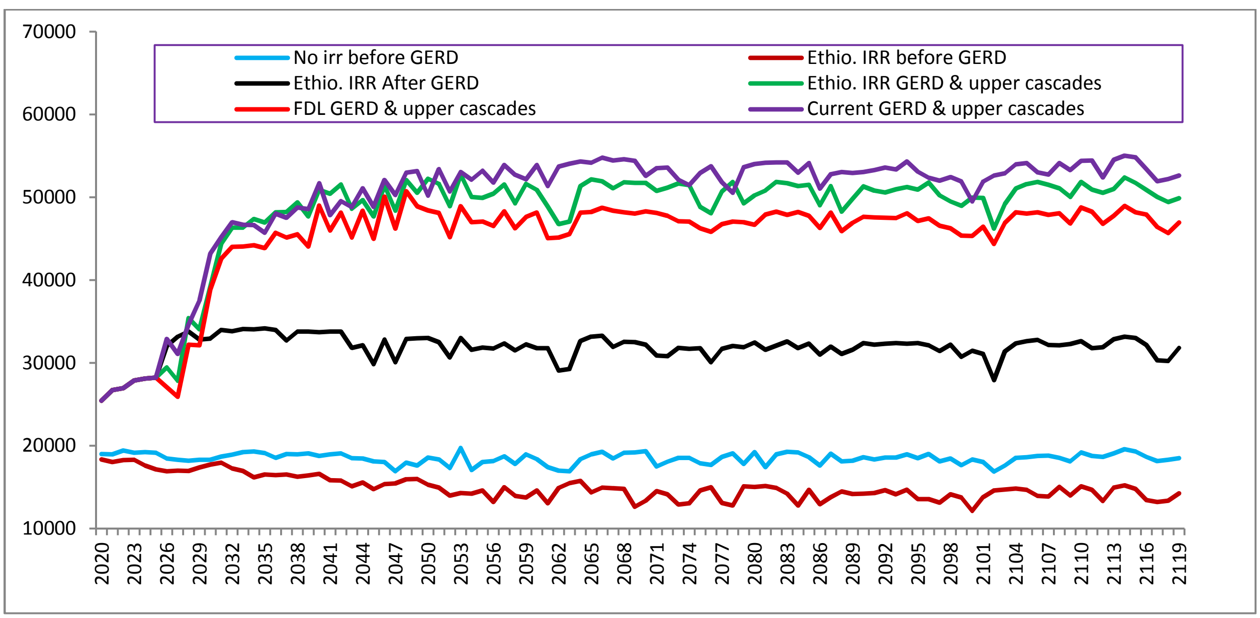

Figure G-7: Cumulative Eastern Nile energy (GWh) for different dams and irrigation development scenarios for TF flow

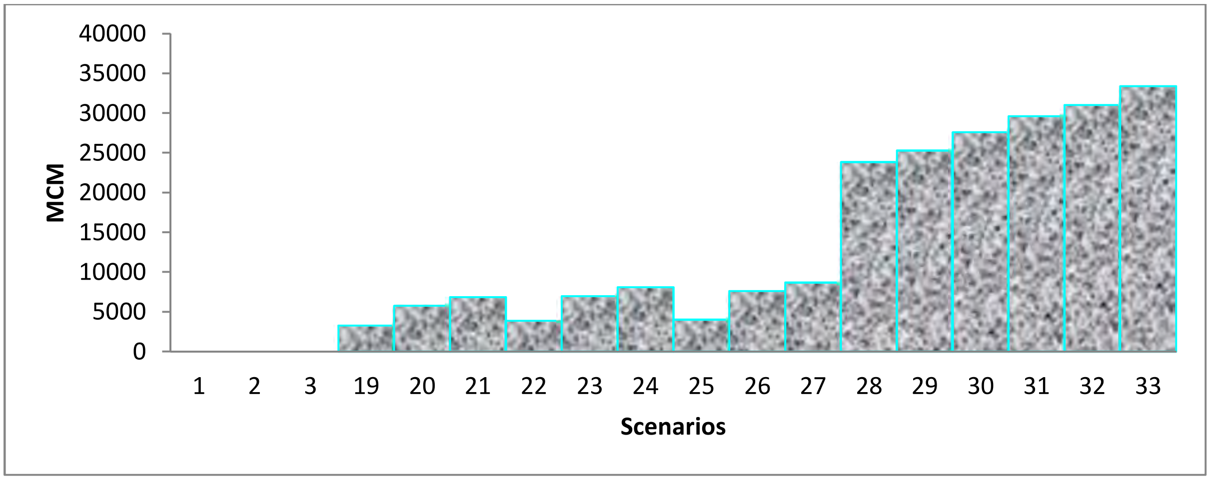

Figure G-8: Eastern Nile irrigation water demand deficit for different development scenario

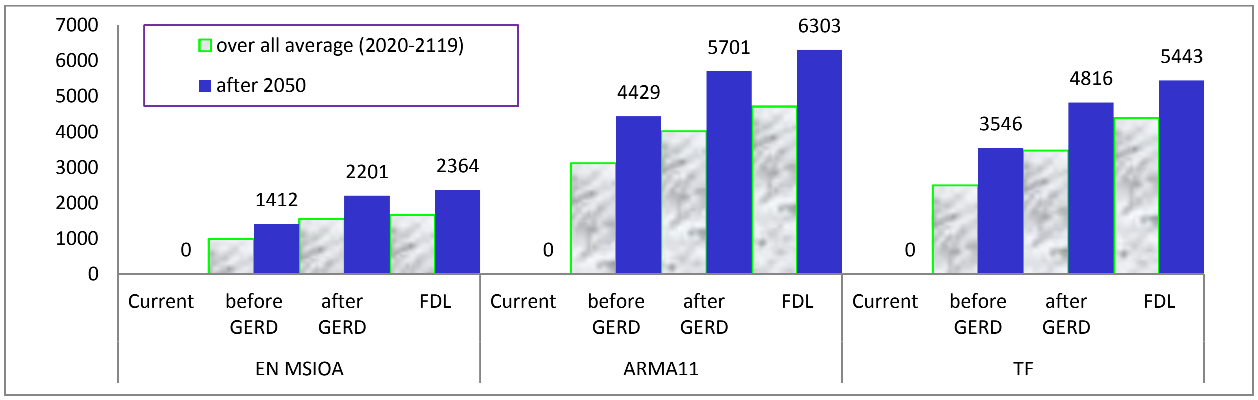

Figure G-9: Mean annual Egypt irrigation water demand deficit due to future Ethiopian hydropower and irrigation development (MCM)

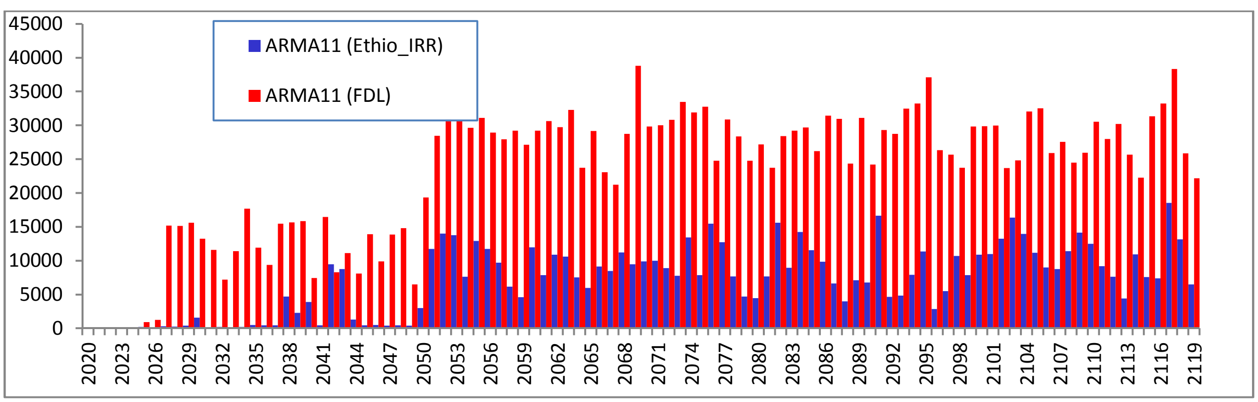

Figure G-10: Annual Eastern Nile irrigation water demand deficit due to future Ethiopian and Sudan hydropower and irrigation development for ARMA11 flow

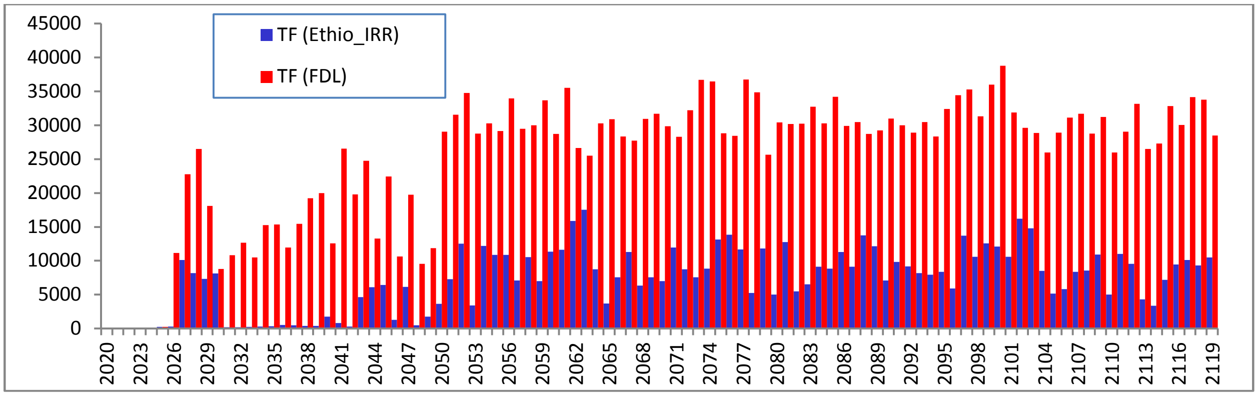

Figure G-11: Annual Eastern Nile irrigation water demand deficit due to future Ethiopian and Sudan hydropower and irrigation development for TF flow

Table G-1: Comparisons of scenarios in energy production income (million UD$)

Country		Current	FDL of hydropower		FDL of Irrigation		
	*price per US$/ KWH	Total (Million US$)	Total (Million US$)	Difference (US$)	Total (Million US$)	difference	
						from current	from potential HPP
Sudan	0.03103	202	223	20	205	3	-17
Egypt	0.0303	273	252	-21	101	-172	-151
Ethiopia	0.0261	91	997	905	967	875	-30
EN		567	1471	904	1273	706	-198

* Source, Zelalem (2014)

Publication

Journal

- Asegdew G M, Semu A M. 2014. Filling Option Assessments for Proposed Reservoirs in Abbay (Upper Blue Nile) River Basin to Minimize Impacts on Energy Generation of Downstream Reservoir. Open Journal of Renewable Energy and Sustainable Development Volume 1, Number 1.
- Asegdew G M, Semu A M. 2014Assessment of the Impact of the Grand Ethiopian Renaissance Dam on the Performance of the High Aswan Dam. Journal of Water Resource and Protection (JWARP).

Book chapter

Asegdew G M, Semu A M, Yosif I. 2014. Impact and Benefit Study of Grand Ethiopian Renaissance Dam (GERD) During Impounding and Operation Phases on Downstream Structures in the Eastern Nile. Springer International Publishing.