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FEASIBILITY STUDY OF FLUSHING SEDIMENTS FROM MOSUL RESERVOIR, IRAQ

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The feasibility of flushing sediment from the Mosul Reservoir located in northern Iraq was examined. Many current criteria and indices for checking the efficiency of flushing sediment from reservoirs have been reviewed by analyzing large amounts of data from many flushed reservoirs, and these have been tested and applied to the Mosul Reservoir. These criteria and indices depend mainly on the hydrological, hydraulic, and topographic properties of the reservoirs, in addition to their operation plan. The main criteria for successful flushing of sediment in this reservoir are the sediment balance ratio (SBR), the long term capacity Ratio (LTCR), the draw down ratio (DDR), the shape of reservoir (L/W), and hydraulic conditions such as the percentages Qf/Qin and Vf/Vin. There is no verification for other criteria such as flushing width ratio (FWR), capacity inflow ratio (C/I) and sediment potential (SP). The results agree with requirements for successful flushing and indicate that flushing sediment in the Mosul Reservoir is feasible to a certain degree, and can be applied in the future to conserve water storage capacity.

INTRODUCTION

Approximately one percent of the storage volume of the world's reservoirs is lost annually due to sediment deposition (Yoon, 1992). The rate of loss of storage varies from region to region and from reservoir to reservoir; the highest rates are found in the smallest reservoirs and the lowest rates in the largest. The estimate of annual loss of storage due to sedimentation has been used in conjunction with the gross storage volume data available in the ICOLD to estimate the magnitude of the sedimentation problem as shown in Figure 1 (White et al., 2000). In most developing countries where population pressures on fragile upland ecosystems has led to accelerated rates of soil erosion, reservoir storage is being lost at much larger rates. While there are some options for reducing the rates at which sediment deposits in reservoirs, flushing offers the only means of recovering lost storage without incurring the expenditure of dredging or other mechanical means of removing sediment. Most of the best sites for reservoirs have already been utilized and interest is increasing nowadays in means of reducing the rate at which storage capacities are being lost. Where it is feasible, flushing can offer an attractive means of recovering and maintaining a useful storage capacity when compared with the cost of alternative methods.

SEDIMENT FLUSHING

Flushing is the scouring out of deposited sediment from reservoirs through the use of low level outlets in a dam to lower the water levels, and so increase the flow velocities in the reservoir. Flushing has been proven to be highly effective at some sites in the world. For example at the Mangahao reservoir in New Zealand 59% of the original operating storage capacity had been lost by 1958, 34 years after the reservoir was first impounded. The reservoir was flushed in 1969 when 75% of the accumulated sediment was removed in a month of operation (Jowett, 1984).

Draw down is the lowering of the water levels in a reservoir. Drawing down a reservoir for a few weeks or months during the flood season is also a form of flushing although the principal purpose of draw down is to pass the high sediment loads carried out by flood flows completely through the reservoir. In the literature this practice is commonly termed “sluicing”. A number of attempts at sediment flushing have proven successful (Atkinson, 1996).

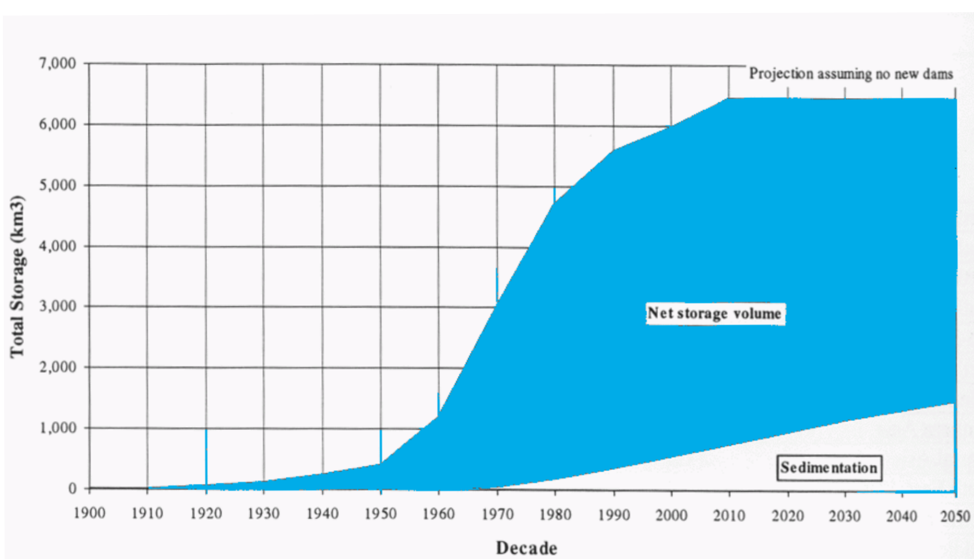

Figure 1. Water storage lost due to sedimentation in reservoirs.

Existing Flushing Criteria

There are two key requirements for effective flushing; first the quantity of sediment removed during flushing should at least match the quantity of sediment that deposits in the reservoir during the periods between flushing operations, and second the useful storage capacity that can be maintained should be a substantial proportion (above about 50%) of the original capacity (Atkinson, 1996). The literature survey on reservoir sedimentation by Sloff (1991) discusses such criteria but they cannot be used to assess the feasibility of flushing. A tentative criterion that the ratio of reservoir capacity to mean annual runoff must be as large as a half or more for reservoirs with a half life shorter than 100 years is reported by Ackers and Thompson (1987). Paul and Dhillon (1988) provide plots to determine the area of low level sluice required for flushing from the initial capacity and annual sediment inflow. Pitt and Thompson (1984) report that effective flushing has generally only been observed where the draw down level is below about half the height of the dam and where the sluice capacity exceeds the mean annual flow by at least a factor of two. Mahmood (1987) presents a number of criteria for quantifying the efficiency and effectiveness of flushing but these can be only be applied after a reservoir has been flushed and thus cannot be used to predict flushing performance. Finally to minimize turbidity impacts on fish, irrigation and tourism, the winter season was recommended by many researchers to perform flushing from reservoirs and to eliminate the negative downstream effects of flushing (Morris and Fan, 1997).

Sediment Balance

When flushing is attempted without drawing down water levels, the high flow velocities at the outlets are very localized and the impact is insignificant. The water level in a reservoir must be drawn down to close to the bed elevation at the dam before flushing can be effective as is shown in Figure 2(a). Moderate lowering of water levels during flushing will still significantly increase flow velocities at the upstream end of the reservoir, where bed levels will be above the water level at the dam (Figure 2(b)). Large sediment volumes will be scoured from these upstream reaches and will redeposit near the dam (Atkinson, 1996). Eventually bed levels upstream from the dam will rise to the water level during flushing and then significant sediment quantities will be transported through the low level outlets (Figure 2(c)). If flushing water levels are close to elevations at the dam (either as in Figure 2(a) or as in Figure 2(c)) then the sediment mass flushed will in the long term balance the sediment mass depositing between flushing operations.

THE AIM OF THE STUDY

The purpose of the research work described here is to assess the feasibility of flushing sediment from the Mosul Reservoir located in northern Iraq using simple widely used criteria and indices which require readily available data. By applying these criteria, reservoirs at which flushing might be viable can be identified. The criteria used in this research work were derived and verified against attempts to flush many world wide reservoirs both successful and unsuccessful (Atkinson, 1996). Use of the assessment of such criteria will help engineers to identify reservoirs where flushing has potential. When sites suitable for flushing are identified at the design stage, the construction of low level outlets with sufficient capacity for flushing is recommended. Flexibility for flushing would then be built into the project design.

Criteria for Successful Flushing (after Atkinson, 1996)

a. Sediment Balance Concept

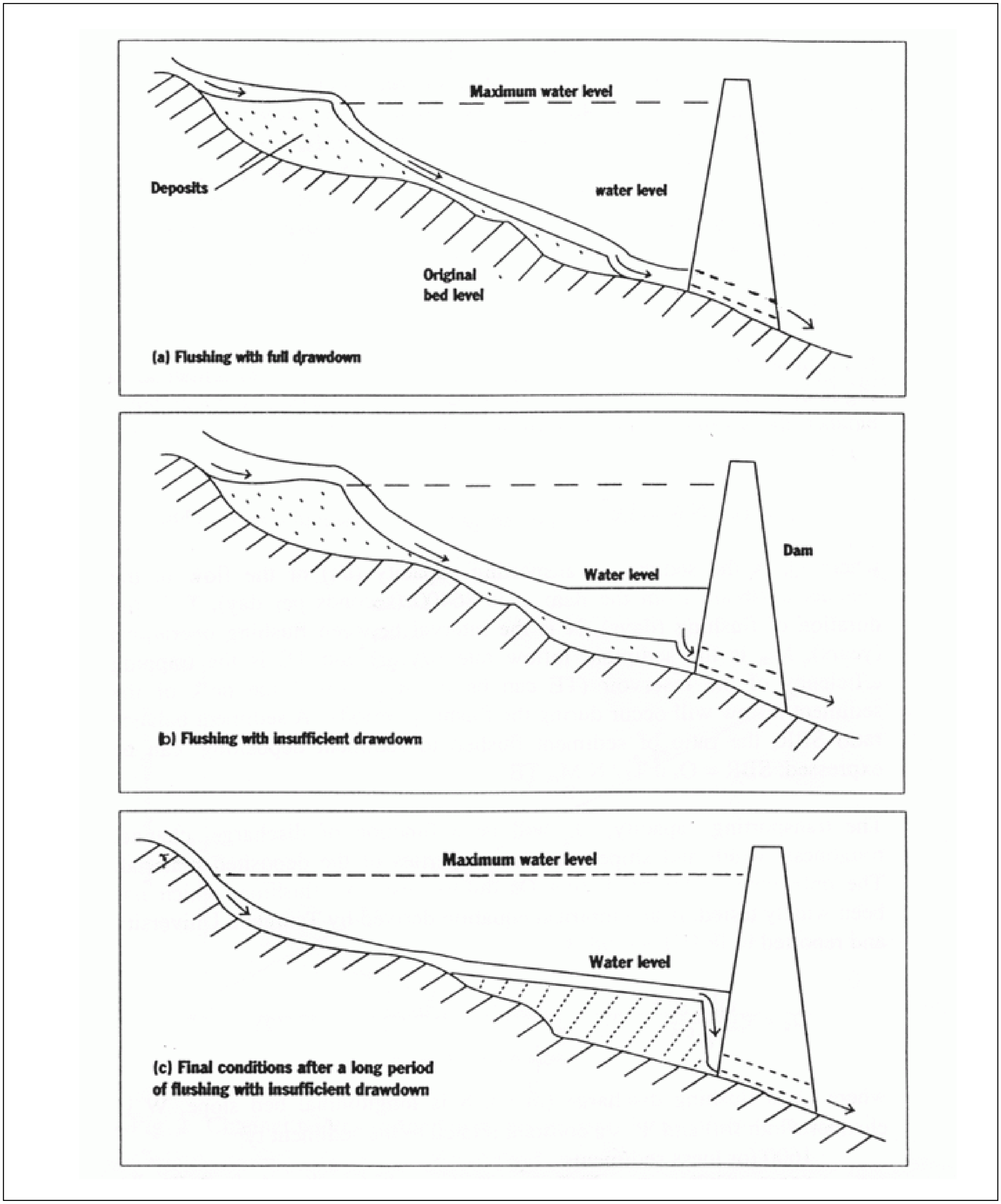

Figure 2. Longitudinal profile of flushing (after Atkinson, 1996).

A sediment balance ratio SBR is defined as:

SBR = sediment mass flushed annually/sediment mass deposited annually

If SBR> 1 then it is expected that a sediment balance can be achieved and so this criterion is satisfied.

$SBR = M_f/M_{dep}$

where:

M_f = mass of sediment flushed annually from the reservoir.

M_{dep} = mass of sediment which deposits annually in the reservoir.

The calculation of SBR is performed as follows:

i. Derive a representative reservoir width in the reach upstream from the dam at the flushing water surface elevation.

$W_{res} = W_{bot}+2SS_{res}(EL_f-EL_{min})$

$W_f = 12.8\ Q_f^{0.5}$

where:

Q_f is the flushing discharge (m^3/sec) and W_f is the flushing width (m).

ii. Take the minimum of W_{res} and W_f as the representative width of flow for flushing conditions, W.

iii. Estimate the longitudinal slope during flushing,

$S = (EL_{max}-EL_f)/L$

iv. Determine the parameter (ø) in the Tsinghua university method for sediment load prediction.

(ø) = 180 if the flushing discharge is low

(ø) = 300 for $D_{50} > 0.1$ mm

(ø) = 650 for $D_{50} < 0.1$ mm

(ø) = 1600 for fine loess sediments.

v. Calculate the sediment load during flushing

$Q_s = øQ_f^{1.6}S^{1.2}/W^{0.6}$

vi. Determine the sediment mass flushed annually (86400 is the number of seconds in a day)

$M_f = 86400T_fQ_s$

vii. Predict Trap Efficiency (TE) using Brunes curves (Brune, 1953)

viii. Calculate the mass depositing annually which must be flushed.

$M_{dep} = (M_{in}TE)/100$

ix. Determine (SBR).

$SBR = M_f/M_{dep}$

b. Long Term Capacity Ratio

The long term capacity ratio LTCR is defined as the sustainable capacity to the original capacity in which the sustainable capacity is the total reservoir volume which can be calculated from the final cross sections after the flushing process.

The calculation of LTCR is performed as follows:

i. Determine scoured valley width at the top water level.

$W_{tf} = W + 2SS_s(El_{max}+El_f)$

ii. Determine the reservoir width at the elevation for the simplified geometry assumed.

$W_t = W_{bot}+2SS_{res}(El_{max}-El_{min})$

iii. If $W_{tf} < W_t$ then the reservoir geometry does not constrict the width of the scoured valley and so scoured valley cross sectional area (A_f) is calculated as:

$A_f = W_t+W/2(El_{max}-El_f)$

iv. If $W_{tf} > W_t$ then the scoured valley will have a constricted end.

$h_m = W_{res}–(W)/2(SS_s–SS_{res})$

$h1 = El_{max}–El_f–h_m$

$h_f = El_{max}–Elf$

$A_f = W_{hf}+(h_f-h1)h_mSS_s+h1^2SS_{res}$

v. Estimate the reservoir cross sectional area.

$A_r = W_t+W_{bot}/2(El_{max}–El_{min})$

vi. Determine LTCR:

$LTCR = A_f/A_r$

c. Draw Down Ratio

$DDR = 1-(El_f–El_{min})/(El_{max}–El_{min})$

d. Flushing Width Ratio

$FWR = W_f/W_{bot}$

e. Top Width Ratio

$TWR = W_{td}/W_t$

where W_{td} is the value for scoured valley width at top water level if complete draw down is assumed and W_t is the reservoir top width calculated in (2) step (ii).

W_{td} and hence TWR is calculated as follows:

i. Determine W_{bf} the bottom width of the scoured valley at full draw down. It is the minimum of W_{bot} and W_t which are calculated in (1).

ii. Calculate W_{td} from the side slope SS_s which is discussed in (2).

$W_{td} = W_{bf}+2SS_s(El_{max}–El_{min})$

iii. Determine

$TWR = W_{td}/W_t$

MOSUL DAM PROJECT

The Mosul dam project is located on the Tigris river in the northern part of the republic of Iraq, in the Governorate of Ninevah, approximately 60 km north of Mosul city (Figure 3). The Mosul

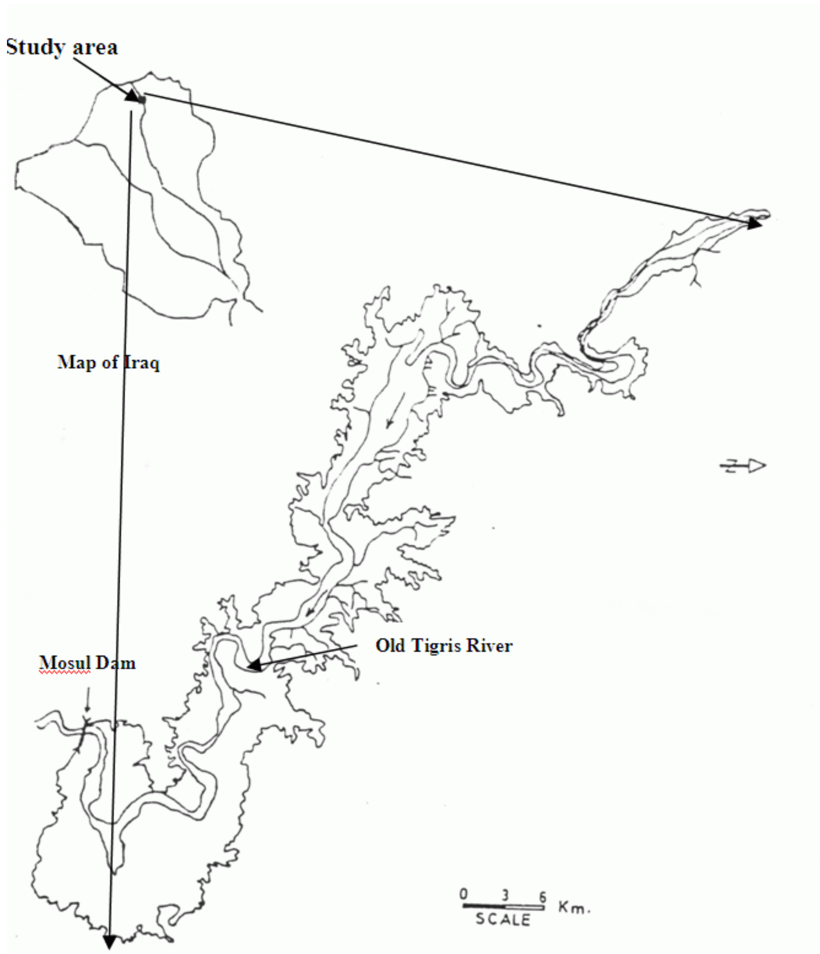

Figure 3. Location Map of Mosul Dam Reservoir in Iraq.

dam is a multipurpose project, its object being to provide storage of water for irrigation, hydropower generation and flood control. Peak control and power regulation capacity of the project was increased by the inclusion of a pumped storage plant.

The Mosul dam project is subdivided into the following schemes: The main scheme comprises the following main structures - the dam formed by 3600 m long fill dam with a maximum height of 100 m. The embankment volume is 35000000 m^3. The reservoir created by the dam will have a usable storage volume of 8160000000 m^3 available for irrigation and power production. The total volume of the reservoir at the retention water level 330 m a.s.l. is 11.1×10^9 m^3 with a surface area of 385 km^2 and reservoir length of about 65 km. The diversion of the river was made by means of two diversion tunnels which transformed into bottom outlets 10 m in diameter, 650 m long, each having a capacity of 1300 m^3/sec at the minimum operating reservoir level of 300 m.a.s.l. The parameters for the Mosul dam and reservoir shown in Table 1 are used as input for the development of the feasibility criteria for sediment flushing in the reservoir.

Application of Atkinson flushing Criteria to the Mosul Reservoir

SBR (sediment balance ratio)

$$SBR = M_f/M_{dep}$$

Table 1. Summary data on Mosul Reservoir.

Original storage capacity (C)	8 $*10^9$ m^3
Reservoir length (L)	65 km^3
Elevation of top water level (El_{max}.)	330 m
The minimum bed elevation which is usually the river bed elevation immediately upstream from the dam (El_{min}.)	245m
Width of the flow at the bed of flushing channel (w_f)	650 m
Representative side slope for the reservoir (SS_{res})	1 : 20
Representative side slope for the deposits exposed by flushing (SS_s)	1 : 5
Mean annual water inflow volume (V_{in}.)	15.5 $*10^9$ m^3
Mean annual sediment inflow (M_{in}.)	40 $*10^6$ m^3
Representative discharge passing through reservoir during flushing (Q_f)	2400 m^3/ sec.
Proposed duration of flushing (T_f)	40 day
Water surface elevation derived from Q_f, outlet sill elevation and outlet design (El_f).	275 m
Constant for sediment type (ψ)	650 for $D_{50} > 0.1$

$M_{dep} = (M_{in}\ TE)/100 = 40x10^6x95/100 = 38x10^6$

$Mf = 86400xTExQ_s$

$Q_s = 650x2500x0.0011^{1.2}/(650)^{0.6} = 1042$

Q_s will be divided by 3 because the condition of Mosul reservoir is not the same as in China.

$Q_s = 347$

$M_f = 1199232000$

$SBR = M_f/M_{dep} = 1199232000/\ 38x10^6 = 31.5$

31.5 > 7 which is satisfactory.

LTCR (Long term capacity ratio)

$H_f = 330\text{-}290 = 40$

$h1 = 330\text{-}290\text{–}h_m$

$h_m = W_{res}\text{–}W_f/2(SS_s\text{-}SS_{res})$

$W_{res} = W_{bot}+2SS_{res}(El_f–El_{min})$

$W_{res} = 2000+2x20(290-245) = 3200$

$h_m = (3200-650)/2(5-20) = -85$

h1 = 40–(-85) = 125

$A_f = 650x40+(40+h1)xh_m xSS_s+h_m^2 xSS_{res} = 100375$

$A_r = W+(W_{bot}/2)(El_{max}–El_{min})$

$W_t = W_{bot}+2SS_{res}(El_{max}–El_{min})$

$W_t = 2000+2x2(330-260) = 2280$

$A_r = 2280+(2000/2)(330-260) = 72280$

LTCR = A_f/A_r = 100375/72280 = 1.3

1.3 > 0.8 which is satisfactory.

DDR (Draw down ratio)

DDR = 1–(El_f–Elmin)/(Elmax–Elmin) = 1–(275-245)/(330-245) = 0.63

FWR (Flushing width ratio)

FWR = W_f/W_{bot} = 650/2000 = 0.32

For successful flushing, values should be SBR > 7, LTCR > 0.8, DDR > 0.7, and FWR > 1.

Additional Criteria and Properties for the Mosul Reservoir

a. Storage capacity of reservoir

If capacity inflow ratio < 0.3, flushing is successful.

For the Mosul reservoir C = $8x10^9$ m^3, I = $15.5x10^9$ m^3

C/I = 0.6

b. Sediment potential (S_p)

Sediment potential > 1-2% original capacity.

$40x10^6$ $m^3/8x10^9$ = 0.005x100% = 0.5%

c. Shape of reservoir basin

Effective flushing will be for narrow steep sided reservoir valleys with steep longitudinal slope.

For the Mosul reservoir, the length width ratio L/W = 65/4 = 16

d. Hydraulic condition required for efficient flushing

i. Flushing discharges must be at least twice the mean annual flow or

$Q_f > 2\ Q_{inflow}$

For the Mosul reservoir Q_f/Q_{inflow} = 2400/500 = 5

ii. Flushing volume should be at least 10% of the mean annual runoff.

For the Mosul reservoir flushing volume = 2400x24x40 = $8.3x10^9$ m^3

Flushing volume / Mean annual runoff = $8.3x10^9/15.5x10^9$ = 53%

According to the capacity inflow ratio value, the Mosul reservoir is classified as a seasonal storage reservoir. The trap efficiency of the reservoir is estimated according to the Brune curve (Brune, 1953). The retention period (residence time) of the reservoir is calculated as the capacity daily inflow ratio, while the sedimentation index of the reservoir is calculated as the retention period divided by the mean transit velocity of the flow in the reservoir. Finally the specific storage of the reservoir is calculated as the capacity of the reservoir divided by the river basin area controlled by the reservoir (Unesco, 1985). These characteristics of reservoirs can be used as supplementary criteria for predicting the feasibility of flushing sediment from reservoirs (see Table 2).

Geographical areas suited to flushing

Erosion rates: The erosion rate depends on a complex interaction of the following factors.

a. Climate: precipitation and runoff, temperature, wind speed and direction.

b. Topography: slope, catchment orientation, drainage basin, and drainage density.

c. Land area and human impact.

The analysis and observations of many flushed reservoirs in the world have shown that low water level provides the most effective conditions for sediment flushing. To allow water levels to be lowered requires confidence that rainfall can be relied upon refill the reservoir. It follows that well defined wet and dry seasons will be favorable for sediment flushing. Such climate is defined by the Koppen classification as tropical wet and dry (Pidwirny, 1999). From this classification of the climate zones, the requirements for successful flushing are most likely to be met in the tropical wet and dry regions. The Mosul reservoir region partly meets such climatic conditions for successful flushing.

Quantity of Water Available for Flushing

Reservoirs where there is regular annual cycle of flows and a defined flood season can be considered as having suitable hydrological conditions for sediment flushing because it is possible to substitute and restore the released water during flushing. This hydrologic condition may be satisfied by the existence of annual snowmelt in the spring and summer months, as is the case with the Mosul reservoir.

DISCUSSION

To predict the feasibility of flushing the Mosul reservoir, the sediment balance ratio (SBR) and the long term capacity ratio (LTCR) were assessed. Some factors which determine the values of the sediment balance ratio and the long term capacity ratio are inherent characteristics of the site

Table 2. Some important predicted parameters for Mosul reservoir.

Capacity Inflow Ratio C/I	Trap Efficiency TE	Retention Period RP	Sedimentation Index SI	Specific Storage SS
0.6	95%	222 day	$191*10^6$ sec/m	2.64 m

which include: the shape and size of the reservoir and the imposed hydrological conditions and the imposed sediment input. Some factors are controllable. These include the operation of the reservoir between flushing operations, the design of the flushing system including elevation, and the capacity and the operation of the flushing system including discharge and duration.

Flushing criteria obtained from the attempts of flushing sediment from number of reservoirs (Atkinson, 1996) is used to test the feasibility of sediment flushing from the Mosul reservoir. Table 3 shows the results of the application of those criteria. It shows that the SBR is more than 7, which agrees with successful flushing. The LTCR gave a value higher than 0.8 which also agrees with successful flushing. The draw down ratio DDR is less than 0.7 by a very small amount. The FWR gave a value less than 1.0, which is not a successful flushing criterion. The Mosul reservoir is hydraulically large. The capacity of this reservoir is believed to be about 60% of the mean annual inflow. The sediment deposition potential (S_p) of the reservoir is about 0.5%, which is close to the criterion of successful flushing for reservoir sediment potential 1-2 %.

Table 3. Final values for the applied criteria for flushing sediment.

SBR	LTCR	DDR	FWR	G_f/Q_i	L/W	V_f/Vi	S_p	C/I
31.5	1.3	0.63	0.32	5	16	53%	0.5%	0.6

The hydraulic conditions required for efficient flushing agree with the available condition in the reservoir in which the flushing discharges must be at least twice the mean annual flow.

Q_f / Q_{in} = 244/500 = 5

Another hydraulic condition for the reservoir which agrees with the criteria for successful flushing is the flushing volume which must be at least 10% of mean annual runoff. For the reservoir flushing volume is 53% of the annual runoff.

The shape of the reservoir agrees with the shape needed for successful flushing, which is a narrow steep sided reservoir valley. The reservoir length width ratio is 16.

Finally a hydrological condition needed for successful sediment flushing is represented in the reservoir where there is regular annual cycle of flows and a defined flood season. Thiscondition is satisfied by the annual snow melt in spring and summer months.

CONCLUSION

From the application of the widely used universal criteria on flushing sediment in reservoirs (for example Atkinson, 1996) to the Mosul reservoir in northern Iraq, and from the analysis of the available field data on flushing sediment in reservoirs, we have reached the following conclusions. The efficiency of sediment flushing can be increased with the lesser depth of stored water, the greater the discharge of the flushing stream, the greater the dimensions of the flushing outlet, the lower the location of the outlet, the more favorable the location of the outlet, the longer the flushing lasts, the narrower the reservoir (steep banks), the steeper the original stream gradient through the reservoir, the shorter the reservoir, the straighter the reservoir, the more advanced the silting (close to dam as possible), the finer the particles in the sediment, the rounder the particles of the sediment, and a younger and less consolidated sediment. Regarding the Mosul dam, it was concluded that the main requirements for flushing sediment can be verified in the reservoir by the

SBR, the LTCR, the topography (shape of reservoirs), and the hydraulic conditions (Q_f/Q_{in}) and (V_f/V_{in}). Except for some hydrological conditions like the capacity inflow ratio and draw down ratio, which did not fit completely with the flushing criteria, the Mosul reservoir can be flushed and sediment can be eliminated successfully. The author recommends flushing the reservoir, and conducting a survey after the flushing process to check the success of this effort. We emphasize that the flushing process must be evaluated with respect to environmental impacts downstream of the dam, and must go forward smoothly integrated with other objectives of the dam.

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