Reservoir Filling Options Assessment for the Great Ethiopian Renaissance Dam using a probabilistic approach

Zelalem Tesfaye,

Water Resource Engineer, ENTRO,

Azeb Mersha,

Water Resource Engineer, ENTRO,

Kevin Wheeler

Water Resource Consultant, USA,

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Contents

ABBREVIATIONS AND ACRONYMS

EN- Eastern Nile

ENTRO - Eastern Nile Technical Regional Office

ENPM – Eastern Nile Planning Model

NBI – Nile Basin Initiative

MCM – Million Cubic Meters

MW -Mega Watts

masl – meters above sea level.

FSL – Full Supply Level

MOL – Minimum Operation Level

WB- World Bank

GDP - Gross Domestic Product

UN – United Nations

GERD - Grand Ethiopian Renaissance Dam

HAD - High Aswan Dam

1 INTRODUCTION AND BACKGROUND

The Nile, 6,695 kilometers in total length is the longest river in the world. Its basin covers an area of 3.18 million square kilometers and some 10 percent of the African continent. This coverage of area is also reflected in the number of the riparian countries, and it's now shared by 11 countries.[1]It makes this long journey from its sources in the Equatorial Lakes Region and the Ethiopian highlands to its outlet into the Mediterranean Sea.

The Nile has connected people, cultures, and civilizations in this region of Africa for millennia. Though it is one of the longest rivers in the world it is comparatively small in terms of flow because of the extremely high evaporation rates and the limited rainfall over vast expanses of the basin. White Nile flows only contribute up to 15 per cent of the annual Nile discharge, but are fairly stable throughout the year. The Eastern Nile region supplies up to 90 percent of annual Nile flows, but its contribution is highly seasonal.[1]

The Eastern Nile (EN), Basin constitutes over 60% of the area of the Nile River Basin but contributes about 90% of the average annual flow of the main Nile River, about 84 BM^3 at the Aswan High Dam in southern Egypt. The EN supports an extraordinary range of ecosystems from high mountain moorlands, afromontane forests, savanna woodlands, extensive wetlands and arid deserts. [2]

The Eastern Nile riparian countries include Egypt, Ethiopia, South Sudan and Sudan. The four riparian countries that share the EN Basin include:

Egypt, the most downstream country in the Nile basin, with more than 96% of its freshwater inflow originating from outside its national boundaries, is the most economically developed country in the region with a population of 83.6 million (UN, 2013) and a GDP per capita of 3187 US$ (WB, 2012). The Nile waters, which flow into Lake Nasser created by the High Aswan Dam (HAD) generate 2.1 GW of hydropower and is extensively used for irrigated agriculture.

Ethiopia, the most upstream country in the Eastern Nile Basin with a population of 86.6 million (UN, 2013) and a GDP per capita of 470 US$ (WB, 2012). The highlands of Ethiopia are the source of over 80% of the main Nile flow. Ethiopia is currently experiencing one of the world’s highest rates of economic growth and is seeking to develop its water resources for both hydropower and irrigation to sustain this high economic growth.

South Sudan, which became independent from the Sudan in July 2011 with a population of 11.3 million (UN, 2013) and a GDP per capita of 861 US$ (WB, 2012) encompasses portions of the White Nile and the Nile above the confluence of the Sobat and White Nile Rivers. This area includes the extraordinary wetland called the Sudd that, because of evaporation, controls the volume of flow from the Equatorial Lakes region into the White Nile. Because of the long period

[1] State of the river Nile Basin 2012 by the NBI
[2] The Eastern Nile State of the basin report 2011 ENTRO

of civil strife and war in South Sudan development of water for agriculture, drinking and livestock is expected to be a very high priority.

Sudan, formerly the continent's largest country by land area now with a population of 37.96 million (UN, 2013) and a GDP per capita of 1580 US$ (WB, 2012), has traditionally used the Nile mostly for flood recession agriculture and pastoralism, but has constructed one of the world's largest irrigation schemes from a single water source at Gezira just downstream of the confluence of the White Nile and the Blue Nile Rivers.

1.1 CHALLENGES IN THE EASTERN NILE

Challenges in the Eastern Nile are of wide variety and affects basic needs of humanity. The major challenges in the basin are highlighted in this section:

1.1.1 Poverty and high population growth:

With an expectancy of the population of the four riparian countries to double in 2050, population increase is the main challenge facing the region. On top of this most of the riparian countries are categorized among the poorest nations in the world. So the need for development versus the growing number of population will increase the stress in the utilization of the natural resources in the countries, water being the major amongst them.

1.1.2 Unbalanced development

Reflected in disparity in access to basic services such as water supply, sanitation and access to electricity across the riparian countries as well as with in different regions of one country.

1.1.3 Complex hydrology:

The Nile Basin in particular the Eastern Nile is characterized by high climatic diversity and variability, a low percentage of rainfall reaching the main river, and an uneven distribution of its water resources. This complex hydrology also lead to a complex eco system comprising of wetlands, lakes, forest, deltas etc.. The variability also introduces an annual risk of drought and flood in many parts of the region. Thus the need for infrastructure development in storage facilities is eminent to address these challenges.

1.1.4 Weak Resilience to climate shocks:

This is generally a risk all developing countries face as a result of poor infrastructure development. But the problem will be aggravated in the Eastern Nile with the above mentioned seasonality of flows on top the global climate change. This fact is unfortunately reflected in the millions of lives lost due to droughts and floods in the region.

1.1.5 Deteriorating water resource infrastructures

This leads to poor performance of major agricultural and power projects due to limited finance for operation and maintenance. This is also a result of weak institutional setup in the countries which leads to a basin wide increase in water system losses and low productivity.

1.1.6 Land degradations and soil losses:

The problem is highly reflected in the upper parts of the basin which leads to sedimentation problem in the downstream. This includes increased operation and maintenance cost of the existing water infrastructures and also affecting the productivity of the livelihood in all parts of the region.

In summery the Eastern Nile is a region of water stress and has a high potential to be a source of conflict if not properly managed.

1.2 OPPORTUNITIES FOR DEVELOPMENT IN THE EASTERN NILE

Opportunities for development in many sectors are still untapped and can be used to address the burning needs of the population in the countries. Some of these sectors include:

1.2.1 Large potential for hydropower development:

The topographic feature of steep slopes from the Ethiopian highlands to the Sudanese plains is a recipe for hydro power production. With only 11.2 % of the total hydropower potential developed in Ethiopia (about 15409 MW untapped), 32.7 % in Sudan (about 3280 MW untapped) and 98.6% in Egypt (40MW untapped)[3].

1.2.2 Potential for Water Saving

There is a potential for water saving by improving the performance of the agricultural sector. Even though there is an increasing demand for water in the agricultural sector there is a possibility of reducing the stress on the system by improving the performance of the existing schemes or by advertising an effective design of agricultural projects for better water use.

1.2.3 Potential for Irrigation expansion:

There is still vast amount of land suitable for irrigated agriculture studied and waiting for investors to be developed. This indicates that irrigable land is not constraining development in the basin. Joint regional irrigation investments are also an option for an integrated water resources development in the Eastern Nile.

[3] State of the river Nile Basin 2012 by the NBI

1.2.4 Potential for improving resilience to climate shock,

Crucial for attaining regional self-sufficiency and water security. This is viable through water storage and proper management of the stored water in the countries.

2 OBJECTIVE OF THE STUDY

The River Nile has a great potential for development in the Eastern Nile Basin but if this development is not planned and well-coordinated it can be the source of conflict in the basin. The current tension observed between Egypt, Ethiopia and Sudan is an example of the water stress in the region and the growing need for development. With this respect the Eastern Nile Riverware model was developed by the Eastern Nile Technical and Regional Office to support the investigation of development options for best utilization of the resources and promote benefit sharing among the Eastern Nile countries. In this paper the model is used for a case study to assess alternative reservoir filling options of the Great Ethiopian Renaissance Dam which is expected to generate 6000 MW of electricity, the biggest hydropower plant in Africa, with some 74 BCM of storage capacity.

2.1 SPECIFIC OBJECTIVES:

- Quantification of Energy Production by GERD
- Quantify the effect of filling the GERD on downstream power production.
- Evaluate the change in water availability downstream of GERD during the filling.
- Quantify the effect of filling the GERD on consumptive downstream users.

3 METHODOLOGY AND MODELING FRAMEWORK

In order to minimize the impact on existing infrastructures a well-studied and coordinated filling option is required since the natural flow of the river at the dam site is 48 BCM per annum on average. The study follows a probabilistic approach in presenting the results to account for future hydrological uncertainties. This was possible by running **35** traces or realization of hydrology and a scenario matrix to represent different filling periods and downstream conditions. A total of **525** runs have been made and results are presented for possible impacts and power generation at the dam using statistical and probabilistic approach.

3.1 THE HYDROLOGICAL MODEL (RIVERWARE)

RiverWare is a general river and reservoir modeling tool widely used to its interpreted language for expression of multi-objective operation policies. RiverWare application includes operational scheduling for forecasting, planning, policy evaluation, and other operational analysis and decision processes. The wide range of applications is made possible by choice of computational time step ranging from 1hr to 1yr. RiverWare have the capability to model

- Hydrology and hydrological processes of reservoirs, river reaches, diversions, distribution canals, consumptive uses,
- Hydropower production and energy uses,
- Water rights, water ownership, and water accounting transactions

3.1.1 Model creation

Objects and Slots: The basic building blocks of a RiverWare river basin model are objects which represent the features of the river basin. The objects are represented by icons on the workspace which can be opened to show the list of slots, which are the variables associated with the physical process model equations for that feature. For example, all reservoirs have slots, among others, called Inflow, Outflow, Storage and Pool Elevation.

3.1.2 Simulation with Riverware

RiverWare operates with three basic modes to determine modeled solutions that include Simulation, Rule-based Simulation and Optimization. The first two modes can be generally considered “descriptive” solutions that provide an output that describes the result of a set of given physical or operational inputs. The latter provides a solution that can generally be considered “prescriptive” of what an optimal operation should be. The rule-based solution method is the most commonly used solution method for planning models and is used for this project.

3.1.3 Data management interface

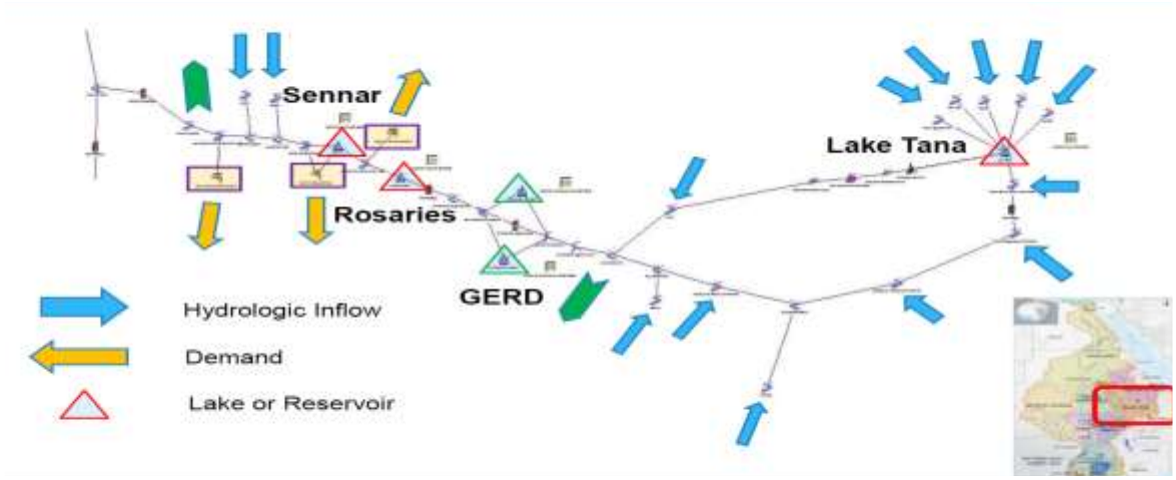
The Data Management Interface (DMI) in RiverWare provides the means of using external programs to automatically load data into RiverWare. These routines are written by the user or the user’s organization in any programming language and invoked through the RiverWare GUI. Scenario-based DMI’s execute a suite of individual routines to bring many data sources together into the model. The DMI can also be used to advance the run control start and end times. The logic that describes the rule-based operation described above is contained in a rule-set file (.rls). A Graphical Policy Analysis Tool (GPAT) is provided by CADSWES that allows the comparative analysis of multiple Excel output files.

3.2 Configuration of the model

The extent of project area includes the EN sub-basins. The coverage of the model area is given in the schematic below.

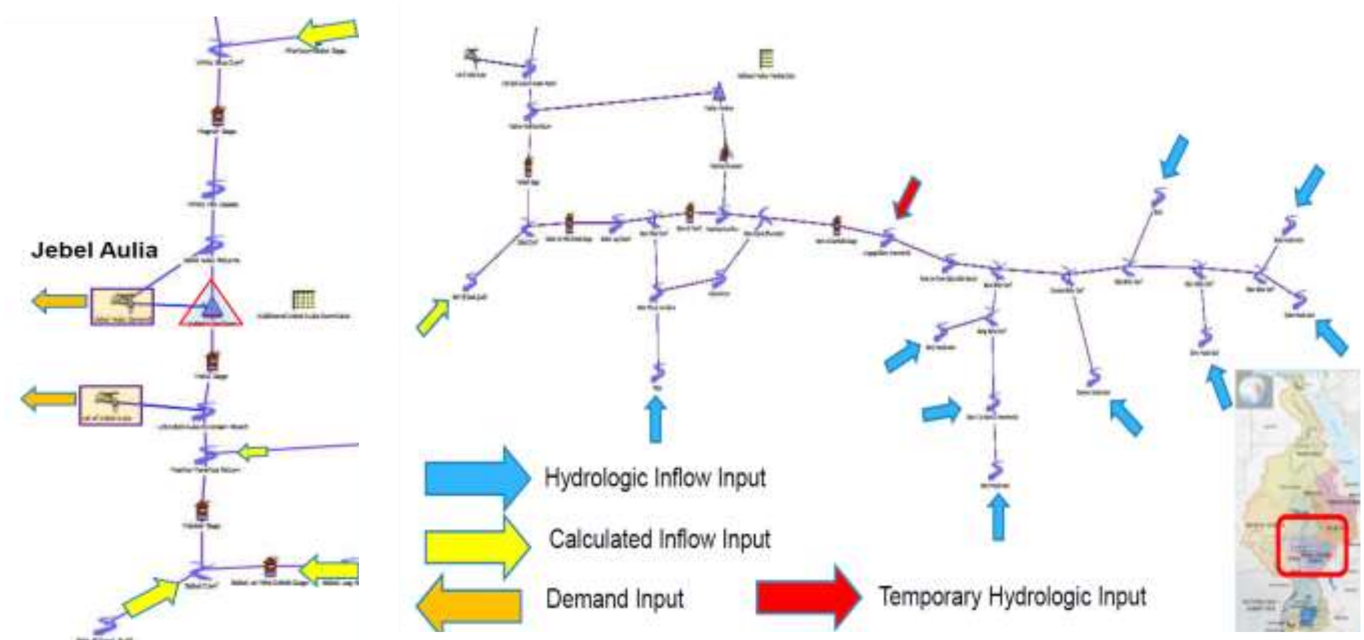
3.2.1 Blue Nile

The Blue Nile sub-basin is modeled from Lake Tana to the confluence with the White Nile at Khartoum. The historical and existing modeled network consists of fourteen inflow locations, three diversions locations and three reservoir sites.



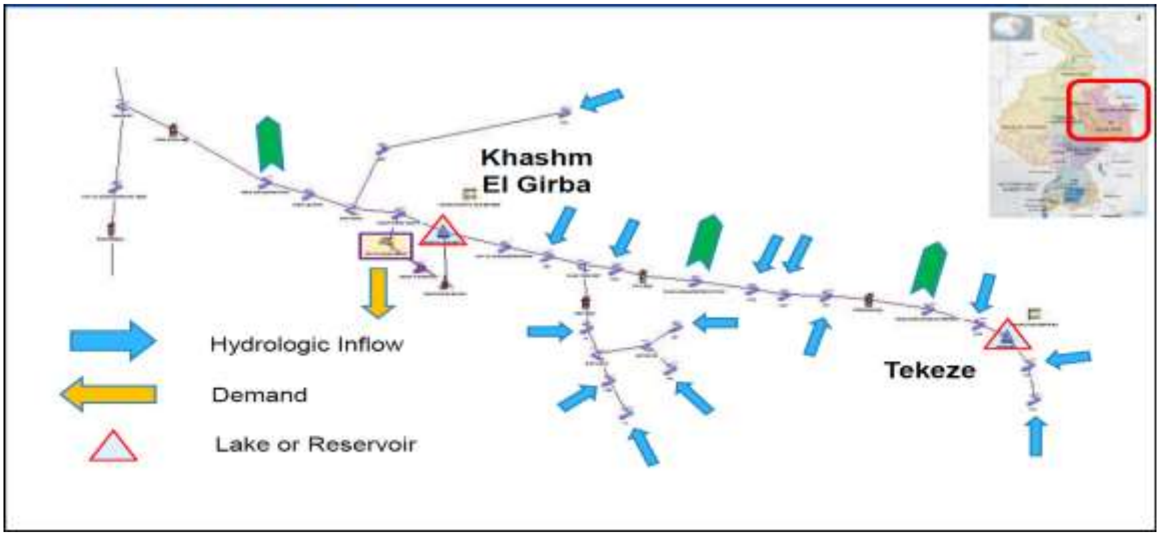
3.2.2 White Nile and BaroAkoboSobat

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



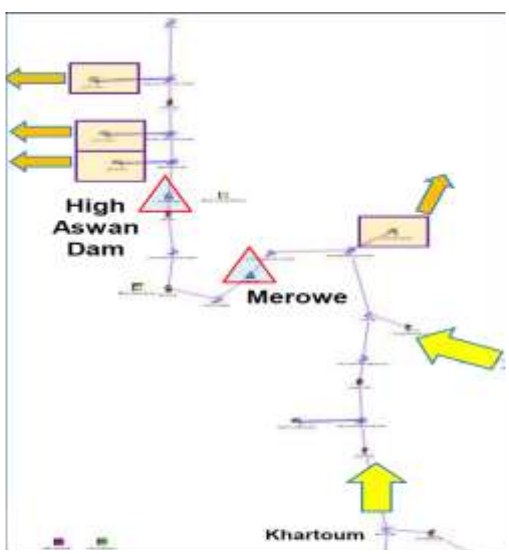
3.2.3 Tekeze- Setit -Atbara River Basin

The primary tributary to the Atbara River is the Tekeze/Setit, which forms part of the border between Eritrea and Ethiopia and originates in the high mountains of northern Ethiopia. The principal reservoirs in the sub-basin are the Khashm El Girba Dam. The primary consumptive use is a direct diversion from the Khashm El Girba Dam.



3.2.4 Main Nile

The Main Nile is from Khartoum gauge station to Nile Delta. The Atbara joins the Nile in this reach and passes through the High Aswan Dam near the Sudan-Egypt border. The recently constructed Merowe Dam and constructed upstream of the High Aswan dam and is therefore included in the Baseline and Scenario models, but not in the historical calibration model. There are five modeled demand locations that represent aggregations of many water users in this region.



4 ANALYSIS, CONCLUSIONS AND RECOMMENDATIONS:

The scenarios are then analyzed to indicate the pros and cons of each case in order to open the table for negotiations between the stakeholders and inform the associated probabilistic risks and opportunities with each, for all parties. Some of the indicators used to compare and evaluate the different scenarios include; Energy production by country, by dam and total in the basin, Water levels at reservoirs, Water Shortage by country etc. The detailed results are presented in **AnnexI**.

This approach is expected to replace the classical method of evaluating the impact of filling under three hydrological conditions i.e. Wet sequence of years, Dry sequence of years, Normal or Average condition. The classical approach only presents decision makers with extreme cases which is still an obstacle for negotiation as each party favors one of those conditions. The approach followed by this paper can provide the probability of energy shortage, energy production, water shortage, water saving, water level drop in downstream reservoirs below a threshold value, probability of meeting/not-meeting environmental flows, evaporation losses, etc. during the filling of the reservoir by running multiple traces of hydrology. This will allow all parties to be aware of the risks in each scenario. The results will be presented for 5, 6 and 7 years filling period while assuming four different initial water levels, 165, 170, 173, 178 masl in High Aswan Dam in Egypt (The most vulnerable downstream infrastructure because of the big volume of the reservoir compared to the annual flow of the Nile).

The objective of this paper is not to identify the best scenario for filling the dam, but rather to present the stake holders with a tool and a wide range of results to weigh the pros and cons of each and reach on a common understanding.

Analysis of results are summarized and presented below.

Table 1. Average annual percentage change of the three filling scenarios from baseline until the system fully recovered. (13 Years From the start of filling). 173 masl for initial water level of High Aswan Dam.

Parameter	Change from the current situation during the first 13 years from the start of impoundment.
Egypt hydropower production	8.34 % (Decrease)
Ethiopia hydropower production	400 % (Increase)
Sudan Hydropower production	14.47% (Increase)
Ethio-Sudan border (El-diem station) stream flow.	3.33 % (Decrease)
Nile at Aswan station stream flow	8.02% (Decrease)
Water released from High Aswan Dam	3.01 % (Decrease) * Assuming the operation of the Dam stays the same

The effect of impoundment on agricultural production in the Main Nile can be roughly approximated by calculating any potential shortage in water use and using the agricultural production value for Egypt as almost all of the agricultural water use in the Main Nile sub-basin is in Egypt[4]. The agricultural losses in Sudan can also be quantified in the same manner.

Table 1. Average annual system shortage in the Main Nile in MCM and associated loss in Million USD. Given as the 13 years average from the start of the filling for the three filling scenarios from baseline until the system fully recovered. 173 masl for initial water level of High Aswan Dam.

Scenario	Average annual system shortage in the Main Nile in MCM. (13 years average from the start of the filling).	Average annual value of the agricultural loss in Million USD[5]
Current Situation (Base-case)	0	0
5 Years filling strategy for GERD	129.208	69.612
6 Years filling strategy for GERD	59.1667	31.876
7 Years filling strategy for GERD	0	0

Flood Damage

The estimated average annual damage in rural villages riparian to the Blue Nile and Main Nile in Sudan is about 25.77 Million USD[6]. After regulation the risk of flood damage in Sudan is almost completely eliminated as is shown in the Annex for El Diem Gage flow data.

To conclude, there is a systematic way of addressing the concerns regarding the filling and long term operation of the GERD. The dam offers a development window for the much needed growth and cooperation in the region and downstream impacts can also be managed and well-studied with an all-inclusive process using tools like Riverware and such. As was indicated in the Annex attached, there is no significant harm expected from the dam if we follow an appropriate filling mechanism, and the long term benefits as a climate shock absorber, flood risk mitigation tool and more importantly a power hub in the region is reflected in the analysis results.

[4]The Agricultural value of 1 MCM of Nile water in Egypt can be extracted from the Agricultural Production Value for Egypt from FAOSTAT and Egypt's current use i.e. 55.5 BCM

[5] The Agricultural Production Value for Egypt was extracted from FAOSTAT. Net agricultural production of Egypt (for 2012) is 21.901 Billion USD.

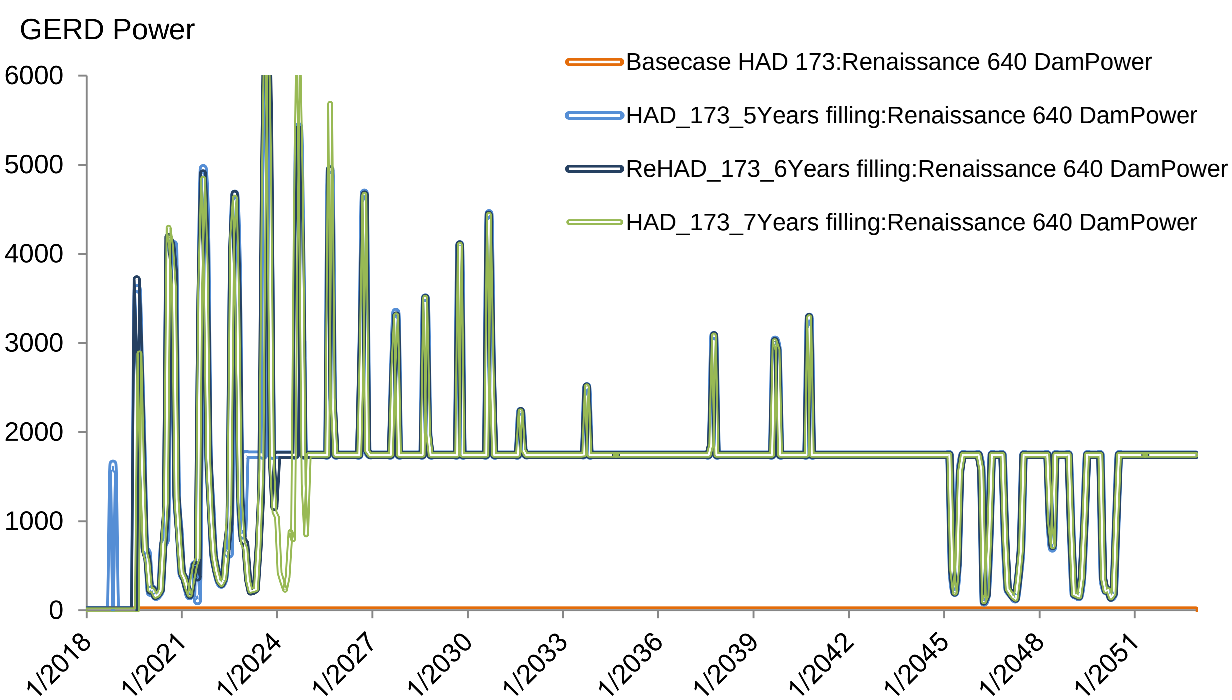
[6] Eastern Nile Flood Preparedness and Early Warning Project report ENTRO, 2009

5 Annex I Energy:

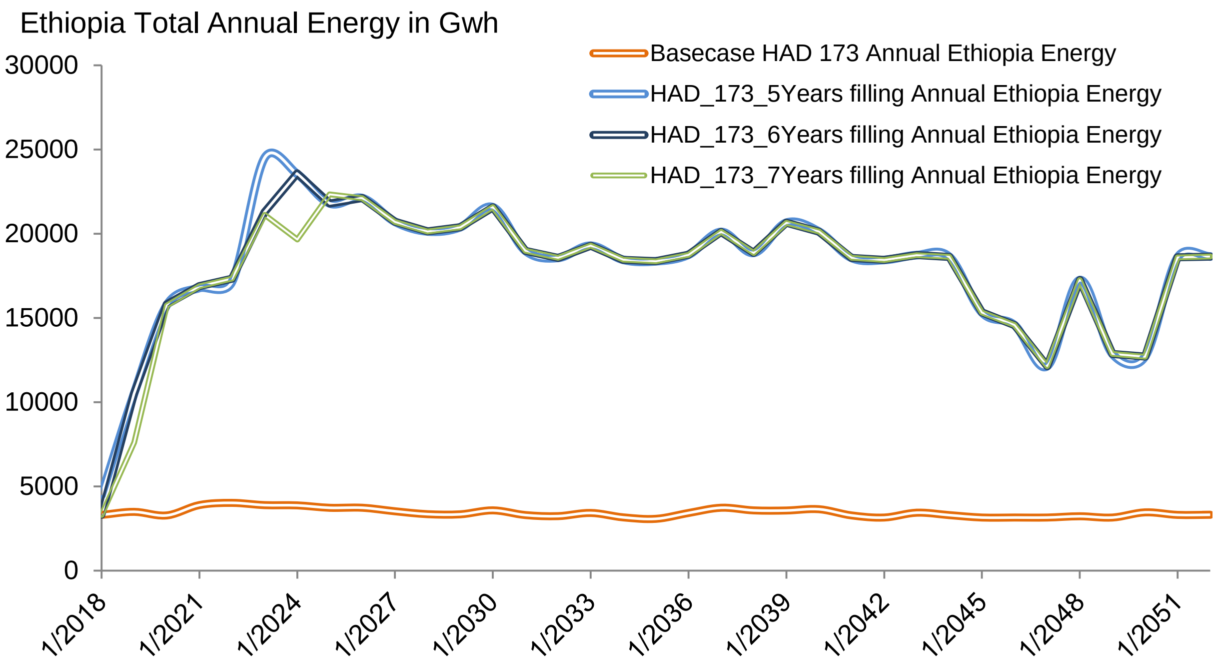
5.1 Section I: Project level and country level energy production during and after the filling

Note: The results reported for Section I are by taking one of the traces of the multiple hydrology which is representing the average condition.

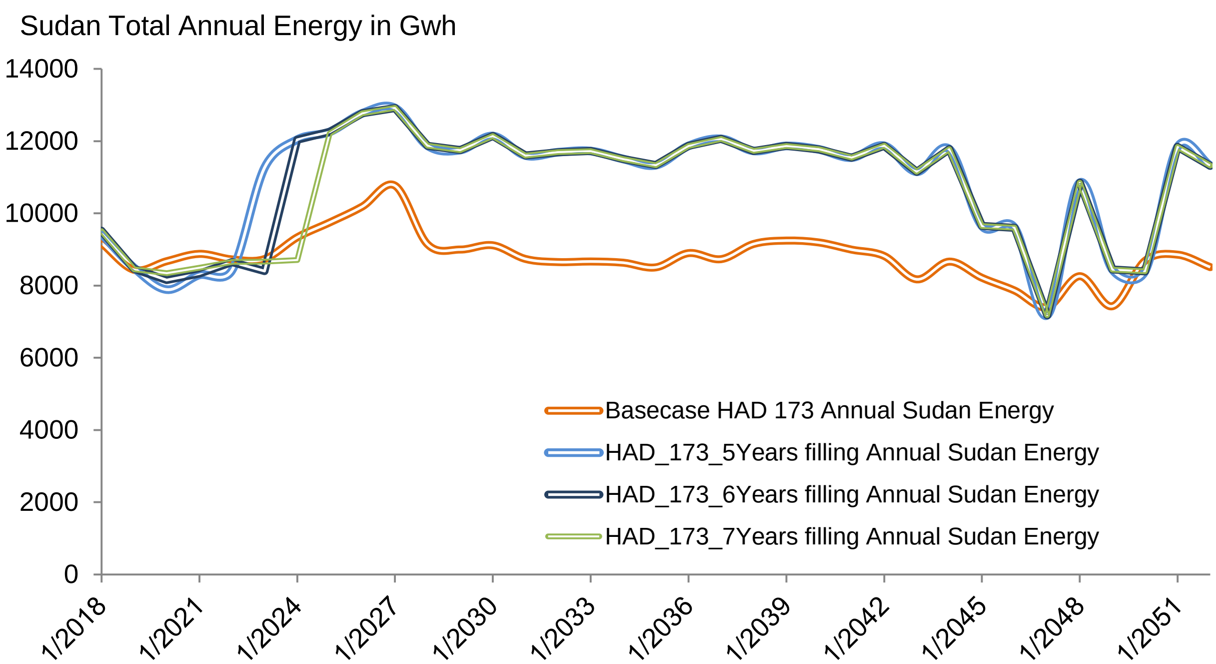
GERD Power generation in MW under different filling Scenarios



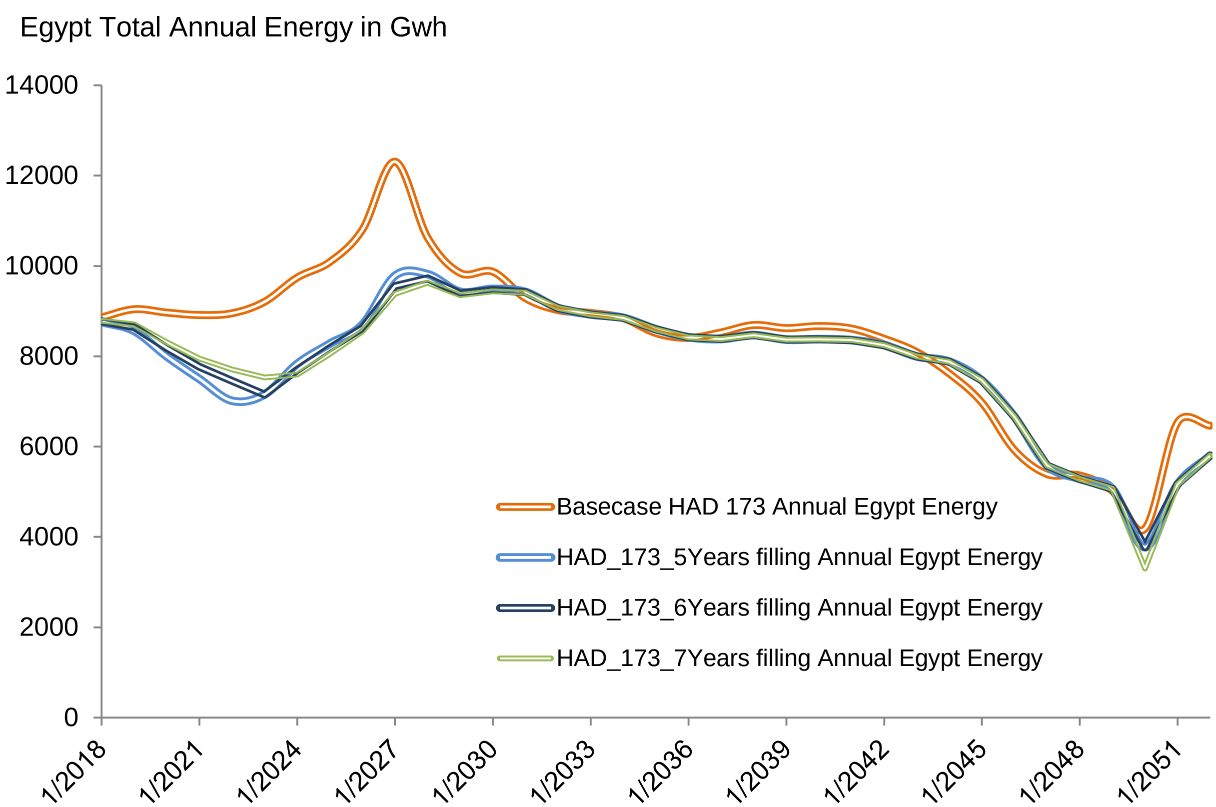
Ethiopia Energy production from the Nile in Gwh under different filling Scenarios



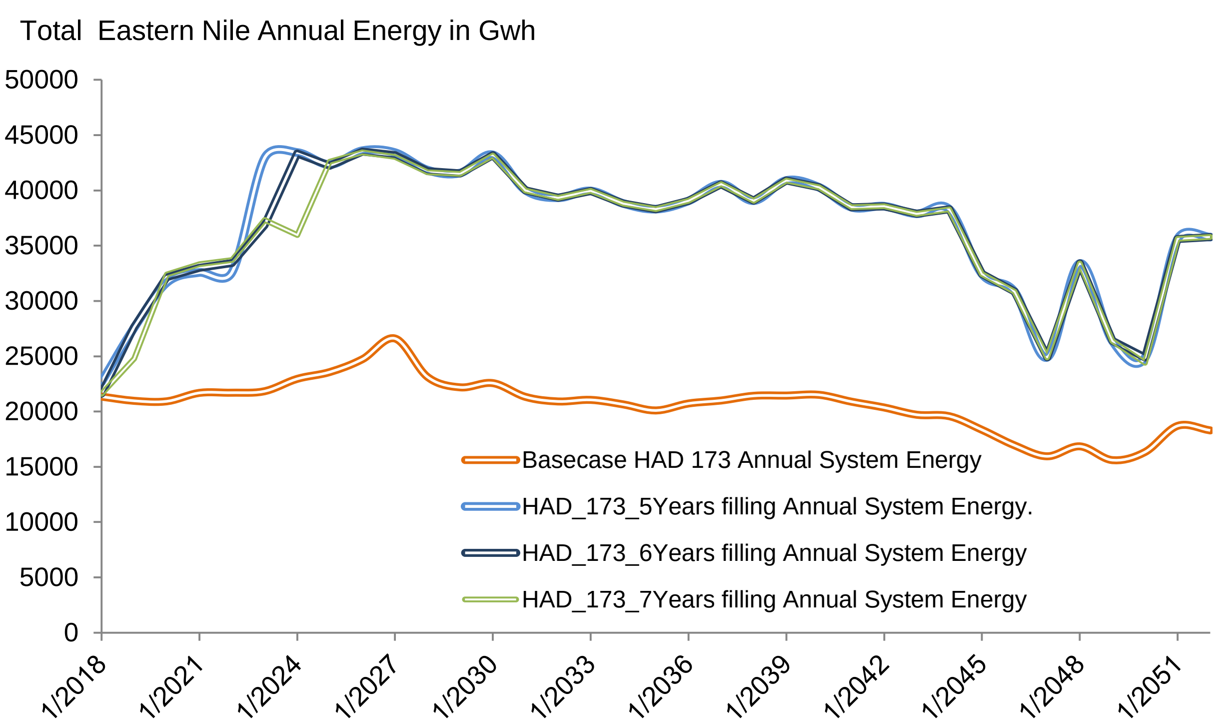
Sudan Energy production from the Nile in Gwh under different filling Scenarios



Egypt Energy production from the Nile in Gwh under different filling Scenarios



Total Eastern Nile Energy production in Gwh under different filling Scenarios



Accumulated Loss or gain of energy during the initial 7 years of the impoundment on country level and on the whole basin

Accumulated First Seven Years Energy for the three countries under different filling Scenarios				
Energy in GWh	**Basecase**	**5Years filling**	**6 Years filling**	**7 Years filling**
Sudan Total Energy	61966.51	65840.37	63567.38	60833.74
Deviance From Base Case	0	3873.86	1600.87	-1132.77
Deviance From 5 Years filling			-2272.99	-5006.63
Deviance From 6 Years filling				-2733.64
Egypt from High Aswan	63688.42	54822.42	55690.4	56600.43
Deviance From Base Case	0	-8866	-7998.02	-7087.99
Deviance From 5 Years filling			867.98	1778.01
Deviance From 6 Years filling				910.03
Ethiopia	25776.15	112784.31	108729.95	101665.68
Deviance From Base Case	0	87008.16	82953.8	75889.53
Deviance From 5 Years filling			-4054.36	-11118.63
Deviance From 6 Years filling				-7064.27
Over All Basin Energy	151431.08	233447.1	227987.73	219099.85
Deviance From Base Case	0	82016.02	76556.65	67668.77
Deviance From 5 Years filling			-5459.37	-14347.25
Deviance From 6 Years filling				-8887.88

Simplified economic analysis of the different scenarios from energy perspective only:

The electricity selling price in the three countries (current figures when the paper was produced) are

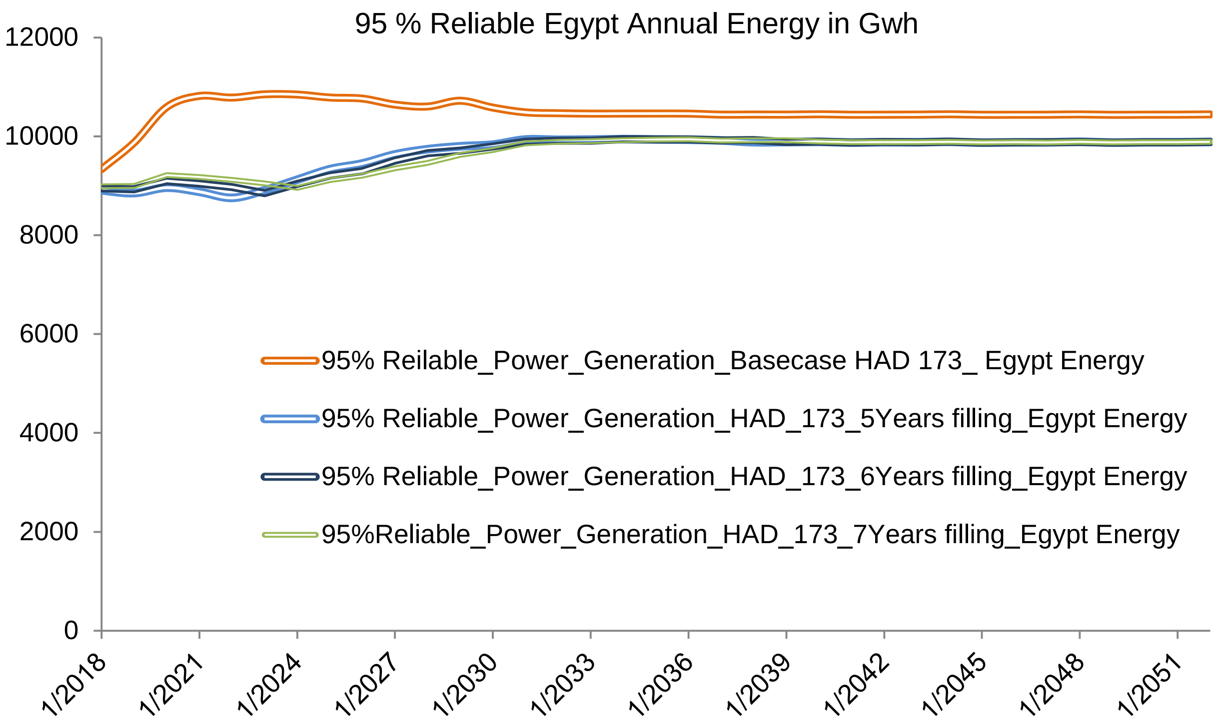
Egypt: 0.0303 USD/KWh, Ethiopia 0.0261 USD/KWh and Sudan 0.03103 USD/KWh.

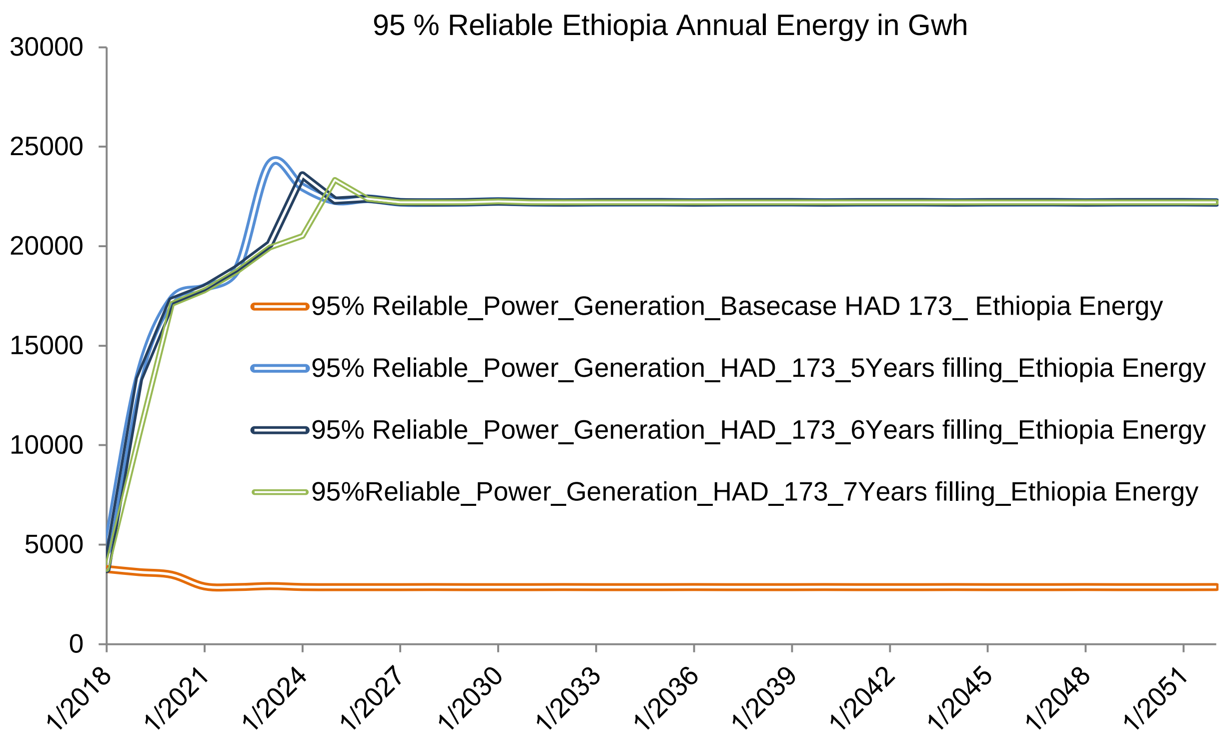
Note: Selling price is much lower than the economic value of electricity and this paper used selling price as a conservative approach.

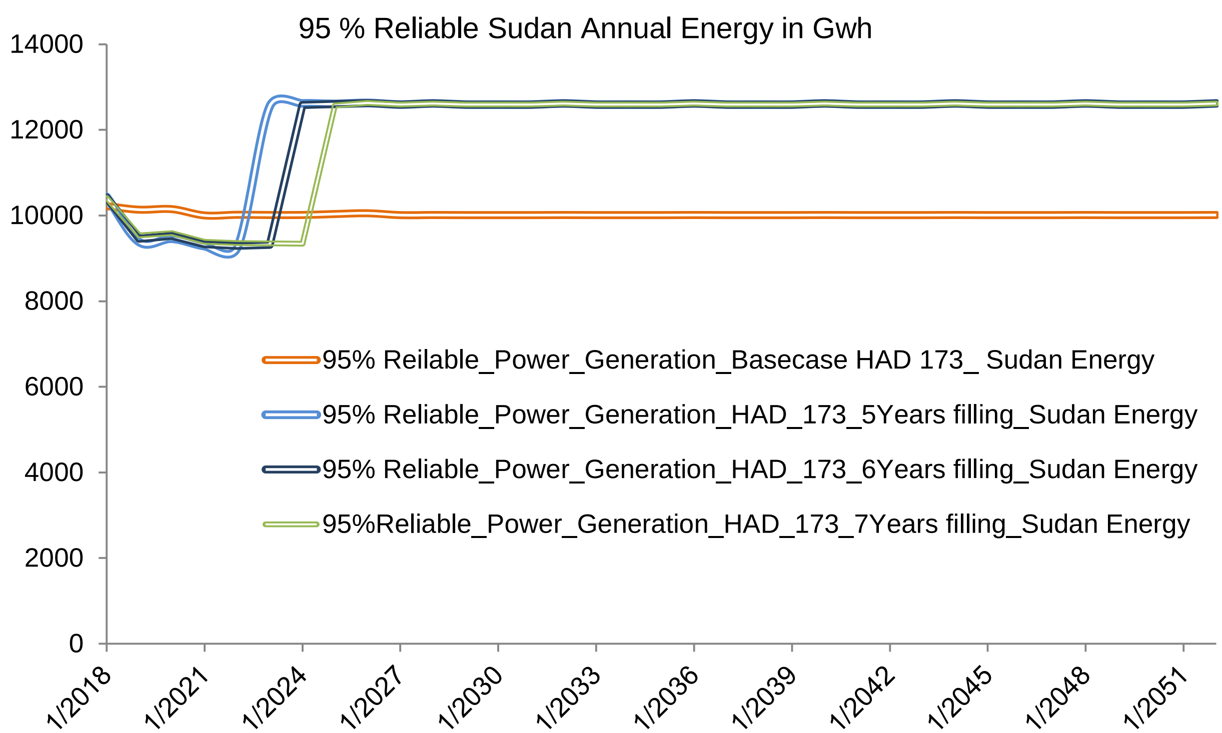
With this assumptions the cost of shifting from 5 years filling plan to a 7 years filling plan from electricity point of view is 14,347.25 GWh or 14,347,250,000 KWh multiplied by basin average cost i.e 0.02941 USD/KWh. Which is around **418 Million USD.**

Note: This analysis didn't assume any appreciation or depreciation in either the currency or the selling rates.

5.2 SECTION II: COUNTRY LEVEL ENERGY PRODUCTION DURING AND AFTER THE FILLING AT A GIVEN RELIABILITY

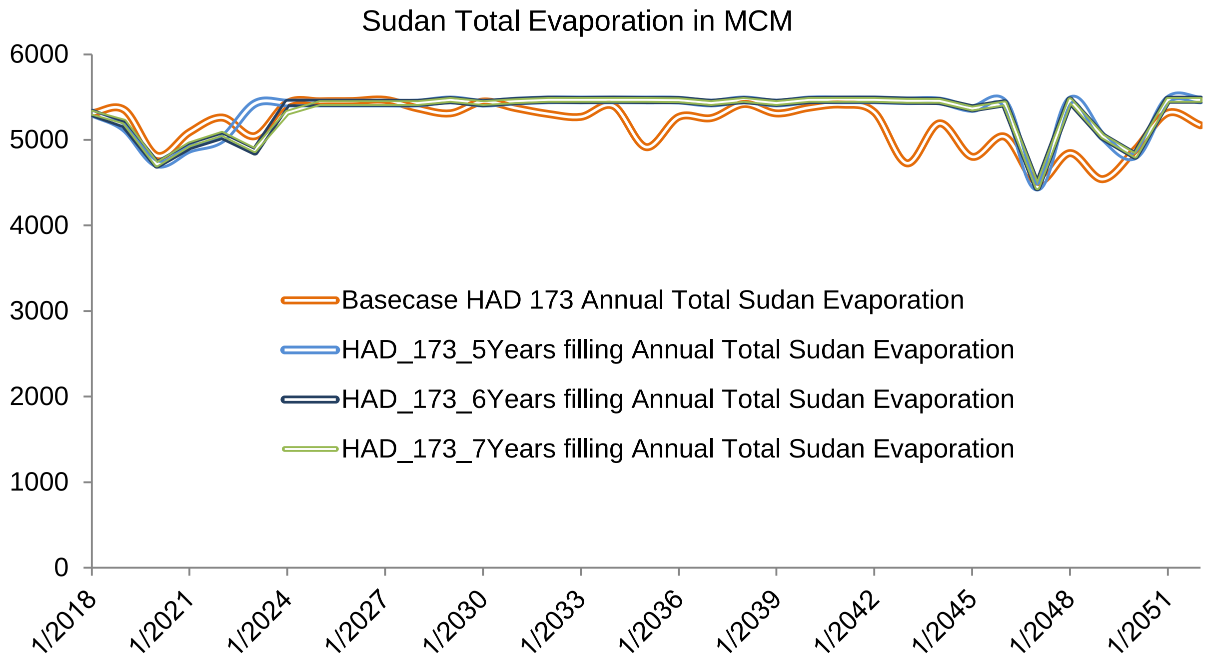


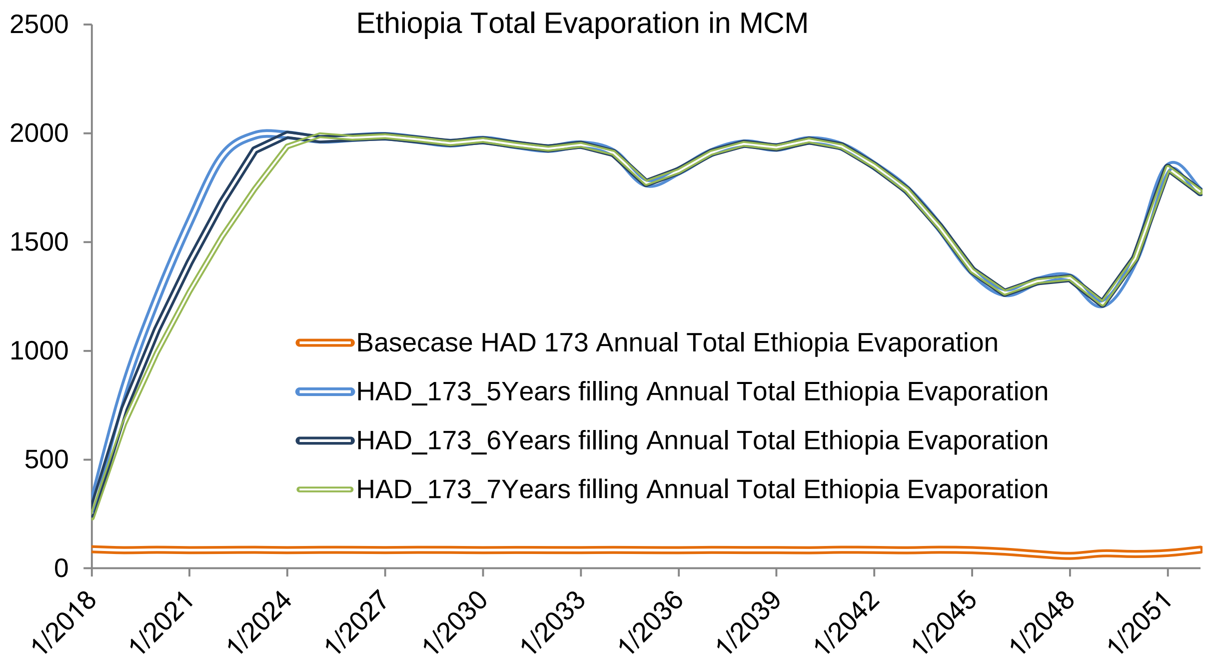

95 % Reliable Ethiopia Annual Energy in Gwh
30000
25000
20000
15000
10000
5000
0
95% Reilable_Power_Generation_Basecase HAD 173_ Ethiopia Energy
95% Reliable_Power_Generation_HAD_173_5Years filling_Ethiopia Energy
95% Reliable_Power_Generation_HAD_173_6Years filling_Ethiopia Energy
95%Reliable_Power_Generation_HAD_173_7Years filling_Ethiopia Energy
1/2018
1/2021
1/2024
1/2027
1/2030
1/2033
1/2036
1/2039
1/2042
1/2045
1/2048
1/2051

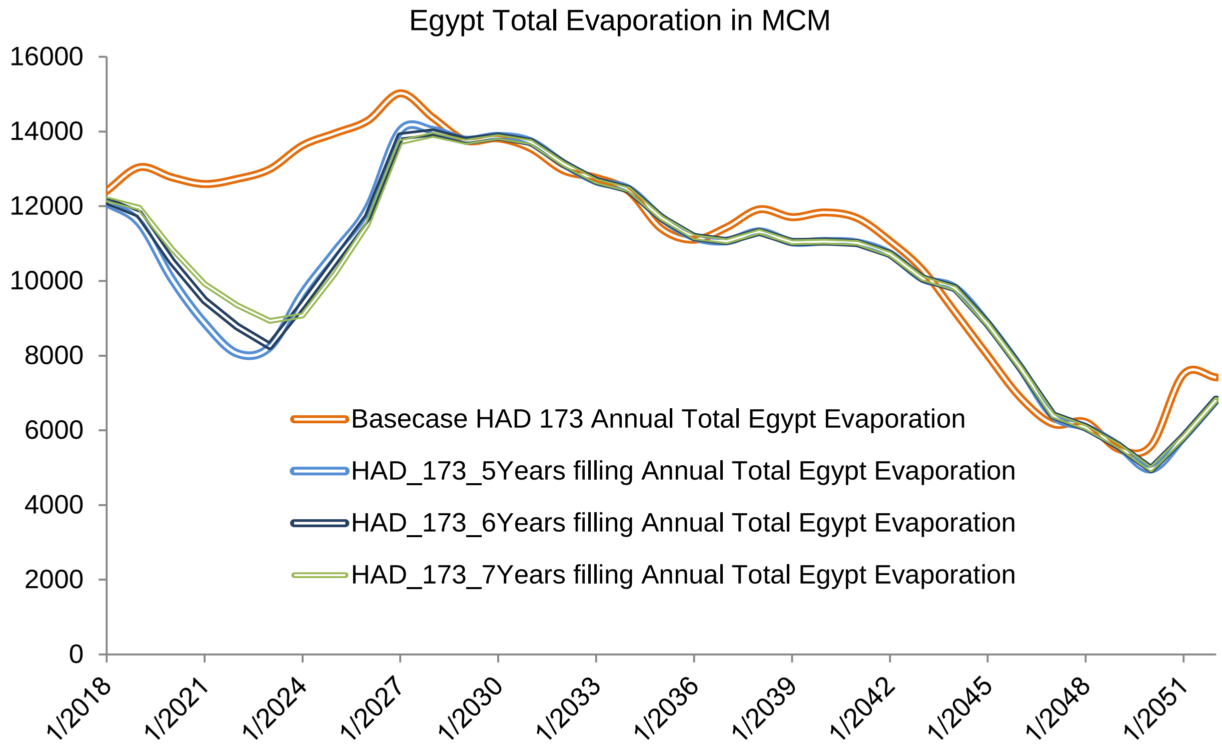

95 % Reliable Sudan Annual Energy in Gwh
14000
12000
10000
8000
6000
4000
2000
0
95% Reilable_Power_Generation_Basecase HAD 173_ Sudan Energy
95% Reliable_Power_Generation_HAD_173_5Years filling_Sudan Energy
95% Reliable_Power_Generation_HAD_173_6Years filling_Sudan Energy
95%Reliable_Power_Generation_HAD_173_7Years filling_Sudan Energy
1/2018
1/2021
1/2024
1/2027
1/2030
1/2033
1/2036
1/2039
1/2042
1/2045
1/2048
1/2051

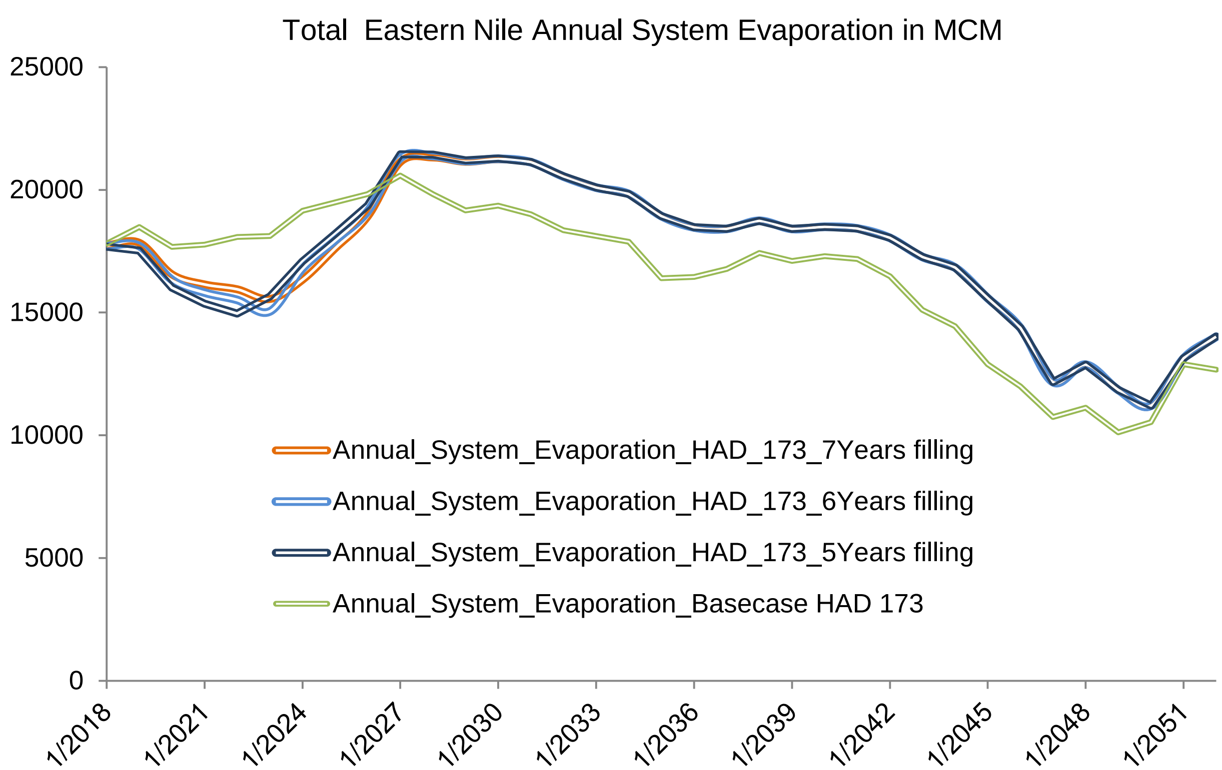
5.3 SECTION III: COUNTRY LEVEL EVAPORATION

Note: The results reported for Section III are by taking one of the traces of the multiple hydrology which is representing the average condition. And the hydrological model did not account for water saving as a result of regulation during the flood season (overbank flows)



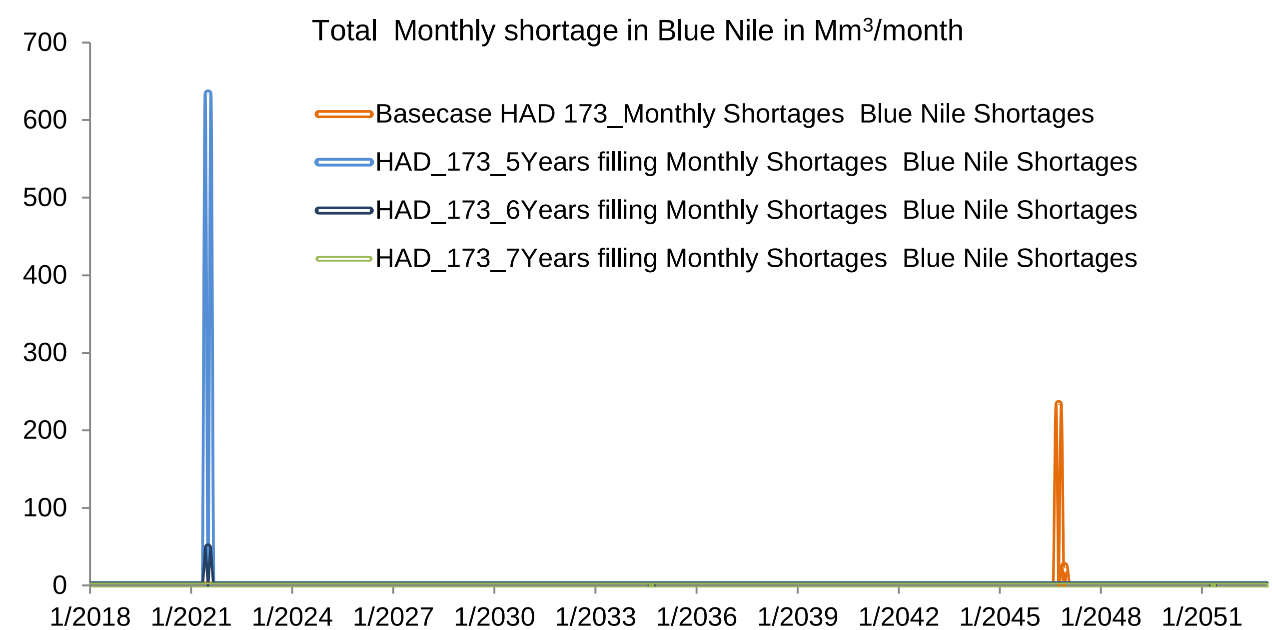


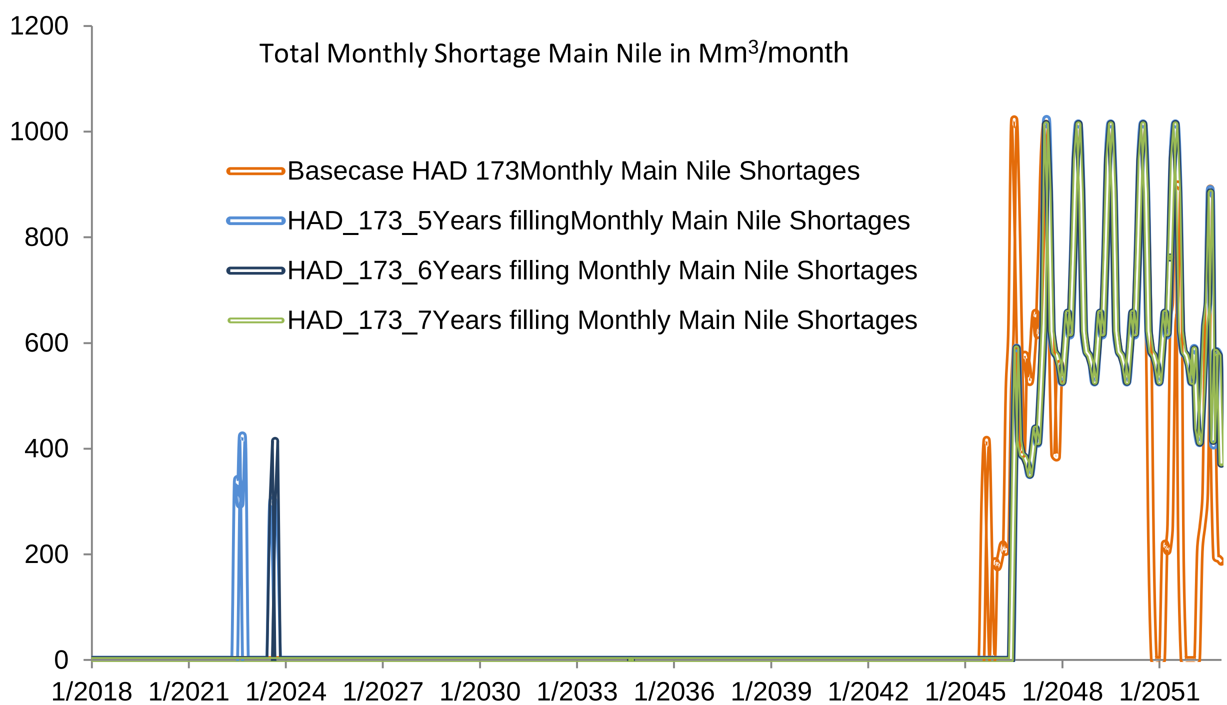

Egypt Total Evaporation in MCM
16000
14000
12000
10000
8000
6000
4000
2000
0
Basecase HAD 173 Annual Total Egypt Evaporation
HAD_173_5Years filling Annual Total Egypt Evaporation
HAD_173_6Years filling Annual Total Egypt Evaporation
HAD_173_7Years filling Annual Total Egypt Evaporation
1/2018
1/2021
1/2024
1/2027
1/2030
1/2033
1/2036
1/2039
1/2042
1/2045
1/2048
1/2051


Total Eastern Nile Annual System Evaporation in MCM
25000
20000
15000
10000
5000
0
Annual_System_Evaporation_HAD_173_7Years filling
Annual_System_Evaporation_HAD_173_6Years filling
Annual_System_Evaporation_HAD_173_5Years filling
Annual_System_Evaporation_Basecase HAD 173
1/2018
1/2021
1/2024
1/2027
1/2030
1/2033
1/2036
1/2039
1/2042
1/2045
1/2048
1/2051

5.4 SECTION V: SUB-BASIN LEVEL WATER DEFICITS

Note: The results reported for Section IV are by taking one of the traces of the multiple hydrology which is representing the average condition.





5.5 SECTION VI: PROBABILISTIC PLOTS AND STATION FLOWS