Evaluating the Impacts of Sedimentation and Water Balance Computations on Reservoir Operation, A Case Study of Girba Dam-Atbara River

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Abstract

Accurate water balance calculation is crucial to operate reservoirs systems efficiently. This paper presents a comprehensive assessment of water balance components and reservoir sedimentation of Girba reservoir at Atbara River in Sudan, which has been suffering from severe storage capacity deterioration that make reservoir lost more than 53% of its design capacity in 40 years of operation, accordingly, the reservoir's ability to meet its design purposes has been directly impacted and leads to shrink the committed irrigation area due to limited amount of stored water.
To have a careful insight for each water balance components, the study methodology based on statistical inflow analysis, calculating evaporation losses using climatic parameters, and correlating the storage capacity for each year based on estimated annual sedimentation rate.
The results show clearly the outperformance of adopted approach comparing to the currently applied MOIWR method, besides necessity of careful data refining, rehabilitating the measuring network system, and importance of developing the current operation policy by applying the updated climatic data and reliable sediment accumulation forecasting.

Key words: Reservoir Water Balance, Reservoir Operation, Sedimentation, Evaporation.

1. INTRODUCTION

One of the big challenges facing human beings is continuous growing demand of water for various purposes such as irrigation, water supply, hydropower, water quality, environmental restoration, recreation facilities, etc. Such an increasing demand will bring serious problems in foreseeable future; specifically in developing countries where the pressure on water resources will become much more intensive. Therefore, water resources planners and managers are faced with the responsibility of developing water policies which equitably and consistently help in water administration.

In arid and semi-arid regions where climate is characterized by two distinct wet and dry seasons, normally most of the rivers flow during wet season, which is relatively short, while the dry season extends over the most of the year, therefore, redistribution of water in time and space through regulation works is considered one of the most important tasks. For that purpose, reservoirs and other hydraulic structures have been built to modify the natural flow pattern by storing water during the flood season and release it when the inflow is much less than demand.

To meet this objective, particularly with world's growing demands, water has to be managed efficiently through operating reservoirs in an optimal manner.

Furthermore, the uncertainty of future flows, climatic factors, and demands affect both the availability and reliability of the stored water, in addition to alarming trends in temperature and the potential of fresh water redistribution, which have understandably led to concerns for the future availability of water resources.

Current studies on potential impacts of climate change remain largely uninformative to policy and decision makers in water resources sector. Although some projections suggest that significant climate change may occur over the same scales as water resources development and management, policy makers continue to rely heavily on the assumption that historical conditions will persist into the future (IPCC). This is largely due to a lack of integrative tools with realism to tie climate to hydrology to water resources and yield meaningful information for decision makers.

On the other hand, reservoirs sedimentation forms an additional problem. Globally, the overall annual loss rate of reservoir storage capacity due to sedimentation is estimated as 1 to 2 percent of the total storage capacity (Yoon, 1992; Yang, 2003). Some reservoirs are filled very rapidly, while others are hardly affected by sedimentation.

In Sudan, almost all reservoirs have been subjected to reduction in their storage capacities due to sedimentation.

According to Abdallah (2012), three major reservoirs (out of 5) in the country shows a sedimentation rate between 9-35 million ton per year which reduced the total reservoirs storage dramatically by more than 50% from above $5.2*10^9$ m^3 in 1966 to less than $2.7*10^9$ m^3 in 2010.

For above mentioned reasons, this paper aims at evaluating, assessing, and improving the water balance computation practice using a set of inflow, bathymetric, climatic and reservoir operation data taking Girba reservoir on the Atbara River as a case study. The results clearly show the feasibility of adopted approach with tangible improvement in reservoir water balance computation.

2. BASIC WATER BALANCE APPROACH

The reservoir water balance can be described using the following equation:

$$S_{t+1}= S_t+Q_{in}+P-Q_{out}-L \quad (1)$$

Where, S_{t+1}, S_t represent the storage at the beginning and end of a computational interval respectively; Q_{in} is the inflow volume; Q_{out} is the water released from reservoir , P is precipitation over reservoir pool surface, L is losses from reservoirs included Evaporation, Seepage, Leakage, and uncontrolled spillage from reservoir.

To calculate the water balance, a defined scale time series of inflow, precipitation, and pan evaporation or meteorological parameters data are normally collected from the nearest available gauging and meteorological stations. In the absence of data, some of these parameters can be derived from simulation.

The above steps have to be updated always using the new system's state such as decreasing the reservoir storage capacity due to sedimentation and its consequents in terms of reservoir surface area evaporation.

3. STUDY AREA AND SYSTEM DESCRIPTION

The Atbara River basin, where Girba reservoir located as shown in Figure (1), lies in Ethiopia has a catchment area of 100.000 km^2, the main tributary is Setit River which drains an area of about 69.000 km^2. The river is characterized by highly seasonal as flood peak occurs on August with average of 2000 m^3/s and almost dry during summer months (April-May) with total average flow of around 12 bcm per year, as shown in Figure (2).

After constructing the high Aswan dam in Egypt, a part of northern Sudan upstream the dam has been inundated by Nasir lake, therefore, the Nile waters agreement of 1959 mandated the government of Egypt to compensate and resettle the affected people, hence, Khasm El- Girba area at Atbara river 200 km downstream Ethiopian boarder has been selected to build the Girba reservoir with storage capacity of 1300 Million m^3 to ensure supplying of around 200000 hectares of Halfa irrigation project as a major purpose.

The dam was built and started operation in 1964, a set of seven deep sluices each of them has a discharge capacity of 1100 m^3/s and five spillways each passes 200 m^3/s have been constructed as shown in Table (1), the reservoir is operated within a range of 12 m between 473m-raised to be 474.5m- as maximum and 462m as minimum operation level, while the tail water downstream varies between 432m to 448m.

Two turbines, three turbine pump stations, and four compensating pumps are installed to generate an average 17.8 MW of hydropower and raised the reservoir level to the main irrigation canal level during summer months and low flow seasons. Atbara River carries a big amount of sediment during flood season July-September approximated by average of 20 Million ton per year as shown in Figure (3); hence, Girba reservoir is exposed to catch part of this quantity. According to Abdallah (2012), Girba reservoir has experienced a severe sediment accumulation during its operation period due to either natural river morphological processes as a major cause or some other operational reasons which leads consequently to decrease the reservoir's capability to meet its design purposes efficiently, therefore, by 2010, Girba reservoir lost over 50% of design capacity as illustrated in Figure (4).

Figure 1: Atbara River and Girba reservoir location

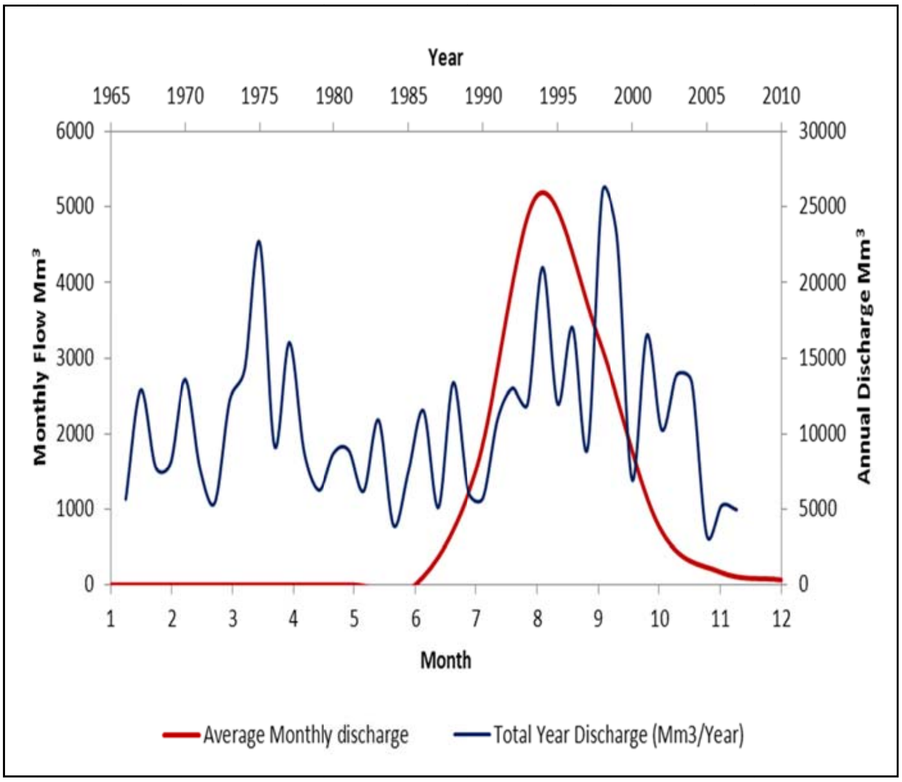


Figure 2: Atbara River flow hydrograph

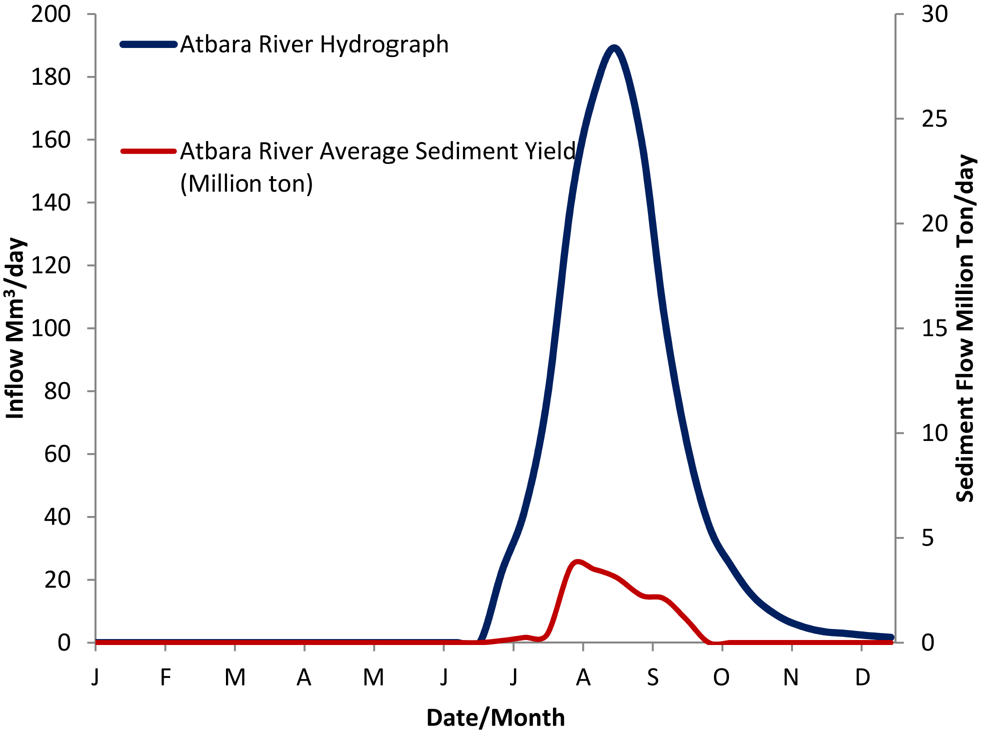


Figure 3: Flow and Sediment hydrograph

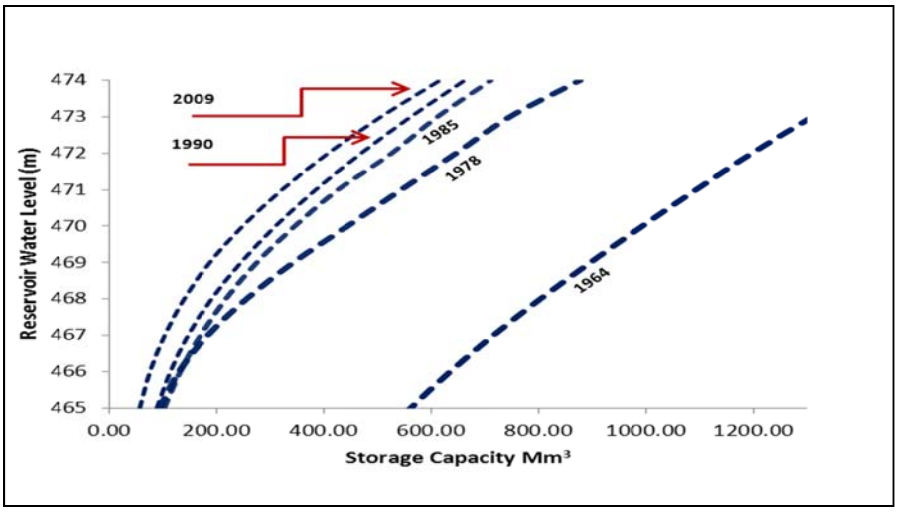


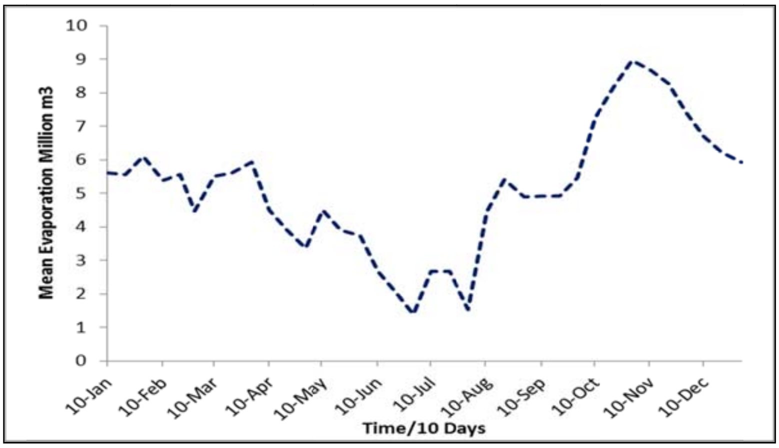
Figure 4: Girba Reservoir Sedimentation

Table 1: Girba reservoir characteristics

Construction Year	1964
River Basin	Atbara River
Drainage Area (Km^2)	100000
Average Flow (109 m^3/year)	11.8
Dam Type	Concrete Buttress
Storage Capacity (Mm^3)	1300
Surface Area (Km^2)	125
Height above Streambed (m)	50
Deep Sluice	7
Spillways	5
Maximum Operation Level(msl)	474.5
Minimum Operation Level(msl)	462
Hydropower (MW)	17.8

The reservoir's leakage and seepage losses are normally minor and can be neglected, nevertheless, this statement need to be revised, hence, still evaporation forms the major losses as reservoir located in semi-arid region which characterized by high temperature and short rainfall season. The reservoir's evaporation loss is the product of the average evaporation depth and the reservoir surface area during certain time. The evaporation depth can be obtaining either by pan test or through applying different evaporation formulas that using meteorological data.

According to the Ministry of Irrigation and Water Resources in Sudan (MOIWR), all reservoirs evaporation is estimated using an average evaporation value of 10 days as shown in Figure (5), however, these figures are average and need to be updated regularly.



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Many attempts have been tried to develop a suitable formulas using either the surface area characteristics or the water balance approach (Abushoura, 1985 and Hamad 1993), however, few researchers have attempted to use meteorological data to calculate the reservoir evaporation due to unavailability of required data.

Yousif (1999) calculated the evaporation at the Sennar and Roseires reservoir using Penman equation with average values of the regional meteorological data, while Bashar.et.al (2009) have applied an adjusted Penman-Monteith at Roseires reservoir to calculate the reservoir evaporation. It’s worth mentioning that, even with feasibility of applying this approach but the system operators still preferred using the old one due to relative complexity of new approach comparing to the old one, in addition to some other technical and financial constraints.

a. Girba reservoir operation procedures

The operation procedures of Girba reservoir is based on storing water during the flood season and use it later, therefore, the hydrological year can be divided to four main periods:

1. 1st to 31st July - rising period;
2. 1st to 20th August - period just before peak;
3. 21st August to 30th September - peak period;
4. 1st October to 30th June - recession and low flow periods.

To decrease the sediment load deposition, the reservoir operated during the first period in a minimum operation level of 462 m, hence, generated power is very low and during this period and the irrigation demands abstraction depends mainly on pumps.

This minimum operation level policy preserved at the second period till the second week of August or when the river flow reach more than 200 Million m^3/day, then the reservoir flushing started for three to five days, afterwards, the policy is resumed again. When the high flood peak starts to recess and most of heavy sediment load is washed out, the reservoir starts filling procedures gradually to reach the maximum operation level by October and keep the maximum water level until the river flow becomes less than water requirements, then withdrawing from reservoir starts and continue till the end of period.

4. METHODOLOGY

In addition to long inflow time series, reservoir operation data, and bathymetric survey data, a global meteorological data have been used to calculate the evaporation, however, due to data gabs and compatibility problem, a monthly based time scale has been adopted. The Girba reservoir inflow analysis used the data from Kubor and Wadelhiliew gauging stations upstream the reservoir at both Atbara river tributaries before the confluence at Showak 80 km upstream the reservoir, however, the data of both stations is questionable, inaccurate, and need to be revised, moreover, there is no consistent inflow records at the dam site, therefore, a carful data refining and statistical analysis have using stochastic modeling system been conducted to increase the data reliability.

To calculate the evaporation, data from New Halfa meteorological station (Latitude.15 19'N, Longitude 33 36'E) as shown in table (2) have been used to derive the reference evapotranspiration after Penman-Monteith equation as described in equation (2) below according to FAO 56 irrigation and drainage paper No.56:

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0{,}34 u_2)} \tag{2}$$

Where
- ET_o reference evapotranspiration [mm day^{-1}],
- R_n net radiation at the crop surface [MJ m^{-2} day^{-1}],
- G soil heat flux density [MJ m^{-2} day^{-1}],
- T mean daily air temperature at 2 m height [°C],
- u_2 wind speed at 2 m height [m s^{-1}],
- e_s saturation vapour pressure [kPa],
- e_a actual vapour pressure [kPa],
- e_s-e_a saturation vapour pressure deficit [kPa],
- Δ slope vapour pressure curve [kPa °C^{-1}],
- γ psychrometric constant [kPa °C^{-1}].

Consequently, surface evaporation E_0 can be obtained from equation (3):

$$ET_o = K_p * E_0 \tag{3}$$

Where K_p is adjusting factor can be obtained from FAO 56 irrigation and drainage paper No.56.

Table 2: Average climatic parameters values of New Halfa meteorological station

Month	Temperature (°C)	Rainfall (mm)	Wind Speed (M.P.H)	Relative Humidity %	Sunshine Duration (hr)	K_p
January	24.1	0.1	7	38	9.4	0.55
February	25.4	0	7	33	9.4	0.55
March	28.4	0.4	7	26	9.6	0.55
April	31.7	2.4	7	21	9.6	0.55
May	33.8	11.7	6	24	7.8	0.55
June	33.3	28	9	31	8.2	0.55
July	30.5	77.4	10	45	7.4	0.55
August	29.6	98.9	8	50	7.7	0.65
September	30.4	33.8	7	45	9.2	0.65
October	31.1	6	5	34	9	0.55
November	28.4	0.6	6	34	9.1	0.55
December	25.3	0	6	38	9.5	0.55

Using the water balance approach as described above in equation (1), reservoir releases and storages can be found for each time step since inflows, rainfall, and evaporation have been calculated. For more accurate results, the years where a bathymetric survey has been considered as a benchmark for updating the reservoir surface area, then comparison was made between actual and calculated release to check the performance of proposed methodology.

To check the accuracy and robustness of the proposed approached, two evaluation methods of - (i) Nash-Sutcliffe efficiency (NSE), (ii) percent bias (PBIAS- were applied as expressed below in equations (4), (5) respectively.

The (NSE) is computed as a ratio of residual variance to measured data variance, the value ranges between −1 and 1; a value between 0 and 1 indicates acceptable model performance whereas a value less than 0 indicate poor model performance (Nash and Sutcliffe, 1970), while the percent bias (PBIAS) measures the average tendency of the simulated data to be larger or smaller than their observed counterparts, the optimal value of PBIAS is 0, with low-magnitude values indicating accurate model simulation. Positive values indicate model underestimation bias, and negative values indicate model overestimation bias (Gupta et al., 1999).

$$NSE = 1 - \left[\frac{\sum_{i}^{n} (X_i^{obs} - X_i^{Calc})^2}{\sum_{i}^{n} (X_i^{obs} - X^{mean})^2} \right] \tag{4}$$

$$PBIAS = \left[\frac{\sum_{i}^{n} (X_i^{obs} - X_i^{Calc}) \times 100}{\sum_{i}^{n} (X_i^{obs})} \right] \tag{5}$$

Where: X_i^{obs} = observed variable (a, m, or storage in Mm^3), X_i^{Calc} = calculated variable (Release in Mm^3), X^{mean} = mean of n values, n= number of observation.

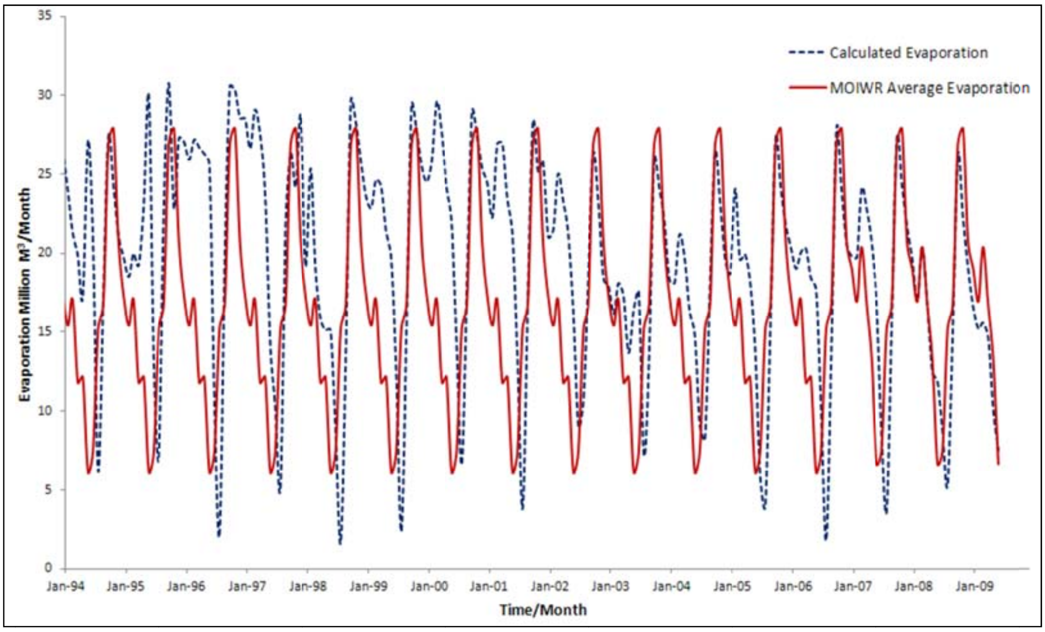
5. ANALYSIS AND RESULTS

To increase the reliability of calculation, each elements of water balance equation has been analyzed carefully, using a stochastic analysis modeling system, a series of 90 years inflow data has been analyzed as shown in tables (3), as well as calculating reservoir evaporation using adjusted Penman-Monteith method in addition to rainfall data for 15 years and compared to the average evaporation method that adopted by MOIWR as demonstrated below in figure (6).

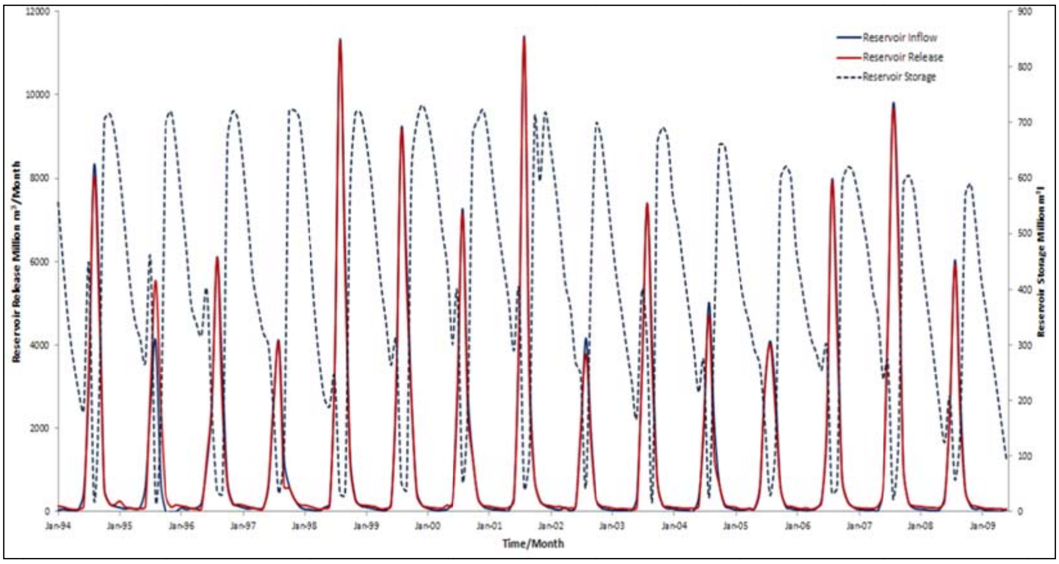
Table 3: Inflow Analysis

Month	Mean (Million m^3)	Minimum (Million m^3)	Maximum (Million m^3)	Standard Deviation	Coefficient of Variation	Skewness
January	22.8	0	165	29.8	103	19.4
February	10	0	135	19.5	2	39.2
March	4.6	0	49.3	10.2	2.2	2.84
April	8.1	0	126	20.7	2.5	3.4
May	14	0	196.2	34	2.4	3.18
June	106	0	430	119.3	1	1.05

July	1715	0	5160	807.7	0.5	1.46
August	5689	1430	15740	2263	0.4	1.66
September	3312	297	9394	1608	0.5	1.04
October	756	80	2140	395.5	0.52	1.01
November	169	0	607	103.4	0.6**1**	1.21
December	61	0	173	44.4	0.73	0.6



Due to scattered rainfall data, a statistical correlation has been made to fill the data gabs, hence; the time series of fully available refined data has been selected to be 1994-2008 as illustrated in figure (7).



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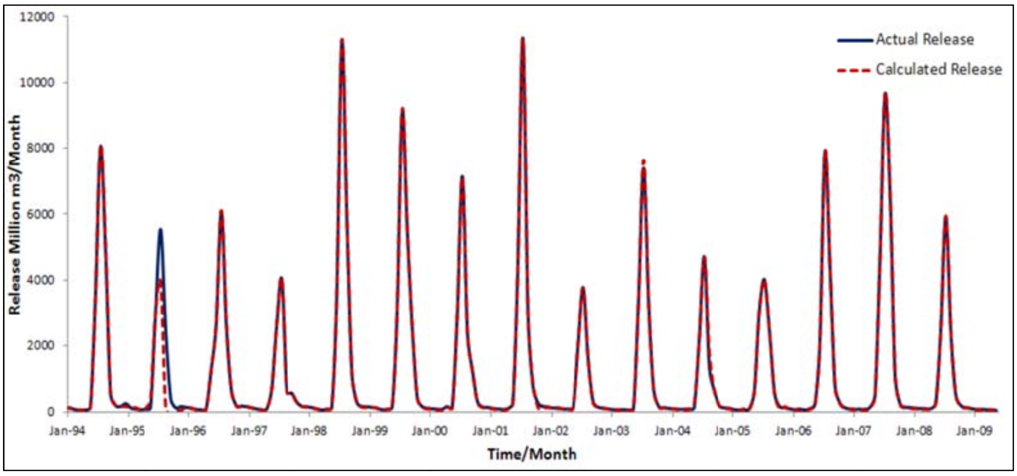
Using water balance equation, the reservoir releases for the period of (1994-2008) have been calculated and compared to the measured release as shown in figure (8), a strong correlation relationship of $R^2=0.99$ has been observed between the actual and calculated release, moreover, the NSE and PBIAS evaluation tests presented a results of 0.0001 and 2.2 respectively, which shows obviously the advantage of this approach besides the real improvement as demonstrated in figure (9) based on direct scientific realistic computational approach.



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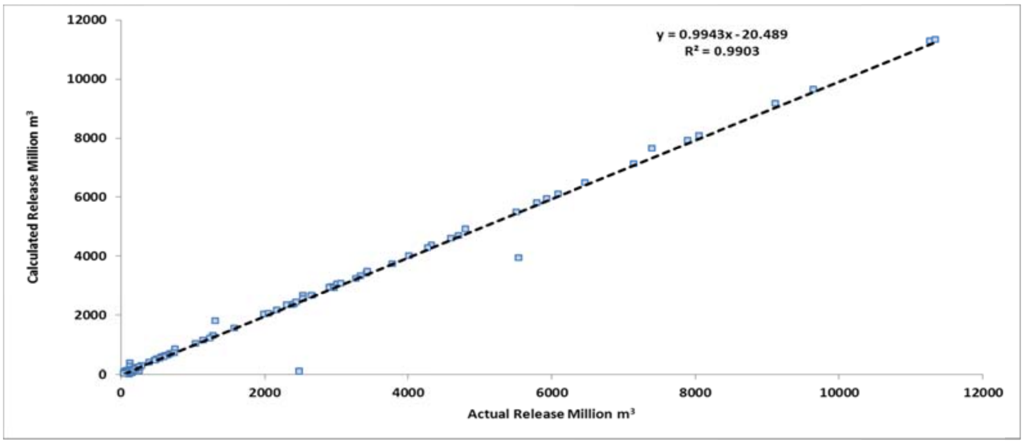

6. CONCLUSION

An improved reservoir water balance approach using climatic data and updated bathymetric survey analysis has been applied in Girba reservoir, the method shows outperformance to calculate the reservoir releases based on refined parameters, however, the adjusted Penman-Monteith method required a large set of climatic data to produce a good outputs, which may be a problem in developing countries where still the availability of funds and technology is difficult to attain.

The study clearly shows the problem of data deficiency, inaccuracy, and inconsistency in Atbara River, mainly, the inflow data as measurements of both key gauge stations upstream are inaccurate and uncertain, which make the Girba reservoir operators in most cases taking their decision without enough real time accurate data, therefore, its highly recommended to renovate both stations and develop a robust dataset as well as modernize Girba reservoir meteorological station where the infrastructure is still existing.

Furthermore, this paper shed the light on importance of updating the average evaporation figures that adopted by Ministry of Irrigation and Water Resources in Sudan (MOIWR), which need a comprehensive review and continuing updating to assure a proper management and optimum operation of reservoir system.

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