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An overview of reservoir sedimentation in some African river basins

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Abstract The flow of water in many African rivers is regulated through storage reservoirs. The service life of some of these reservoirs is exercising a continuous reduction due to the unexpectedly high rate of siltation. Sedimentation of six reservoirs together with their operation rules are reviewed. These are the reservoirs formed by the Old and the High Aswan dams in Egypt, the Sennar, the Roseires and the Khashm el-Girba in the Sudan, and the Koka in Ethiopia. The present paper emphasizes the effectiveness of the operation rules as a means of reducing reservoir sedimentation.

INTRODUCTION

The sediment yield, as measured at the inlet of a storage reservoir, is the end product of a complex interaction of geomorphological processes. It depends on those characteristics of the basin(s) of river(s) flowing into the reservoir, such as climate, land slope and topography, land cover and pattern of land use.

As such, one should expect the sediment yield in a continent to vary widely from one river basin to another. Walling (1984) upon reviewing the available data for Africa concluded that the annual yield of river draining basins of the order of 10 000 km^2 ranges between 1 and 4000 t km^{-2}. No less than four-fifths of the surface area of Africa produce less than 100 t km^{-2} yr^{-1}. Rates of sediment yield in Africa are by world standards not especially high.

Although measurements of sediment transport by some rivers dates back to the last century, what so far is known is limited in quantity and modest in quality. Misjudgment of sediment yield causes the reservoir performance to differ from the design performance. Mostly the reservoirs get filled with sediments faster than originally thought, and the useful life age becomes shorter.

REVIEW OF CASE STUDIES

Six storage reservoirs are reviewed in this paper. These are the reservoirs formed by the Old and the High Aswan dams on the Main Nile, Egypt, the Sennar and the Roseires on the Blue Nile and the Khashm el-Girba on the Atbara, all three in the Sudan, and the Koka on the Awash, Ethiopia. The locations of these reservoirs are shown on the map, Fig. 1.

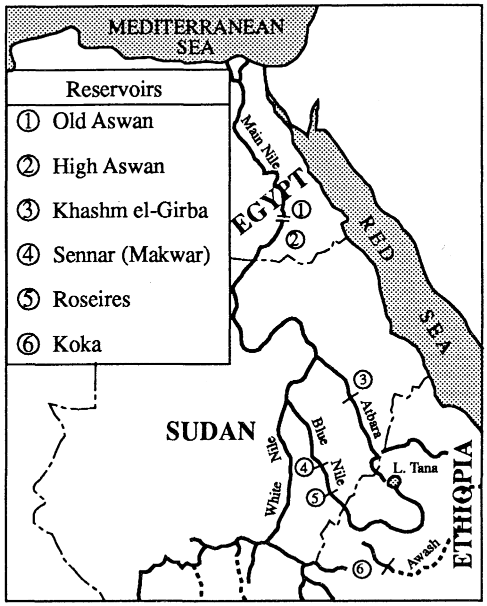

Fig. 1 Location map of the six reservoirs used in this paper.

Old Aswan reservoir

The original capacity of the reservoir of 1 km^3 in 1901 increased due to the dam heightening in 1912 and further in 1937 to reach 2.3 km^3 and 5.1 km^3, respectively. The stored water used to augment the natural supply in May and June each year up to 1964, when the High Aswan Dam was constructed.

The average concentration of the water reaching the reservoir is shown in Fig. 2, based on the data given by Semeika & Sherbini (1957). These data give an average

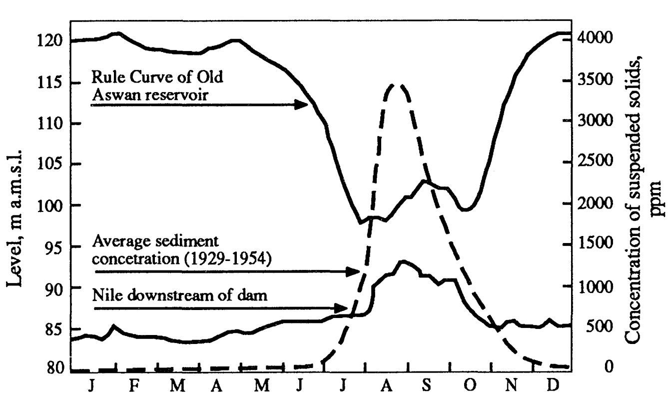

Fig. 2 Sediment concentration at Aswan and the rule curve of the Old Aswan reservoir.

load of 130 Mt yr^{-1}. To avoid any significant accumulation of sediments in the reservoir the operation rule that was used then is that shown in Fig. 2. This curve shows that filling used to begin when the downstream level reached 90.5 m a.m.s.l. or the river flow reached 0.53 km^3 day^{-1}. The corresponding sediment concentration had practically no effect on the reservoir capacity.

During the flood season, however, some siltation used to take place in the reservoir. The concentration C_o of the outflow from the reservoir is related to the concentration C_i of the inflow to the reservoir, both during the flood season, by the expression (Shahin, 1986)

$$C_i - C_o = 123 + 0.12\ \bar{C}_f\ ,\ \text{ppm} \tag{1}$$

where C_f is the average concentration of the flood water. Under normal flood conditions the annual sedimentation used to be about 15 Mm^3. This was flushed out by water in the subsequent flood season leaving room for the new sediments. With this annual cycle of sedimentation and flushing there was no chance for sediments to accumulate in the reservoir.

The High Aswan Dam reservoir

The High Aswan Dam built in 1964-1968 on the Main Nile in Egypt has created a storage reservoir with a total capacity 162 km^3, of which 31.5 km^3 constitute the dead storage capacity. Assuming 100% trap efficiency and 62 Mm^3 as average volume of suspended sediments the life age of the reservoir becomes 510 years.

Shalash & Makary (1986) reported that the mean annual suspended load is about (130 $\pm$ 5) Mt, corresponding to a volume of 91.7 Mm^3. With a trap efficiency of 98% the life age becomes 350 years only. Makary (1992) reported that the total inflow to the reservoir in the period 1964-1989 was 1 864 km^3 carrying 2 861 Mt of sediments of which 2 800 Mt have accumulated in the reservoir. The density and the volume of the deposited sediments are 1.34 t m^{-2} and 2.09 km^3, respectively. This huge amount has led to the rise of the original bed level as shown in Fig. 3. Assuming that this

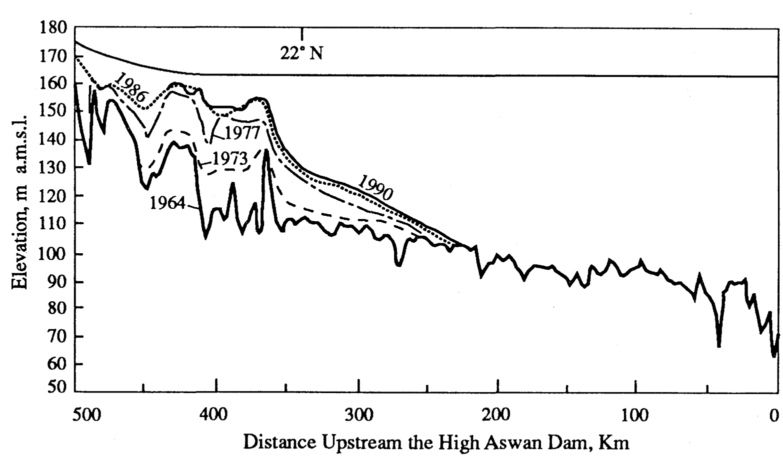

Fig. 3 Accumulation of sediments in the reservoir of the High Aswan Dam.

average rate of sedimentation will continue in future, the estimate of the life age must be about 390 years.

Using the available sedimentation data, Abdel-Aziz & De Smedt (1992) reported that for the period 1964-1988 the sediment mass, density and volume were 3330 Mt, 1.12 t m^{-3} and 2.97 km^3, respectively. Would this be the case, the dead storage capacity will then be filled by sediments in about 265 years, which is nearly 50% of the design life-age of the reservoir.

Khashm el-Girba

The Khashm el-Girba reservoir is located on the Atbara River some 400 km south east of the river mouth at Atbara. The initial (1964) reservoir capacity was about 1.3 km^3 corresponding to water level 473.2 m a.m.s.l. Due to excessive sedimentation the reservoir capacity at the same level has dropped to slightly less than 0.6 km^3 by the year 1990. That is to say, the reservoir has lost 55% of its original capacity in 25 years (see Fig. 4).

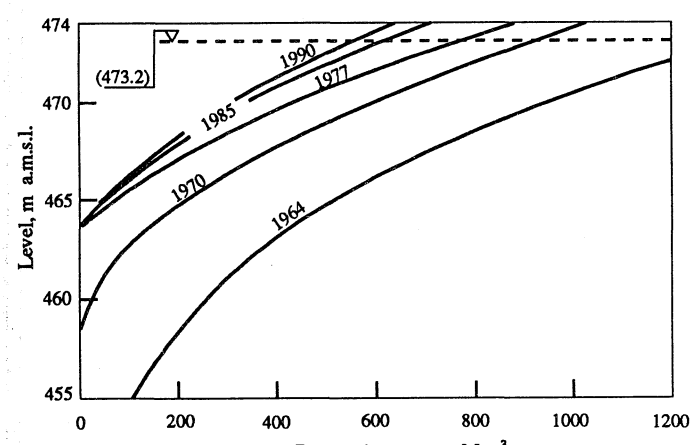

Fig. 4 Decrease of live storage capacity of the Khashm el-Girba reservoir with time.

The first filling of the reservoir up to level 462 m a.m.s.l. starts in the period 1-10 July each year. During this operation the upper sluices are kept open to let the silt-laden water flow to the downstream. This goes on till the end of August or when the river discharge becomes about 1 270 m^3 s^{-1}. The second part of the filling phase then begins and goes on till the beginning of October when the reservoir level reaches 473.2 m a.m.s.l.

At present the possibilities of dredging the sediments out of the reservoir and/or implementing new operation rules are under investigation.

The Sennar (Makwar) reservoir

The Sennar reservoir is under operation since 1925, shortly after the construction of the Sennar dam. It is located 350 km south east of Khartoum, on the Blue Nile, in the Sudan.

The outflow from the reservoir exceeds the natural supply during the low-flow season of the river, from January to July. The difference represents the irrigation requirements of the Gezirah land (area located between the White and the Blue Niles) during the same period. As such, the reservoir contents are gradually emptied as shown in Fig. 5. The first filling is accomplished in the second half of July so that on the first of August the level upstream the dam is raised to just 417.2 m a.m.s.l. to enable the canal to draw its full share from the river. Below this level the reservoir contents have nothing to do with live storage. The second filling starts around mid October when the Blue Nile water is sufficiently clear of suspended matter (concentration is about 200 ppm). The reservoir is considered completely full when its surface reaches the level of 421.7 m a.m.s.l., which coincides mostly with the beginning of December.

The initial, 1925, live storage capacity of 0.93 km^3 has been reduced in the course of time to just 0.61 km^3 by the year 1986, i.e. to 65% of the original capacity after 62 years of operation. Extrapolation of these figures can show that 50% of the reservoir's initial capacity will be filled with sediments in no less than 100 years after the construction of the dam. This result reflects the efficiency of the operation rules of the reservoir.

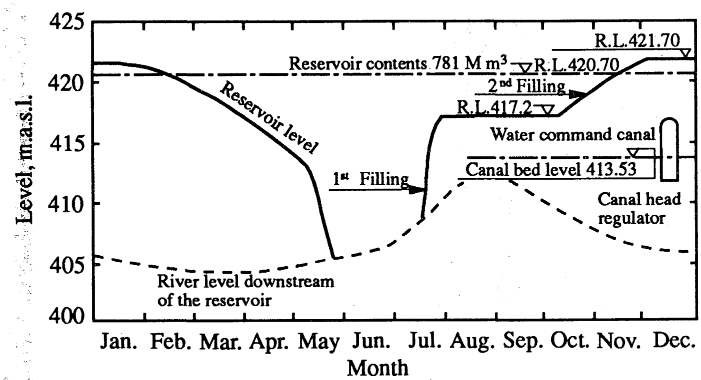

Fig. 5 Operation rule curve of the Sennar reservoir.

The Roseires reservoir

The storage reservoir formed by the Roseires Dam was designed to retain water up to level 480 (481 as from 1984) m a.m.s.l. in its first phase and up to 490 m in its second phase. The corresponding storage capacities are 3.0 (later 3.3) and 6.8 km^3, respectively.

The Roseires reservoir is operated conjunctively with Sennar reservoir for irrigation and power generation in the Sudan. The filling of the former is delayed to the latest possible time during the falling flood. As such, the filling operation begins around mid September or some days later when the river flow is at or below 0.325 km^3 day^{-1}. By the end of October the reservoir is full and remains so till the beginning of December, after which the reservoir storage is drawn down slowly till it reaches the minimum storage level by mid-June.

In spite of the deep sluices in the dam body to help flush the sediments deposited in the reservoir the problem is not entirely solved and the live storage at full reservoir level has been reduced by 20% in the period 1966-1981. The reduction of the storage

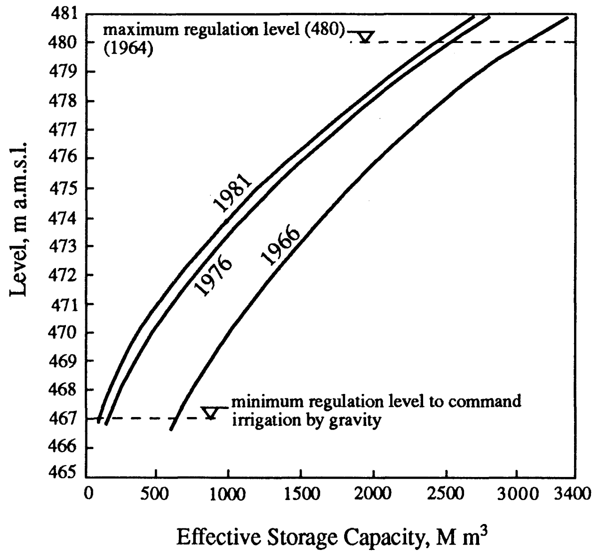

Fig. 6 Decrease of live storage capacity of the Roseires reservoir from 1966 up to 1981.

contents at the different reservoir levels can be seen from Fig. 6.

In an attempt to increase the effective storage capacity, in the mean time to increase the head for generating more hydroelectric power, the maximum storage level, as from 1984, has been raised by 1 m. Such a rise could be achieved by beginning the impoundment at an earlier date each year and by increasing the maximum discharge from 0.325 km^3 day^{-1} to almost 0.5 km^3 day^{-1}. This policy has led, unfortunately, to further sediment accumulation in the reservoir.

The operation of this reservoir has recently been investigated with the aim of improving the silt flushing capacity of the deep sluices in the dam. In that investigation the operation of this Roseires reservoir, was performed conjunctively with the Sennar reservoir.

Different policies have been suggested to trade off between hydropower generation and reservoir sedimentation, wherein the Roseires and the Sennar reservoirs are assumed to follow the same operation rules (Ali, 1990). The response of the system, basically the silt deposited and the energy generated, is determined. The rule curve in each scenario has two parameters; date of beginning of filling and rate of reservoir filling or date of end of filling. Thirty-three scenarios were run in which the beginning of filling varied between 3 July and 3 September and the completion of filling between 1 September and 2 November. Each run simulated the conditions in the 20 year period, 1968-1987.

Consider the minimum sediment deposition scenario. Assuming that the sedimentation rate remains constant with time, the annual accumulation rate of sediments will drop from the presently 39.1 Mm^3 to 33.4 Mm^3. This will lead to the filling of the reservoir in 85 years instead of 72 years, as with the historical operation rule. By full reservoir here is meant that the live storage at the maximum reservoir level drops down to 0.5 km^3 only.

Koka reservoir

The Koka reservoir has been formed as a result of the construction of the Koka dam in 1959 for developing hydroelectric power for Ethiopia. The inflow to the reservoir is supplied by the Awash and the Mojo rivers. During the flood season both rivers are heavily laden with suspended matter (concentration up to 30 000 ppm). Sedimentation in the said reservoir has been surveyed three times; in 1969 spot levels of the reservoir bed were taken and in 1973 and 1981 contour surveys were done.

The total sediment deposited in the Koka reservoir in the period 1961-1981 has been estimated at 0.34 km^3, yielding an average of 17 Mm^3 yr^{-1}. A certain sediment prediction formula yielded 0.362 km^3 and 18 Mm^3 yr^{-1}, respectively (Imru, 1992). This volume corresponds to a trap efficiency of 95% and to a general rise of the reservoir's initial bed by 3 m.

Under the current rules of operation the reservoir will not be able to function effectively after the next 16 years or so. These rules aim at maintaining as much water in storage as possible all the year round, without any consideration to sediment control. During the first half of July, in spite of the high sediment concentration, the reservoir water level is kept above 27 m + datum level (Fig. 7), causing excessive accumulation of sediments in the reservoir.

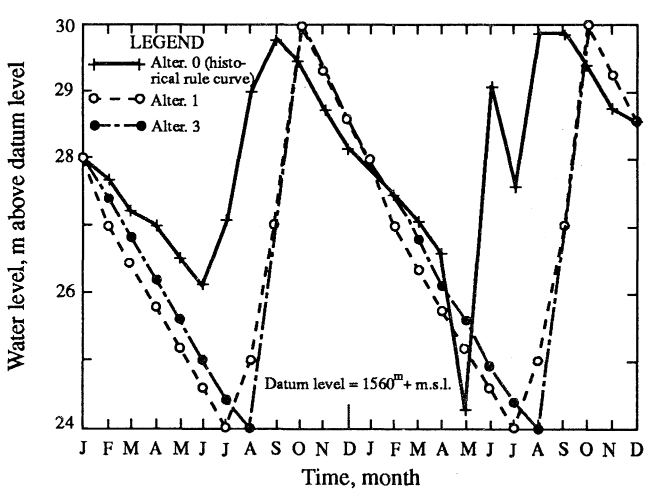

Fig. 7 Three alternatives for the rule curve of the Koka reservoir.

The historical operation rule is referred to as alternative 0. Four more alternatives were examined. In which the filling of the reservoir started at level 24 m + datum level on July 1 for alternatives 1 and 2 and on August 1 for 3 and 4. The end of the filling period was August 31 for alternatives 2 and 4 and September 30 for 1 and 3. That model study showed that at the end of 20 years of reservoir operation the volume of accumulated sediments would be 0.3, 0.236, 0.303, 0.205 and 0.221 km^3 for alternatives 0, 1, 2, 3 and 4, respectively. Figure 7 shows that the half life of the reservoir can be augmented from 16 to 23 and 26 years for the 0, 1 and 3 alternatives, respectively.

CONCLUSIONS

The case studies already reviewed lead us to some principal conclusions. These are:

(a) The design sediment inflow to some storage reservoirs has been underestimated. As a result, those reservoirs have become filled with sediments faster than was expected.

(b) There is a need for more frequent and accurate bathymetric surveys of the existing reservoirs. Inconsistent observations have led to a wide range of estimates of the life age 260 to 510 years for dead storage capacity of the High Aswan Dam reservoir.

(c) Model investigation of the Roseires and the Koka reservoirs has shown that by changing the current operation rules the rate of sediment accumulation, can be changed thereby increasing the reservoirs life age.

(d) The operation rules securing the maximum benefit of hydro power production and/or land irrigation might be in conflict with the strategy aiming at reducing reservoir sedimentation. A cost-benefit analysis might help settle the conflict of interests.

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