Multi-purpose Reservoir Operation Analysis in the Blue Nile Basin, Ethiopia

Dereje M. Ayenew[1], Mamaru A. Moges[2,3](✉), Fasikaw A. Zimale[3], and Asegdew G. Mulat[2,3]

[1] Water, Irrigation and Energy Development Bureau, Bahir Dar, Ethiopia
[2] Blue Nile Water Institute, Bahir Dar University, Bahir Dar, Ethiopia
mamarumoges@gmail.com
[3] Bahir Dar Institute of Technology, Bahir Dar University, Bahir Dar, Ethiopia

Abstract. This study focused on developing rule curves for multi-purpose cascade reservoirs operation to optimize the available water for hydropower production, irrigation development, water supply, and environmental flow in Blue Nile Basin using HEC-ResSim reservoir simulation model. The model tried to represent the physical behavior of cascade reservoirs in the basin with its high speed hydraulic computations for flows through control structures, and hydrologic routing to represent the lag and attenuation of flows through the main and tributaries of the river based on the current projects operation, and future likely development projects implementation period. Therefore, the management of multi-purpose cascade reservoirs is complex due to conflicting interests between these objectives. Thus, the optimal operation of cascade reservoirs is important to address trade-offs between multiple objectives to achieve the water management goals. From the simulation of cascade reservoirs operation, Hydropower power guide curve operation rule was selected to optimize the basin's available water.

Keywords: Cascade · HEC-ResSim · Optimize · Simulation · Blue Nile Basin

1 Introduction

Reservoir operation is a complex problem that involves many decision variables, multiple objectives as well as considerable risk and uncertainty [1]. In addition, the conflicting objectives lead to significant challenges for operators when making operational decisions. Different reservoir operation models have been developed and applied for planning studies to formulate and evaluate for solving water resources management problems; for feasibility studies of proposed projects as well as for re-operation of existing reservoir systems. However, the selection of an appropriate model for the derivation of reservoir operation is difficult and there is a scope for further improvement [2]. For this study, HEC-ResSim reservoir simulation model was used. Since its versatility, freely available, interface with other HEC models and applicable for both series and parallel reservoirs operation [3].

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There are a number of existing, under construction, and planed development projects in Abbay basin. According to the Abbay basin master plan [4], joint multi-purpose projects upstream of Grand Ethiopian Renaissance Dam (i.e. Karadobi, Beko Abo and Mendaya) projects were identified. There were no recent studies directly in Blue Nile basin on optimal multi-purpose cascade reservoirs operation. But, few investigations have been conducted on the hydrology of the upper Blue Nile basin due to absence of data and other limitations. In the past, some related research and development projects were conducted in the Blue Nile basin [4–8] investigated that the total hydropower generation in the basin is about 13,000 MW [4] and around 815,581 ha of irrigable command area [9]. However, all of the studies were conducted at feasibility level and are not detail studies.

Thus, the objective of this study was to develop optimum rule curves for multi-purpose cascade reservoirs system for Blue Nile basin, this study has the importance of the implementation of good water resources management and allocation among the upstream and downstream users (water supply, irrigation, power generation requirement and environmental releases for downstream ecosystem).

2 Description of Blue Nile Basin

The Ethiopia part of Blue Nile also called Abbay basin in Ethiopia is located in the northwestern region of Ethiopia between 847705 m N and 1420688 m N latitude, and 656255 m E and 588616 m E longitude. It covers an area of approximately 199,812 km2 and it shares a boundary with the Tekeze basin to the north, the Awash basin to the east and southeast, the Omo-Gibe basin to the south, and the Baro-Akobo basin to the southwest. The Blue Nile River is the most important tributary of the Nile River, providing over 62% of the Nile‘s flow at Aswan [10]. Both Egypt, and to a lesser extent Sudan, are almost wholly dependent on water that originates from the Nile. This dependency makes the challenges of water resources management in this region an international issue [11].

From its source Gish (approximately 2744 masl) in West Gojam, flows northward as the Gilgel into Lake Tana. The Blue Nile River exits from the south east of Lake Tana and flows south and then westwards cutting a deep gorge towards the western part of Ethiopia. The basin accounts for a major share of the country’s irrigation and hydropower potential. It has an irrigation potential of 815,581 ha and a hydropower potential of 78,820 GWh/y [9]. A number of tributaries joined River in Ethiopia: Beshilo, Derame, Jema, Muger, Finchaa, Didessa and Dabus from the east and south; and the Suha, Chemoga, Keshem, Dera and Beles from the north. The Dinder and Rahad rise to the west of Lake Tana and flow westwards across the border joining the Blue Nile below Sennar. In the Sudan, the Blue Nile flows on the plain desert until it reaches the confluence, where it meets with White Nile in Khartoum.

The topography of the Blue Nile basin signifies two distinct features; the highlands, ragged mountainous areas in the center and eastern part of the basin and the lowlands in the western part of the basin. The altitude in the basin ranges from 498 masl in the lowlands up to 4261 masl in the highlands. The Ethiopian highlands extend from 1500 masl up to as high as 4260 masl, with a slope of greater than 25% in the eastern part. Whereas the Ethiopian lowlands flatten 1000 masl to 500 masl with a slope of less than 7%, in Dinder and Rahad sub basins [12].

Lake Tana is Located at an altitude of 1,786 m above sea level. The catchment area at the lake outlet is 15,321 km^2. Geographically, it extends between 1211257 m N and 1412924 m N in latitude and from 269408 m E to 418595 m E in longitude. The elevation ranges between 914 m to 4096 m above sea level. More than 40 rivers and streams feed Lake Tana; but 93% of the water comes from four major rivers: Gilgel Abbay, Ribb, Gumara and Megech [13].

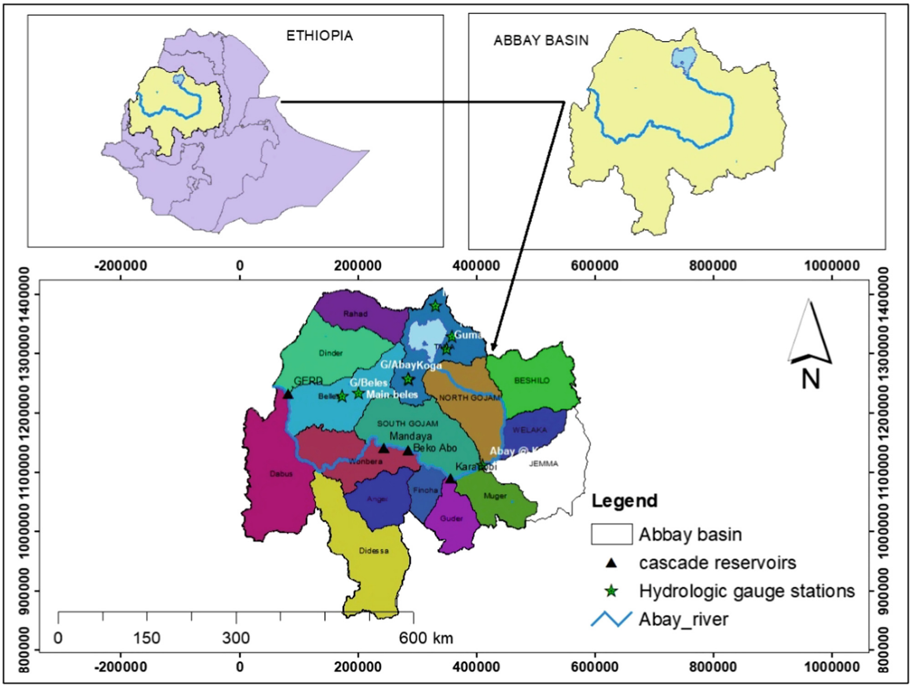

Fig. 1. Location of Blue Nile cascade reservoirs

3 Materials and Methods

3.1 HEC-ResSim Model Approach and Data Sets

The tool used in this study was HEC-ResSim reservoir simulation software with the intensive data needs for reservoir simulation and flow routing in the river basin system. The model used times series (observed and local flow) data, physical and operational reservoir (elevation-storage-area, dam elevation and length data).

HEC-ResSim has a graphical user interface which utilizes the HEC data storage system (HEC-DSS) for storage and retrieval of input and output time series data. HEC-DSS is designed as the data base system, which effectively store and retrieve data, such as time series data, and spatially oriented girded data and more [3]. It is unique among reservoir simulation models because it attempts to reduce the decision making process that human reservoir operators must use to set releases. The program represents the physical behavior of reservoir system with a combination of hydraulic computations for flows through control structures and hydrologic routing to represent the lag and attenuation of flows through segments of streams. It represents operating goals and constraints with an original system of rule based logic that has been specifically developed to represent the decision-making process reservoir operation [3].

Stream flows are needed and estimated at each site where management decisions are being considered based on the results of rainfall-runoff models or on measured historical flows at gage sites. Since, there are no stream flow gauge stations at the inlet of Lake Tana and river flow did not fully reach at the mouth of the Lake due to the effect of flood plains and back water effect in the catchments, the stream flow were simulated using a semi-distributed conceptual Parameter Efficient Distributed Watershed Model (PED-W) rainfall runoff and sediment loss model applied to catchments ranging from a few square kilometers to hundreds of thousands of square kilometers with minimum calibration parameters based on the saturation excess runoff process [13–15] and input for HEC-ResSim model simulation. The ungauged parts of the major watersheds as well as additional ungauged areas of the Lake Tana basin were simulated using [16]. Below Lake Tana sub basin, stream flow gauge stations in the basin are poorly distributed in the area of interest; gauged stream flows were transferred to ungauged sites using the recommended area ratio method [17] described in Eq. (1). This method uses the drainage areas to interpolate flow values between or near gauged sites on the same stream. Flow values are transferred from a gauged site, either upstream or downstream to the ungauged site. Having these, the inflow regime of the downstream reservoirs are governed by the upstream hydropower reservoirs and contributing catchments (incremental flow) and tributaries.

$$Q_{site} = Q_{gaug}[\frac{DA_{site}}{DA_{gaug}}]^n \tag{1}$$

where DAsite is drainage area of site of interest, DAgauge drainage area of the gauge site, Qsite discharge at site of interest (m^3/s), Qgauge discharge at gauge (m^3/s), and n a parameter typically varies between 0.6 and 1.2.

If the DAsite is within 20% of the DAgauge (0.8 < -[DAsite/DAgauge] < -1.2). Then n = 1 to be used. The estimated discharge at the site will then be within 10% of actual discharge. When DAsite is within 50% of the DAgauge two station data are considered for data transferring. Relation can be developed to estimate a weighted average flow at a site lying between upstream and downstream gauges.

$$Q_{site} = \frac{(DA_{gaug1} - DA_{gaug2gaug1} + (DA_{site} - DA_{gaug2}))}{(DA_{gaug1} - DA_{gaug2})} \tag{2}$$

where gauge1 upstream gauging site and gauge2 downstream gauge site. These methods were applied to transfer all river discharge to the proposed dam site and river confluence locations (mainly confluence to Abay River).

The aim of this study was to develop the optimal reservoir operation rule curves, reservoir and power guide curves using the three reservoir operation rules under HEC-ResSim simulation for the period of 1973–2014 on monthly basis of stream flow data;

the total stream flow (including rainfall over the reservoir surface area and the total demand (irrigation releases, hydropower releases, environmental release, water supply), water losses (evaporation), useful storage, water spilled and water stress analysis were also undergo using excel spreadsheet.

Simulation was performed to select the optimal reservoir operation rule that optimize the available water resources of the basin for hydropower energy generation, environmental release and irrigation demand satisfaction as well as flood control each year. Accordingly, simulation was performed using the defined three reservoir operation alternatives for each four scenarios taking into account the present reservoirs operation and future likely development projects considering similar future hydrologic condition of the basin using monthly time series of inflow data from 1973–2014 (Fig. 2).

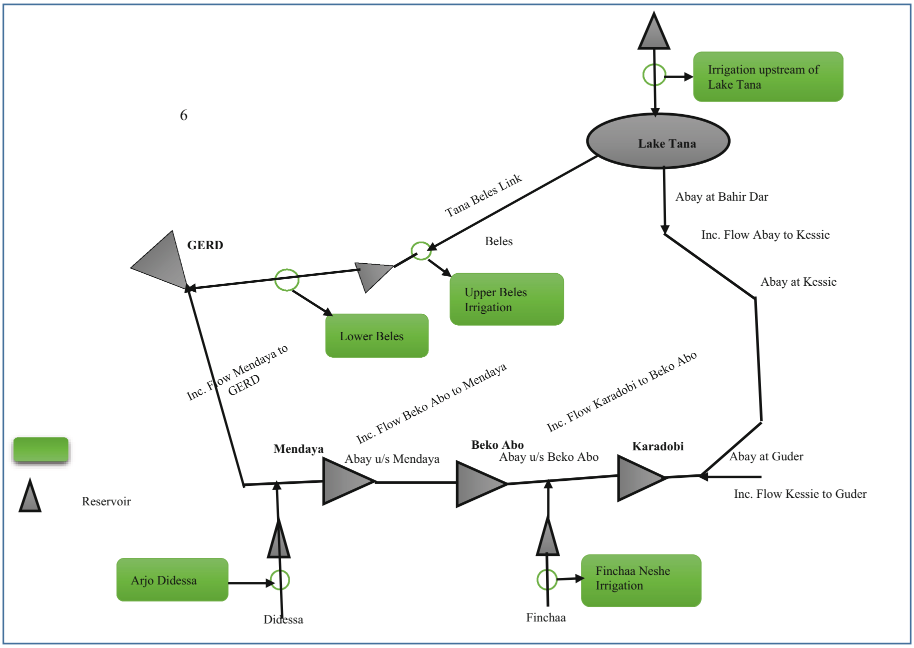

Fig. 2. Blue Nile Basin reservoirs schematics

Scenarios for Blue Nile Basin cascade multi-purpose reservoirs were set based on the present and likely future projects implementation in the basin to see their future likely effects when they are operational in similar time periods. The scenarios are:

Scenario one: Lake Tana only,
Scenario two: Lake Tana, GERD,
Scenario three: Lake Tana, GERD, Karadobi,
Scenario four: Lake Tana, GERD, Karadobi, Bekoabo, Mendaya

Based on this, the simulation results were presented below for the four scenarios based on the three alternatives for the reservoirs operation to optimize the available water resources in the Blue Nile River Basin. Lake Tana was developed basically for the Lake's future situation by considering Beles transfer project, irrigation projects directly pumped from the Lake, environmental flow requirement for Tis Isat fall and irrigation projects upstream of Lake Tana basin.

On the basis of modeling of the cascade reservoirs in the basin to optimize the available water for hydropower, irrigation water demand satisfaction, water supply, environmental and flood controlling in the cascade reservoir system, the alternatives were drawn for each scenario to select the best reservoir operation which provides the maximum power generation. The reservoir operation rules applied on cascade dam/reservoirs for the three alternatives are tandem reservoir operation (alt-1), hydropower schedule (alt-2) and hydropower guide curve (alt-3). Tandem reservoir operation rule operates the reservoir operation in the system and storage distribution among the reservoirs on the same river system. In tandem reservoir operation rule; the model determines the volume of water release from the upper reservoir in such a way that the downstream reservoir is operating to achieve a storage balance. For every decision interval an end-of-period, storage is first estimated for each reservoir based on the sum of the beginning of period storage and period average inflow value, minus all potential outflow volumes. The estimated end of date storage for each reservoir is computed to a de-sired storage that's determined by using a system storage balance scheme. The priority for release is then given to the reservoir that is furthest above the desired storage. When a final release decision is made, the end of period storage is recomputed. Depending on other constraints or higher priority rules, system operation strives for a storage balance such that the reservoirs have either reached their guide curve or they are operating at the desired storage [3]. On the other hand, Hydropower schedule operation rule has an option to define a regular monthly or user specified seasonally varying hydropower requirements while power guide curve rule permits defining a function that describes the hydropower generation requirement with respect to the available storage in the power pool.

Water Demand

Water demand is the sum of all water requirements for the different water uses served by the reservoir for the time period t. The demand varies with time (e.g., due to seasonal agricultural demand or due to some rule, usually based on the quantity of water in the reservoir). The possibility of supplying as much water to the irrigation area as is needed during each period of the irrigation season depends primarily on the availability of the water at its source. Availability may vary within a year, or from year to year. For this study, the computation of irrigation water demand for each dam was done using crop wat model and ENTRO tool kit and presented in Table 1.

Table 1. Water demand of current, proposed and under development projects (ENTRO, 2009)

Water demand (MCM)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Ribb (19920 ha)	37.3	42.7	26.4	14	21	0	0	0	0	0	5.4	18.6
Koga (7000 ha)	14.2	15	6.4	0	0	0	0	0	0	0	4.1	9
Megech (7310 ha)	16.6	26.4	21.5	10.3	2.4	0	0	0	0	0.5	4.9	8.3
G/Abbay (14552 ha)	34.2	39.6	31.9	5	4.8	12.3	3.9	1.7	1.8	1.9	7.1	24.7
Gumara (14000 ha)	20	26.4	26.6	14	0	0	0	0	0	0	18	18.1
Arjo Didessa (13665)	18.9	23.5	12.7	1.9	0	0	0	0	0	0	12	15.3
Finchaa Nesh (21000 ha)	18.9	20.5	13.5	10.6	1	0	0	0	3.3	14.3	23.9	23.4
Upper Beles (53720 ha)	84.1	87.9	75.8	72.9	23.1	0	0	0	0	0	81.4	39
Lower Beles (85000 ha)	148.3	185	173.2	91.7	5.2	0	0	0	0	0	121.6	47.1
NE Tana (5475 ha)	8.2	10.5	11.0	5.1	0.0	0.0	0.0	0.0	0.0	0.0	6.2	6.9
SW Tana (11632 ha)	16.2	23.5	23.4	13.6	0.0	0.0	0.0	0.0	0.0	0.0	10.9	16.2
NW Tana (6720 ha)	8.9	11.9	13.2	6.5	0.0	0.0	0.0	0.0	0.0	1.6	8.5	9.2
Megech Pump (24510 ha)	32.0	42.9	47.6	23.2	0.0	0.0	0.0	0.0	0.0	5.3	30.8	33.3

Hydropower Energy Requirement

The monthly energy requirement is input data for the model for the allocation of the release through the outlet of the hydropower based on the reservoir operation and these monthly energy requirements were considered as constant throughout the simulation period by the assumption that the hydropower projects were designed at least for 50 years (Table 2).

Table 2. Monthly energy generation requirements in GWh for the hydropower reservoirs

Reservoir	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Lake Tana	–	–	–	–	–	–	–	–	–	–	–	–
Karadobi	235	161	195	187	200	286	2208	4374	2090	937	486	326
Bekoabo	328	236	286	271	310	434	2371	5325	2506	1268	600	423
Mendaya	260	187	220	208	254	456	1598	3935	2285	1322	521	335
GERD	342	244	279	254	326	605	2174	4678	3191	1865	760	468

3.2 HEC-ResSim Simulation Model

HEC-ResSim represents a significant advancement in the decision support tools available to the water managers and used to model reservoir operations at one or more reservoirs for a variety of computational goals and constraints. The software simulates reservoir operations for flood risk management, low flow augmentation and water supply for planning studies, and real-time decision support. The software can be used as a decision support tool that meets the needs of modelers performing reservoir project studies as well as meeting the needs of reservoir regulators during the real time events.

The model has three separate modules which are watershed setup, reservoir network definition and simulation scenario management each with unique purpose and an associated set of functions accessible through means, toolbars, and schematic elements. The model development began with the establishment of watershed schematics followed by establishment of reservoir network that represents a collection of watershed elements connected by routing reaches. The network includes reservoirs, reaches and junctions. Finally, the model development was completed by defining the development of alternatives for each scenarios and running simulations and analyzing results accordingly and best alternative was selected for cascade dams and reservoirs operation.

4 Result and Discussion

4.1 Reservoir Inflow Generation

4.1.1 Calibration and Validation of PED-W Model

The PED-W model was calibrated and validated on the daily basis from 2000–2009 and 2010–2014 respectively for the major gauged watersheds of the Lake Tana basin (Ribb, Gumara, Megech, and Gilgel Abbay) by adjusting all the nine parameters of the physical model parameters repeatedly until the model performs well. The initial values were based on the previous model runs of [13] and [14], and these initial values were changed manually through randomly varying calibrated parameters in order that the best “closeness” or “goodness-of-fit” was achieved between simulated and observed subsurface and overland flow in the watersheds. The goodness-of-fit and the model performance were measured and evaluated using the Nash–Sutcliffe efficiency (NSE) coefficient [18], coefficient of determination (R^2) and the root mean squared error (RMSE), percent bias (Pbias) and relative volume error (RVE) (Table 3).

Table 3. Calibrated parameters used in the PED model for the major gauged watersheds of Lake Tana basin at river gauge stations

Parameter	Unit	Watersheds			
		Gumara at Bahir Dar	Gilgel Abbay at Merawi	Ribb at Addis Zemen	Megech at Azezo
Area A1	%	0.05	0.05	0.05	0.05
Smax-A1	Mm	43	45	100	100
Area A2	%	0.11	0.1	0.1	0.02
Smax-A2	Mm	95	70	30	25
Area A3	%	0.84	0.85	0.5	0.58
Smax-A3	Mm	105	135	125	150
Bsmax	mm	85	115	75	75
t1/2	days	40	50	40	20
τ^*	days	45	60	60	30

A calibrated model should be valid before it is recommended for use. For validation, the simulated data as predicted by the model must be computed with the observed data and statistical tests of error functions must be created on. The overall results for PED model validation were summarized in Table 4 below.

As we see the tabular values (Table 4), the PED-W model performed quite well for the three watersheds both at daily and monthly basis except Megech watershed. This is due to the regulating effect of the Angereb dam that was used for Gondar town water supply purpose. Due to this, Megech River flow was attenuated as this was described in [13].

The total inflow in to the Lake mouth was determined after having the inflow from gauged, ungauged and incremental flow from each catchments separately and later the total inflow was taken as the aggregate of inflow series from gauged and ungauged catchments. From the model result obtained, the annual inflow to Lake Tana reservoir was estimated to be 5.6 BCM.

Detail description for the inflow for the Abbay river basin below the Lake Tana was discussed in Sect. 3.1. The inflow for each reservoirs is described in such a way that, reservoirs will get inflow from the contributing catchments (i.e. incremental flow) and from tributaries. Due to the release of water from upstream reservoirs, the downstream reservoirs will get higher amounts of water (Fig. 3).

4.2 Simulation in HEC-ResSim

As the simulation result showed that, the guide pool of the Lake Tana was above the conservation pool and overflow over the spillway. This is due to the high river flows which attributes of high rainfall pattern in August, September and in some extent on October that increased its reservoir level to the flood zone. This clearly showed average, maximum

Table 4. Model Efficiency for calibration and validation of discharge in mm/day for the major watersheds at river gauge stations

Watershed	Description		Calibration		Validation	
			Daily	Monthly	Daily	Monthly
Gumara	Mean	Predicted	2.05	62.41	1.89	57.56
		Observed	2.46	74.88	2.39	72.98
		R^2	0.74	0.89	0.78	0.94
		NSE	0.73	0.88	0.76	0.89
		RMSE	1.5	37.8	1.8	35.4
		RVE	0.2	0.2	0.21	0.2
		Pbias	16.7	16.7	21.1	21.1
Ribb	Mean	Predicted	1.5	45.99	1.05	32.05
		Observed	1.28	38.98	0.82	24.84
		R^2	0.79	0.91	0.76	0.95
		NSE	0.78	0.90	0.6	0.84
		RMSE	1.2	28.02	0.85	14.3
		RVE	−0.28	−0.18	−0.3	−0.3
		Pbias	−18	−27.6	−29	−29
G/Abay	Mean	Predicted	3.271	99.56	3.226	98.2
		Observed	2.96	90.1	2.675	81.4
		R^2	0.72	0.93	0.73	0.87
		NSE	0.70	0.92	0.64	0.80
		RMSE	2.14	30.7	2.22	46.5
		RVE	−0.11	−0.11	−0.2	−0.2
		Pbias	−10.5	−10.6	−20.6	−20.6
Megech	Mean	Predicted	1.19	36.308	1.49	45.4
		Observed	1.13	34.55	1.43	43.6
		R^2	0.41	0.77	0.46	0.88
		NSE	0.40	0.76	0.45	0.83
		RMSE	1.9	27.3	2.18	24.3
		RVE	−0.2	−0.05	−0.04	−0.04
		Pbias	−19.5	−5.1	−4	−4

and minimum reservoir level of 1786.76 m, 1787.29 m and 1785.66 m respectively for scenario one, scenario two, and scenario3. However, scenario four showed the average, maximum and minimum water surface level of 1784.56 m, 1786 m, and 1782.76 m respectively.

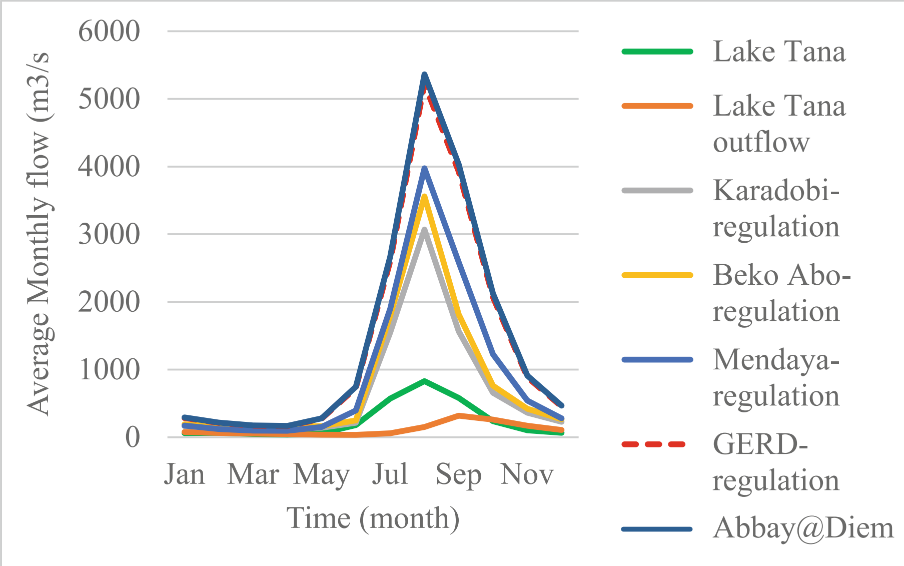

Fig. 3. Discharge of Abbay River at Blue Nile basin (1973-2014)

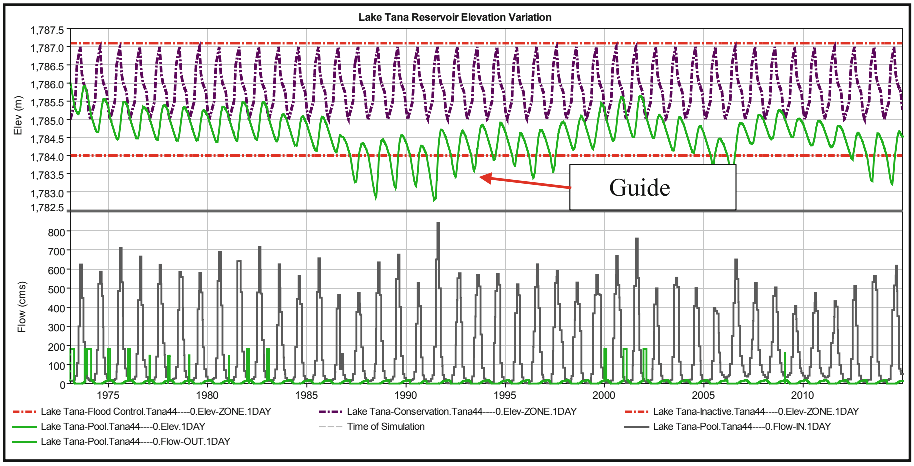

Fig. 4. Lake Tana Elevation variation under scenario four

A simple water balance was done on the system and the total useful volume of the reservoir was checked in balance of the total water requirement of the project under the each scenario. From these, scenario one, two, and scenario three has no deficit in its water balance. Since the allowable lake level for Navigation is 1784.75 m; but, in scenario four, the Lake's water level was lowered by 1.99 m and this will impose and cease hydropower, irrigation as well as navigation purposes in the Lake in the future and shown graphically in Fig. 4.

Using the three reservoir operation rules for the four cascade hydropower projects, different reservoir simulations were computed for each scenario and average the simulation results of the all the scenarios were based on the three alternatives shown in Table 5 below.

Table 5. Simulation results of scenario two, three and four for each alternatives

Scenarios	Scenario 2			Scenario 3			Scenario 4		
Location/parameter	alt1	alt2	alt3	alt1	alt2	alt3	alt1	alt2	alt3
GERD-Power Plant									
Energy generated per time step (MWh)	–	46892	39339	16318	57488	44560	21600	71271	49307
Power generated (MW)	–	1954	1639	680	2395	1857	900	2970	2054
Karadobi-Power Plant									
Energy generated per time step (MWh)				36774	36188	34857	21181	31714	31819
Power Generated (MW)				1532	1507	1452	883	1321	1326
Bekoabo-Power Plant									
Energy generated per time step (MWh)							34929	46493	43407
Power generated (MW)							1455	1937	1809
Mendaya-power plant									
Energy generated per time step (MWh)							35271	35940	32928
Power generated (MW)							1470	1498	1372

From Table 5 above, alternative two gives higher values of average energy generation per simulation daily time step for the three alternatives which are significantly larger value than the remaining alternatives. Thus, Hydropower power generation guide curve was selected for modeling of the cascade reservoirs operation in the basin to optimize the available water for hydropower, water supply, environmental and flood control in the cascade reservoirs system.

The GERD reservoir showed a lowered pool level shown in Fig. 5 in hydropower power guide curve operation rule in which the reservoir released more water to produce high amount of energy (Fig. 6).

Scenario three considered both GERD and Karadobi hydropower projects and the reservoir operations are defined by the same rule as scenario two. From the simulation results shown in Table 5 above, the hydropower power guide curve (alt2) generates 57488, and 36774 MWh of energy per simulation daily time step for GERD and Karadobi respectively. Hence, hydropower power guide curve was selected for modeling the cascade reservoirs to optimize the water for hydropower in the basin.

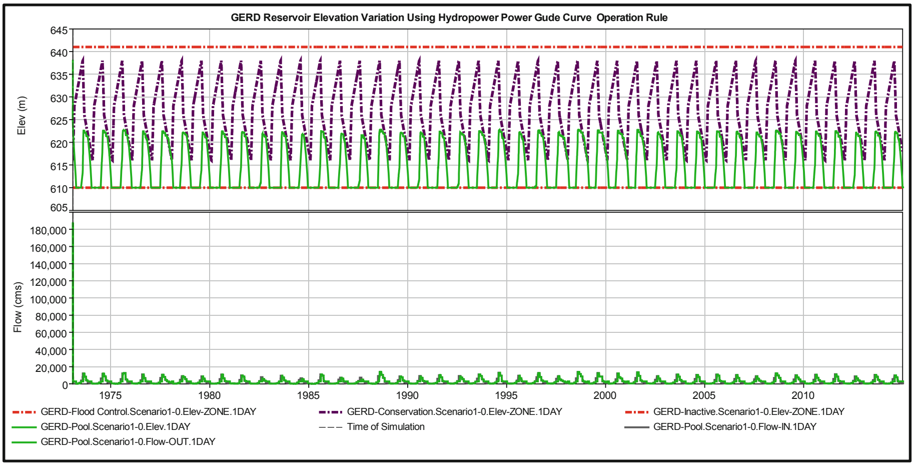

Fig. 5. GERD reservoir elevation variation using Hydropower power guide curve for scenario two

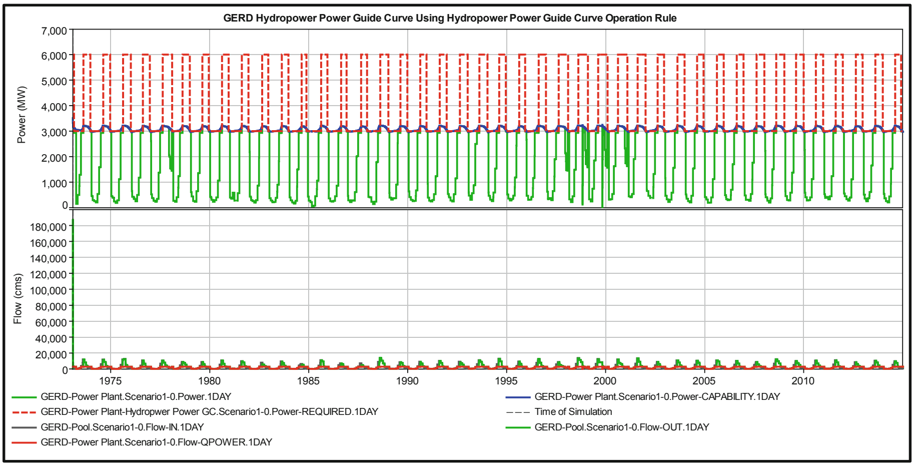

Fig. 6. GERD hydropower power guide curve using scenario two

Using the same approach of simulation, scenario four considered GERD, Karadobi, Bekoabo and Mendaya cascade dam/reservoirs. As the simulation result showed, alt2 generates 71271, 31714, 46493 and 35940 MWh of average energy per simulation day time step for GERD, Karadobi, Bekoabo and Mendaya hydropower projects. The average energy generated per daily time step for each alternatives showed that, alternative two gives the higher value of average energy generation per simulation day time step which are considerably higher values than the other alternatives. Along this, 38745 GWh/yr. of average energy will be produced when Karadobi, Bekoabo, Mendaya and GERD are in operation simultaneously. However, this finding didn't consider and incorporate all the proposed development projects of the Abbay River sub basins (only considered Finchaa, Beles, and Didessa projects). Thus, the hydropower power guide curve operation rule was selected on the basis of modeling of the cascade reservoirs in the basin to optimize the available water for hydropower, environmental and flood controlling in the cascade reservoir system and increased the reservoir power guide curve average yearly energy generation than the others. When we compare the average total energy production; total energy of the Blue Nile basin was increased by 27% from the basin's master plan study with the newly updated operation rule.

In terms of energy generated in the basin, from previous studies by [19], considering the economic benefits of energy production and irrigation water demand satisfaction in the Eastern Nile, Ethiopia could have maximum energy (38200 GWh/yr.) could be achieved when Karadobi, Bekoabo low, Mendaya and GERD are in operation simultaneously. The maximum energy of 36525 GWh/yr. could be also achieved when Bekoabo high, Mendaya and GERD are combined. Energy in the eastern Nile will increase at least by 126% for GERD only case and could increase by 258% for Karadobi, Bekoabo low, Mendaya and GERD combination. On the other hand, considering the economic benefits energy production and irrigation water demand satisfaction in the Eastern Nile [20] investigated that, upstream storage in Ethiopia (and their regulation capacity) will generate positive externalities in Ethiopia and Sudan. In Ethiopia, the production of hydroelectricity is boosted by 40 TWh (+1666%), amongst which 14.3 TWh due to the regulation capacity of Karadobi, Beko-Abo, Mendaya and Border.

5 Conclusion

Water resource planning and management has become more important to maximize benefits, these need to be managed and operated in best possible manner due to perceivable overall increase in water demand for various needs and attempts have been made to establish an operation guide rules that would enable operation of Blue Nile cascade dam using HEC-ResSim simulation model. Thus, The ways in which management of the available and water resources of the basin is achieved by improving the operation of reservoirs using the updated guide curves which brings substantial benefits. Indeed, this can be achieved by selecting the reservoir operation rule which optimizes the available water resources of the Blue Nile River Basin. Three alternatives were established for three scenarios to simulate the cascade dams and reservoirs operation based on the simulation outputs of the average energy generation per daily time step and the best reservoir operation rule was selected from the three alternatives in which that optimizes the available water resources. From the three scenarios simulation results obtained, hydropower power guide curve operation rule gives maximum average energy generation and availability of water. Thus, hydropower power guide curve was selected for cascade dam/reservoirs operation of Blue Nile Basin.

The scenarios were applied for each reservoir operation to determine current operational and the likely future development projects impact on the cascade reservoirs operation. From the simulation result in scenario four, Lake Tan reservoir showed the Lake level is lowered by 1.99 m and thus, the upstream irrigation projects will have significant effect on the Lake's operation. On the other hand, if the planned development occurs on average, GERD hydropower operation was not influenced by the proposed development projects.

As the simulation result indicated, the average yearly energy generation using Tandem reservoir operation rule, hydropower schedule operation rule and hydropower power guide curve increased from the designed reservoir operation. Of these, the hydropower power guide curve operation rule increased the reservoir and power guide curves average yearly energy generation than the others.

The overall results of the study showed that, the model improves the performance of the cascade hydropower plants to generate more than the expected design of the previous studies in the basin.

In the Abbay basin, the development water infrastructures were at feasibility stage and did not studied well in detail. So, further study will be necessary taking into account the time of construction and all the existing and proposed small, medium, and large scale multipurpose projects in the basin.

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Conflicts of Interest. The authors declare no conflict of interest.

References

1. Oliveira, R., Loucks, D.P.: Operating rules for multi reservoir systems. Water Resour. Res. **33**(4), 839–852 (1997)
2. Jothiprakash, V., Ganesan, S.: Single reservoir operating policies using genetic. Water Resour. Res. **20**, 917–929 (2006)
3. Hydrologic engineering center: HEC-ResSim, Reservoir System Simulation, User's Manual Version 3.1. U.S. Army corps of Engineers (2013)
4. BCEOM: Abbay River Basin Integrated Development Master Plan Project, Phase 2 Section II, Vol. III: Part 1 – Climatology and Part 2–Hydrology, Ethiopia (1999)
5. SMEC: Hydrological Study of The Tana – Beles Sub-basins, main report, Ministry of Water Addis Ababa Ethiopia (2008)
6. Pietrangeli, S.: Tana-Beles Project part 2. hydrological report, Addis Ababa (1990)
7. USBR: Land and Water Resources of the Blue Nile Basin Main Report, United States Department of Interior Bureau of Reclamation, Washington, DC (1964)
8. Lahmeyer Consulting Engineers: Gilgel Abbay Scheme, Imperial Ethiopian Government, Ministry of Public Works, Addis Ahaba, Ethiopia (1962)
9. Awulachew, S.B., Yilma, A.D., Loulseged, M., Loiskandl, W., Ayana, M., Alamirew, T.: Water resources and irrigation development in Ethiopia Colombo, Sri Lanka. International Water Management Institute. Working Paper 123 (2007)
10. World Bank: Managing Water Resources to Maximize Sustainable Growth: A Country Water Resources Assistance Strategy for Ethiopia. World Bank, Washington DC (2006)
11. Waterbury, J.: The Nile Basin: National Determinants of Collective Action. Yale University Press, New Haven (2002)

12. Yilma, D.A., Awulachew, S.B.: Characteristics and atlas of the Blue Nile Basin and its sub basins, the improved water and land management in the Ethiopian highlands: its impact on downstream stakeholders dependent on the Blue Nile. In: Awulachew, S.B., Erkosa, T., Smakhtin, V., Ashra, F. (eds.) Intermediate Results Dissemination Workshop Held at the International Livestock Research Institute (ILRI), 5–6 February, Addis Ababa, Ethiopia (2009)
13. Steenhuis, T.S., et al.: Predicting discharge and erosion for the Abay (Blue Nile) with a simple model. Hydrol. Process. **23**, 3728–3737 (2009)
14. Tilahun, S., et al.: An efficient semi-distributed hillslope erosion model for the sub humid Ethiopian Highlands. Hydrol. Earth Syst. Sci. **17**, 1051–1063 (2013). https://doi.org/10.5194/hess-17-1051-2013
15. Tilahun, S., et al.: Distributed discharge and sediment concentration predictions in the sub-humid Ethiopian highlands: the Debre Mawi watershed. Hydrol. Process. **29**, 1817–1828 (2015)
16. Fasikaw, A.Z., et al.: Budgeting suspended sediment fluxes in tropical monsoonal watersheds with. J. Hydrol. Hydromech. **66**(1), 65–78 (2017)
17. Ries and Friesz: Development of regression equations to estimate flow durations and low-flow frequency statistics in New Hampshire streams U.S. Geological survey (2000)
18. Nash, J.E., Sutcliffe, J.V.: River flow forecasting through conceptual models part I-a discussion of principles. J. Hydrol. **10**(3), 282–290 (1970)
19. Mulat, A.G., Moges, S.A., Moges, M.A.: Evaluation of multi-storage hydropower development in the upper Blue Nile River (Ethiopia). J. Hydrol. Reg. Stud. **16**, 1–14 (2018)
20. Goor, Q., Halleux, C., Mohamed, Y., Tilmant, A.: Optimal operation of a multipurpose multi-reservoir system in the Eastern Nile River Basin. Hydrology Earth System Sciences **14**(10), 1895–1908 (2010)