**Evaluation of present sediment sluicing in Sennar reservoir**

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**Abstract**
Sennar Dam was constructed across the Blue Nile in 1925 for supplementary irrigation in Gezira Scheme. First the river was left to flow naturally without impoundment in the reservoir during the flood period and then filled in November after the sediment is passed. This operation was changed after the installation of hydropower turbines and intensification of rotation and diversification of crops introduced in Gezira scheme. The dam was then operated in accordance to rules that aim at sluicing the sediment during the flood season. In its first operation period the sedimentation rate was ½ % per year but, the sedimentation rate rise to 5.8% per year after changing the operation. The reservoir has lost 60% of original storage capacity of 930 Mm3. The objective of this paper is to investigate the present sediment sluicing operation in Sennar reservoir using contemporary knowledge and to evaluate economic impacts of reservoir sedimentation. The study showed that the present reservoir operation is in agreement with the classification of Basson's (1997) for initial sediment management strategy, Paul & Dhillion (1988) and Wu (1989) equations for flushing. The annual cost of foregone power generation due to lowering reservoir water level during the flood season was m$65.

***Keywords***: sediment sluicing, Blue Nile, Sennar reservoir

## 1. INTRODUCTION

Sennar dam is the first large dam built across the Blue Nile in Sudan in 1925, some 300 km south of its confluence with the White Nile at Khartoum. The main purpose of the dam is to store and divert water for irrigating cotton in Gezira Scheme and secure drinking water supply during the dry season. The dam has played an important role in Sudan's economy.

The initial storage capacity of Sennar reservoir was 930 million $m^3$. The dam was designed with 80 deep sluices and 112 spillways gates spreading across the river capable of passing the maximum flood. Later, in 1962, two turbines, 7.5 MW each, were installed in the dam for hydropower generation. The Blue Nile River originates from the Ethiopian highlands having an annual average flow of 50 Billion $m^3$. About 80% of the river flow occurs during the flood season (July–October). During the flood season, the Blue Nile brings large amounts of sediment that originates mainly from heavy erosion in the upper catchment area in Ethiopia.

This high sediment load has major influences on the design and operation of Sennar reservoir. The original operation rule for the dam was to leave river flows naturally without any impoundment in the reservoir during the flood period. The reservoir is then filled in November after the sediment is passed. The installation of the power turbines required changing the operation of the reservoir to maintain the required minimum water level for power generation of 417.5m. Furthermore, the intensification of rotation and diversification of crops introduced in Gezira scheme in mid 70's required the supply of irrigation water all the year round. Sennar reservoir is then operated according to operation rules that aim at reducing sediment deposition. During the flood season the water level in the reservoir is kept at the minimum operation level of 417.5m to increase flow velocities, keep sediment particles in suspension and sluice the sediment downstream.

The reservoir is then filled after mid September when the sediment concentrations have dropped significantly. Four bathymetric surveys of the reservoir were conducted in the years 1981, 1986, 2008 and 2009. Analysis showed that the sedimentation rate in the reservoir in the period (1925-1981) was ½ % per year. Therefore, only 28 % reduction in the reservoir capacity occurred during the 56 years of operation. The reason behind this perfect performance is the good operation of the dam as the river is left to flow freely without impoundment in reservoir during the flood season. The following period (1981-1986), sedimentation rate increased drastically to 5.8 % per year i.e. a reduction of 29% in only 5 years. As a fact there is an increase of incoming sediment loads to the reservoir in the last two decades due to climate change and climate variability, Gismalla (2010). However, the main reason behind the heavy sedimentation in the period (1981-1986) is the change of the operational rules to satisfy the irrigation requirements, for the agricultural schemes, upstream and downstream the dam, Ahmed (2003). Despite of these operation rules that aim at minimizing sediment deposition, Sennar reservoir lost 559 $Mm^3$ (60%) of its original storage capacity. This reduction in the reservoir storage capacity due to sedimentation has reduced the benefits from the dam such as irrigation water, power generation and flood attenuation capabilities. The current function of the dam now is maintaining the required water levels for irrigation of Gezira Scheme and other schemes and power generation.

## 2. OBJECTIVES

Sedimentation has interfered with the operation of Sennar reservoir since mid eighties. The reservoir is now approaching its end of life stage due to continuous sedimentation. Therefore, it is important at this crucial stage to investigate the current dam's operation using new developed knowledge in reservoir sedimentation. The costs of lost storage due to sediment deposition and operation policy have never being evaluated before. The objective of this paper is to investigate the present reservoir's sediment management strategy using contemporary knowledge in reservoir sediment management and evaluate the economic impacts of reservoir sedimentation in present reservoir operation.

## 3. MATERIAL AND METHODS

Many datasets and information were collected from different sources, collated and analyzed. These include Blue Nile flow time-series, sediment concentrations and loads time-series', reservoir surveys, operation rules, power generation and economic data. Sediment rating curves downstream Sennar reservoir were developed and compared with a number of contemporary sediment sluicing and flushing equations. Economic impacts of the present reservoir operation were assessed using economic values of water in agriculture and power generation.

The sediment concentrations in the Blue Nile vary throughout the flood season. The flood starts with low sediment concentrations in mid-June and increases gradually until it reaches its maximum concentration in the second period of July and then decreases again to its lowest value at the beginning of November (Gismalla, 2014). The maximum recorded sediment concentration was 2.6% by weight at Roseires, upstream Sennar dam during the 1988 flood (Hussein and Yousif 1994). The transported sediment in the Blue Nile consists of significant quantities of very fine material composed of silt and clay which is transported in suspension and accounts for approximately 85-90% of the total sediment load in the Blue Nile (Gismalla, 2016).

Part of the sediment load entering the reservoir is trapped and the remaining is released downstream. Out flowing sediment discharge from reservoir become smaller than the inflow during the rising water level of a flood, because of a decrease in flow velocity and the backwater effect (Fan, 1985). To increase the outflow of sediment from reservoirs, the flow velocity is increased by lowering reservoir water level resulting in decreasing flow area. This operation is known as sediment sluicing which is defined as that operational technique whereby the incoming bulk sediment is kept in suspension and released through the dam mostly before it can settle down and deposit on the bottom of reservoirs (Fan and Morris, 1992). Sediment flushing differs from sluicing in that; in flushing, previously accumulated sediments in the reservoirs are remobilized and transported downstream.

The operation rules of Sennar reservoir require the water level to be kept minimal at 417.5 m during the flood season. Thus the flow area is minimized and hence the flow velocity is increased transporting the heavy sediment load to downstream. The reservoir is then filled after the sediment concentration has dropped significantly in mid-September, as shown in Figure 1.

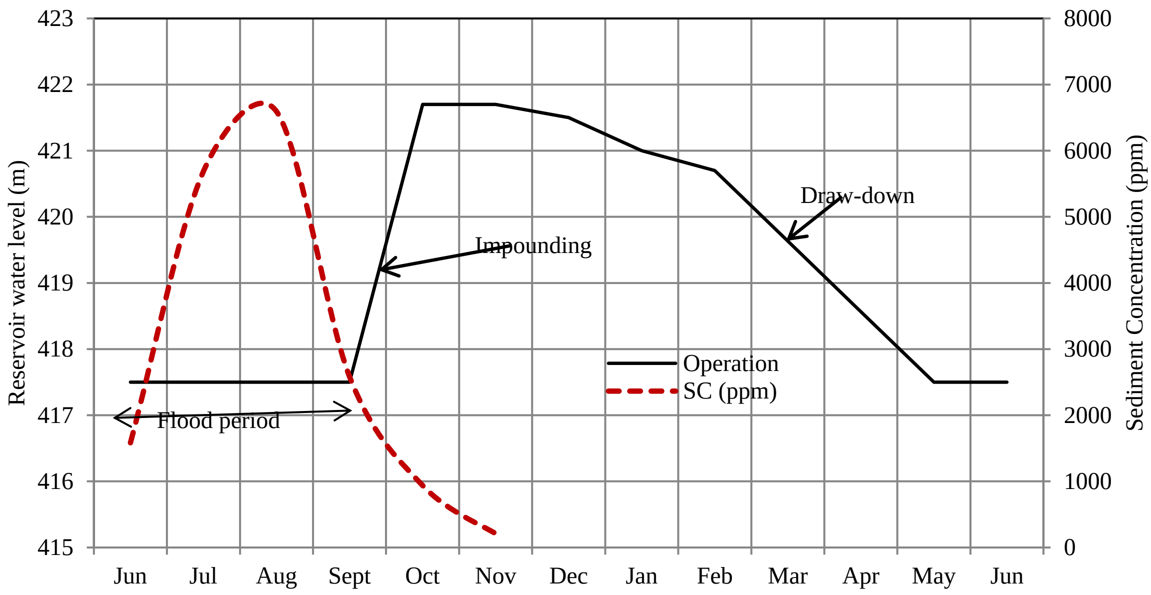


**Figure 1: Average operation curve for Sennar dam**

The sediment in the Blue Nile is monitored at three stations namely Eddeim and Wad Elais upstream the reservoir and Sennar station downstream the reservoir. The Flow-Duration, Sediment-Rating Curve method developed by Miller (1951) was used for estimating the long term average sediment yield of the Blue Nile at Eddeim. The short-term sediment-rating curves for the years (1970, 73, 75, 93, and 1994) were combined with long-term flow-duration curve for the years 1966-2009 for the same station. The estimated long-term average sediment yield for the Blue Nile at Eddeim is found to be 146 million tons. This figure is in agreement with a value of 140 million tons given by Hussein et al. (2005). Bashar and Ahmed (2010) reported that the sedimentation rate in Roseires reservoir for the first 10 years (1966-1976) is 55 million $m^3$ per year. This sedimentation rate decreases annually as the inverse of the square root of the operation time in years since first impoundment in 1966 to reach 34.3 million $m^3$ in 2007.

To check whether sediment sluicing is the appropriate operation option for Sennar or not, the Basson diagram was employed. Basson (1997), after analyzing data from 177 dams developed a diagram for making a preliminary judgment on which reservoir operation mode should be selected for sedimentation control. The two indices in the diagram are the water index Kw, which is the ratio of reservoir capacity to mean annual runoff, and the sediment index Kt, defined as the ratio of reservoir capacity to mean annual sediment yield. Sennar reservoir, Kw=930/50,000=0.0186 and Kt=930/146 = 6.4, falls in the area of sediment sluicing, Figure 2.

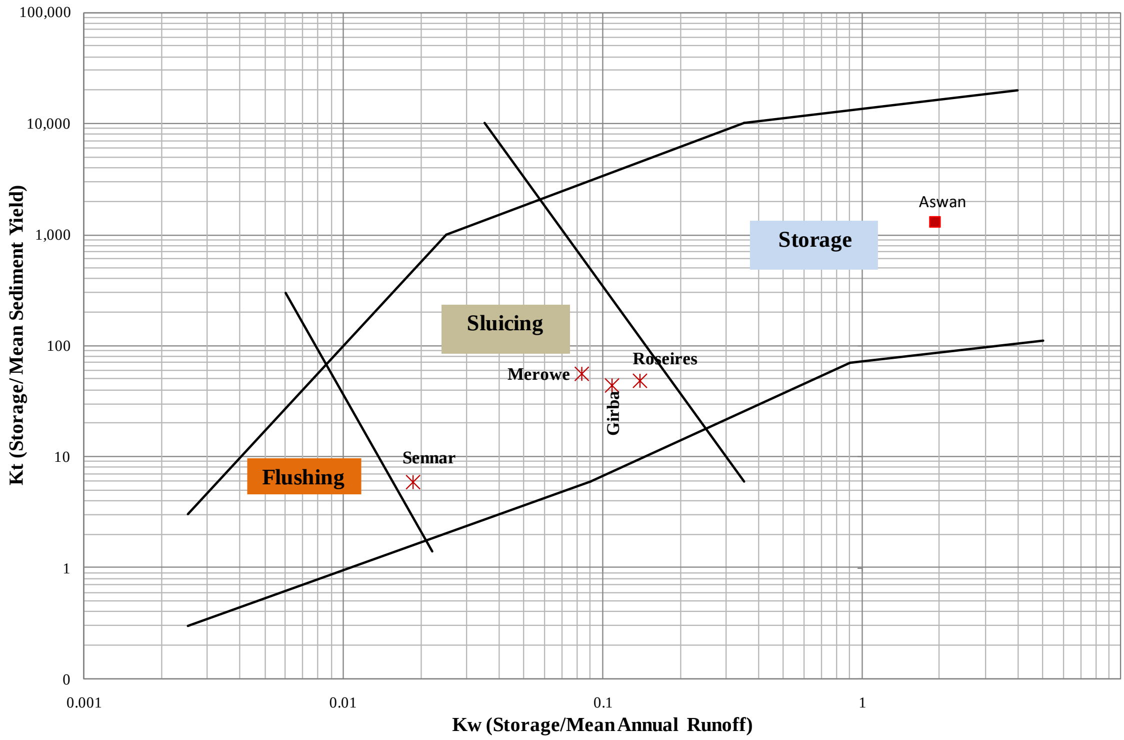


**Figure 2: Sennar reservoir operation type according to Basson's diagram for initial reservoir sediment management**

The annual volumes of sediment passing downstream Sennar dam were plotted versus the respective volume of water released during each season, for the period 2002 – 2014. Paul and Dhillon (1988) equation for free-surface flushing was then plotted on the same plot as shown in Figure 3.

Paul and Dhillon (1988) equation is: $V_s = 0.1048V^{0.687}$ ……………………... (1)

Where:

$V_s$ is volume of sediment ($m^3$), V is the volume of water used in the flushing ($m^3$).

Two sediment rating curves namely a rising and a falling curve, were developed for Sennar station downstream the dam for the period 2002 – 2014, as shown in equation (2) and equation (3).

Rising Flood Limb (Mid-June – August 20th)

$\mathbf{Q_s} = 0.491\mathbf{Q}^{1.412}$ [$R^2 = 0.7$] …………………... (2)

Falling Flood Limb (August 21st – Mid November)

$\mathbf{Q_s} = 0.004\mathbf{Q}^{2.013}$ [$R^2 = 0.8$] …………………... (3)

Where:

**Q**= released water discharge in $10^6$ $m^3$/day, Qs= sediment discharge in $10^3$ Tons/day.

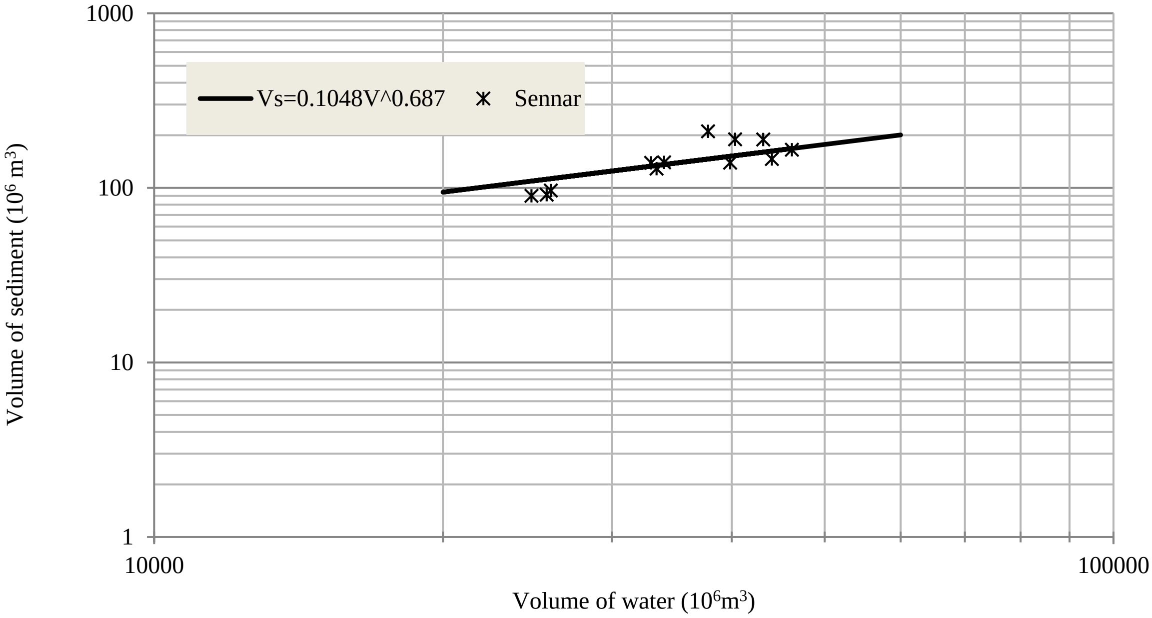


**Figure 3: Volumes of sediment sluiced versus volumes of water used for sluicing downstream Sennar (2002-2014)**

Sediment discharges for the different dam releases were calculated using the above sediment rating curves. The sediment concentrations predicted by Wu (1989) empirical equations for pressurized flushing, equation (4), free surface flushing, equation (5), and Tsinghua University equation for calculating sediment-transporting capacity of the deep sluice at flushing, equation (6) were converted into sediment discharges and compared with the computed sediment released from the reservoir at Sennar station, as shown in Figure 4.

Wu (1989) empirical equation for free surface flushing:

$$C_w = 847.1 \left[\frac{V^3}{gdw}\right]^{-0.49} \quad (4)$$

Wu (1989) empirical equation for pressurized conditions:

$$C_w = 64.9 \left[\frac{V^3}{gdw}\right]^{-0.45} \quad (5)$$

Where, V = the flow velocity in m/s; d= the flow depth in m;
w= the falling velocity of the sediment particles (m/s); g= the gravitational acceleration in $m/s^2$.
The Tsinghua equation for calculating sediment-transporting capacity of the deep sluice at flushing is given by (Atkinson, 1996):

$$Q_s = \Psi \frac{Q_f^{1.6} S^{1.2}}{W^{0.6}} \quad (6)$$

Where:

Ψ is the multiplier in the Tsinghua University method for sediment load prediction during flushing; S=longitudinal slope during flushing; W= is the representative width of flow for flushing conditions (m). In situ settling velocity measurements were conducted to determine the falling velocity 'w'.

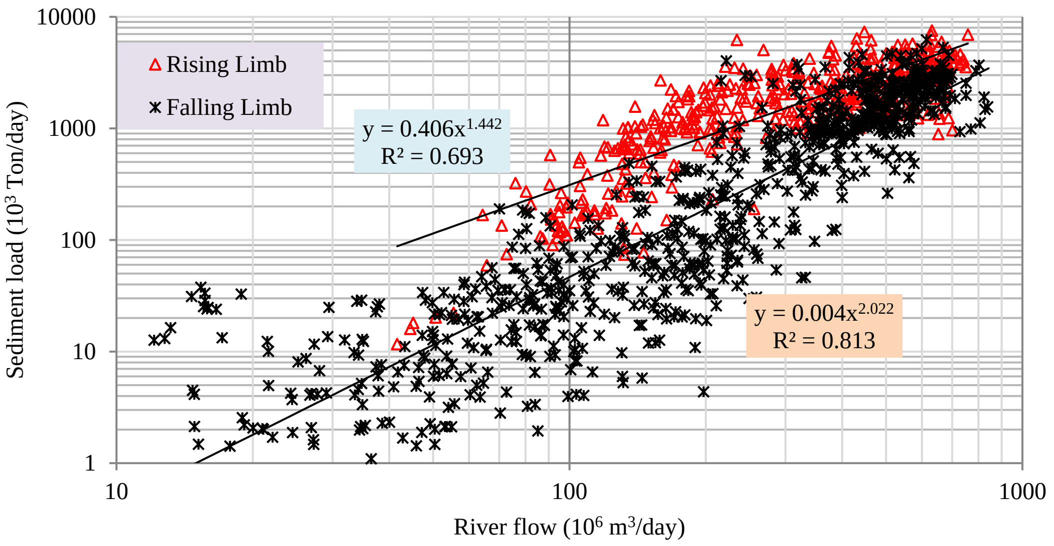


**Figure 4 : Sediment rating curves for the Blue Nile downstream Sennar dam (2002 – 2014)**

Four methods were used for calculating the sediment trap efficiency of Sennar reservoir. These are the Brune (1953) curves, the empirical equation of Dendy (1974), the sediment balance, and reservoir resurveys. Dendy (1974) empirical equation is given as:

$$TE = 0.97^{0.19^{\log(\frac{V}{I})}} \qquad (7)$$

Where, TE= Trap efficiency; V = initial reservoir volume ($930 \times 10^6 m^3$); and I= annual river flow ($50 \times 10^9 m^3$)

The sediment balance is done by subtracting the sediment passing downstream from that entering the reservoir. Daily sediment loads entering the reservoir at Wad Elais station are predicted using the daily river flows and the sediment rating curves at Wad Elais, equations (8) and (9). While the released sediment loads downstream the dam are computed from the daily released water and sediment rating curves downstream Sennar dam viz. equations (2) and (3). The sediment balance is done on annual basis.

The sediment rating curves for Wad Elais station (1999-2014):

Rising Flood Limb (Mid-June – August 20th)

$Q_s = 0.0707Q^{1.7309}$ [$R^2 = 0.69$] …………….…..…..….. (8)

Falling Flood Limb (August 21st – Mid November)

$Q_s = 9 \times 10^{-4} Q^{2.3361}$ [$R^2 = 0.75$] ………....…..….…….. (9)

The trap efficiency as calculated from the reservoir survey results for the years 1981, 1986, 2008 and 2009 is given by:

$$TE(\%) = \frac{(Vo - V)\gamma}{TQs} \qquad (10)$$

Where;

TE = trap efficiency after T years of operation;
$V_o$ = original reservoir volume ($m^3$);
V = volume remaining after T years of operation;
Qs= annual sediment inflow (Ton);
T = number of operation years since first impoundment,
$\gamma$ = average specific weight of deposited sediment over T years ($t/m^3$). $\gamma$ is calculated using Miller's equation (Miller, 1953) as:

$$\gamma = \gamma i + 0.434K\left[\frac{T}{T-1}(\ln T)\right] \qquad (11)$$

Where γi the initial value of γ and is given by:

$$\gamma_i = W_{cl}\,P_{cl} + W_{si}\,P_{si} + W_{sa}\,P_{sa} \ldots\ldots\ldots\ldots (12)$$

and;

$$K = K_{cl}\,P_{cl} + K_{si}\,P_{si} + K_{sa}\,P_{sa} \ldots\ldots\ldots\ldots (13)$$

Where, $P_{cl}$, $P_{sl}$ and $P_{sa}$ are fractions of clay, silt and sand respectively of the incoming sediment. While $W_{cl}$, $W_{sl}$ and $W_{sa}$ are coefficients of clay, silt and sand respectively. These coefficients depend on the type of reservoir operation, which can be obtained from the tables prepared by Lara and Pemberton, Annandale (1987).

The lowering of the reservoir water level during the flood season June, July and August results in reducing the power generation. The daily average power generated in Sennar dam for the years 2007-2013 is shown in Table 2. The daily average power generated during the flood season June, July and August are 175.5, 38.4 and 88.9 MWH, respectively. While the daily average power generated for the remaining months of the year is 228.4 MWH. Therefore, the total power generation foregone during the three-month period of flood due to lowering the water level in the reservoir is 11.71 GWH.

## 4. RESULTS & DISCUSSIONS

The plotted  indices of Sennar reservoir in Basson's (1997) diagram shows that, Sennar reservoir falls in the zone of sediment sluicing, Figure 2. Therefore, selection of sediment sluicing as an initial sediment control for Sennar reservoir was successful.

The plotted annual volumes of sediment sluiced downstream Sennar versus the corresponding flood water released during sluicing showed good agreement with Paul and Dhillon (1988) equation for free-surface flushing, Figure 3.

The sediment loads released downstream Sennar reservoir were as high as those calculated by Wu (1989) equation for free surface flushing, while Wu (1989) equation for pressurized flushing resulted in lower sediment loads, Figure 5. It is also clear from Figure 5 that Tsinghua equation with a reduction factor of 3 gives much higher sediment concentrations than those in the present operation of the reservoir. This gives a clue for increasing the released sediment from Sennar reservoir by flushing.

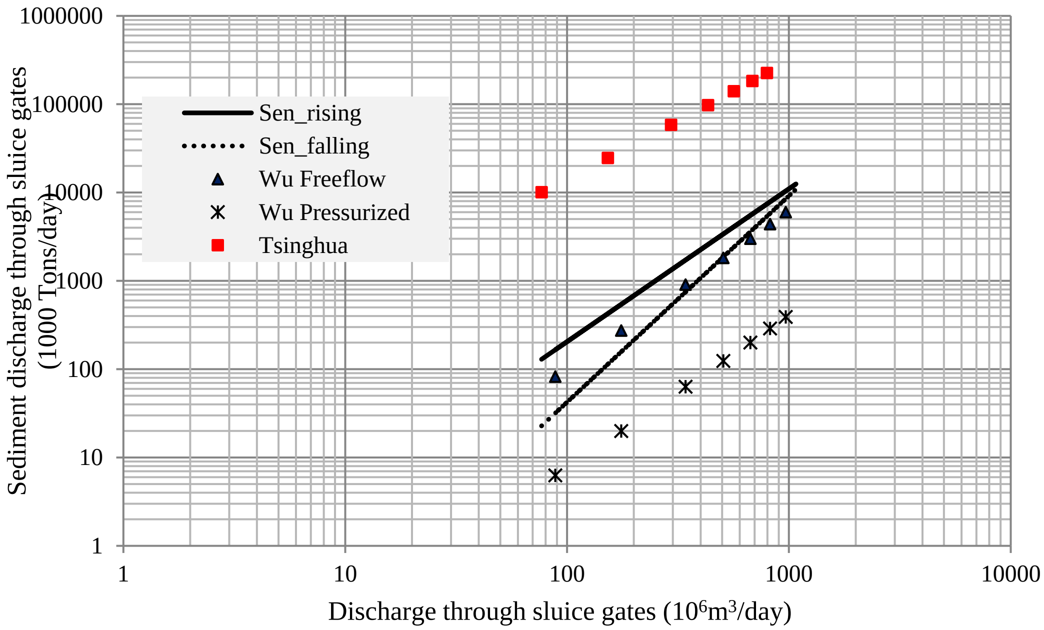


**Figure 5: Sluice gates sediment discharge versus water released**

Based on the last survey of 2009, the sediment trap efficiency of Sennar reservoir as calculated from reservoir surveys is found to be 5.5%, while those calculated by Dendy, Brune equations and sediment balance methods are 35.1%,18.6% and 17.8%; respectively, Table 1. It is clear that Dendy and Brune methods gave higher estimates of the sediment trap efficiency because they did not consider the sediment trapped in Roseires reservoir and the effect of sediment sluicing practiced in Sennar reservoir.

**Table 1: Sediment trap efficiency of Sennar reservoir**

| Survey | T | $\gamma_T$ | C | C/I | Sennar TE | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | Re-survey | Dendy | Brune | Sed. Balance |
| **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** |
| 1925 | 0 | 1.065 | 930 | 0.0186 | | 58.3 | 59.1 | |
| 1981 | 56 | 1.2064 | 640 | 0.0128 | 4.3 | 49.4 | 51.2 | |
| 1986 | 61 | 1.2101 | 370 | 0.0074 | 7.6 | 35.0 | 36.9 | 23.2 |
| 2008 | 83 | 1.2235 | 328 | 0.0066 | 6.1 | 31.9 | 34.2 | 21.7 |
| 2009 | 85 | 1.2245 | 371 | 0.0074 | 5.5 | 35.1 | 18.6 | 17.8 |

On the other hand, the sediment rating curves used in sediment balance computations were developed using collected sediment data for the last three decades. These rating curves may not be applicable to earlier river sediment loads and therefore over estimated the sediment loads.

The cost of the present operation is the foregone benefits from dam's services due to lowering the reservoir's water levels for sluicing sediment and damage due to release of high sediment concentrations. Power generation and irrigation water supply are the main sectors being seriously affected by lowering the reservoir's water level. Power generation foregone during June, July and August is 11,712 MWh, Table 2. Annual lost revenue due to power forgone during June, July and August is about 1.0 million dollars, at $0.084/kwh, 50% of it being during August. If the foregone power is substituted by gas-turbine generation then the total cost will be 65 million dollars annually. Lowering of the reservoir level during the rainy season has minor or no effect on irrigated crops if rain is good. Anyhow, the lost revenue from the reservoir could have been higher if sediment sluicing is not practiced in the reservoir and large volume of storage capacity being lost due to sedimentation. This fact is reflected in the reduced trap efficiency of the reservoir as compared to Dendy and Brune values.

**Table 2 : Average power generated in Sennar dam (2007-2013)**

| **Month** | **Power (MWH/day)** | | **Monthly Forgone** |
|---|---|---|---|
| | **Generated** | **Foregone** | |
| **Oct-June** | 228.4 | - | - |
| **July** | 175.5 | 52.9 | 1,640 |
| **August** | 38.4 | 190.0 | 5,890 |
| **September** | 88.9 | 139.4 | 4,182 |
| **Total** | | | 11,712 |

## 5. CONCLUSIONS AND RECOMMENDATIONS:

The present sediment sluicing in Sennar reservoir agrees with Basson's (1997) diagram classification and Paul and Dhillon (1988) equation. The sediment concentrations downstream Sennar reservoir is as high as that calculated from Wu (1989) equation for free surface flushing. The released sediment concentrations downstream Sennar dam are lower than those predicted by Tsinghua equation for flushing. This gives a clue that flushing may be technically feasible for Sennar reservoir. Sediment sluicing in the current reservoir operation has positive impacts in prolonging the useful life of the dam as about 95% of the incoming sediment is sluiced. The present operation of Sennar reservoir is not sustainable as standalone option since part of the incoming sediment is trapped every year. It is recommended to explore some feasible reservoir sediment removal techniques that make reservoir operation sustainable. It is also recommended to have such investigations in other reservoirs subject to similar conditions of sedimentation.

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