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Hydropower Generation in Merowe Dam in response to Grand Ethiopian Renaissance Dam (GERD)

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Abstract: This paper aims to quantify the influence of Grand Ethiopian Renaissance Dam (GERD) on Merowe Dam (MD) in the context of hydropower generation. MD is located on River Nile (RN) in the North Sudan, about 800 km downstream Khartoum with a total storage capacity of 12.4 Km^3. It worth mentioning that, RN annual runoff is estimated to an average of 85 Km^3, formed from Blue Nile (57%), White Nile (29%) and Atbara River (14%).GERD reservoir capacity is estimated to be 74 Km^3, with installed capacity of about 6000 Megawatts, while the installed capacity of MD is 1250 Megawatts; the average annual energy output is about 6000 Giga-watts 85% of the required water for the generation in MD comes from the runoff river, while the reservoir provides 15% of water per year.The two main objectives of this study are to quantify the impacts of GERD during first filling and long term run. Comprehensive study for the RN Hydrological system was performed, using Excel Sheets designed with Visual Basic for Applications VBA, calibrated and tested. Boundary conditions were established and different operation policies were applied. It should be noted that, five different scenarios were studied, for the first impounding during 6 years with a total retaining of water between 10-50% of the Blue Nile yield; the impacts were limited to a deficit of 10% max.In summary, the effects of GERD on MD are quantified by decreasing in energy by 10% during first impounding and, increasing in energy by 27% annually for long run.

Keywords:*Merowe Dam, Specific Water Consumption S.W.C, Routing, Operation Rule Curve, Megawat*

1. INTRODUCTION

1.1 *Background*

Merowe Dam is located near the fourth cataract of the River Nile, northern of Sudan, approximately 350 kilometer (215 miles) to the northwest of Sudan's capital, Khartoum.[1].
The total length of the dam is about 9.5 Km, composed from five different types of Dams as shown in Fig. (1).

1.2 *Problem Statement*

Grand Ethiopia Renaissance Dam GERD is under construction since 2011. The dam is considered as the biggest dam ever constructed in the Blue Nile Basin with a reservoir of 74 Billion m^3, [2]. It worth mentioning that, the Blue Nile, is the main tributary of the Nile, and the source of about 80% of the water during flood season (July-October).

No doubt that GERD is going to regulate Blue Nile and change its hydrological regime, which will affect the regime of the River Nile accordingly. This will put Merowe Dam under new unknown circumstances that will result in changing hydropower generation scope and magnitude. The two main situations are highlighted below:

1. The expected influence of First Filling of GERD on Merowe Dam Generation.
2. The Effects of GERD Long-Run Operation on Merowe Dam hydropower Generation.

1.3*Objectives:*

This research aims to quantify the effects of GERD on Merowe Dam generation during the first GERD reservoir impounding, and also in the long run operation.

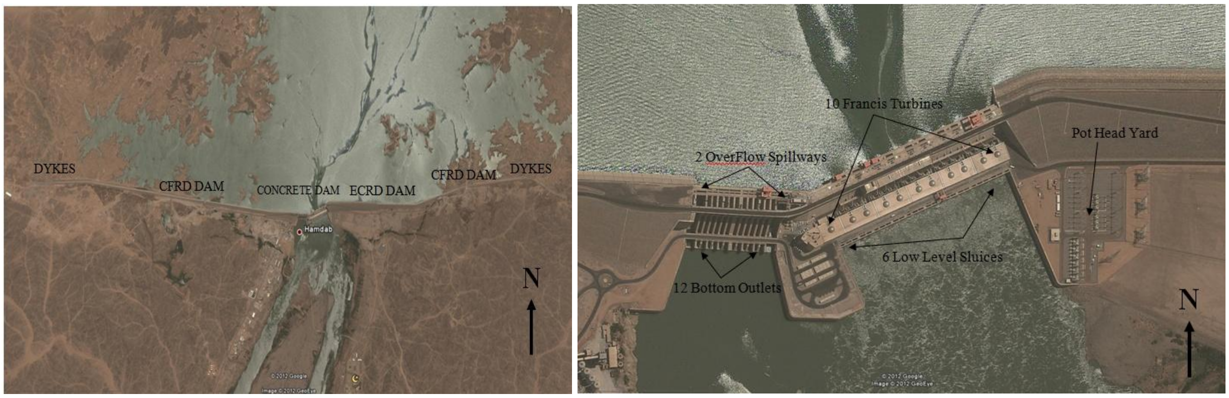

Fig. 1: Merowe Dam Layout (Source: Google Earth)

1.4*Nile Hydrology*

1.4.1 *River Nile Sources:* TheSources of the Nile are:

a. Ethiopia Highlands: source of Blue Nile, Atbara and Sobat Rivers
b. Equatorial Lakes: source of Bahr EL Jebel
c. Bahr El Ghazal Basin (Sudan): source of Bahr El Ghazal Rivers

The annual discharge of the Nile varies from 154 Milliards m^3 (1878/79) to 42 Milliards m^3 (1913/14). The average annual flow for the period (1905-55) is estimated at 84 milliards m^3, measured at Aswan equivalent to 93 milliards m^3 at Sinnar (Central Sudan). See [3].

1.4.2*Existing Control Structures*

Four seasonal storage dams control the Nile system in Sudan. Two dams were built to satisfy other countries' needs. (Sinnar Dam was built in 1925to irrigate Gezira Scheme for benefit of Britain and Jebel Aulia Dam in 1937 for benefit of Egypt). Sudan had constructed El Girba dam in 1965 and Rosaries Dam in 1966 to utilize some of it share in Nile waters and to irrigate New Halfa Scheme for the benefit of the people displaced due to the construction ofthe High Aswan Dam.
The design storage capacity of Sudan's dams is 8.7 bm^3 while the live storage is about 7.6 bm^3. It worth mentioning that, a small Barrage was constructed on Rahad River to divert floodwater to Rahad Agricultural Scheme and Siphon underneath Dinder River to augment water supply during dry season from Meina Pump Station on the Blue Nile.Jonglei Canal (between Bahr el Jebel and the White Nile) was under construction, but the work halted since 1983.

1.5*GERD General Information*

The GERD project site is located on the Abbaye/Blue Nile River some 20 km upstream of the Ethiopia - Sudan border [4]. The GERD is a Roller Compacted Concrete (RCC) dam with a dam height of 145 meters, complemented by a saddle dam about 5 km long and about 50 meters high[4]. The scheme, from the root of its reservoir to the dam site, extends over a corridor approximately 246 km. The reservoir area will cover 1,874 square kilometers at full supply level (FSL) of 640 meters above sea level a M.S.L[4]. The total storage volume is 74 billion cubic meters with an active storage volume of 59.2 billion cubic meters.For a design flow o f 4,305 cubic meters per second and a maximum net head of 133 meters and plant factor of 0.31, the expected average energy production per year is 15,692 GWH, with installed capacity of up to 6000 MW [4]. The plant has two surface powerhouses equipped with sixteen power generating units and a switchyard. The installed power is flexible (base or peak) and the plant has been designed so that the installed capacity may be built in several stages [4].

2. METHODOLOGY

2.1 *Inflows*

A set of data covering the years 1965-2012 on daily basis, for Eldeim station (Sudan-Ethiopia boarder), Rosaries, Sennar, KhashmElgerba and Jebel Aulia releases for the same period [1], were used.It should be noted that, the data was analyzed using excel sheet especially designed for calculation of probability of exceeding and averaging of time series. Furthermore, average discharges were calculated in time series for daily basis, and then aggregated to monthly time steps. Figure 2 shows Eldeim average time series extracted from the data.

It worth mentioning that, the same analysis was applied for the whole set of data, and average time series were created. A correlation between Eldeim average and Sennar release average was obtained, and thus daily discharge factors were computed

and applied later on during simulation, in order to identify the different scenarios. It should be noted that, the demand for different purposes for the reaches between Merowe and Eldeim are estimated to be between 0-9% for different time zones.
All power generation parameters are considered from Merowe operation manual, or calculated from real daily historical data for the period 2012-2015. The mean demand was estimated in daily basis, shown in Figure 3.

For the purpose of this analysis, instead of using the efficiency; average Specific Water Consumption S.W.C (the amount of water needed to generate one energy unit (Gig watt) were calculated from real daily data and used. The computation covered different head ranging from 33 - 53 m using the historical data of Merowe Power Plant for the period 2012-2015.Average S.W.C in Mm^3/Giga-watt, were estimated in daily basis for one average year to be used in calculation are shown in Fig. 4. It is worth mentioning that power plant availability factor was taken as 0.9 (n+1)**[5].** where**:** n: is Number of units needed for generation.

2.3 *Inflows Routing*

In a stream channel (river), a flood wave may be reduced in magnitude and lengthened intravel time. It is usually, attenuated by storage in the reach between two sections, which is normally, divided into two parts, prism storage and wedge storage[6].

Generally, it is found that two Types of Hydrograph Routing are classified [7].

1. Storage or Reservoir Routing
2. Channel Routing

In this simulation, Muskingum-Cunge routing model [7] was used to route all the three dams' releases down to EL koru station at Abu Hamed (Entrance of Merowe Reservoir). Nevertheless, the model of routing was calibrated and verified as shown in figure 5.

2.4 *Merowe Reservoir Parameters*

effect of GERD on the hydrograph during first impounding in

2.2 *Power Plant Parameters*

Merowe reservoir is operated in yearly mode of emptying and filling, the hydrological year is assumed to start at first of January and ends by 31st of December every year. Starting from January Merowe reservoir is drawn down from the full supply level 300 m down to level 287 m by mid of July, then build up the level up to 290 m.

Maintaining the minimum level of 290 m during flood season, s very important to flush the sediment and accommodate the flood peak. During this period, it is highly advised to observe the net head avoiding cavitations zone, beside safe-guard enough net head for the generation.

Starting at September, the filling takes place, completed by end of October. The reservoir is suspended at the full supply level until mid to end of December every year.

Operation average rule curve in Fig. 6 was developed based on averaging historical data of water level for the period 2011-2014, however, 2015 rule curve were excluded for the oddness of this year [5].

2.5 *GERD Scenarios*

GERD has been studied for two conditions: Firstly, First impounding of reservoi and Secondly long run simulation.

2.5.1 *First Impounding of GERD Reservoir*

GERD first filling scenario is very crucial, because it affects, directly, the hydrology of Blue Nile which affects the hydrological regime of the main Nile.Although, the first filling could start on 2016, but no agreed scenario is confirmed up to the time of this paper.The proposed scenario in table 1 is considered as filling method for the purpose of the study. However, the real scenario might differ slightly from this proposal.

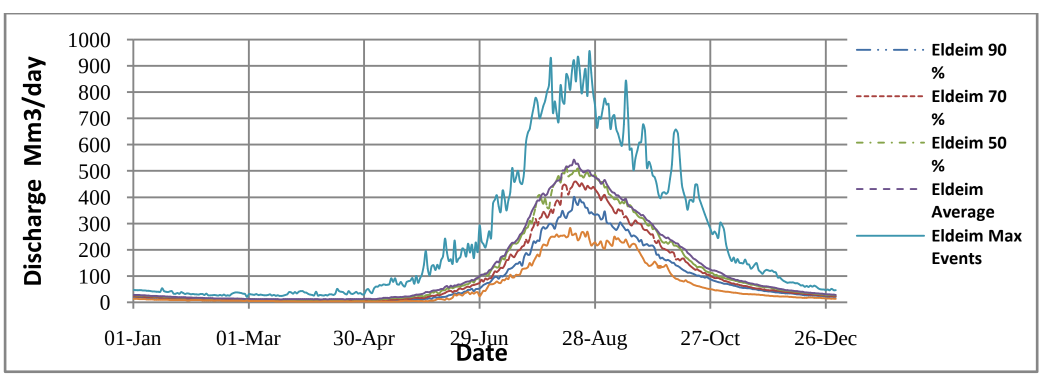

Fig. 2: Eldeim Analyzed Discharge Daily Hydrograph (1965-2012)

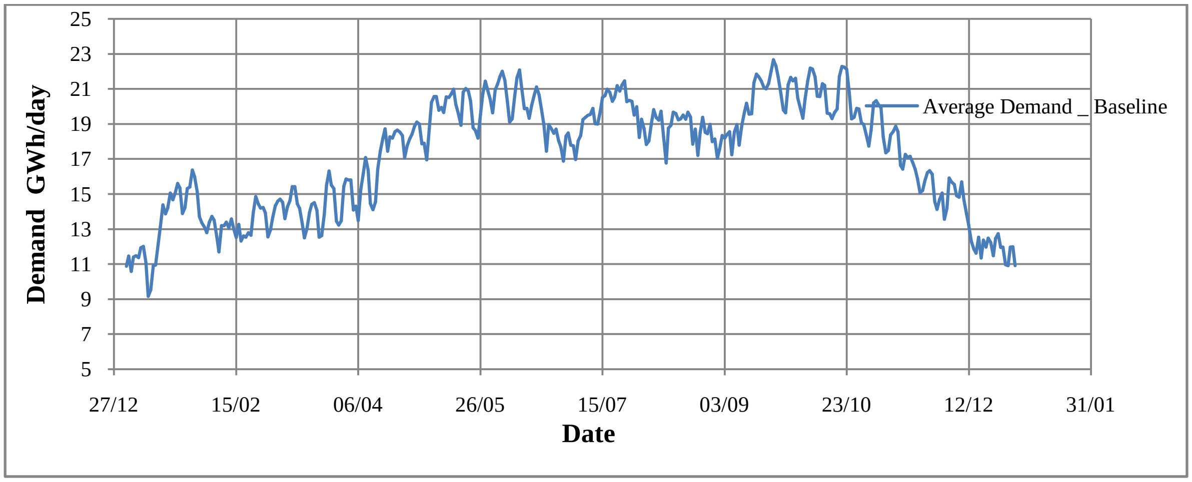

Fig. 3: Average Daily Electricity Demand Baseline at Merowe Dam

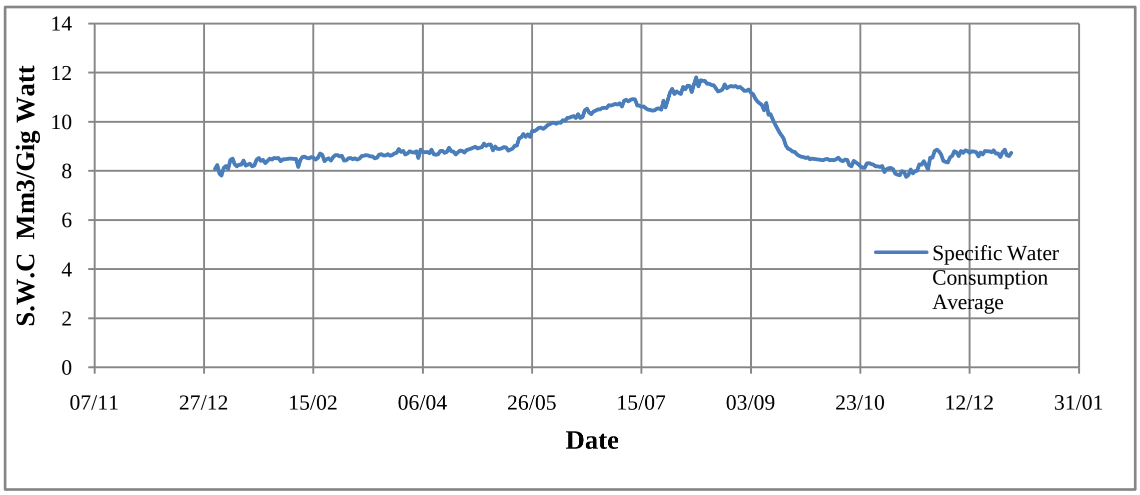

Fig. 4: Average Specific Water Consumption S.W.C

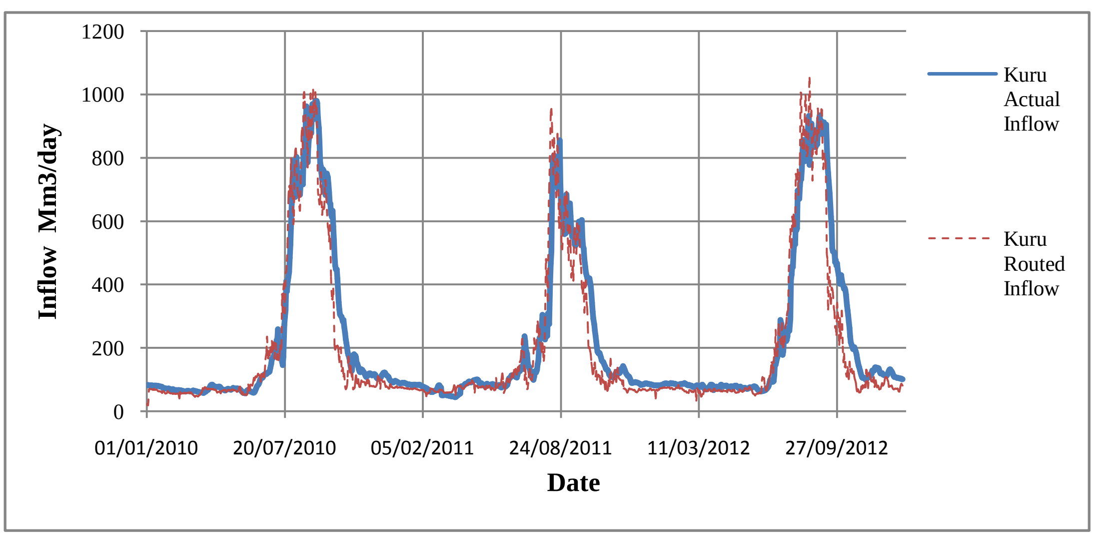

Fig. 5: Kuru Routed Vs Actual Inflows 2010-2012

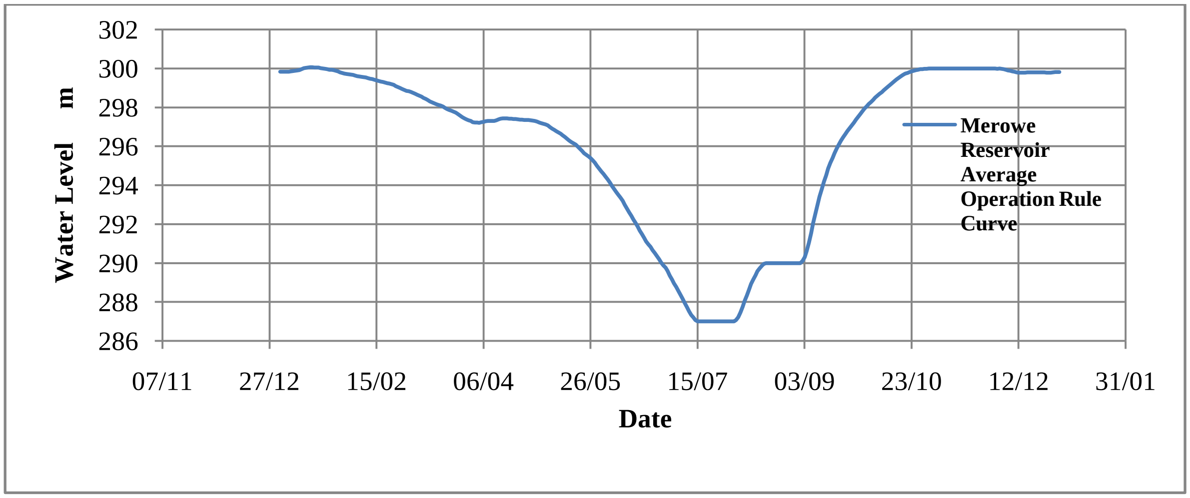

Fig. 6: Merowe Reservoir Average Operation Rule Curve

The scenarios considered were retaining a certain amount of Blue Nile water to satisfy the requirements during filling stages, it was assumed to run the model for different scenarios of retention by: 10, 20, 30, 40, 50 % of the average discharges at Eldeim and conclude the results respectively.

2.5.2 Long Run Simulation after first filling

Generally, GERD is intended to be operated as presented in Table 2. The mean monthly outflows from GERDP were taken and correlated with Sennar, then routed to Merowe and used in Merowe generation calculation for long run as inputs.

2.6*Power Calculation*

From the general water power equation

$$P = \eta.\gamma.Q.H \qquad (1)$$

Where: $\boldsymbol{P}$ = power in Watts; $\boldsymbol{\gamma}$ = specific gravity of water in N/m^3; $\boldsymbol{H}$ = net head m; $\boldsymbol{Q}$ = Discharge m^3/s and $\boldsymbol{\eta}$ = efficiency. Applying equation number (1), energy calculation at Merowe was obtained, for different scenarios and conditions, the results were obtained and discussions and conclusions are here-below presented.

3.RESULTS

Generally, the model outputs are two sets of results, one representing the first impounding period which is taken as six years starting from 2016 up to 2021. The other period is considered to start after the GERD reservoir is completely filled and GERD is fully operational.

3.1 *Impounding Period Results*

The following results are obtained from running the model with adequate data set and boundary conditions, and presented in Fig. 7. The results show an average energy output of 6465 GWh/Year for the baseline, While, for the scenarios of retaining water for first impounding between 10-50 % of Blue Nile yield, the results range between 6333 - 5668 GWH/Year respectively, the mean monthly generation during GERD impounding are found between 539 - 474 GWH/month. It should be noted that, from the results the Energy generation in August is similar for all scenarios.

3.2 *Long Run Results*

The results show an average (Baseline) energy output of 6465 GWH/Year before GERD effect. However, it is found that the generation due to Blue Nile contribution after GERD filling completion is 7891 GWH/Year for an average discharge year. The mean monthly generation is found about 658 GWH/month.

Table 1: First Filling of GERD proposed Scenario:[2]

Year	Inflows	Losses	Outflows	Srored water	Energy
2011	48655		48655		
2012	46969		46969		
2013	32194		32194		
2014	46547	81	43120	3427	700
2015	51418	427	30439	20979	2507
2016	55615	1016	37677	17938	9900
2017	47242	1369	35349	11893	10300
2018	49615	1603	35177	14438	11000
2019	47735	1848	38145	9591	12600

Table 2:GERD Impounding Stage-average sequence-yealy inflows, losses, outflows and energy generation. Unit: Mm3/yr

Month	Mm3/yr			Mean Water Level	GWh/yr
	Inflows	Losses	Outflows		Total energy
January	429	221	3534	629	1155
February	498	215	3168	627	1032
March	408	261	3440	625	1091
April	390	230	3348	623	1045
May	649	149	3503	621	1058
June	1765	62	3476	620	1028
July	77232	-5	3922	622	1170
August	14293	1	4014	629	1235
September	11966	22	6241	633	1871
October	6581	153	5430	634	1728
November	2768	194	3505	633	1152
December	13392	194	3533	632	1164
Year	48770	1698	477113	627	14729

4.DISCUSSION

During the assumed impounding years (6 years), the monthly effect in % compared to baseline average generation before GERD is presented in figure 9.

It is observed that the effects for the five expected scenarios is limited to a deficit of 5% during summer season (January-June), while in July significant deficit occurred ranging from 2-22%. Nevertheless, August remains with no changes and no energy losses were observed.

For the period September to December, it seems to be as a bottle neck due to the high demand and low generation, which will create a dilemma (33% Deficit in October) that will affect power generation in Merowe Dam. In general, the total energy is going to be reduced by 2-12 % from the average baseline.

4.1 Demand Satisfaction during first Impounding

The average demand has been compared with the five scenarios output and shown in fig. 10. During summer season (January – June), It is found that, the demand is satisfied with slight deficit of about 5%.For the period July to December, except, August, the demand satisfaction could not be achieved when the retained water for first impounding is bigger than 30% of Blue Nile yield. It is noted that, the period from September to October is affected by both GERD impounding, and national dams of Sudan impounding, including Merowe Dam itself. The total yearly energy, generated at Merowe Dam, during first impounding of GERD based on the five scenarios, annual demand is satisfied by a range of 90-100%.

4.2 *Long Run Effect*

The monthly power generation in Merowe Dam is going to be affected by controlling Blue Nile by GERD. Furthermore GERD operation for Long-Run is going, defiantly, to affect hydropower generation at Merowe Dam as shown in Fig. 11 below:
No doubt, redistributed water among year, causes a lot of disturbance for the hydrological system, this effects are clearly observed when carefully examining Fig.5.

High potential due to water increase from GERD generation is highlighted. Especially during summer times which might reach up to 116% increment extra of the generation at Merowe.An average increase of about 60% in energy is considered as a result of GERD operation during summer period (January-June). On the other hand, a drastic draw down in generation took place in July due to GERD annual impounding and low generation during this month, the power generation is significantly reduced by 46% of the average baseline which is considerable magnitude, and so happens for September by 20% of energy reduction.

From October, it is observed that the generation recovers again and rises up above the average. It is clearly observed that GERD is going to increase hydropower generation at Merowe Dam by an average of 33% monthly, compared to the design baseline.

The total energy is going to be increased by 27 % from the average design baseline.Demand Satisfaction during Long Run. The average demand satisfaction has been highlighted from the results of long run operation for GERD, and shown in fig. (12)

For the summer season (January-June), most likely, an amount from 120% to 190% of the demand is satisfied, which indicated high opportunity of more generation to be considered at the future. Nevertheless, July seems to be problematic, since only 60% of the demand is satisfied, which should be paid especial caution. Furthermore, August, September both reflected high deficit with about only 80% satisfaction.

Annually, Merowe dam could cover extra 26% of the demand, energy wise, but still has the problematic flood months (July-September) in terms of power capacity; it is highly advised to change the operation policy regarding the rule curve of the reservoir to meet the requirements, and to cope with the new situation.

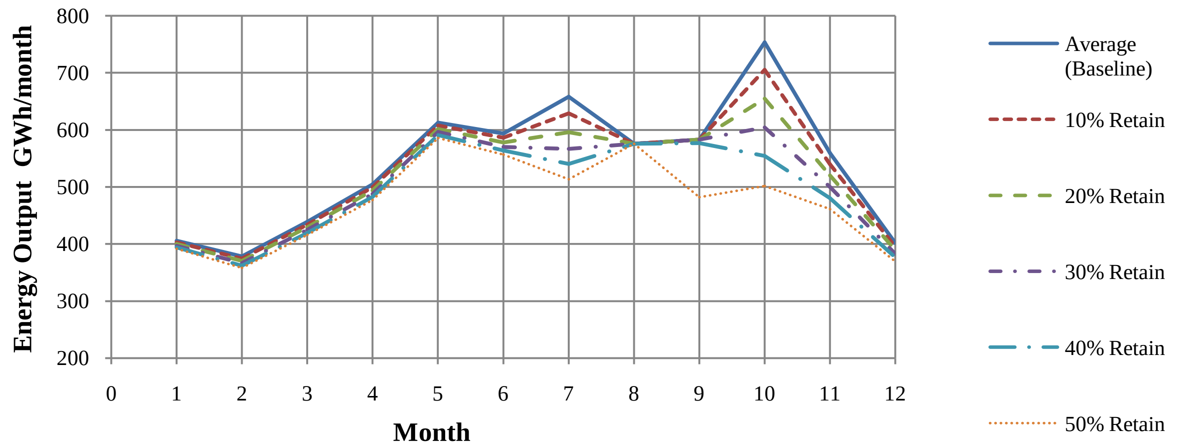

Fig. 7: Monthly Energy Output at Merowe Dam During 1st GERD Impounding (10 - 50 % Water Retain) for the Years (2016 -2021)

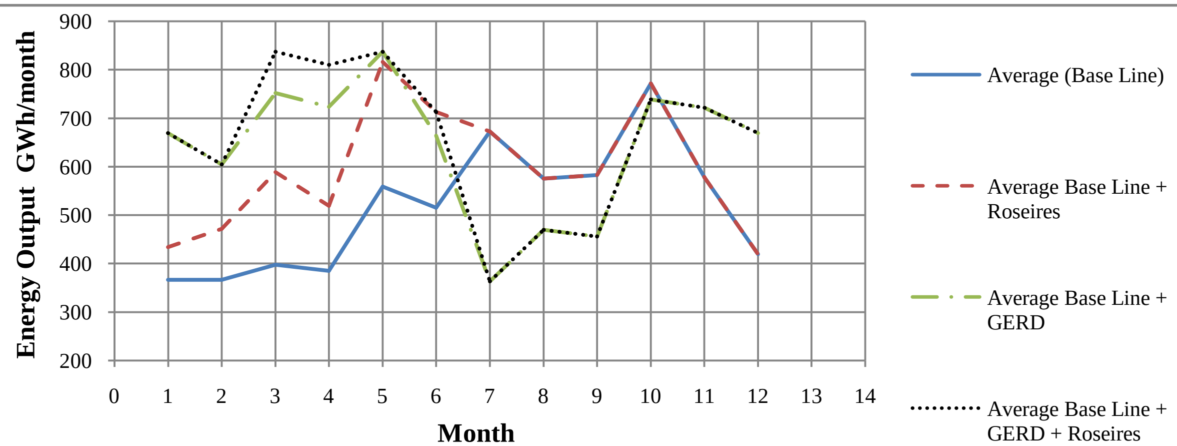

Fig. 8: Monthly Energy Output at Merowe Dam Afeter GERD Impounding Starting from Year 2022

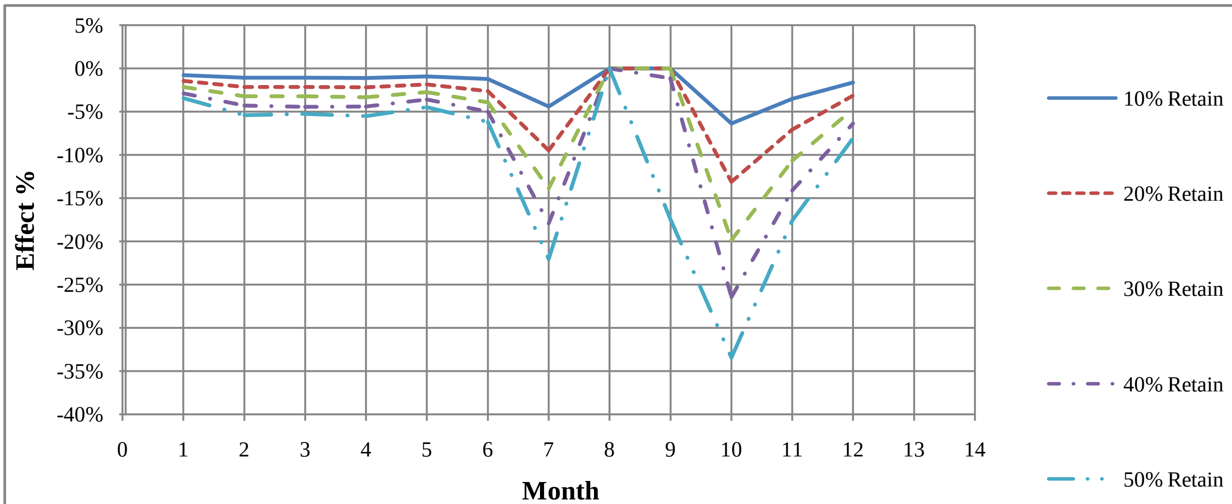

Fig. 9: Average monthly effect on energy Output at Merowe Dam compared to average during 1st GERD impounding (10 - 50 % water retain) for the years (2016 -2021)

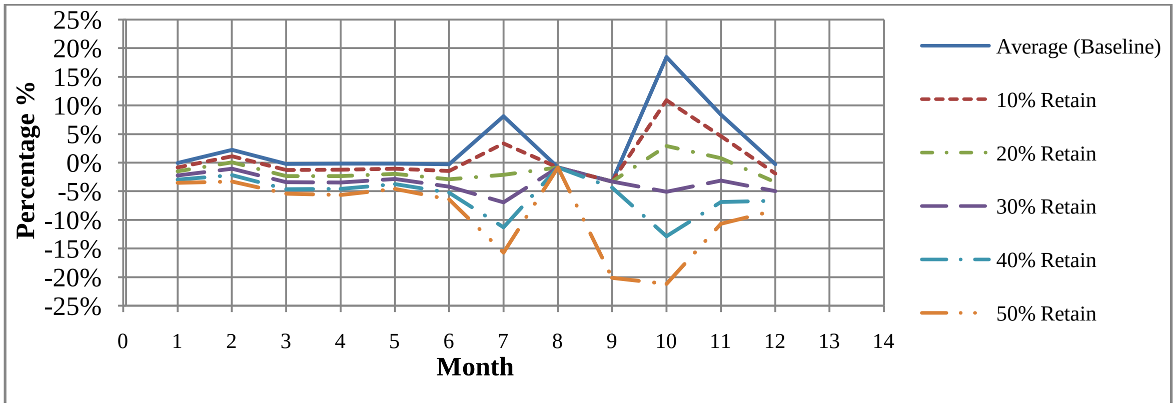

Fig. 10: Deficits (-), satisfaction (0) and surplus (+) in demand at Merowe Dam compared to average demand during 1st GERD impounding (10 - 50 % Water Retain) for the years (2016-2021)

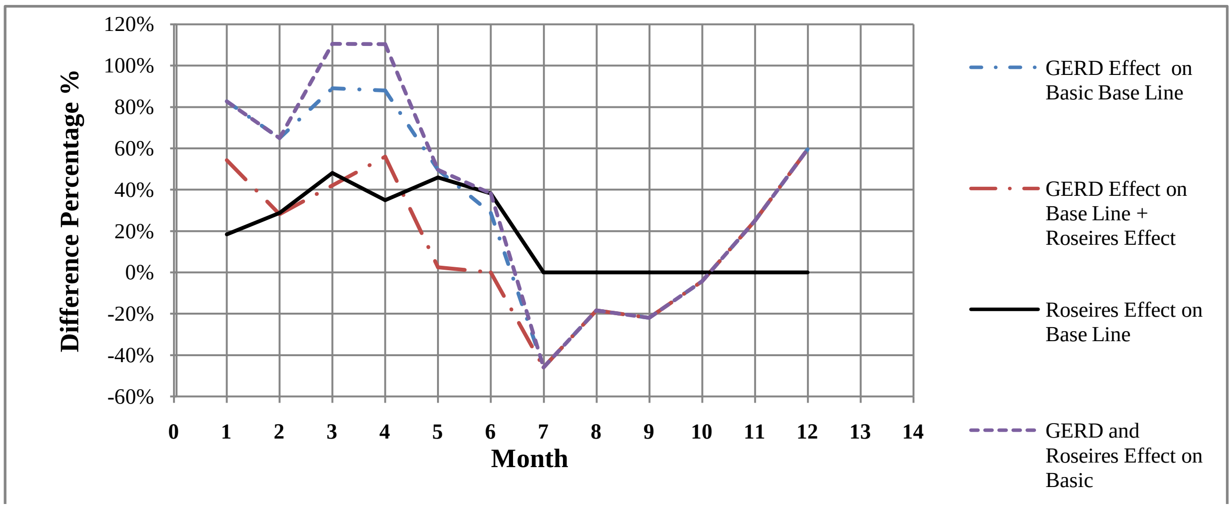

Fig.11: Average Monthly Differences in Energy Output at Merowe Dam Afeter GERD Fully Operational Starting from Year 2022

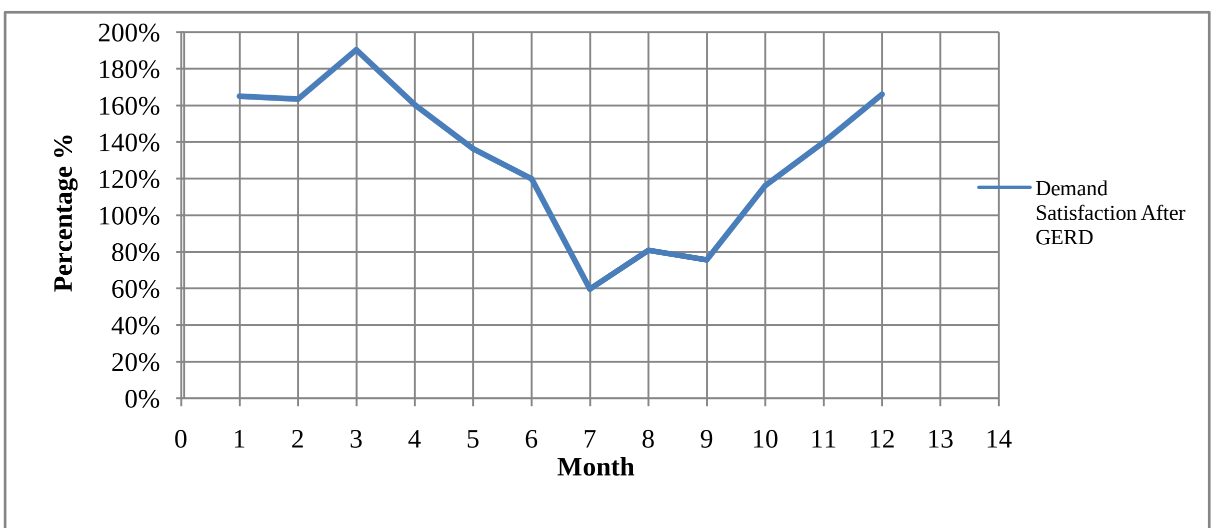

Fig. 12: Demand satisfaction at Merowe Dam compared to average demand after GERD fully operational starting year 2022

4.3 *Dependability*

From the above mentioned findings, it is clearly obvious that, special attention should be paid for Merowe Dam in order to overcome the expected deficits in terms of both energy and power generation. It is clearly stated that during flood season months (July-September) important shortage most likely occur, and this needs to be reviewed again and try to investigate the application of one of the following measures:

1. Reduce spilling reserve (n+1) will increase units availability.
2. Increase the efficiency of the units by allocates more loads, and will enhance the S.W.C.
3. Changing the operation rules slightly, and carefully to fit with the new situation after GERD.

Other measures from different firms could be a solution like load shedding or increasing tariff may effectively mitigates the negative impact of energy deficit.

5. CONCLUSIONS

5.1 *Conclusions for the first Impounding Period*

The Baseline generation of Merowe Dam for average year is 6465 GWH/Year. During GERD first impounding, it was assumed that GERD will retain water for different percentage from 10 to 50 % with step of 10. The results of generated power ranged between 6333-5668 GWH/Year respectively. Mean monthly generation during GERD impounding are found between 539-474 GWH/month. The total energy is going to be reduced by 2-12 % from the average baseline. Deficit of 5% during summer season (January –June) will occur. In July significant deficit occurred ranging from 2-22%. The most observed results the deficit in October by 33%. For the period from July to December, except, August, the demand satisfaction could not be achieved when the retained water for first impounding is higher than 30% of Blue Nile yield. During first impounding of GERD 100-90 % of the annual demand is satisfied.

5.2 *Conclusions for Long Run Period*

Generation at Merowe Dam due to Blue Nile contribution after GERD filling completion is 7891 GWH/Year for average discharge year. The mean monthly generation after GERD is found to be about 658 GWH/month. An increase of about 60%, with an instant shooting of 116% in energy is considered as a result of GERD operation during summer period (January-June). The power generation is significantly reduced by 46% of the average baseline which is considerable magnitude, and so happens for September by 20% of energy reduction. GERD will increase the recent generation of Merowe Dam by 15%, by 33% from the design energy monthly. Annual energy is going to be increased by 27 % from the average baseline (Design Average) and by 10% from recent average. During summer season (January-June), between 120% to 190% of the demand is satisfied, while only 60-80% of the demand is satisfied during July-September. Extra 26% of the demand, energy wise is available after generation. Further actions and measures are of important such as reduction of spilling reserve, increasing the efficiency and changing the rule curve of the reservoir.

REFERENCES

[1] Merowe Dam Electricity Company (MDEC), Ministry of Water Resources and Electricity, 2013, Rosaries Effect on Merowe Generation, Merowe, Sudan.
[2] TRACTEBEL Engineering, COYNE ET BELLEIR, Hydrological and Reservoir Simulations Studies, Grand Ethiopian Renaissance Dam Project Impounding and Operation Simulations Impact Study on High Aswan Dam, 2011, Addis Ababa, Ethiopia.
[3] Hydro-project Institute (HPI), Merowe Dam Project, Detailed Project Report, Volume III- 4, Water Management, Economics, Electric Energy Production, Moscow, 2001.
[4] Ministry of Water Resources and Irrigation of Ethiopia, International Panel of Experts Report on GERD, Addis Ababa, Ethiopia. May 2013.
[5] Lahmeyer International (LI), for Ministry of Water Resources and Electricity, October 2012, Long and Medium Term Power System Plans in Sudan, Badvilbel, Germany: LI / GE7 26 0690
[6] Hydrology, Principles, Analysis, Design, H. M. Raghunath, New Age International Publisher, New Delhi, India, 2015, ISBN : 978-81-224-3618-1.
[7] Lecture Note, GEOLOGY 711 - PRINCIPLES OF HYDROLOGY, BY DR., UNIVERSITY OF NEVADA, LAS VEGAS, USA, 2014. http://hydro.nevada.edu/courses/gey711/