Saudi Journal of Civil Engineering
A Publication by "Scholars Middle East Publishers", Dubai, United Arab Emirates
ISSN 2523-2657 (Print)
ISSN 2523-2231 (Online)

The Impacts of Reservoir Operation Modification Assessment; Case study Jebel Aulia Reservoir in Sudan

Yasir S. A. Ali*
Jubail University College, Jubail, Jubail industrial City 31961, Saudi Arabia

***Corresponding author**
Yasir S. A. Ali

Article History
Received: 04.10.2018
Accepted: 14.10.2018
Published: 30.10.2018

Abstract: Variation of Jebel Aulia Reservoir levels along White Nile River causes wider variation of the wetted area. This adds to the challenges for the pumping water for irrigation. Historically, there was always the tendency to maintain high reservoir levels in favor of the upstream pumping stations. The aim of this study is to assess possible impacts of changing the operation rules of Jebel Aulia Reservoir. Water balance approach has been applied to investigate the existing and three modified operation policy. The evaluated parameters include duration of high reservoir levels preferred by pumping schemes, satisfaction of downstream water demands and area of flood plain agriculture (Guroof), evaporation and hydropower generation. Scenario 2 was found to be the best in obtaining high reservoir level and given the highest annual hydropower production. Scenario 3 was found to be the best in terms of evaporation losses and the downstream demands.
Keywords: White Nile River, water uses, Jebel Aulia, Reservoir modification.

INTRODUCTION

Water resource management is increasingly challenging due to stakeholders demands conflict, population increase, rapid urbanization, climate change impacts and natural disasters [1]. Upstream flow variability in the Nile River Basin is critical issue to downstream countries [2, 3].

Cooperative management of the Nile waters has become urgent, considering climate variations [4-7] in particular the need to construct dams for hydropower in Ethiopia, South Sudan and Uganda, which has significance in the downstream water resources [8, 9]. For this, the Nile Basin (Figure-1) countries are currently negotiating to find a common agreement how to share the Nile waters [10, 11].

White Nile River joins Blue Nile River at Khartoum the capital city of Sudan to form the Main Nile River [3, 12, 13]. Unlike Blue Nile, White Nile is a very flat and wide river. Large variation of the river levels means wider variation of the wetted area that is an unfavorable condition for the various pumping schemes abstracting water from the river. Therefore, historically, there was always the tendency to maintain high levels for the upstream pumping stations via Jebel Aulia Dam. The dam; the only dam a cross White Nile River in Sudan is crucial to maintain high water level for the agriculture schemes along both sides of the river. The dam was used to provide river flows for Egypt during summer times before completion of the Aswan High Dam in 1966 [12, 14, 15]. Thereafter, the operation of the dam has been modified to supply downstream water requirements for the Main Nile River and to maintain command level for pumping schemes abstraction upstream the dam [12].

In this paper, the possibility of modification the operation rules of the reservoir is investigated in-order to maintain sustainable irrigation [16, 17]. The operation of the dam serves two main requirements; providing sufficient command level to the pumping schemes upstream the dam and supplying downstream demands during recession time of the Blue Nile River (around 65 M m3/day in the Main Nile River) [18].

The possible impacts of the modified operation scenarios were assessed including downstream requirements in the Main Nile Reach, maintenance of the dam and the embankments, floodplain recession agriculture, reservoir evaporation losses, and hydropower generation.

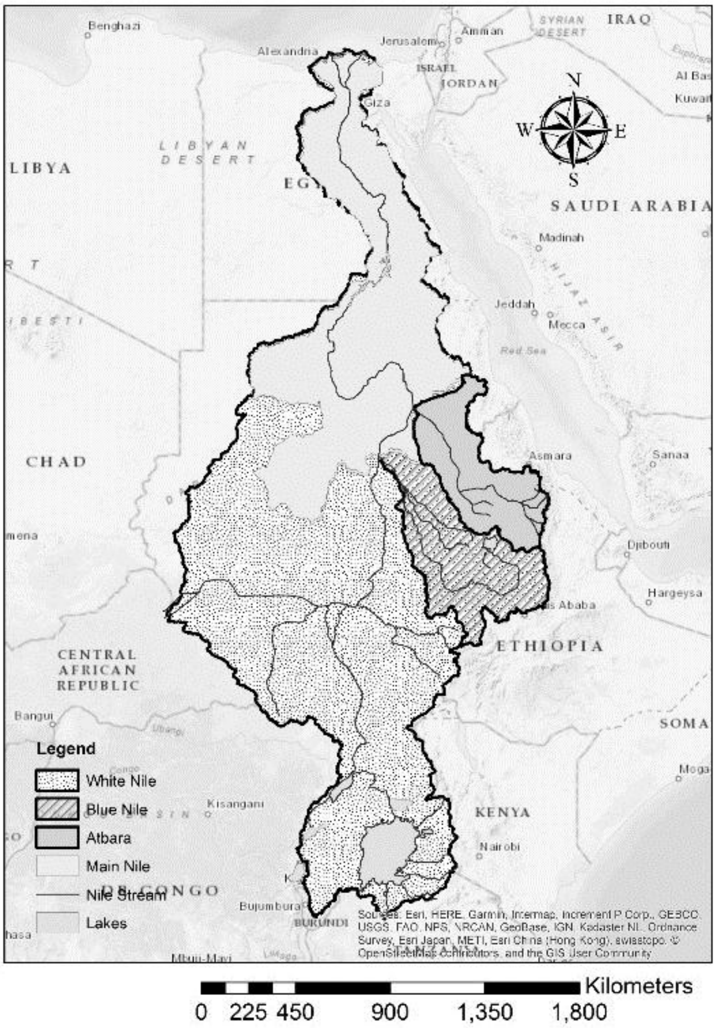

Fig-1: Nile River Basin including While Nile River sub-basin

MATERIALS AND METHODS

Geography of the White Nile Basin

The White Nile is the longest tributary of the Nile River; approximately 3,700 km long, and contributes about 30% of its flow, with an average annual discharge of about 28 billion m^3/year at Khartoum. The river headwaters flow through major lakes in the Equatorial Lakes Plateau of Eastern Africa. From Lake Albert, the river flows for about 500 km down to the vast seasonal swamps of the Sudd, in South Sudan, one of the largest freshwater wetlands in the world [19]. Leaving the Sudd, the river meets the Bahr el Gazal, flowing from west, at Lake No, forming the White Nile River [14]. Short after it is joined by the Sobat River, flowing from the Ethiopian highlands. The bimodal rainfall system, large storage lakes, and the vast wetlands along the way of the White Nile, make its flow regime quite steady. The river has a very mild slope of 1.2 cm/km between Malakal and Khartoum. The reservoir lake extends to about 629 km up to Melut Town (Fig-1). The Blue Nile River joins the White Nile River to form the Nile River at Khartoum after having travelled for about 1,700 km [20, 21].

Jebel Aulia Reservoir System

The Jebel Aulia Dam is a masonry dam, constructed in 1937 across the White Nile River about 50 km south of the capital Khartoum (Fig-2). It is 4.3 km long and 22 m high [18]. The operation of the dam has been handed over to the Sudanese authorities in 1970s.

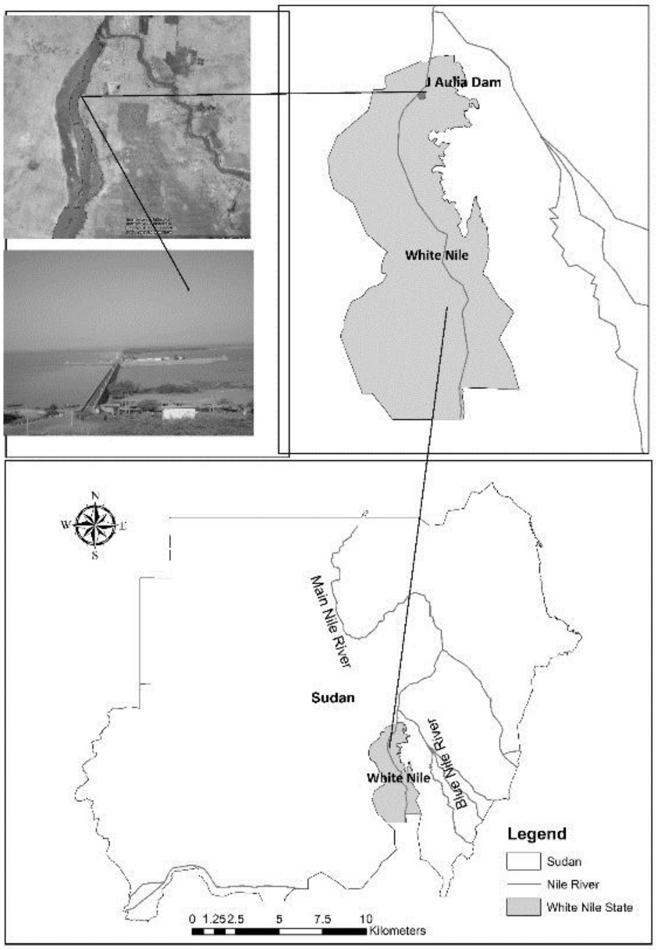

Fig-2: Location of Jebel Aulia Dam along the While Nile River

The Jebel Aulia Reservoir is different from Sennar and Roseires dams along the Blue Nile River in that its storage also serves maintaining high command level for the pumping schemes upstream the dam. Almost all the content is then released downstream to satisfy downstream demands during recession time of the Blue Nile River. Small hydropower turbines were installed in 2004 to produce 116.4 GWh/year on average [22, 23]. The main hydrological features of the reservoir could be summarized in Table-1.

Table-1: Jebel Aulia Dam Main characteristics

Item	Value	Unit
Top water level	377.2	m.a.s.l
Highest flood level recorded	377.5	m.a.s.l
Length of full reservoir	629	km
Maximum width of full reservoir	7250	km
Minimum width of full reservoir	2000	km
Average width of full reservoir	4200	Km
Area covered by full reservoir	1700	Km^2
Area covered by natural river	480	Km^2
Volume of full reservoir	3.5	Km^3

*m.a.s.l: meter above sea level

The average operating policy during the last 20 years as reported in the dam operation book [18] shows start of filling around third week of June to reach level 376.5 m by July 31st. The emptying usually starts by mid-March, and ends by May 15th at average level of 373.2 m but in the design it is 372.5 m (Fig-3).

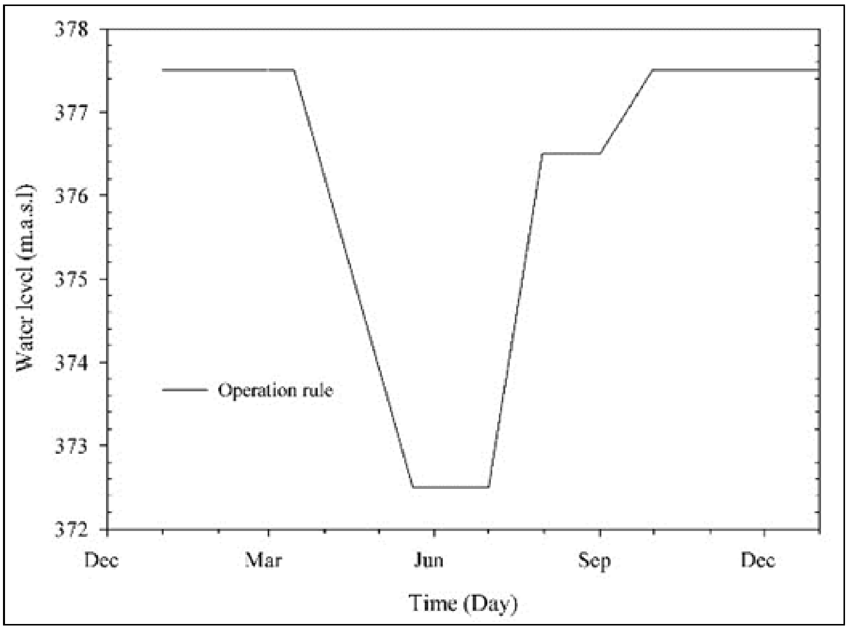

Fig-3: Jebel Aulia Reservoir Design operation curve

Operation modification is needed to extend the cropping season for both winter and summer crops via maintaining a maximum reservoir levels to later than March, and recover to the same level by early July. However, modifying the filling and emptying of the Jebel Aulia Reservoir may have consequences to the other uses of the reservoirs such as downstream requirements in the Main Nile River, reduction of flood plain agriculture (Guroof farming), hydropower generation and open water evaporation. Three modified operation rule scenarios were attempted in the analysis, as given in Fig-4.

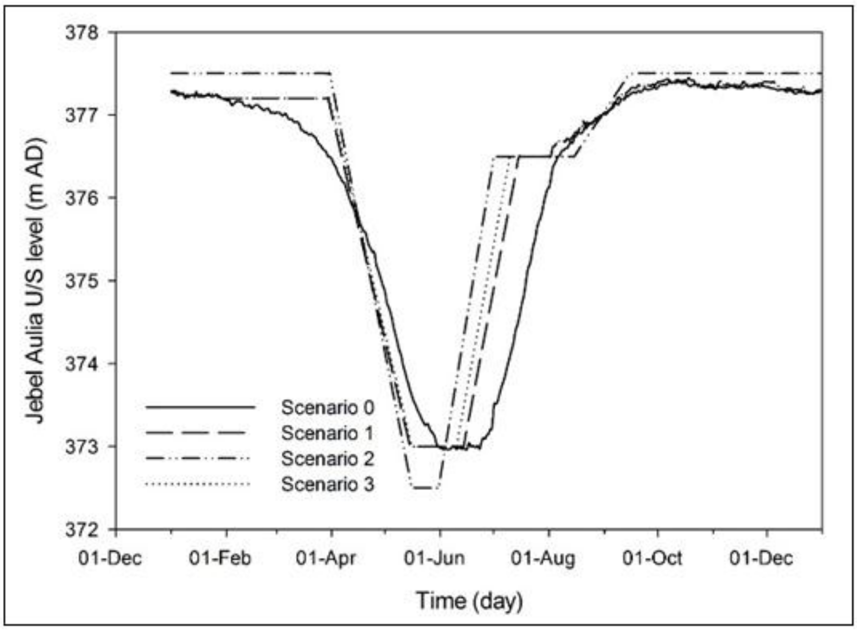

Fig-4: Jebel Aulia Dam; Scenarios operation curves

Water Balance

Water balance techniques, one of the main subjects in hydrology are a solution of important theoretical and practical hydrological problems. On the basis of the water balance approach it is possible to make a quantitative evaluation of water resources and their change under the influence of man's activities [24].

The importance of a good water balance in the reach Malakal – Jebel Aulia is needed to properly operate the Jebel Aulia Dam for optimum utilization of the White Nile water, as well as for better flood management for the downstream users [25, 26].

First, the water balance equation was applied to the existing operation policy, and outputs parameters were evaluated including the number of days of high reservoir levels, area of flood plain agriculture, open water evaporation from the reservoir, satisfaction of downstream water demands, duration of minimum water level, required for maintenance, and hydropower generation. The same model was then used for modified operating rules, and the same parameters were reevaluated. Then the most optimal operating policy has been recommended.

The water balance equation of Jebel Aulia Reservoir is given by equation below:

$$Q_{in} + P * A = Q_{out} + E * A + \Delta S + Q_{abs}$$

Where,

Q_{in}= inflow measured at Malakal in Mm^3/day
P = Rainfall over the reservoir in mm/day
Q_{out}= Outflow from the reservoir in Mm^3/day
E = open water evaporation in mm/day
A = Area of the reservoir in km^2
ΔS = Seepage losses in Mm^3/day
Q_{abs}= Abstraction by irrigation schemes and domestic stations in Mm^3/day

Different time steps of water balance computation have been used, including daily, 10-daily and monthly [27, 28]. One complexity of the water balance in Jebel Aulia is the strong effect of the southerly winds, creating a surge of 30 to 40 cm on the measured water level at different gauging stations. For this, the calculations have been conducted by splitting the reservoir length into the 22 reaches [18] (appendix 1).

Inflow at Malakal Station

This station is located at Malakal town about 650 km upstream the dam and started operation since 1905. Gauge level and discharge measurements are carried out 3 times a week and daily respectively. The daily discharge was from developed rating curve using equation below

$$Q_{Malakal} = 47.946(h - 9.6)^{0.743}$$

The comparison between the measured discharge time series and discharge obtained from the rating curve is shown in Fig. 5. It could be seen that the two series are almost similar.

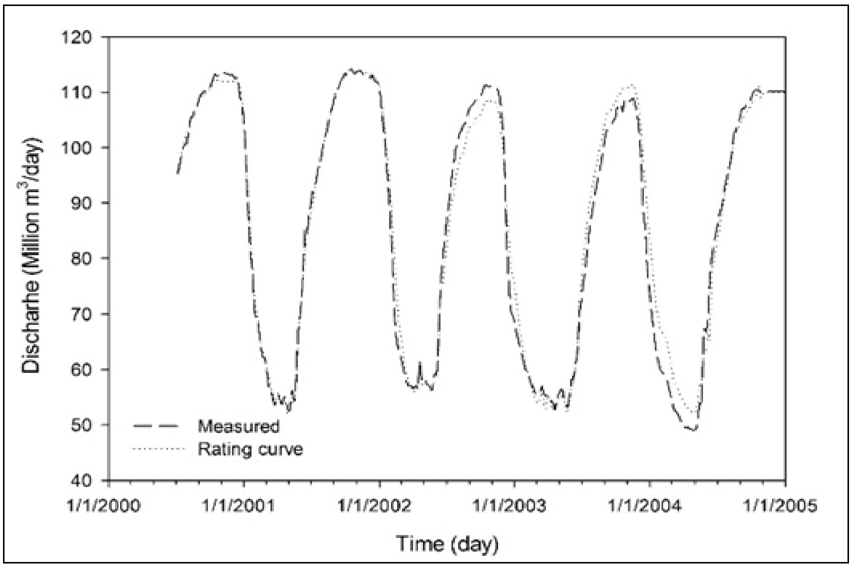

Fig-5: Comparison between measured and calculated discharge at Malakal Station.

Jebel Aulia Dam downstream release

The released discharge from the dam (Q_{out}) is computed by the dam operation engineer using gate equation.

$$Q_{out} = cA\sqrt{2gh}$$

Where A is the gate opening, c is gate coefficient (is obtained from dam operation tables), g is gravity acceleration and h is the head difference between upstream and downstream water levels.

The mean monthly discharge (1989-2009) at Malakal station and dam release is given in Fig-6. The mean monthly difference between the two stations varies between 6.2 Mm^3/day in March and reaches 60 Mm^3/day in July when filling started.

White Nile basin in Sudan is sparsely vegetated as a results of the low amount of rainfall. So this area is prone to water scarcity and thus, drought-like conditions prevail [29], therefore the rainfall in the water balance is neglected.

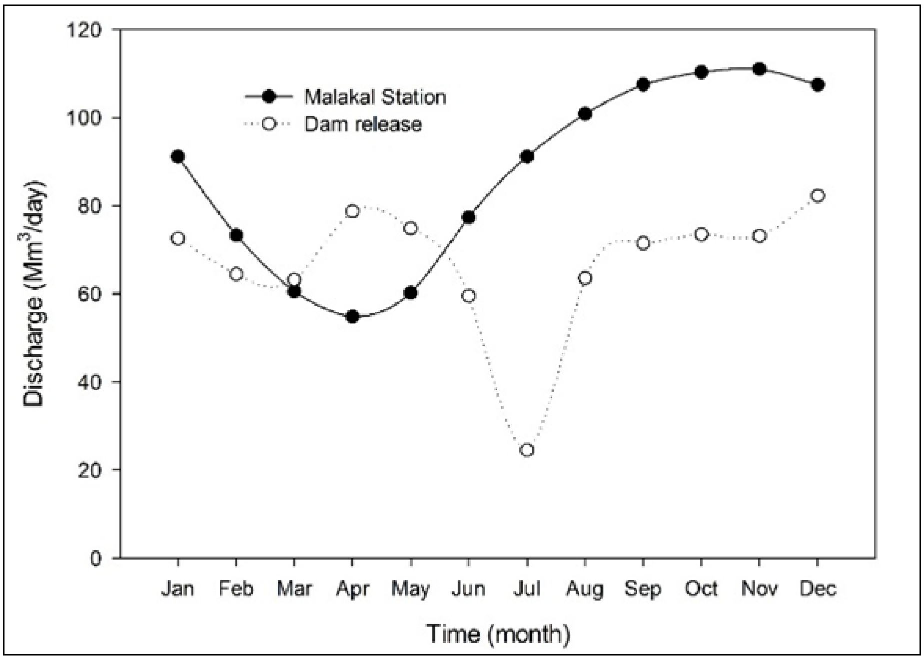

Fig-6: The mean monthly discharge (1989-2009) at Malakal station and dam release

Evaporation losses

Open water evaporation from Jebel Aulia reservoir is a significant component of the water balance because of large reservoir area. Here, 10 days average evaporation coefficients values (rates) are given based on Penman method in 1940s as reported by dam staff and these factors have been used by the operation engineer of the dam since 1961. Therefore, evaporation losses was computed using Penman equation for more accurate and recent actual climate data, Evaporation coefficients were estimated at the beginning, middle and end of the reservoir namely Jebel Aulia, Kosti (located approximately at the middle of the reservoir) and Malakal using the collected temperature, relative humidity, wind speed and sun hour data (1980-2010) from Sudan Meteorological Authority public. The most common of the combined equations was derived by Penman (1948) which in its general form is written as:

$$\lambda E_w = \frac{\Delta R_n + \gamma \left[2.7 \left(1 + \frac{u_z}{100} \right) (e_s - e_a) \right]}{(\Delta + \gamma)}$$

Where, λE is the latent heat of evaporation in MJ m^{-2} t^{-1}, γ is the psychometric constant in kPa oC^{-1}, Δ is the slope of the saturation vapor pressure curve at temperature Ta in kPa oC^{-1}, (Rn - Qt) is the net radiation minus the change in energy storage in MJ m^{-2} t^{-1}, u_z is wind speed at the z height, km day-1. Variables es is the saturation vapor pressure and ea is the actual vapor pressure at height z. various values for the empirical coefficients a_w and b_w have been proposed [30]. Penman [30] initially proposed aw = 1.0, but later revised it to 0.5 [31], and b_w = 0.54 s m^{-1} for open water for z = 2 m. The comparison between the monthly average evaporation coefficients computed at the selected stations Fig-7.

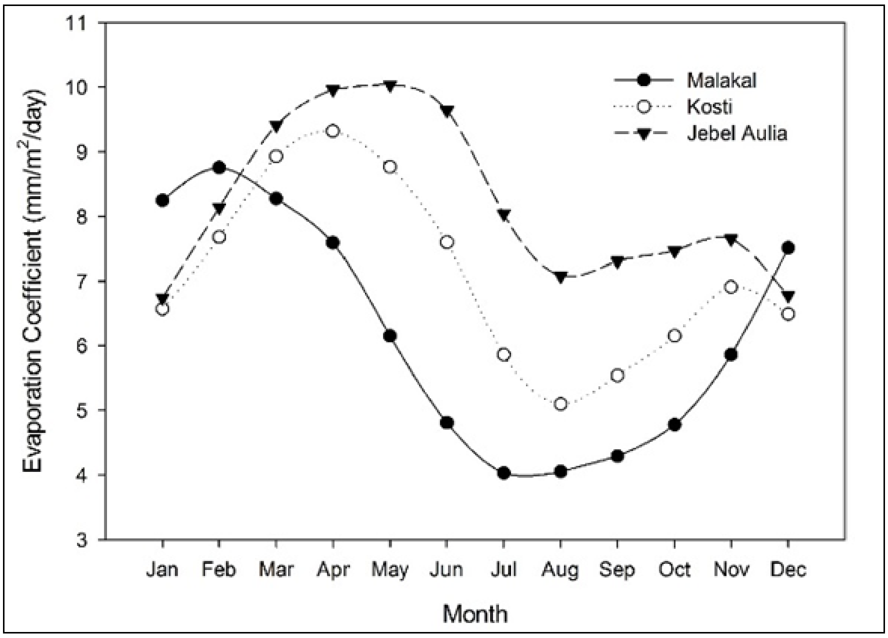

Fig-7: Comparison between Monthly average evaporation coefficient at Malakal, Kosti and Jebel Aulia

Irrigation water requirement

Many agriculture schemes are located along the river banks to cultivate sorghum, cotton, wheat and sugar cane (Fig-9). The numbers of schemes are 153 and extend to a distance of 300 km in both sides of the river covering an area of 393,000 feddan (165,060 hectare). Moreover, several sugar schemes exist along the White Nile River namely Asalaya , Kenana and White Nile Sugar projects had with an area of 24,000, 80,000 and 80,000 feddan respectively [32, 33]. The volume of pumped water can was estimated based on actual cultivated areas and crop area requirement factors. Irrigation demands were estimated based on Farbrother crop water requirements for different crops [34]. The actual cultivated areas and volume water pumped during the period from 1989 to 2009 were obtained from the technical office of the Ministry of Water Recourses and Electricity in Kosti. The mean monthly water requirement for different crops is shown in Fig-8.

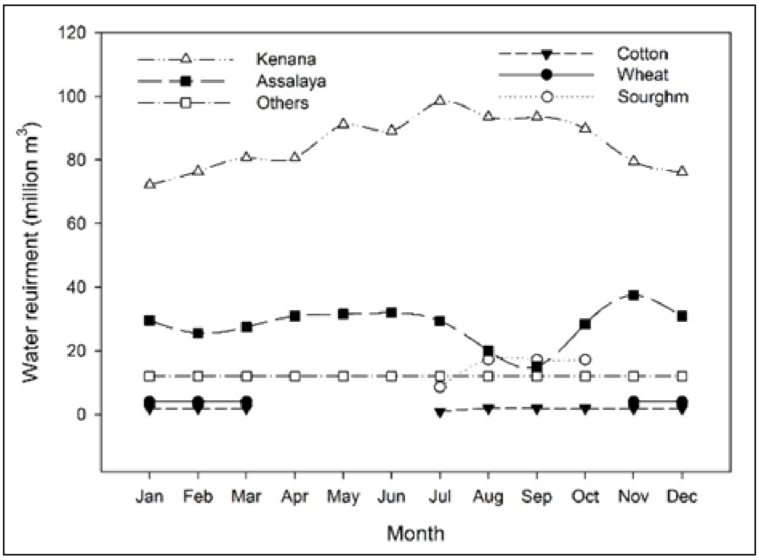

Fig-8: The mean monthly (1989-2009) water requirement for different crops in million m^3

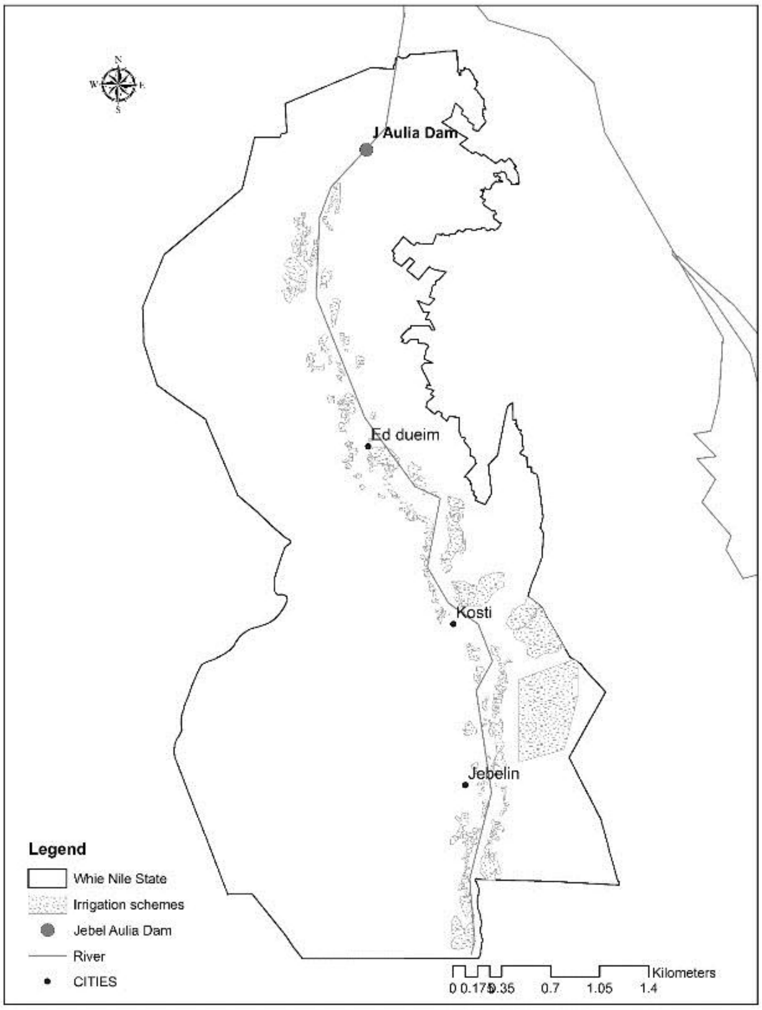

Fig-9: Agriculture Schemes along White Nile River

RESULTS AND DISCUSSION

The water balance computation is performed using the input data discussed above. The water balance results are performed using annual, monthly and 10 daily average time step computations for the 21 years record from 1989 to 2009. The results for different time step computation are discussed below.

Water balance (10 daily time step)

The measured dam releases are compared with the computed releases from the water balance as given in Fig-10 (a). The variation between the measured and estimated flows were found to be high having a maximum differences between the two series vary between -500 to +200 Mm3/10-days, and usually occur during emptying or filling. The average 10-daily time series gives much smoother results as given by Fig-10(b). Moreover, the average 10-daily time series provides much smoother results while aggregated values – computed from 10-daily time steps to annual values steps with much smaller differences, as given in Fig-10(c).

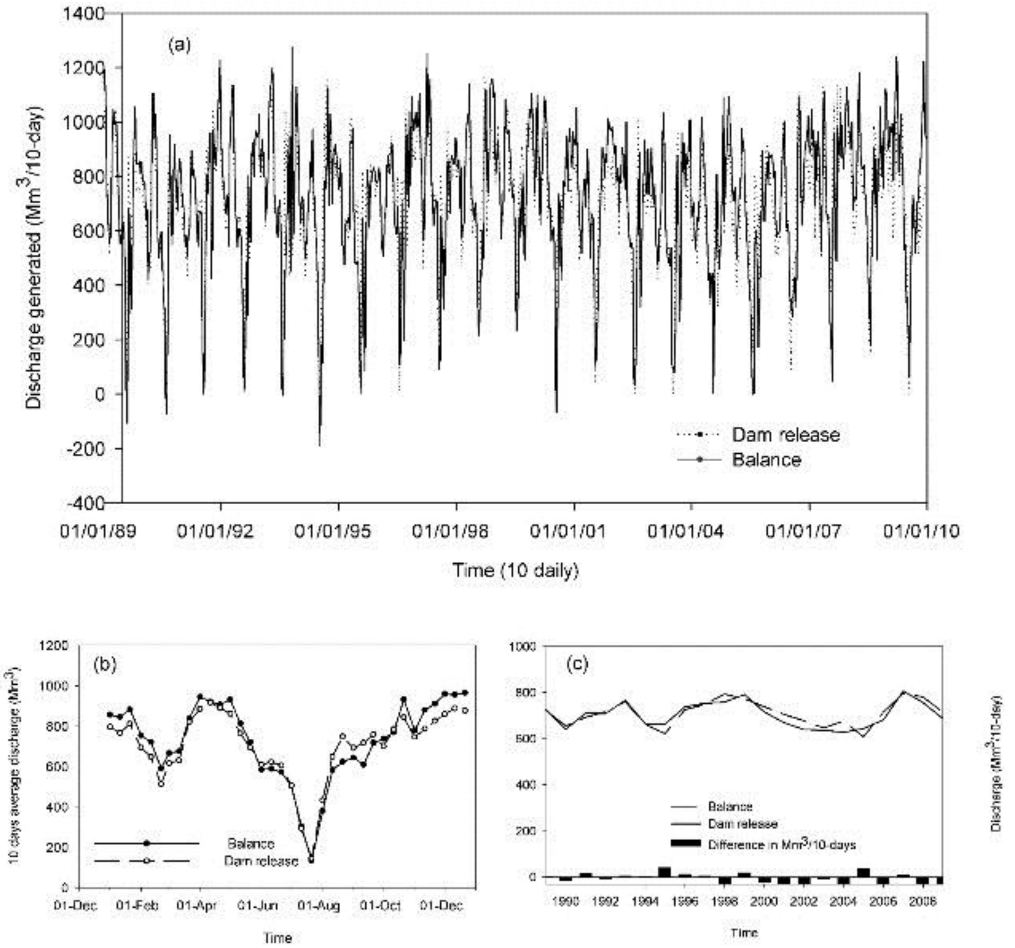

Fig-10: Comparison between average 10 daily measured and balance discharge (1989 to 2009) using 10 daily time step (a), average (b) and aggregated to annual values (c)

Water balance (monthly time step)

The variation between the measured release and the computed release from the water balance using monthly time step is found to be bigger that the 10 daily computation as given in Fig-11. This is expected because monthly time step is too coarse to capture variation in inflows, but more important the variation during filling and emptying of the reservoir.

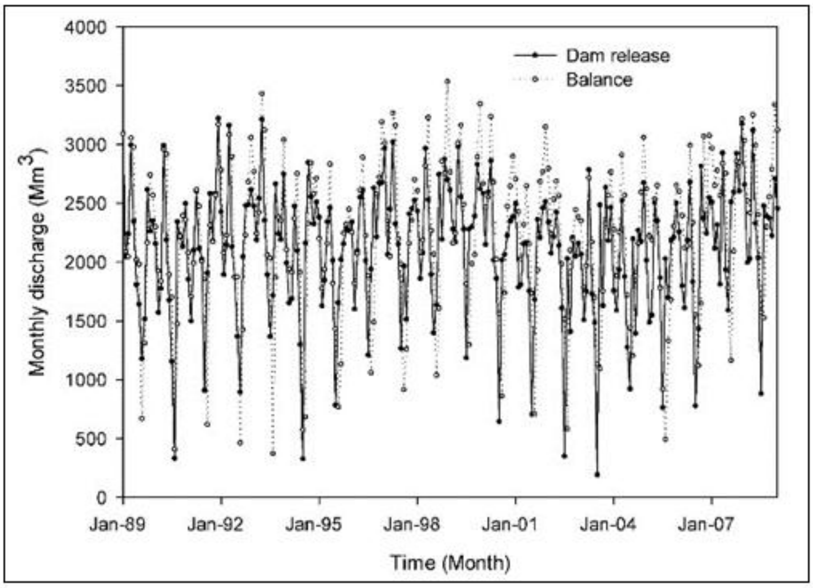

Fig-11: Comparison between monthly measured and balance discharge (1989 to 2009) using monthly daily time step

Annual time step computations

The water balance computations using annual time step have the same order of magnitude with small difference between the measured and estimated except for year flow in some years such as 2001 -2004 (Fig-12). It seems that the balance almost overestimate the dam release outflow, most likely because of additional abstraction not accounted for, in the order of 1200 Mm^3/year.

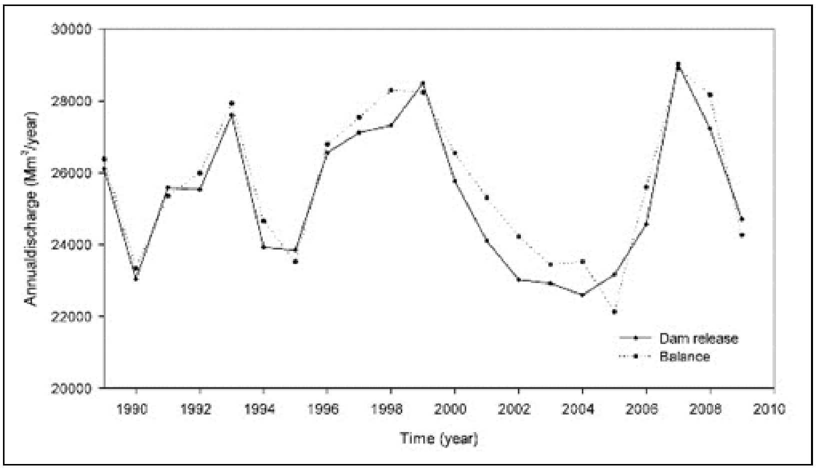

Fig-12: Comparison between monthly measured and balance discharge (1989 to 2009) using annual time step

Sensitivity analysis

The parameters affecting the calculation results were subjected to sensitivity analysis [35, 36]. The computations were performed on 10 daily time step computations; these parameters are evaporation, irrigation water requirement and inflow discharge from Malakal.

Evaporation

This parameter was selected for sensitivity analysis since it has the most uncertainty. The sensitivity analysis results performed with increasing and decreasing the evaporation by 20%. It was observed that the released discharge is higher with the decrease of evaporation and lower with the increase of evaporation as given in Fig-13 (a).

Irrigation water requirement

This parameter was selected for sensitivity analysis since it has higher uncertainty due to the fact that the actual cultivated areas and the pumping discharges (pumps flows are not calibrated) are not well known. The sensitivity analysis was performed by increasing the water abstraction by 20% and decreasing by 20%. It was observed that the released discharge is higher with the decrease of abstraction and lower with the increase of abstraction as shown in Fig-13(b).

Inflow at Malakal

Along the river reach between Malakal and Khartoum, there is no important tributary or streams joins the river except Adar stream which contributing significantly to the river flow as reported by Yahia Abd El Mageed [37]. The stream connects the Machar marshes with the White Nile through an extended grass filled channel. The outflow through Adar stream has been measured for short periods (0.058 km3 in 1948 and 0.029 km3 in 1957) and is considered negligible except after years of heavy rainfall and inflow to the swamps [12]. The Wol Stream is similar and the average outflow from the Machar marshes to the White Nile was estimated at about 0.10 km3, though in exceptional years like 1947 it might reach 0.50 km3 or even 1.00 km3 [12].

The average total contribution of these two streams is about 0.6% of the average annual river flows. Sensitivity analysis was carried out considering an increase of 0.5 and 1.0% of the inflow from Malakal. The results are depicted in Figure-13 (c). The contribution of the two streams in the water balance computation is slight but recent measurements are needed to know their exact inflows.

Surface area (river banking)

Previous work reported by Yahia Abd El Mageed [37] gave a brief account of possibility of reclamation. The study excepted that about 75.000 to 100.000 feddan can be reclaimed with most economical banking. The results of the reclamation will reduce the evaporation losses by 350-500 Mm^3/year and providing more areas for continuous agriculture. Sensitivity analysis was carried out for banking 50.000 to 90.000 feddan and the comparison between annual measured and balance discharge-sensitivity analysis results of river banking is shown in Fig-13(d).

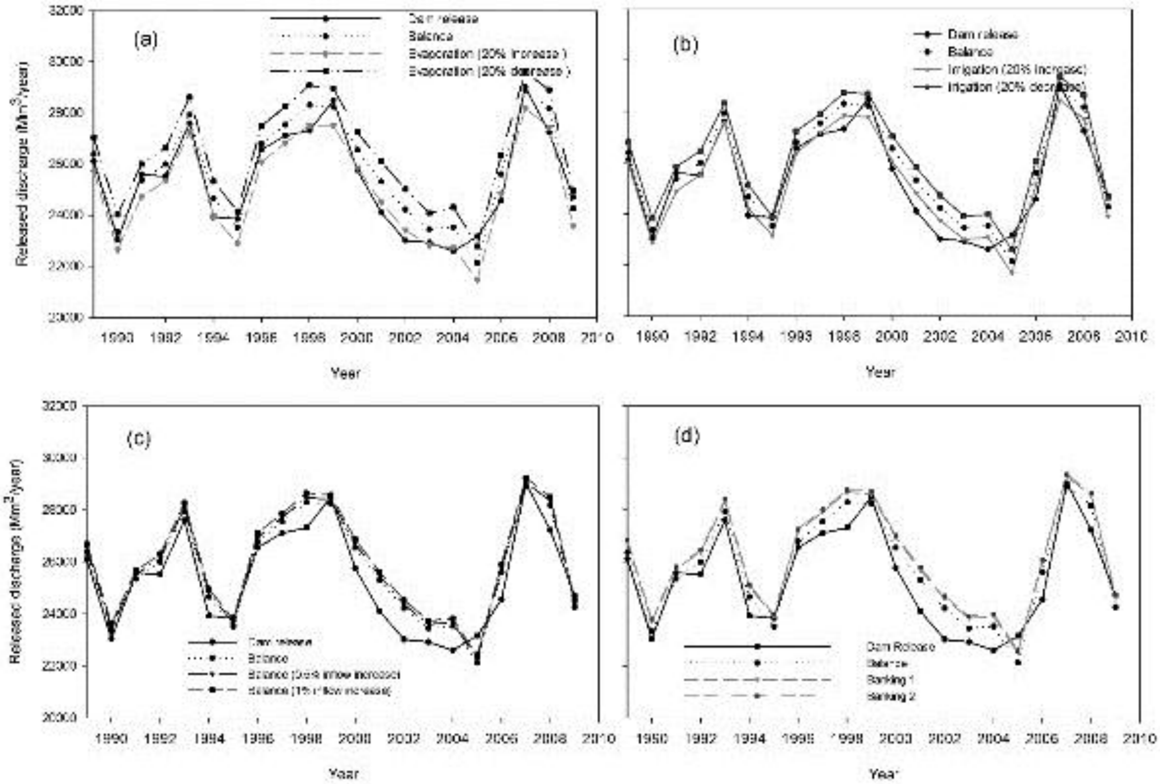

Fig-13: Comparison between annual measured and balance discharge-sensitivity analysis results of evaporation (a), water abstraction (b), inflow from Malakal (c) and river banking (d)

Modified operation rules for Jebel Aulia Reservoir

Three modified operation rule scenarios were attempted in our analysis, as given Fig-4. The six variables results from the operation of Jebel Aulia Dam are evaluated as given in the following sections, including: (i) The duration of high reservoir levels (number of days), (ii) Area of flood plain agriculture (Guroof), (iii) Open water evaporation from the reservoir, (iv) Satisfaction of downstream water demands, (v) Duration of minimum water level, required for maintenance, and (vi) Hydropower generation.

Reservoir water level

The water levels were checked at the middle of the reservoir length namely Rabak Station. The obtained level for different scenarios is shown in Fig-14(a). It could be seen that the three scenarios allow acquiring good operation level to meet the requirements of the White Nile Pump Schemes. It is reported that the White Nile Projects are designed to be irrigated from the river at a level of 376.5 m AD. Number of days with levels greater than 376.5 for scenario 0, 1, 2 and 3 are found to be 236, 266, 272 and 250 days respectively.

Downstream Release

Comparison between the released discharges downstream Jebel Aulia Dam for different scenarios are depicted in Fig-14(b). It is to be noted that, the minimum requirement for the reach downstream Main Nile River to Merowe Dam is 65 Million Mm^3/day. This is approximately minimum of 55 Mm^3/day for releases from Jebel Aulia Dam. This seems to be possible after heightening Roseires dam [38, 39].

The release discharge from different scenarios shows an increase in the month of April which will benefit both the water abstraction for irrigation and the hydropower generation from Merowe Dam. Scenario 1 and scenario 2 showed significant deficit in June and July. The reduced release from Jebel Aulia to below 55 Mm^3/day is only possible if the deficit can be supplied by releases from Sennar dam (Blue Nile River). Table-2 shows the 10-daily average (2013-2014) release from Sennar dam after heightening Rosaries dam (300 km upstream Sennar Dam).

Table-3: The 10-daily average (2013-2014) release from Sennar dam after heightening Rosaries dam (Mm^3/day)

Period	Average DS Sennar Dam	Scenario 3 Released	Main Nile River
Jan I	15	33	47
Jan II	15	85	100
Jan III	21	72	93
Feb I	24	71	96
Feb II	23	58	81
Feb III	21	42	63
March I	20	47	67
March II	19	43	62
March III	31	44	75
April I	53	151	204
April II	54	193	247
April III	47	145	193
May I	24	118	141
May II	29	98	127
May III	45	67	112
June I	63	65	128
June II	53	51	104
June III	59	36	95

Evaporation

The annual evaporation losses from the stored water and the natural river are estimated to be 3.77, 3.98 and 3.55 billion m3 for scenario 1, 2 and 3 respectively (Fig-14(c)). However, the average annual evaporation loss during the period 1989 to 2009 is estimated to be 3.4 billion m^3. The month of March shows the highest increase in the evaporation loss compared with the other months. It could be concluded that the impacts of evaporation loss for different scenarios is insignificant.

Electricity generation

The hydro-generation at Gebel Aulia Reservoir was increased according to increase of water level. The result of the increase in hydro-generation for different scenarios is shown in Fig-14(d). It could be seen that there slight increase in October to February and significant increase during the March and April of summer period. The annual was estimated to be 66.03, 70.95, 74.2 and 70.7 GW/year for average operation rule, scenario 1, scenario 2 and scenario 3 respectively.

Area of flood recession agriculture (Guroof)

It could be concluded that modification of the reservoir operation will affect the area of flood recession agriculture. The impacts of guroof areas for different scenarios is higher in some months inparticular during March and July (Fig-14(e)). It should be noticed that the cultivated crops need less than two month from planting to harvesting such as water melon and Okra.

Time for maintenance

The gates maintenance period will be affected by reservoir operation rules modification since the filling starts after 34, 27, 30 days after the low level is obtained in the reservoir. However, the current practice in the reservoir showed that there is no exact maintenance program and the gate that have problems are maintained.

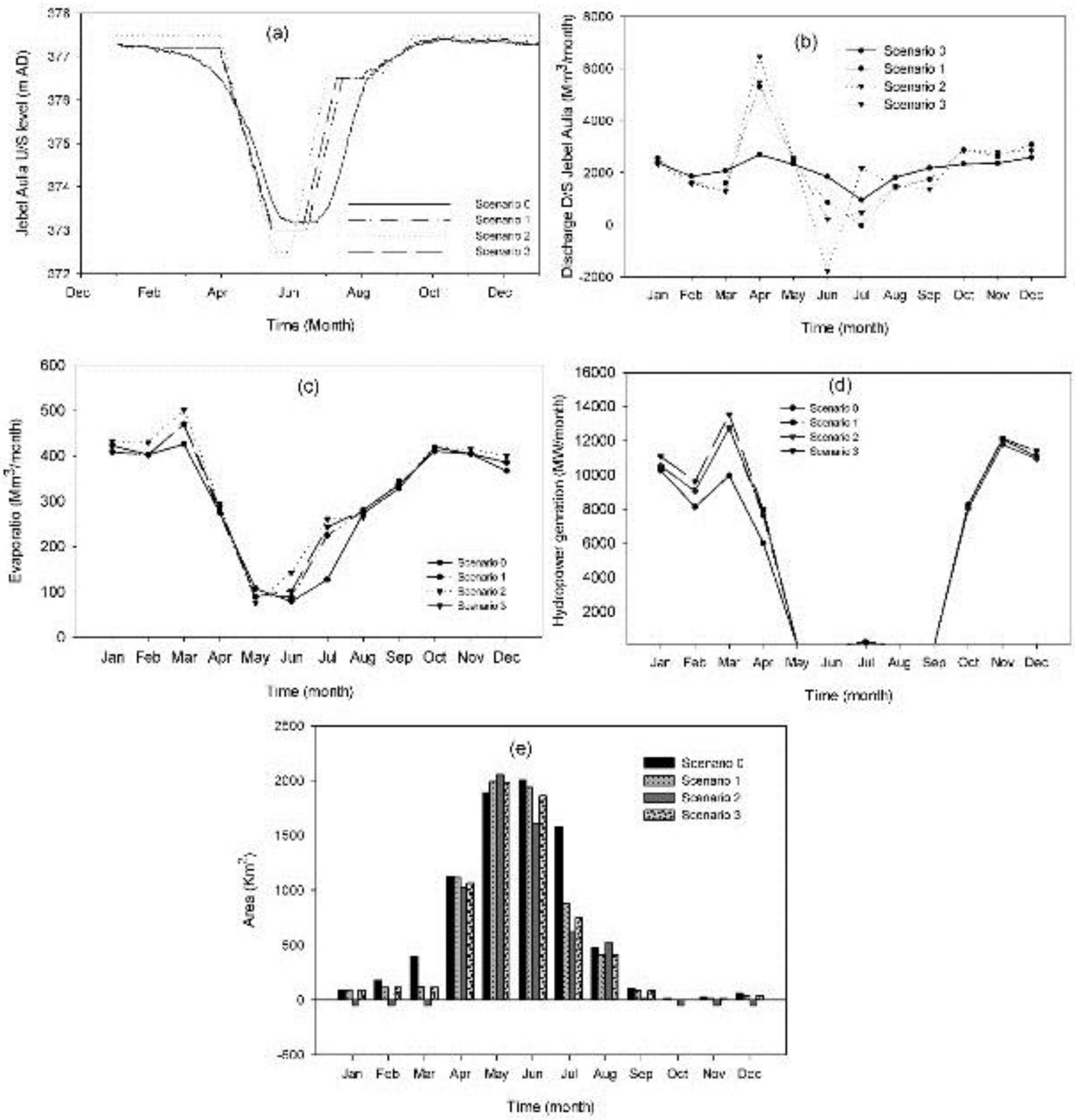

Fig-14: Reservoir modification scenarios impacts, Water level at Rabak gauging station(a), inflow downstream (b), evaporation (c), hydropower generation (d) and guroof area (e)

CONCLUSIONS AND RECOMMENDATIONS

Given the increasing irrigated agriculture along the White Nile upstream Jebel Aulia dam, and the increased releases from Sennar reservoir after heightening of Roseires reservoir, there is a tendency to increase the time of high reservoir level at Jebel Aulia.

The key conclusions and recommendations obtained are as follows:

Given the increased releases from Sennar dam, increased from 10 to 30 Mm3/day after heightening of Roseires reservoir, it is possible to delay the filling of Jebel Aulia reservoir from 15 March to 31 March, while satisfying downstream demands (65 Mm^3/day in the Main Nile).

The earliest time of filling, while satisfying downstream demands is 10 June, to ensure full reservoir (376.5 m) by July 31 (Scenario 3). This has only been possible because of increased releases from Sennar dam.

Starting filling earlier to ensure full reservoir before July 31st is not possible even with the current releases from Sennar reservoir after heightening

(Scenario 1 and 2). This is simply because the inflow coming from Malakal in June and July is not sufficient to provide 3500 Mm^3 of storage needed to raise the level from 373 to 376.5 m.

It is obvious that modifying the filling and emptying of Jebel Aulia reservoir will have impacts on other water uses, namely: Guroof area; Requirements for maintenance of the dam; Evaporation losses; Hydropower generation; and the safety of the embankments. These has been quantified both for the current policy (Scenario 0), and for the other three scenarios 1, 2, and 3:

Therefore, Scenario 3 can be recommended for the modified operation of the Jebel Aulia reservoir, i.e., to start emptying on 01 April (instead of 15 March), finishes on 15 May (same as current policy). Filling should start on 10 June (instead of 15 June), and complete filling by 31 July (same as current policy). This is possible given current releases from Sennar reservoirs in the order of 30 to 60 during March and April.

This study clearly showed the missed opportunity of utilizing the potential water resources of the country by coordinated operation of all reservoirs in the system. Therefore, it is strongly recommended, to link all water supplies and abstraction to one system, and to see how optimally to satisfy all demands. This should include existing and new reservoirs in the system.

Appendix-1: The locations of gauge stations & reaches along Jebel Aulia Reservoir.

Station name	Reach No.	Distance from the dam(km)	Distance between stations(km)	Distance between reaches (km)	Zero gauge of the station (m.a.s.l)
Jebel Aulia Dam	-	0.00	-	-	360.00
	1	13	-	13	
Geteina	2	47	47	34	361.04
	3	81	-	34	
Wad Elzaki	-	101	54	-	368.50
	4	111	-	10	
	5	141	-	30	
Duem	-	159	58	-	362.04
	6	175	-	16	
	7	210	-	35	
Shawal	-	222	63	-	368.50
	8	242	-	32	
Rabak	9	275	53	33	363.64
Abu zeid	-	297	22	-	364.52
	10	304	-	7	
	11	328	-	24	
Jebelein	-	347	50	-	365.38
	12	355	-	8	
	13	381	-	26	
	14	407	-	26	
	15	433	-	26	
Renk	-	446	99	-	366.86
	16	459	-	26	
	17	485	-	26	
	18	511	-	26	
	19	537	-	26	
	20	563	-	26	
	21	589	-	26	
	22	615	-	26	
Melute	-	629	183	-	369.79

ACKNOWLEDGMENTS

The study was carried out as a project within a larger research program called “Jenel Aulia Dam modification of the operation role”, funded by the Hydraulics Research Center (HRC Sudan). The authors are grateful to the Ministry of Irrigation and Water Resources, Hydraulic Research Station, Wad Madani, and the Jebl Aulia Dam Authority, Khartoum, Sudan, for providing data free of charge.

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