FEASIBILITY STUDY OF SEDIMENT FLUSHING FROM MOSUL RESERVOIR, IRAQ

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ABSTRACT

The Feasibility of sediment flushing from Mosul reservoir located northern iraq was conducted. Many upto date world criteria and indices for checking the efficiency of sediment flushing from reservoir which have been got through analyzing large amount of data from many flushed reservoirs in the world which were depended tested and applied in the present case study (Mosul Reservoir). These criteria and indices depend mainly on the hydrological , hydraulic and topographical properties of the reservoirs in-addition to the operation plan of the reservoirs. They gave a good indication for checking the efficiency of the sediment flushing process in the reservoirs. It was concluded that approximately the main criteria for the successful flushing sediment was verified in Mosul reservoir such as Sediment Balance Ratio (SBR) and the Long Term Capacity Ratio (LTCR),the shape factor of reservoir (W/L) and the hydraulic condition such as the percentage of (Q_f/Q_{in}) and (V_f/V_{in}). This gave an indication that the processes of flushing sediment in Mosul reservoir is probably feasible and may be applied in the future to maintain the water storage in the reservoir.

KEYWORDS: Flushing Sediment, Sluicing, Reservoirs

Notations

M_f mass of sediment flushed annually from the reservoir.

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

W_{res} representative reservoir width in the each upstream, from the dam at the flushing water surface elevation, m

W_{bot} a representative bottom width for the reservoir ,m.

SS_{res} A representative side slope for the reservoir

EL_f water surface elevation at the dam during flushing ,m.

EL_{min} the minimum bed elevation which is usually the river bed elevation immediately upstream from the dam (m)

W_f the width of flow at the bed of the flushing channel (m)

W_{tf} the top width of the scoured valley, (m)

Q_f the flushing discharge from outlet, (m^3/sec)

L The longitudinal length of the reservoir (m)

Q_s the sediment transporting capacity passed through outlet (tones/ sec)

S The longitudinal energy gradient through reservoir

W The channel width of the reservoir (m)

T_f the duration of flushing (days)

M_{in} the mean annual sediment inflow to reservoir

SS_s Representative side slope for the deposits exposed by flushing.

W_t the reservoir top width

W_{td} the value for scoured valley width at top water level if complete draw down is assumed in (m)

W_{bf}, the bottom width of the scoured valley at full draw down

INTRODUCTION

Approximately 1% of the storage volume of the world reservoirs is lost annually due to sediment deposition [1] . 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 have been used in conjunction with the gross storage volume data available in the **ICOLD** (International commission of large dams) to estimate the magnitude of sedimentation problem as shown in Figure 1,[2] .In most developing countries where population pressures on fragile upland, ecosystems has led to accelerated rates of soil erosion, then 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. Interests 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 proved 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 using flushing process in a month of operation, [3].

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 principle purpose of draw down is to pass the high sediment loads carried out by flood flows through the reservoir. In the literature this practice is commonly termed "sluicing". A number of attempts at the sediment flushing have been proved successful [4].

Existing Flushing Criteria

Two key requirements for effective flushing :firstly 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 secondly the useful storage capacity that can be maintained should be substantial proportion (above about 50%) of the original capacity,[4]. The literature survey on reservoir sedimentation by [5] discusses such criteria but they cannot be used to asses the feasibility of flushing. A tentative criteria that the ratio of reservoir capacity to mean annual runoff (C/I) must be as large as a half or more for reservoirs with a half life shorter than 100 year is reported by [6].

[7] provide plots to determine the area of low level sluice required for flushing from the initial capacity and annual sediment inflow. [8] 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 2. [9] presents 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, winter was advised by many researchers to perform flushing from reservoirs and to eliminate the negative downstream effects of flushing, [10].

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, (Figure 2a). 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 2b). Large sediment volumes will be scoured from these upstream reaches and will redeposit near the dam, [4]. ventually 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 2c).

The aim of the study

The aim of the current study is to asses the feasibility of sediment flushing from Mosul reservoir located Northern Iraq using simple worldwide criteria and indices which require readily available data. Applying these criteria ,reservoirs at flushing which might be viable can be identified. Some of the used criteria in this study were derived and verified by [4] from the data existed in the successful and unsuccessful world wide reservoirs ,while other criteria were predicted and suggested by the author. Using 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.

A Criterion for Successful Flushing

1. **Sediment Balance Concept**

A sediment balance ratio SBR is defined as :

SBR= sediment mass flushed annually/ sediment mass deposit annually

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

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

The calculation of SBR is performed as follows [4]:

i. Derive a representative reservoir width in the reach upstream (Figure 3) from the dam at the flushing water surface elevation.

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

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 (ψ) in the Tsinghua university method for sediment load prediction, [11].

(ψ) = 180 for D_{50} >0.5 mm (ψ) = 300 for D_{50} > 0.1 mm

(ψ) = 650 for D_{50} < 0.1 mm (ψ) =1600 for fine loess sediments.

v. Calculate the sediment load during flushing

$$Q_s = \psi\, Q_f^{1.6}\, S^{1..2} / W^{0.6}$$

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

$$M_f = 86400\, T_f\, Q_s$$

vii. Predict Trap Efficiency (TE) using Brunes curves, [12], (Figure 4).

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

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

ix. Determine SBR,

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

2. **Long Term Capacity Ratio**

The long term capacity ratio LTCR is defined as the sustainable flushing, 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 flushing process.

The calculation of LTCR is performed as follows [4]:

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

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

W_{tf} is the top width of the scoured valley (m)

ii. Determine the reservoir top width at the elevation for the simplified geometry assumed in Figure (3).

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

iv. 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 in (m^2) as:

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

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

$$h_m = W_{res} – (W) / 2(SS_s – SS_{res})$$

$$h1 = El_{max} – El_f – h_m$$

$$h_f = El_{max} – Elf$$

$$A_f = W*h_f + (h_f -h1)\ h_m\ SS_s + h1^2\ SS_{res}$$

v. Estimate the reservoir cross sectional area (A_r) in (m^2):

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

vi. Determine LTCR,

$$LTCR = A_f / A_r$$

3. Draw Down Ratio

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

4. Flushing Width Ratio

$$FWR = W_f /W_{bot}$$

5. Top width ratio

$$TWR = W_{td}/ W_t$$

W_t is the reservoir top width calculated in (2) step (ii) in (m).

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

i. Determine W_{bf}. (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

Mosul dam project is located on Tigris river in the northern part of the Republic of Iraq in the governorate of Ninawah approximately 60 km north of Mosul city, (Figure 5). The Mosul 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 pumped storage plant.

The Mosul dam project is subdivided into the following schemes; The main scheme comprises of the following main structures: The dam formed by 3600 m long earthfill 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 at (330 a.m.s.l) available for irrigation and power production. The total volume of the reservoir at the retention water level (330 a.m.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 2 diversion tunnels which converted into bottom outlets 10 m Dia. 650 m long, each having a capacity of 1300 m^3 /sec at the minimum operating reservoir level of (300 a.m.s.l.), [13]. The following parameters for Mosul dam and reservoir are used as input for the application of the feasibility criteria of Mosul reservoir, (Table 1).

Application of flushing Criteria

SBR (sediment balance ratio)

$SBR = M_f / M_{dep}$

$M_{dep} = (M_{in}\ TE) / 100 = 40 * 10^6 * 95 / 100 = 38 * 10^6$

$M_f = 86400 * T_f * Q_s$

$Q_s = 650 * 2500^{1.6} * 0.0011^{1.2} / (650)^{0.6} = 1027$ ton/sec

Q_s will be divided by 3 because the rates of erosion in Mosul reservoir is about the third as in china according to the universal aerial iso-erosion maps [10].

$Q_s = 342$

$M_f = 1181952000$ ton/year

$SBR = M_f/M_{dep} = 1199232000/38*10^6 = 31.16$ According to [4] for successful flushing SBR must be more than 7.

LTCR (Long term capacity ratio)

$H_f = 330 - 290 = 40$

$h1 = 330 - 290 - h_m$

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

$W_{res} = W_{bot} + 2\, SS_{res}\, (El_f - El_{min})$

$W_{res} = 2000 + 2 * 20(290 - 245) = 3800$

$h_m = (3200 - 650) / 2(5-20) = -105$

$h1 = 40 - (-85) = 125$

$A_f = 650 * 40 + (40 + h1) * h_m * SS_s + h_m^2 * SS_{res} = 186250\ m^2$

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

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

$W_t = 2000 + 2*20(330 - 245) = 5400$

$A_r = 5400 + (2000/2)(330 - 245) = 90400\ m^2$

LTCR = A_f / A_r = 186250/90400 = 2 > 0.8 (where 0.8 is the max ratio for the LTCR [4]). o.k

DDR (Draw down ratio)

DDR = 1 – (El_f –Elmin)/ (Elmax – Elmin) = 1 –(290 -245)/(330 -245) = 0.47 < 0.8

FWR (Flushing width ratio)

FWR = W_f / W_{bot}

= 650 / 2000 = 0.32 < 1

For successful flushing SBR > 7, LTCR > o.7 , DDR >0.8 , FWR >1, (Atkinson,1996).

Additional Criteria and Properties for Mosul reservoir

1. Storage capacity of reservoir. If capacity inflow ratio < 0.3(successful flushing)

For Mosul reservoir C = $8 * 10^9\ m^3$, I = $15.5 * 10^9\ m^3$

C / I = 0.6

2. Sediment potential

sediment potential > (0.5 -1)% original capacity

$40 * 10^6\ m^3 / 8 * 10^9 = 0.005 * 100\% = 0.5\ \%$

3. Shape of reservoir basin

Effective flushing will be for narrow steep sided reservoir valleys with steep longitudinal slope and W/L should be less than 0.1.

For Mosul reservoir the width length ratio W/ L = 4 /65 = 0.062

4. Hydraulic condition required for efficient flushing.

* Flushing discharges must be at least twice of the mean annual flow.

($Q_f > 2\, Q_{inflow}$)

For Mosul reservoir

$Q_f / Q_{inflow} = 2500 / 500 = 5$ O.K

* Flushing volume at least 10% of the mean annual runoff:

For Mosul reservoir flushing volume =

$$2500*24*3600*40 = 8.3 * 10^9 \ m^3$$

Flushing volume / Mean annual runoff

$$= 8.3*10^9/15.5*10^9 = 55.7\%$$

According to the capacity inflow ratio value, Mosul reservoir is classified as seasonal storage reservoir. The trap efficiency of Mosul reservoir is estimated according to Brune curve [12]. The retention period (residence time) of Mosul reservoir is calculated as the capacity of reservoir divided by 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 reservoir is calculated as the capacity of reservoir divided by the river basin area controlled by the reservoir [11]. The above parameters of reservoir was used as a supplementary criteria for predicting the feasibility of sediment flushing from Mosul reservoir.

Quantity of water available for flushing

Reservoir where there is regular annual cycle of flows and defined flood season can be considered as a suitable hydrological condition for sediment flushing to substitute and restore the released water amount during flushing . This hydrologic condition may be represented by the existence of annual snowmelt in spring and summer months such as in the present case study (Mosul reservoir).

DISCUSSION

To predict the flushing feasibility of Mosul reservoir, the sediment balance ratio SBR and the long term capacity ratio LTCR was assessed. Some factors which determine the values of the sediment balance ratio and the long term capacity ratio are inherent characteristics of the site 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 , 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 [4] are used to test the feasibility sediment from Mosul reservoir. Table 3 shows the results of the application of those criteria. The calculation of these criteria shows that the SBR is more than 7 which agree with successful flushing. The LTCR gave a value higher than 0.8 which agree also with the successful flushing. While the draw down ratio DDr is less than 0.8. The FWR gave a value less than 1.0 which disagree with the successful flushing criteria. Moreover Mosul reservoir is hydraulically large in which the capacity of this reservoir about 60% of the mean annual inflow. The sediment deposition potential of Mosul reservoir is about 0.5% which is close to the criteria of successful flushing for sediment potential of reservoir which is (0.5-1)%. The hydraulic conditions required for efficient flushing agree with the available condition in Mosul reservoir in which the flushing discharges must be at least twice the mean annual flow in which:

$$Q_f / Q_{in} = 2500 /500 = 5$$

Another hydraulic condition for Mosul reservoir which agree with the criteria for successful flushing is the flushing volume which must be at least 10% of mean annual runoff. For Mosul reservoir flushing volume is 55.7% of the annual runoff.

The shape of Mosul reservoir agree with the shape needed for successful flushing which is a narrow steep sided reservoir valleys. Mosul reservoir width length ratio is 0.062 which agree with the required reservoir width depth <1.

Finally a hydrological condition needed for successful sediment flushing is represented in reservoir when there is regular annual cycle of flows and defined flood season. This may be represented by existing annual snow melt is spring and summer months which is existed in the watershed of Mosul reservoir.

CONCLUSIONS

From the application of the world wide universal criteria on sediment flushing in reservoir predicted by many scientists such as [4] ,these criteria were applied on Mosul reservoir in north Iraq and from the analysis of the available field actual data concerning flushing sediment in many reservoirs in the world, the author in general concluded that the efficiency of sediment flushing can be increased with the lesser the 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, the younger and the less consolidated the sediment. Concerning Mosul dam it was concluded that the main requirements in the used and applied criteria for flushing sediment can be verified in Mosul reservoir like the SBR, the LTCR, the topography (shape of reservoirs) (i.e. the ratio W/L), the hydraulic conditions (Q_f/Q_{in}) and (V_f/V_{in}) except some hydrological conditions like the capacity inflow ratio and draw down ratio which did not fit completely with the criteria. In general, Mosul reservoir may be flushed and sediment can be reduced successfully which means that the flushing process may be considered feasible. It is recommended to apply flushing procedure on Mosul reservoir and studying its effectiveness through making reservoir surveying after the flushing process if possible to check the degree of the success of this process. The flushing process must be evaluated briefly with the environmental effects of this process downstream of the dam especially the effect of flowing discharges on the stability of the bed in-front of the bottom outlet structures of the dam and must go forward smoothly with other objectives of the dam.

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Table (1) Summary data on Mosul reservoir (Ministry of Irrigation,1985)

Original storage capacity (C)	8 $*10^9$ m^3
Reservoir length (L)	65 km
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)	2500 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).	290 m
Constant for sediment type (ψ)	650 for D_{50} > 0.1

Table (2) Some important predicted parameters and properties for Mosul reservoirs

Capacity Inflow Ratio C/I	Trap Efficiency T.E	Retention Period R.P	Sedimentation Index S.I	Specific Storage S.S
0.6	95%	222 day	$191*10^6$ sec/m	2.64 m

Table (3) Application of sediment flushing criteria on Mosul dam

	SBR	LTCR	DDR	FWR	G_f/Q_i	W/L	V_f/Vi	S_p	C/I
Calculated criteria	31.5	1.3	0.57	0.32	5	0.062	55.7%	0.5%	0.6
Successful flushing criteria	>7	>0.7	<0.8	>1	>2	<1	>10	>0.5	<0.3

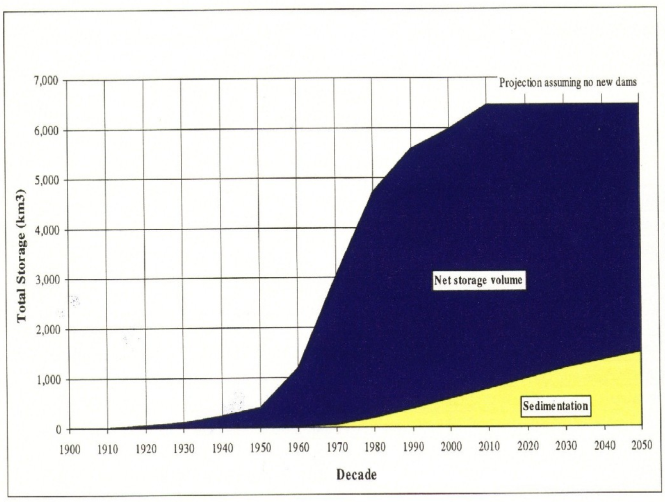

Figure (1) Water storage lost due to Sedimentation in reservoirs

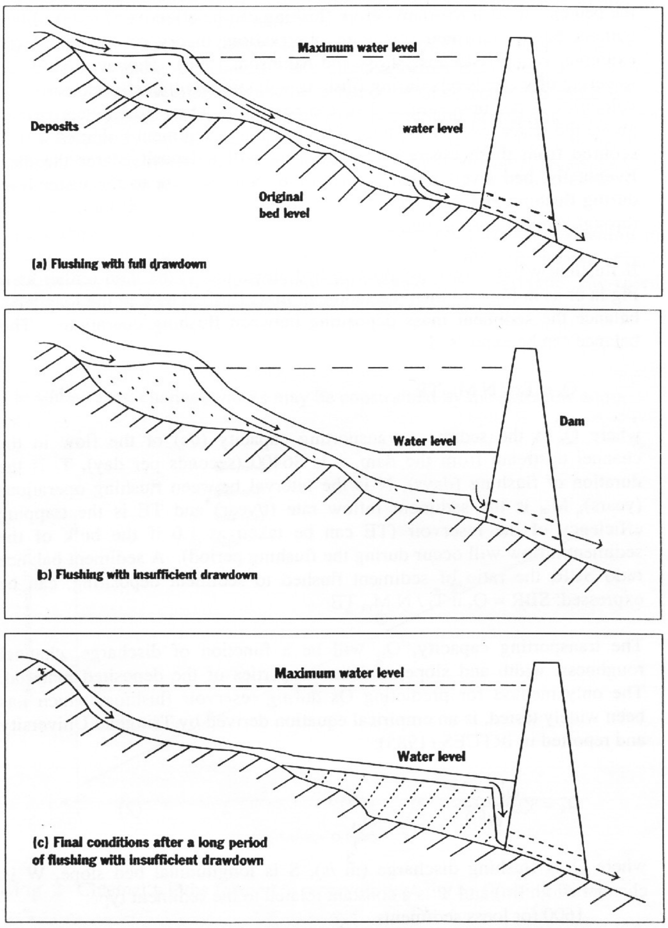

Figure (2) Longitudinal profile of flushing process (after Atkinson,1996)

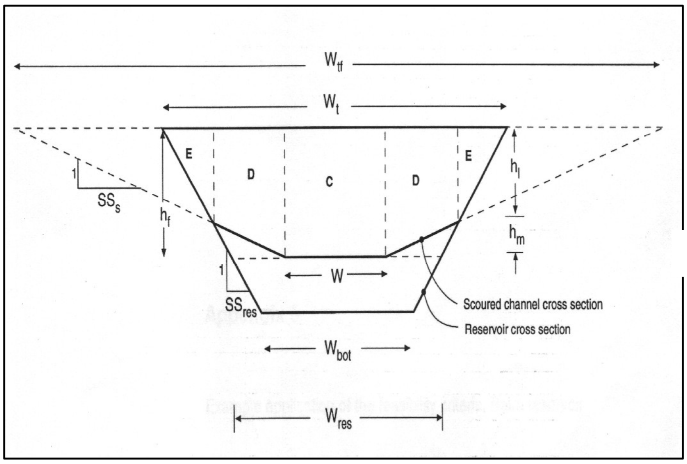

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Figure (3) Cross section immediately upstream of dam for simplified reservoir geometry.

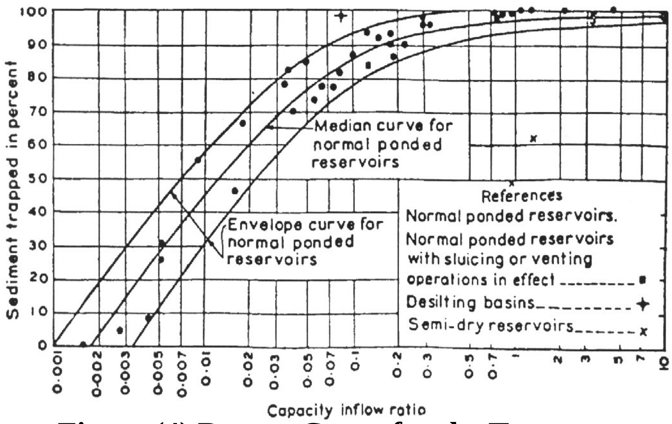

Figure (4) Brunes Curve for the Trap efficiency calculation.

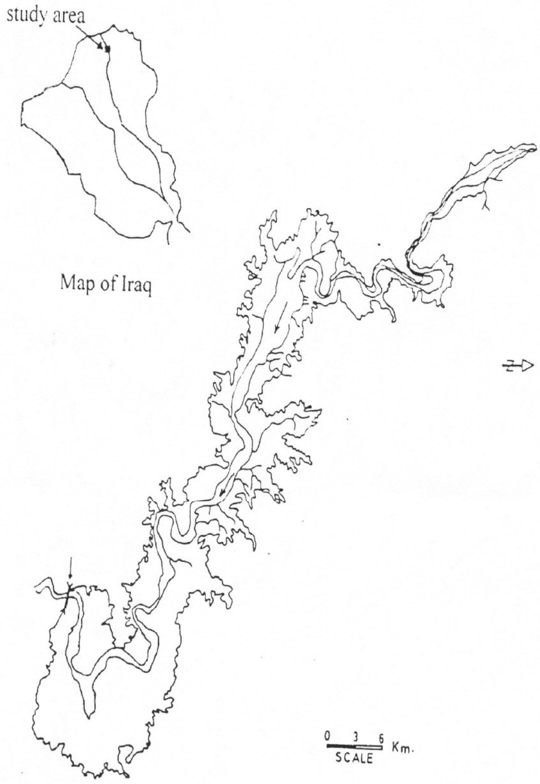

Figure (5) Location Map of Mosul Dam Reservoir in Iraq

الجدوى الفنية لعملية غسل الرسوبيات في خزان سد الموصل/العراق

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الخلاصة

تمت دراسة الجدوى الفنية لعملية غسل الرسوبيات في الخزانات وتطبيقها على خزان سد الموصل حيث تم تطبيق بعض المعايير الهيدرولوجية والهيدروليكية والطوبغرافية والتشغيلية المستخدمة على العديد من الخزانات في العالم كما تم ايجاد معايير اضافية اخرى وتطبيقها للتعرف على نجاح تطبيق عملية الغسل في سد الموصل. توصل البحث الى العديد من الاستنتاجات التي تخص عملية الغسل الناجح للرسوبيات في الخزانات كما أوصى بامكانية تطبيق هذه العملية على خزان سد الموصل في المستقبل مع دراسة التاثيرات البيئية لعملية الغسل على المناطق الواقعة مؤخر السدود.

الكلمات الدالة : غسل الرسوبيات، الدفق الفيضي، الخزانات