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Trap efficiency of reservoirs on the Nile River

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ABSTRACT: The reservoir trap efficiency is defined as the ratio of deposited sediment to the total sediment inflow for a given period within the reservoirs economic life time. The curves presented by Brune are still widely used to estimate the reservoir trap efficiencies. These curves are based on data collected from 40 normal ponded reservoirs in the USA. In the Nile River, the transported sediment is mainly cohesive material from which about 85% to 95% are suspended sediment. Data from the Roseires Reservoir on the Blue Nile show that trap efficiency decreased from 45.5% after 10 years to 26% after 30 years of operation. However, by applying Brune's curves the estimated trap efficiency is about 79%. Recently, Siyam (2000) showed that Brune's curves are a special case of a more general trap efficiency function which can be described by an exponential decay function. The so-called sedimentation factor β which is integrated in the equation of Siyam reflects the reduction in reservoir storage capacity. The upper and lower Brune's trap efficiency curves can be well described with β=0.0055 and β=0.015 respectively for normal ponded reservoirs. Siyam (2000) provided an explanation for Brune's extreme data in the semi-dry reservoirs (β=0.75) and de-silting basins (β=0.00012). The observed trap efficiency in the Roseires reservoir can be well estimated using a value of β=0.056. The simulation of the long-term morphological changes in the Nile River due to construction of Merowe and Shereik dams in Sudan using 1D numerical morphological model revealed that the trap efficiencies of these reservoirs did not follow Brune's curves for normal ponded reservoirs. The calculated sedimentation factor β has a range between 0.015 and 0.056. In addition, the relation between trap efficiency and years of operation in these reservoirs is presented.

Keywords: Trap efficiency, Reservoir Sedimentation, Nile River, Numerical Modelling

1 INTRODUCTION

Reservoirs are built either as single or multi-purpose reservoirs. Most reservoirs are multi-purpose schemes combining two or more of the following requirements: irrigation, hydropower, water supply, flood control, navigation, fishery, recreation, and environmental issues. On the Nile River system, there are several man-made reservoirs, e.g. in Uganda, Ethiopia, Sudan and Egypt. Further plans for new dams however are under way (Abdelsalam, 2008).

Normally, smaller reservoirs (e.g. Angereb, Koka, Sennar, and Khashm El Girba) are affected more by sedimentation than the larger ones (e.g. Aswan and Merowe) because the relative loss in capacity is faster. However, Owen and Bujagali reservoirs receive almost negligible or limited amount of sediment since they are located only few kilometres downstream of the Victoria Lake on the White Nile, where almost all suspended sediments are being deposited.

Reservoir trap efficiency is defined as the ratio of deposited sediment to the total sediment inflow for a given period within the reservoir economic life time. Trap efficiency is influenced by many factors, of which primarily factors are: the sediment fall velocity, the flow rate through the reservoir and the reservoir operation rules. The relative influence of each of these factors on the trap efficiency has not been evaluated to the extent that quantitative values can be assigned to individual factors. The detention-storage time with respect to character of sediment appears to be the most significant governing factor in most reservoirs (Gottschalk, 1964). Trap efficiency estimates are empirically based upon measurements of deposited sediment in a large number of reservoirs mainly in the USA. Among others, Brune's curves are the most widely used (Figure 1). Brune presented a set of envelope curves applicable to normal ponded reservoirs using the capacity-inflow relationship.

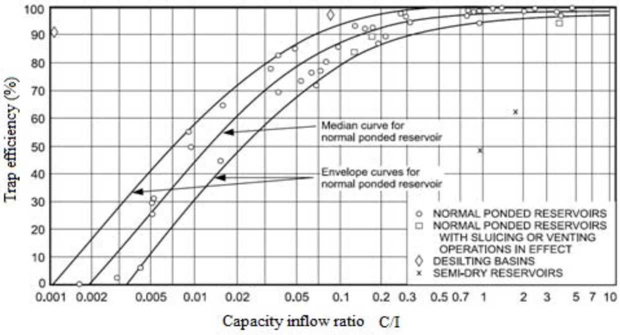

Figure 1. Reservoir trap efficiency as a function of capacity inflow ratio (Brune, 1953).

Recently, Siyam (2000) developed a new relationship for the trap efficiency of reservoirs showing that Brune's curves are a special case of a more general trap efficiency relation given in the form of an exponential function:

$$E(\%) = 100.e^{-\beta I/C} \quad (1)$$

where I/C is the ratio between average annual inflow and reservoir capacity, β is a sedimentation parameter that reflects the reduction in the reservoir storage capacity due to the sedimentation processes as shown in Figure 2. Siyam (2000) demonstrated that Eq.1 with β equal to 0.0055, 0.0079 and 0.015 describes well the upper, median, and lower Brune's curves. Figure 2 shows Brune's data for semi-dry reservoirs i.e. β=0.75 and in case of mixer tank, where all the sediment is kept in suspension i.e. β=1.0.

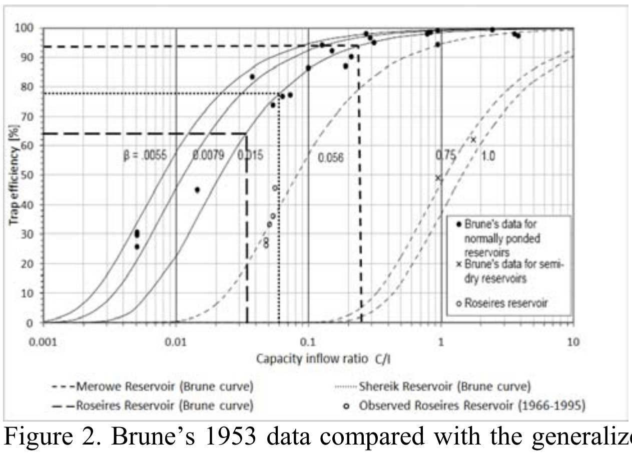

Figure 2. Brune's 1953 data compared with the generalized trap efficiency function (Siyam, 2000).

2 EXISTING NILE RESERVOIRS

2.1 *Aswan High Dam Reservoir*

The Aswan High Dam (AHD) was built in 1964-1968 on the Main Nile River in Egypt (Figure 6). It created a storage reservoir with a total capacity of 162 billion m^3. Investigations and analyses of sediment depositions have been carried out since 1973. Figure 3 shows the longitudinal profiles of deposited sediment along AHD reservoir, which indicates that the accumulative volume of the deposited sediment during the period from 1964 to 2003 was estimated to be 3.1 billion m^3 (Makary et al., 2004). The annual suspended sediment rate entering the reservoir varied from 50 to 300 billion tons as shown in Figure 4. Up to now the trap efficiency of AHD reservoir is almost 98%. The average annual flow rate of the Nile River was estimated to be 84 billion m^3. This estimation was based on the records during the period from 1905 to 1959. However the long term average inflow of the Nile River at Dongola gauging station amounts to 73 billion m^3 as shown in Figure 5.

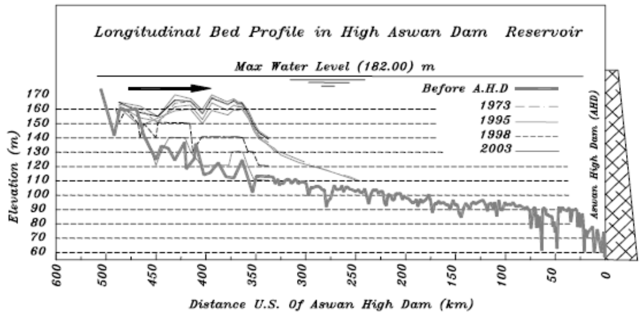

Figure 3. Longitudinal bed profiles in AHD Reservoir.

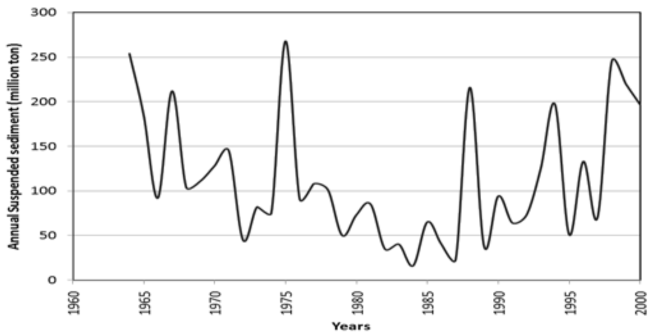

Figure 4. Suspended sediment entering AHD Reservoir.

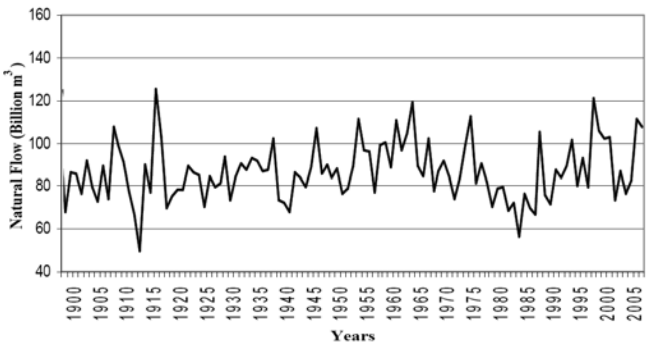

Figure 5. Average long-term flow rate at Dongola.

2.2 *Roseires Reservoir*

Roseires dam was constructed in 1966 on the Blue Nile about 700 km south of the city of Khartoum (Figure 6) with an initial reservoir capacity of 3.3 billion m^3 at retention level 481 m asl. Based on Brune's curves the estimated value of the trap efficiency of the Roseires reservoir was estimated to be about 79%. However, after 10 years of operation the sediment deposited in the reservoir revealed that the trap efficiency was 45.5% and then decreased dramatically to 26.2% after 30 years (see Figure 12). After 30 years, the total remaining storage volume was 63% (see Figure 12); it is noticeable that Brune's method overestimated the trap efficiency of the Roseires reservoir considerably. The observed trap efficiencies of the Roseires reservoir are between Brunes's data for normally ponded and for semi-dry reservoirs. Siyam (2000) showed that the trap efficiencies in the Roseires reservoir can be well estimated using Eq.1 with a sedimentation parameter $\beta=0.056$. Further, the relation between the observed trap efficiency E and the years of operation T can be expressed as $E \sim T^{-0.5}$ (see Figure 12). From Figure 12 the predicted trap efficiency of Roseires reservoir after 100 years will reach a value of 14% (Hussein et al., 2005).

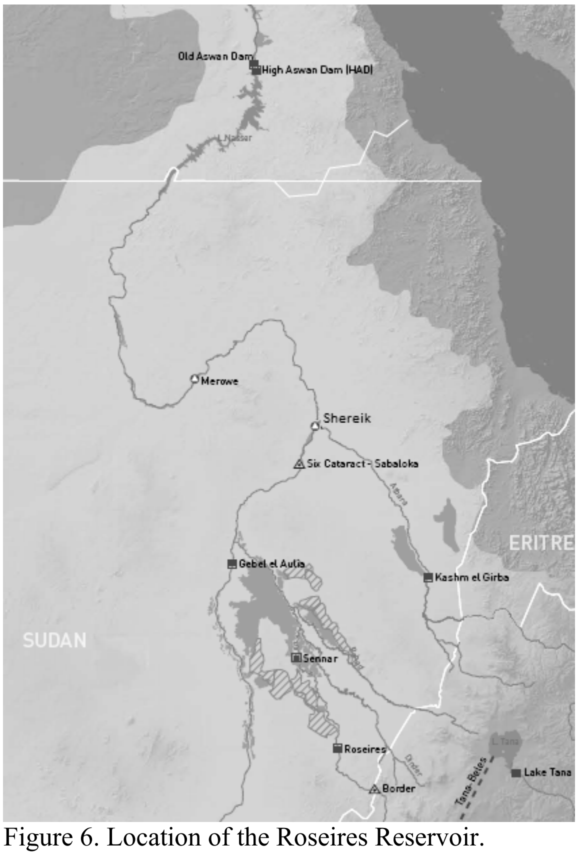

Figure 6. Location of the Roseires Reservoir.

2.3 *Merowe Reservoir*

The Merowe dam reservoir is located some 350 km north of Khartoum near the 4th cataract of Nile River (Figure 6) and some 550 km upstream of the Aswan High Dam in Egypt.

In 2007 Lahmeyer International (LI) conducted a study in the Nile River for a reach extending 220 km upstream of Merowe dam to determine the reservoir boundaries after 10, 30, 50, and 100 years of dam operation, the losses of reservoir storage volume due to sediment deposition, and the efficiency of the reservoir flushing operation modes. A 1D numerical model using the commercial software MIKE11 developed by the Danish Hydraulic Institute (DHI) has been setup by LI with geo-referenced data points obtained from a bathymetric survey. The model consists of a hydraulic module coupled with a sediment transport module for cohesive and non-cohesive material.

It is known that reservoir sedimentation can be reduced by flushing activities, which means that for certain periods the reservoir level is lowered in order to increase the flow velocity so that larger amounts of sediment can be passed through the reservoir. The numerical simulations were carried out by LI for two proposed reservoir operation rules (with and without flushing) to quantify their effects on reservoir sedimentation. The model was setup with sediment input data based on measurements of the hydrological department of Egypt from 1929 to 1955 at Kajnarty, located 399 km upstream of the AHD. These measurements were evaluated and summarized by Shalash (1982) as shown in Figure 7. According to these measurements, the average annual suspended sediment load amounts to about 137 million tons. The numerical model assumed that 15% of the total load was non-cohesive sediment. Further, from the historical data series at Dongola gauging station, the mean annual inflow was estimated to be 72.5 billion m^3. The recorded discharges of the year 1977 were used as input flow data in the long term morphological simulation. The maximum daily discharge in this year was 9,436 m^3/s (see MDPIU, 2007).

The calculated trap efficiency for the case without flushing will decrease from 86 % after 10 years up to 67.2 % after 100 years. Due to flushing operations the trap efficiency was reduced with a rate of about 6% compared to that in the case without flushing (see Figure 12). Based on Brune's curves, the trap efficiency of the Merowe reservoir was estimated to 94%. Comparing these values indicates that Brune's curves overestimate the trap efficiencies in Merowe as well as in Roseires reservoirs. Based on the LI numerical results and Eq.1, the sedimentation parameter β of the Merowe reservoir was found for the two considered cases:

without flushing → $\beta = (0.020 – 0.032)$
with flushing → $\beta = (0.030 – 0.045)$

Figure 11 shows that the reservoir will lose about 41% of its storage capacity due to sedimentation after 100 years with flushing schemes. Further, the relation between expected trap efficiency E and years of operation T can be expressed as: $E \sim T^{-0.11}$.

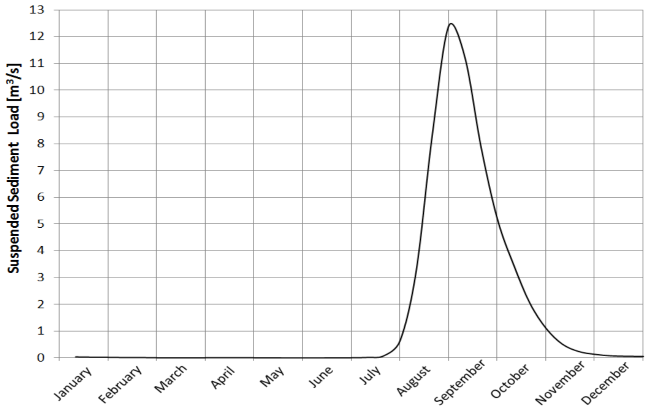

Figure 7. Suspended sediment rates (Shalash, 1982).

3 PROPOSED SHEREIK RESERVOIR

In the 5th cataract of the Nile River, the Dams Implementation Unit (DIU) plans to build the Shereik Dam in northern Sudan with a total capacity of 3 billion m^3. The Shereik Hydropower project will form a significant part of the hydropower development scheme of the main Nile River downstream of the confluence of the White Nile and Blue Nile at Khartoum. The Shereik hydropower plant is located about 478 km north of Khartoum.

A numerical study using one, two and three dimensional models has been carried out by the Institute of Hydraulic and Water Resources Engineering and the Oskar-von Miller Laboratory, Technical University of Munich (TUM) for a 236 km long river reach from the city of Atbara (km 327.5) to the El-Koro gauging station (km 563.5). For the 1D numerical model MIKE11 was used as required by the consultant (LI) to estimate the long-term water and bed level changes due to reservoir impounding and to optimize the effects of sediment flushing activities during flood times both on the reservoir capacity and on backwater effects.

3.1 *1D Model Setup and Available Data*

The model geometry has been setup by using 92 cross sections covering a 150 km long river reach upstream of the proposed dam site, from Atbara (km 327.5) to the dam site (km 478.0). Another and 79 cross sections were used, these cross sections covering an 85 km long stretch of the downstream river reach from the dam site to El Koro (km 563.5). Each cross section consists of about 700 to 2600 Geo-referenced points, which were provided by DIU and LI (see Figure 8).

A set of rating curves at Berber (km 366.2), Shereik Ferry (km 479.3), Shereik Old (km 481.7), and El Koro (km 563.5) were used for calibration of the hydraulic model. Minor and major flood events in 2005 and 2007 with a maximum discharge of Q = 9,200 m^3/s and 11,300 m^3/s respectively were observed. The annual inflow during these years amounted to 73.5 km^3 and 106 km^3 respectively.

Based on the measurements of suspended sediment load, which were conducted by DIU on several days during the flood in 2005 at El Koro, TU Braunschweig developed a functional relationship between discharge and suspended sediment concentration (Koll, 2007). Figure 9 shows a predicted suspended sediment hydrograph. By applying these functions for the flow discharges in 2005 the annual amount of the suspended sediment is 262 million tons.

Related to the large difference between the two data sets for suspended sediment rates (see Figs.7 and 9) it was decided to use two scenarios for the long-term simulation of the hydro-morphological changes. These scenarios are presented in Tab.1.

Table 1. Two Scenarios of data used in numerical model.

Data number	Flow hydrograph +Sediment Hydrograph
1	2007 + Shalash, 1982 (Figure 7)
2	2005 + Koll, 2007 (Figure 9)

Available data of sediment transport in the Nile River system suggested that the suspended sediment rate commonly accounts for approximately 90% of the total load (Abdelsalam, 2008). Hence, in the numerical model bed load was assumed to be 15 % and 9% of the total load for data sets no.1 and no.2 respectively.

3.2 *Hydraulic Model Calibration and Validation*

Initially, the hydraulic model was calibrated by altering model parameters within reasonable ranges and then comparing calculated results with measured data. In this study, differing Manning's roughness factors were specified for the entire river reach based on the type of profile and the water discharges.

In the first step, calculations were carried out for different steady flow discharges ranging from 430 m^3/s to 19,900 m^3/s. These discharge values were applied in the model as inflow boundary conditions. The water levels from the discharge/stage relation measured at El Koro gauging station were used as outlet boundary condition. It was found that Manning's coefficients varied between n=0.0169 $s/m^{1/3}$ and n=0.0434 $s/m^{1/3}$ in the upstream reach (from Atbara to Shereik dam) and between n=0.0384 $s/m^{1/3}$ and n=0.0555 $s/m^{1/3}$ in the downstream reach (from Shereik dam to El Koro). Using these Manning's coefficient values a good agreement between the predicted and observed water elevations was obtained.

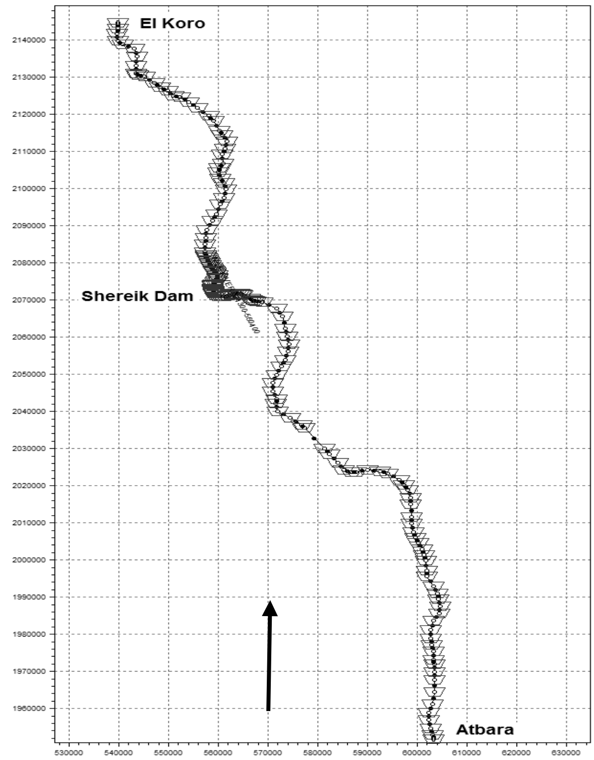

Figure 8. Model setup area (MIKE 11).

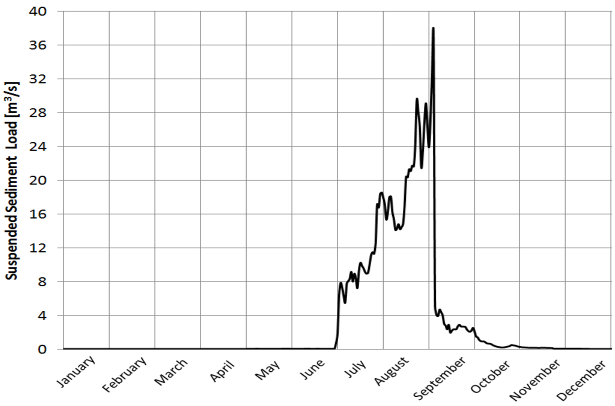

Figure 9. predicted suspended sediment based on flow hydrograph at El Koro 2005 (Koll, 2007).

MIKE 11 provides an option where Manning's n can be calculated as a function of hydraulic parameters such as water depth, hydraulic radius, and flow velocity (MIKE11, 2008). In our model the bed resistance was calculated as a function of the flow velocity according to the equation $n = aV^b$, where a and b are calibration coefficients, and V is the flow velocity. From the calibrated results a set of coefficients a and b were defined for different river cross sections.

Further, the hydraulic model was validated by applying it to the unsteady flow observations in 2007. The calculated variation in the water levels were then compared with the measurements obtained at Berber, Shereik Ferry and Shereik Old, and El Koro gauging stations, which were in an exemplary agreement with the measured data (Figure 10).

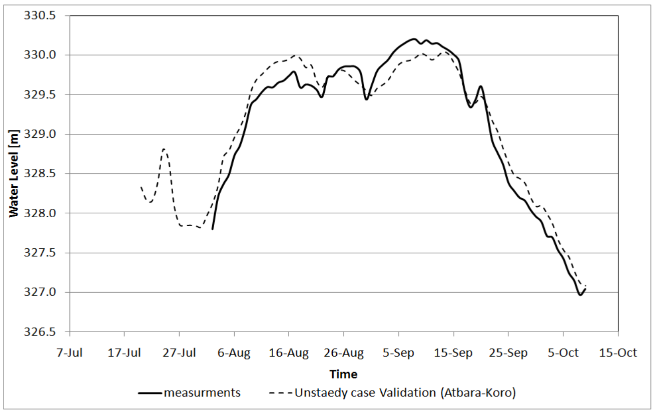

Figure 10. Water level change at Shereik Ferry.

3.3 *Sediment Transport Model Calibration*

It is well known that the Van Rijn bed load approach was developed on the basis of a range of fine sediments (0.2 mm to 2.0 mm). By comparing several sediment formulas with measured sediment records in the Nile reach downstream of the Aswan High Dam, Abdel-Fattah et al. (2004) found out that the Van Rijn formula is well suited to determine the bed and suspended sediment transport rate in the Nile River. Hence, this formula was applied in our model.

The sediment transport model was calibrated at first only for bed load. The so-called calibration coefficients of bed load rates in the MIKE11 model were adjusted. By assuming that the river reach before dam construction was in a quasi-equilibrium state, the deviation in bed load transport at different cross sections of the domain should be small after simulation of several years. In the numerical model, the calibration of bed load has been carried out for several simulation-years with the assumption that the deviation values of the calculated bed load rates along the river reach were not larger than 20 % from the maximum bed load rate at the inlet. The calibration results showed that most morphological changes occurred during the first 5 years and after that, a quasi-stable bed was obtained.

For the cohesive sediment the values for fall velocity 0.04 mm/s and critical shear velocity 0.035 m/s which resulted from calibration at Merowe Dam (see MDPIU, 2007) were used in the numerical model. The model prediction results show that deviation from observed suspended load at different cross sections along the river reach is quite small. Changing these values by ± 20% did not affect the calculated suspended sediment and bed change in case without dam. Suspended sediment load had only minor effects on the bed changes for the case without dam.

3.4 *Model Application for Expected Hydro-morphological Changes*

The calibrated model was applied for the prediction of long-term simulations of the water and bed level changes in the river reach and the effect of flushing activities on the trap efficiency of the reservoir. Figure 11 presents the predicted results of reservoir capacity changes due to sedimentation for a long time period. It can be seen that after 100 years the reservoir will lose between 41.6% (based on data set no.1) and 66.3% (based on data set no.2) of its initial volume. By applying flushing schemes we can reasonably extend the reservoirs life time; after 100 years the reservoir will lose only 35.6% storage volume (based on data set no.1).

The predicted trap efficiencies will decrease due to the reduction of reservoir storage capacity. Based on the numerical results using data set no.1, the trap efficiency will decrease from 39% after 10 years to 30.3% after 100 years for the case without flushing. Applying flushing schemes, the trap efficiency will decrease from 25.5% after 10 years to 23% after 100 years. Using the data set no.2, the trap efficiency will decrease from 53.1% after 10 years to 28.1% after 100 years for the case without flushing. For the flushing scheme, the trap efficiency will decrease from 22.5% after 10 years to 18.3% after 100 years. According to Brune's curves, the estimated trap efficiency of Shereik reservoir is 64%, which is greater than that based on numerical results, showing a significant overestimation.

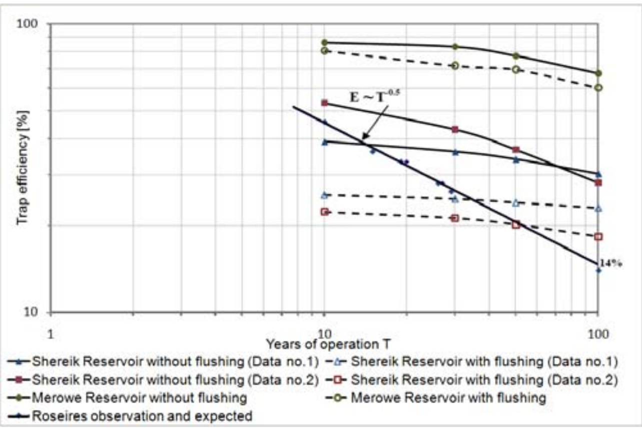

Figure 11. Remaining storage volume.

Evaluating the numerical results for Shereik reservoir, the sedimentation parameter β in Eq. (1) can be estimated as follows:

- Data 1 without flushing → β={0.019 - 0.026}
- Data 1 with flushing → β={0.026 - 0.038}
- Data 2 without flushing → β={0.016 - 0.026}
- Data 2 with flushing → β={0.034 - 0.061}

In addition, the relationship between expected trap efficiency and years of operation can be expressed as:

- Data no.1 without flushing → $E \sim T^{-0.11}$
- Data no.1 with flushing → $E \sim T^{-0.045}$
- Data no.2 without flushing → $E \sim T^{-0.085}$
- Data no.2 with flushing → $E \sim T^{-0.027}$

This relationship can be depicted also in Figure 12.

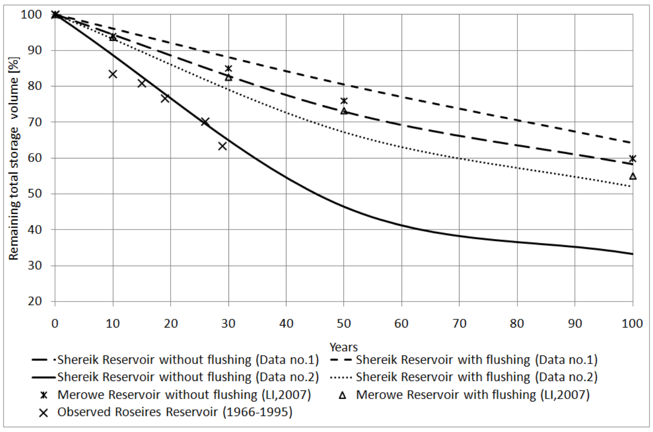

Figure 12. Relation between trap efficiency and years of reservoir operation.

4 CONCLUSIONS

Brune's curves overestimate the trap efficiencies of the Nile Reservoirs. Observations and hydromorphological numerical simulations showed that the equation proposed by Siyam (2000) with definition of the sedimentation parameter β can better describe the relationship between trap efficiency of the reservoir and the average annual inflow as well as the reservoir capacity.

Based on the observed data, the trap efficiency of the Roseires reservoir after 30 years of operation can be calculated by using a sedimentation parameter of β=0.056 Analysing the hydromorphological numerical results, it was found that the calculated trap efficiencies for Merowe and Shereik reservoirs within 100 years of operation fitted best with β values within the range of β =0.015 to β =0.056. For any reservoir, which is or will be constructed in the Nile River, the trap efficiency can be calculated by using Eq.1 with a sedimentation parameter ranging between β=0.015 and β=0.056. Furthermore the trap efficiency and the reservoirs lifetime within the Nile River basin can be well quantified using these findings.

NOTATION

The following symbols are used in this paper:

C = reservoir capacity [m^3]
E = trap efficiency
I = average annual inflow [m^3/year]
T = years of operation [years]
β = sedimentation parameter

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