Design and Operation of Sustainable Reservoirs, a New Approach

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Abstract

A reservoir is an artificial lake which begins to fill with sediment as soon as it is commissioned causing a gradual loss of storage capacity. Today, most dams of substantial size are engineered to have a practically unlimited life so far as the structure itself is concerned, provided it is given adequate maintenance. Modern geotechnics can be applied to dam site exploration and engineering skill in design reduces the risk of almost all types of structural and foundation failure. Present day knowledge of probable maximum precipitation (PMP) and probable maximum flood (PMF) has led to spillway design that leaves only a very small chance of failure from floods. Despite the above achievements, the reservoir sedimentation received less attention in study, design and operation stages. According to ICOLD sedimentation committee (March, 2009), the total storage capacity of the world reservoirs is about 7000 billion m^3, of which 2000 billion m^3 is the volume of deposited sediment, corresponding to an annual loss of .8%. It means that the half-life of the world's reservoirs in average is about 60 years, 2/3 of which is already past. Therefor it is very clear that the present rate of reservoir sedimentation along with such a huge amount of accumulated sediment will impose a very costly liability upon the next generation, hence a better understanding is urgently needed. The author believes that the present generation particularly those who are in the position of making key decisions must answer the following question. "What shall the future dam operators do while facing with the abandoned reservoirs full of sediment?" This paper describes a new approach of design and operation of dam reservoirs based on sustainable development principles, the reservoirs with almost unlimited life-cycles. The philosophy of the new approach is described as below.

1. A river system is a live element of the nature because it moves, it digs, it deposits, it carries, and it changes the environment to stabilize itself.
2. All the live elements of the nature need a part of their power to survive their live.

As a reservoir is a part of a river system, thus the above philosophy should be fulfilled in its design and operation. Steps taken in the new approach have been elaborated using 15 years field experiences on de-siltation operations carried out at Sefidrud Reservoir, Iran.

Keywords: Required Trap Efficiency, Long-Term Capacity Ratio, Life-Cycle, Useful-Life, Rehabilitation Period.

1. INTRODUCTION

1.1. NEED FOR SUSTAINABLE RESERVOIRS

A reservoir is an artificial lake which begins to fill with sediment as soon as it is commissioned, causing a gradual loss of storage capacity.

Reservoir sedimentation affects the lives of the people who benefit from the stored water, and it may have both long-term and short-term consequences. In the short-term, the effect of sedimentation is the economics of the reservoir scheme. The rate of sedimentation may be so rapid as to prevent amortization of the cost of development. Most dams of substantial size are engineered to have a practically unlimited life so far as the structure itself is concerned, provided it is given adequate maintenance.

Today, modern geotechnics is applied to dam site exploration and engineering skill in design reduced the risk of almost all type of structural and foundation failure. Despite these measures, the useful life of the dam project can be greatly reduced by reservoir sedimentation. The most obvious effect is the depletion of storage capacity which prevents the reservoir from supplying the services for which it was designed, thus disturbing the economy of the region which it serves. Regulated water supply is also reduced by increased evaporation losses especially in arid and semi-arid regions, as the sediment accumulation will change the area-capacity relationship of the reservoir so that larger surface area is exposed for equal storage. The consequences of sediment accumulation in the upper reaches of a reservoir will reduce the flood routing efficiency and also flooding of upstream river valley developments, such as towns, highways, railroads, etc. an increase in the evapotranspiration due to vegetation at the head of Elephant Butte Reservoir in USA, quoted by Murthy(1968), is about 37% of the evaporation losses from the reservoir surface.

The most favorable measure to control reservoir sedimentation may be watershed management, which is not always justified from technical and economical point of views, as the sediment yield is product of many natural and artificial interrelated factors such as rainfall characteristics, rainfall-runoff relationship, susceptibility of soil and valley alluvium to erosion, land use and density of vegetative cover on the watershed. Almost all of the significant factors mentioned above are worse in arid and semi-arid regions of the world, particularly in developing countries, where favorable natural conditions may be aggravated by the lack of programming and cooperation among the relevant authorities and the huge amount of capital and maintenance costs required in long-term plans.

Data collected by Murthy(1968) and Zhang-Qian(1985) with the Sefidrud Reservoir(Iran) added, are presented in Table 1.1.The table shows that reservoir sedimentation has not been avoided even in developed countries, so an improved understanding is needed.

The main goal of this paper is the steps in the study, design and operation stages necessary to minimize the capacity loss of reservoirs by controlling the trap efficiency, so that useful life of the reservoirs be prolonged, also the periodic rehabilitation of the reservoir capacity be possible, using hydrodynamic energy of the stored/inflow water to remove deposited sediment, thus achieving a sustainable development.

Table 1.1. Representative data of rates of reservoir sedimentation

COUNTRY	RESERVOIR	CATCHMENT AREA (KM^2)	PERIOD OF RECORD (YEAR)	ORIGINAL CAPACITY (MCM)	ANNUAL AVERAGE STORAGE LOSS (%)
1	2	3	4	5	6
USA	Boysen	20050	13	20	6.25
USA	Mississippi	308200	15	456	2.00
AFRICA	Lake Arthur	5880	10	78	4.10
AFRICA	Lake Mentz	12490	12	117	2.90
JAPAN	Soyama	1500	19	33	2.40
ITALY	Mont Reale	435	1	1.50	2.60
INDIA	Pahari	7840	28	47	2.19
CHINA	Qingtongxia	285000	12	620	6.52
CHINA	Yanguoxia	182800	18	220	4.04
CHINA	Sanmenxia [1]	688420	1.5	9640	10 [+]
IRAN	Sefidrud [2]	56200	17	1760	2.13 [*]

+ Normal operation period (1960-1962)

* Normal operation period (1963-1980)

Notes:

(1): The trap efficiency at Sanmenxia Reservoir in its normal operation period (1960-62) was 93.2%, but this value was reduced in subsequent years, due to de-siltation operations as below, Zhang and Long(1981).

- In the 1st stage of de-siltation operation (1962-66), TE=42%
- In the 2nd stage of de-siltation operation (1966-70), TE=18%
- In the 3rd stage of de-siltation operation (1970-73), TE=0.0%, no storage loss thereafter.

Originally the outlet system in Sanmenxia Dam was not capable to an efficient de-siltation operation, therefore an extensive structural measures have been taken.

(2): The trap efficiency at Sefidrud Reservoir during its normal operation period (1963-80) was 79%, but its value was reduced in the subsequent years due to de-siltation operations as described below, Tolouie(1989).

- In the 1st stage of de-siltation operation (Partial drawdown, 1980-82), TE=53%
- In the 2nd stage of de-siltation operation (empty flushing, 1982-90), TE=-75%

As a result of foregoing de-siltation operations, 358 mcm of the reservoir capacity was rehabilitated. It should be mentioned that the bottom outlet system at Sefidrud Dam was originally capable to partial drawdown/ empty flushing of the reservoir, thus no structural measure was needed (5 bottom outlets with total capacity of 980 m^3/s, 6.5 times the long-term average inflow discharge, located at about river bed elevation).

1.2. CONCEPTUAL DEFINITIONS

(1). Variation of traditional reservoir capacity against time (Fig. 1.1),

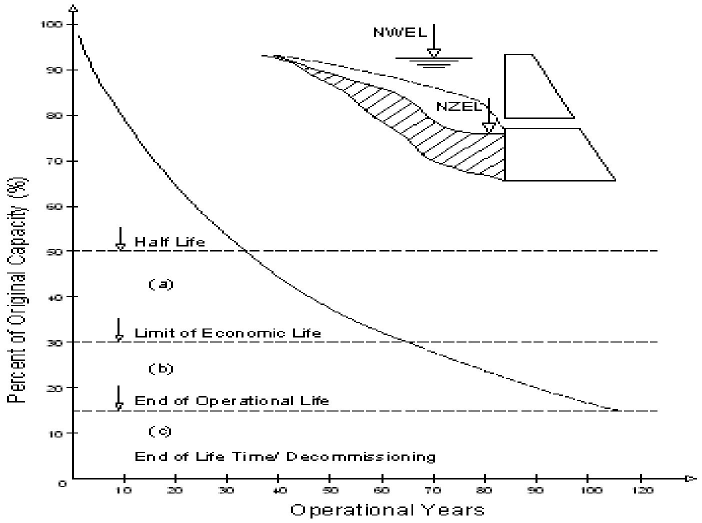


Figure 1.1. Typical variation of reservoir capacity against time, traditional design

Notes: NWEL = Normal Water Elevation, NZEL = New Zero Elevation

Fig. 1.1 shows that, in traditional design there is just one life-cycle which includes useful life/ economic life (a), uneconomic life (b), and abandonment of the whole facility or decommissioning stage (c). In addition, the volume of dead storage in traditional design which is usually allocated for deposition of 50 years inflow sediment may take up to 80% of the total original capacity of the reservoir, resulting high investment and environmental costs.

(2). Variation of sustainable reservoir capacity against time (Fig. 1.2),

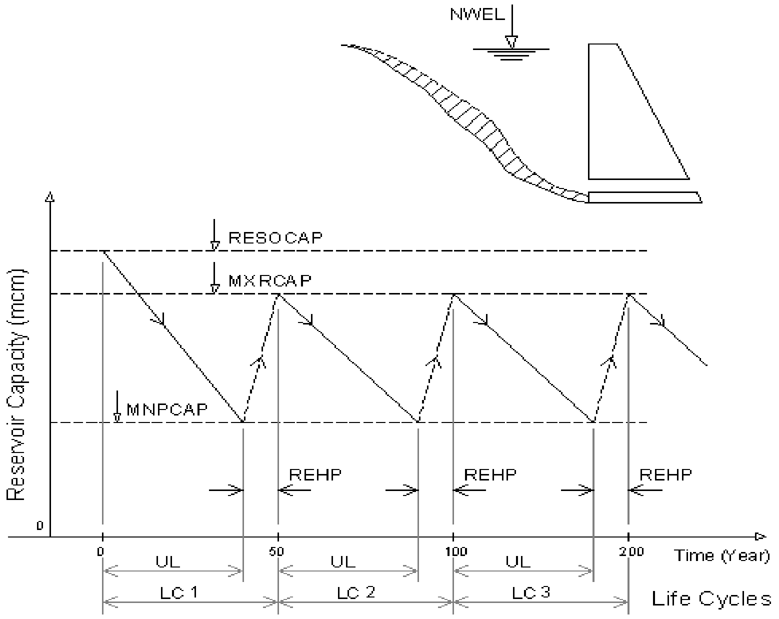


Figure 1.2. Typical variation of reservoir capacity against time, sustainable design

Notes:

RESOCAP = Reservoir Original Capacity, MXREHCAP = Maximum Rehabilitation Capacity
MNPCAP = Minimum Permissible Capacity, REHP = Rehabilitation Period, UL = Useful Life
LC = Life Cycle

Fig. 1.2 shows that in sustainable design, the reservoir operation can be carried out in different life-cycles as long as the structural life of the dam. In addition, no dead storage for sediment accumulation is required, so the height of the dam and the reservoir capacity is considerably reduced.

2. REQUIRED TRAP EFFICIENCY OF THE RESERVOIR

2.1. REQUIRED TRAP EFFICIENCY DURING USEFUL LIFE (RULTE)

The following steps are taken:

STEP 1: Plot long-term average demand shortage against trap efficiency of the reservoir for a certain value of useful life, say UL = 40 years (Fig. 2.1)

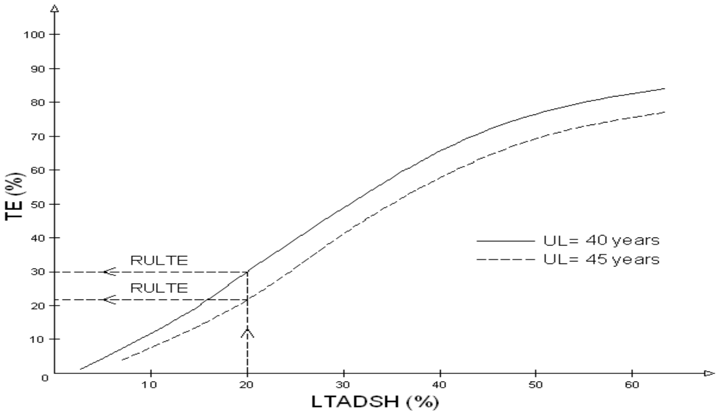


Figure 2.1. Typical variation of LTADSH against TE

Notes: TE = Trap Efficiency, RULTE = Required Useful Life Trap Efficiency, LTADSH = Long- Term Average Demand Shortage

STEP 2: From Fig. 2.1, find RULTE corresponding to the accepted value of LTADSH

2.2. REQUIRED TRAP EFFICIENCY DURING REHABILITATION PERIOD (RREHTE)

The following steps are taken:

STEP 1: Plot long-term capacity ratio of the reservoir against trap efficiency, for the same useful life as taken in Fig. 2.1, as shown in Fig. 2.2.

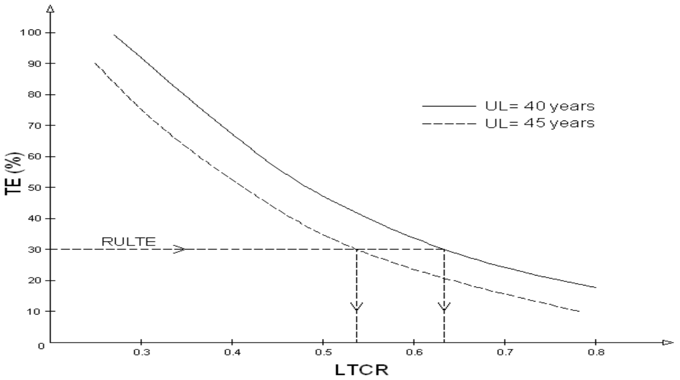


Figure 2.2. Typical variation of LTCR against TE

Notes: LTCR = Long –Term Capacity Ratio, the ratio of the reservoir capacity at the end of its useful life to the original capacity of the reservoir.

STEP 2: In Fig. 2.2, locate RULTE (found in paragraph 2.1) and find the corresponding value of LTCR.

STEP 3: Plot rehabilitation trap efficiency of the reservoir (REHTE) against LTCR for different values of rehabilitation periods (Fig. 2.3).

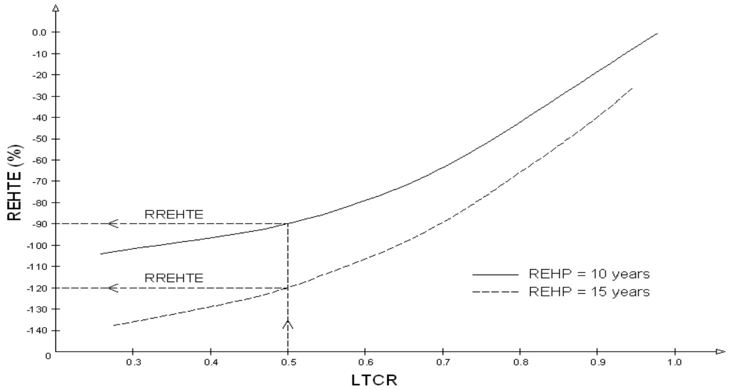


Figure 2.3. Typical variation of REHTE against LTCR for different values of REHP

Notes: REHP = Rehabilitation Period, REHTE = Rehabilitation Trap Efficiency, RREHTE = Required Rehabilitation Trap Efficiency

STEP 4: From Fig. 2.3, find RREHTE corresponding to the known values of LTCR and REHP.

STEP 5: Check feasibility of obtaining the calculated value of RREHTE, hence change the REHP and/ or UL accordingly.

An example to calculate RREHTE

- Reservoir Original Capacity, RESOCAP = 500mcm
- Annual Average Inflow Sediment = 10 mcm/yr
- Long Term Capacity Ratio, LTCR = 0.6
- Available Capacity of the Reservoir at the end of its useful life = 500 * 0.6 = 300 mcm
- Maximum extent of reservoir rehabilitation = 90%
- Maximum Recovered Capacity of the reservoir = MXRCAP = 500 * 0.9 = 450 mcm

a: Reservoir Rehabilitation Period, REHP = 5 years
Total Outflow sediment during rehabilitation period = 5 * 10 + (450 – 300) = 200 mcm
RREHTE = (5 * 10 - 200)/ (5 * 10) = -300%
b: Reservoir Rehabilitation Period, REHP = 10 years
Total outflow sediment during rehabilitation period = 10 *10 +(450 -300) = 250 mcm
RREHTE = (10 * 10 – 250)/ (10 * 10) = - 150%
c: Reservoir Rehabilitation Period. REHP = 15 years
Total outflow sediment during rehabilitation period = 15 * 10 + (450 – 300) = 300 mcm
RREHTE = (15 * 10 – 300)/ (15 * 10) = - 100%
Referring to Fig. 1.2, the Minimum Permissible Capacity of the Reservoir is,
MNPCAP = LTCR * RESOCAP = 500 * 0.6 = 300 mcm

3. FEASIBILITY OF APPLYING DIFFERENT DE-SILTATION METHODS

3.1. OVERVIEW

Among the different de-siltation methods, the scope of the paper is utilization of hydraulic energy of the stored and / or inflow water to control the trap efficiency of reservoirs. That is, allocation a certain budget out of available water for conservation of the river system. In other words, those techniques such as dredging and siphoning are not considered as the main elements in de-siltation operations, but these techniques may be used as supplementary measures in small scales such as cleaning the areas around intakes or dredging a pilot channel along the impounded reservoirs to facilitate the passage of density-currents. Therefore, the paper will focus on density-current venting, sluicing, flushing, and bypassing (as an alternative to density-current).

3.2. ESTIMATION OF RESERVOIR TRAP EFFICIENCY BY DENSITY-CURRENT VENTING

Based upon the principle that density-current occurs during floods, the following steps are taken:

Step 1: Sort out monthly inflow discharges based on probability of occurrence, select base flow, hence split the long-term inflow discharge into base flow and flood discharge.

Step 2: Using a reliable simulation model, estimate long-term series of the following parameters: Sample of output files resulted from density-current simulation are represented in figures 3.1 to 3.5. The model (DENFLOW) was developed and calibrated during Sefidrud Reservoir de-siltation operations (1980 – 1994).

An example to calculate flood discharge (FDIS)

DFDIS = [MFLOW – BASFLOW * (30.5 - NOFD) / 30.5] / NOFD

FDIS = 11.57 * DFDIS

Where

DFDIS = Daily flood discharge in mcm/day

FDIS = Instantaneous flood discharge in m^3/s

MFLOW = Monthly average flow in mcm/month

BASFLOW = Base flow in mcm/month

NOFD = Number of flood days per month

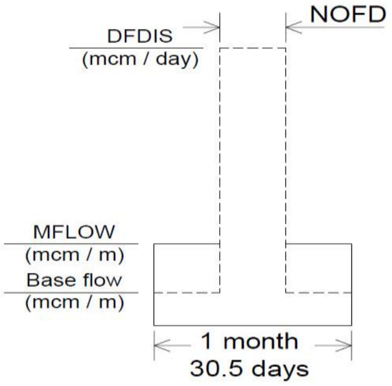
For example, MFLOW = 248 mcm/m

BASFLOW = 190 mcm/m, NOFD = 6

We have,

DFDIS = [(248– 190 * (24.5 /30.5)] / 6 = 15.9 mcm/day

FDIS = 11.57 * 15.9 = 184 m3/s



Converting monthly av. flow (mcm/m) to instantaneous flood discharge (cms)

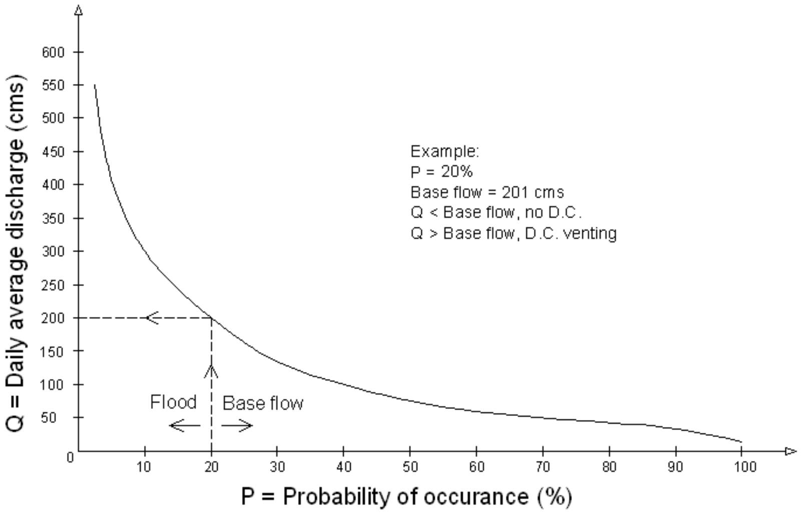


Figure 3.1. Flow – probability curve at SAMP Reservoir

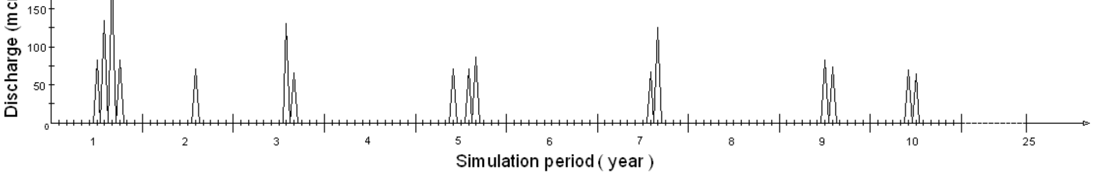


Figure 3.2. Density-current outflow discharge at SAMP Reservoir

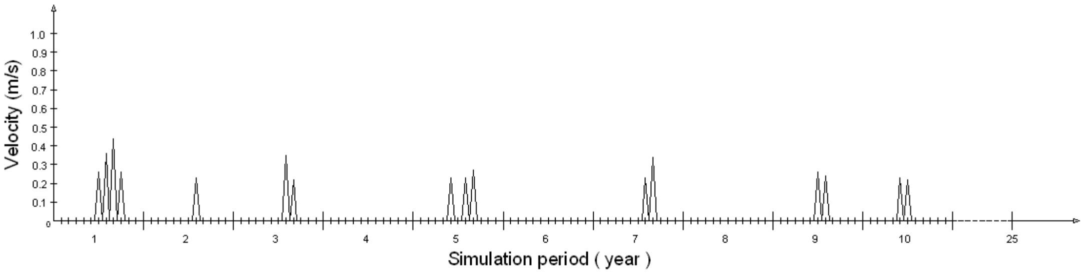


Figure 3.3. Density-current velocity at SAMP Reservoir

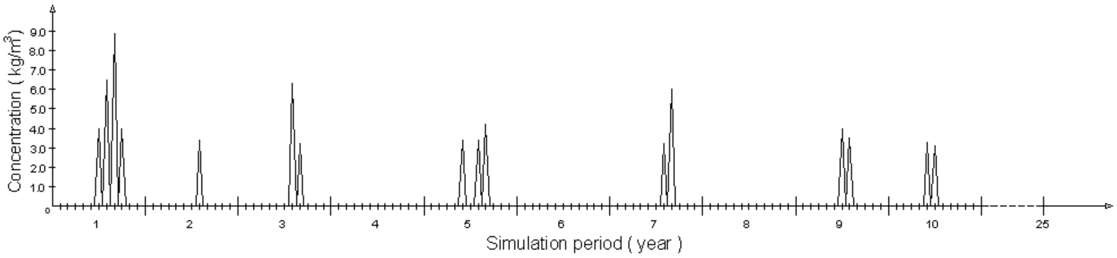


Figure 3.4. Density-current outflow concentration at SAMP Reservoir

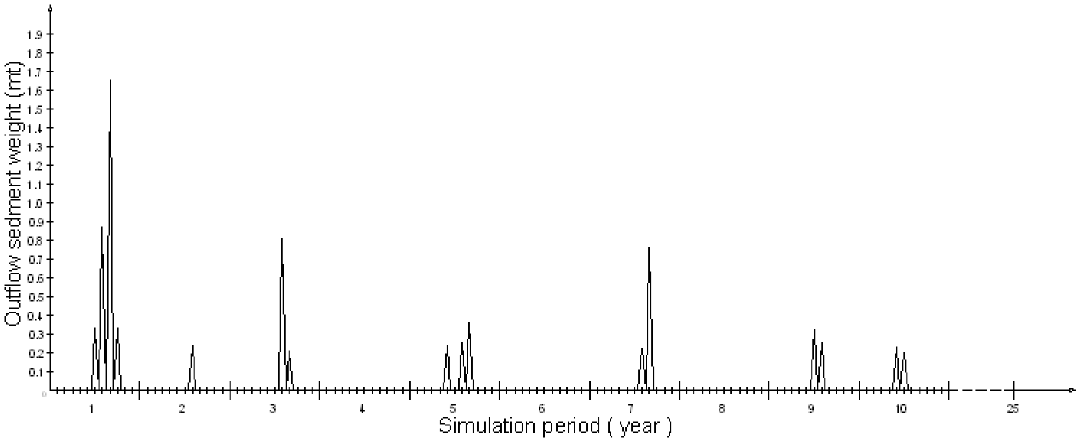


Figure 3.5. Density-current outflow sediment at SAMP Reservoir

3.3. ESTIMATION OF RESERVOIR TRAP EFFICIENCY BY PARTIAL DRAW DOWN FLUSHING

In partial draw down flushing (Sluicing), the reservoir water level is drawn down to minimum operating level, and the bottom outlets are opened allowing the development of a conical scour hole in front of the outlets. Maintaining the reservoir water level between the minimum operating level and the minimum draw down level, causes transport of the sediment from the upper reaches of the reservoir (where the river flow forms) towards the dam. This phenomenon is often more remarkable in hydropower reservoirs where the minimum operating level is relatively high.

Taking into consideration that drawdown flushing is more efficient during flood season, it will be clear that maintaining the reservoir water level in lower stages of the reservoir (between minimum operating level and minimum draw down level), necessitate high–capacity bottom outlets at low sill elevation. Draw down Ratio (DDR) is a criterion which defines a suitable stage of the reservoir during draw down flushing;

DDR = 1 - (HD /HH) > 0.7

Where,

HD = Reservoir water depth during draw down operation

HH = Hydraulic height of the dam (depth of water at normal water level)

That means, the depth of water behind the dam during draw down flushing should be maintained below 30% of the hydraulic height of the dm.

Alternative emptying and refilling of the reservoir within a certain range of water level, is also an effective measure to increase de-siltation efficiency in draw down flushing.

At Sefidrud Reservoir the draw down flushing was carried out in the first 2 years of de-siltation operations, but in subsequent years it was combined with the free flushing operations, in fact draw down flushing was a transient operation to empty flushing operation.

It should be mentioned that draw down flushing is generally not an effective flushing technique, but possibility of controlling outflow sediment concentration by proper maneuvering the bottom outlet gates, is an advantage of this technique as compared with free flushing operation. The said advantage is particularly valuable at those sites with downstream environmental limitations. Based on the field experiences at Sefidrud site, an empirical simulation model (SLUICE) was developed. The cone geometry in front of the bottom outlets is defined in the model based upon the field data.

A sample output file of the partial drawdown model (SLUICE), is represented as figure 3.6.

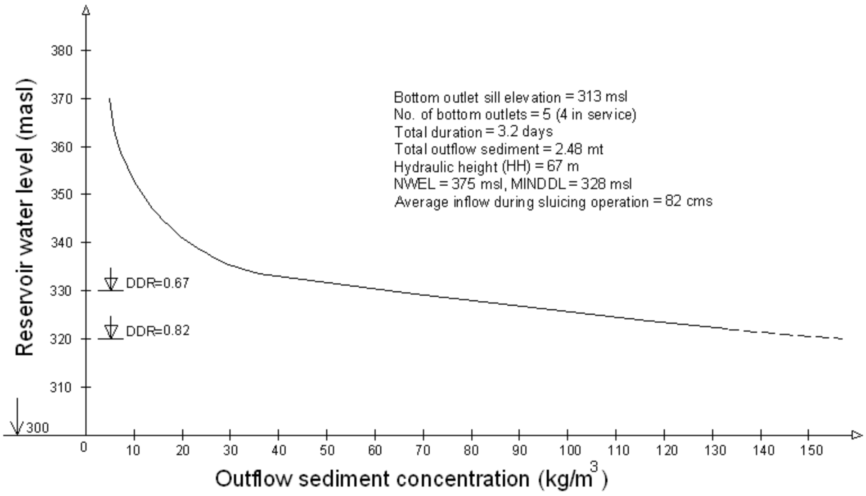


Figure 3.6. Result of partial drawdown (sluicing) operation at SAMP Reservoir

Notes: NWEL = 375 masl, MINDDL = 328 masl, Average inflow discharge during sluicing operation = 82cms
Sill elevation of bottom outlets = 313 masl, Number of bottom outlets = 5, Duration of operation = 3.2 days
Total outflow sediment = 2.48 mt

3.4. ESTIMATION OF RESERVOIR TRAP EFFICIENCY BY EMPTY FLUSHING

In empty flushing (complete drawdown), the flow regime along the reservoir changes to river flow, resulting a very high shear stress over the deposited sediment, hence increasing the outflow sediment concentration. In general, the efficiency of empty flushing depends on the following parameters;

(1): Inflow water discharge.

(2): Longitudinal slope of the water surface profile along the reservoir/ sill elevation of bottom outlets.

(3): Layout and capacity of bottom outlet system. As far as the layout is concerned, the concrete dams are more favorable as locating several outlets across the valley is possible. The in-service capacity of the bottom outlet system should be such that a river flow could be maintained during flushing operations and no back water is formed behind the dam.

A simulation model to estimate outflow sediment concentration in empty flushing operations "FLUSHING" was developed and calibrated using field data collected during 10 years of flushing operations at Sefidrud Reservoir. Three experimental sediment transport equations were found to be in good agreement with the field observations, these are;

1. Xia (1983) equation

$$QS_1 = 300 * Q^{1,6} * S_f^{1.2} / B^{.6} \qquad [1]$$

where,

$$B = 12.8 * Q^{.5}$$

2. Fan and Jiang (1980) equation

$QS_2 = .35 * Qw^{1.2} * (.8 * S_f * 10^4)^{1.8}$ [2]

3. Rooseboom (1975) equation

$QS_3 = 2 * 10^5 * (V_m\ Sf)^{.283}$ [3]

where

$V_m S_f = P * Qw^3/(C^2 * A^4)$
V_m = mean velocity
S_f = water suface longitudinal slope
P = wet perimeter
Qw = inflow water discharge
C = Chezy coefficient
A = wet area

4. Sefidrud – calibrated equation

$QS_4 = .3 * (\mathrm{Log}\ (1 + Qw)^{1.5} * S_f^{-.7)}$ [4]

Out of the above equations, equation 4 yields lower results because of consolidated deposit at Sefidrud site, i.e. Starting flushing operation after about 20 years of commissioning.
Figures 3.7 and 3.8 illustrate the sample output files resulted by FLUSHING model.

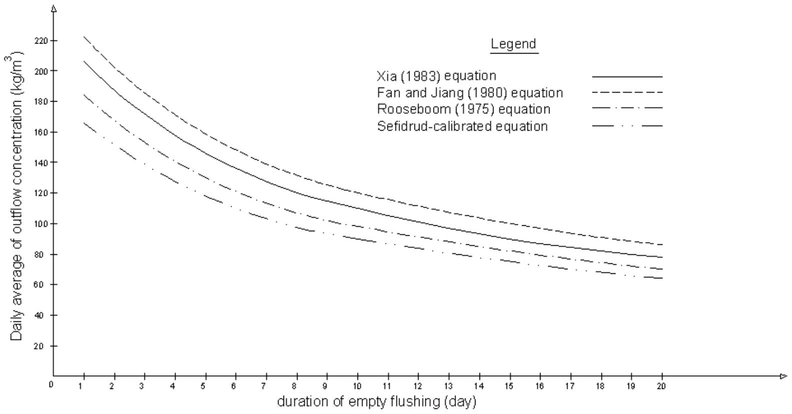


Figure 3.7. Outflow sediment concentration resulted by FLUSHING model at SAMP Reservoir

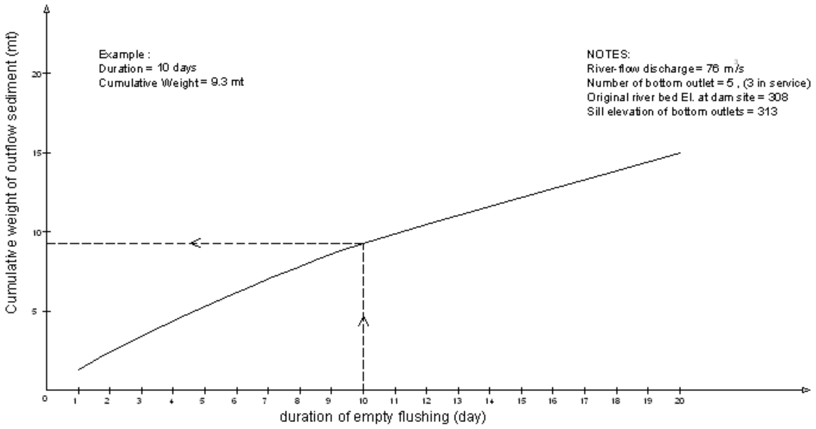


Figure 3.8. Weight of outflow sediment resulted by FLUSHING model at SAMP Reservoir

3.5. OVERALL TRAP EFFICIENCY OF SUSTAINABLE RESERVOIRS

Overall trap efficiency of a sustainable reservoir is the trap efficiency obtained by applying above mentioned de-siltation techniques, that is density-current venting, sluicing, and empty flushing. Summary of the results obtained by applying these techniques in a sample reservoir is represented in table 3.1. It is to be noted that, the outflow sediment resulted by density-current venting is for the entire simulation period, whereas those obtained by sluicing and empty flushing are just for a single operation.

Table 3.1. Summary of outflow sediments and resulted trap efficiencies in a sustainable reservoir in different alternatives

ALTERNATIVE	FLUSHING INTERVAL (YEAR)	FLUSHING DURATION (DAY)	WEIGHT OF OUTFLOW SEDIMENT (MT)				RESULTED TRAP EFFICIENCY (%)	REMARKS
			DENSITY-CURRENT VENTING	SLUICING	EMPTY FLUSHING	TOTAL		
1	1	5	37.4	62	134	233.4	-33	Inflow sediment = 7 $^{mt}/_{yr}$ Sediment outflow in single sluicing operation = 2.48 mt Simulation period = 25 years
		10	37.4	62	230	329.4	-88	
		15	37.4	62	307	406.4	-132	
		20	37.4	62	373	472.4	-170	
2	2	5	37.4	30	67	134.4	+23	
		10	37.4	30	115	182.4	-4	
		15	37.4	30	153	220.4	-26	
		20	37.4	30	186	253.4	-45	
3	3	5	37.4	20	44	101.4	+42	
		10	37.4	20	76	133.4	+24	
		15	37.4	20	102	159.4	+9	
		20	37.4	20	124	181.4	-3	
4	4	5	37.4	15	33	85.4	+51	
		10	37.4	15	57	109.4	+37	
		15	37.4	15	77	129.4	+26	
		20	37.4	15	93	145.4	+17	
5	5	5	37.4	12	27	76.4	+56	
		10	37.4	12	46	95.4	+45	
		15	37.4	12	61	110.4	+37	
		20	37.4	12	75	124.4	+29	

According to table 3.1, the interval of empty flushing operations has got a very important role in overall trap efficiency of the reservoir. The table shows a very wide range of trap efficiencies from + 56% to – 170%. The negative trap efficiency indicates the rehabilitation of reservoir capacity therefore it is applicable in rehabilitation period of the life–cycle (see Fig. 1.2).Based on the field experiences at Sefidrud Site, an approximate estimation of the water-budget which should be assigned for implementation of de-siltation operations ranges from 15% to 20% of the annual water inflow, provided that a suitable arrangement of bottom outlet system is available (in fact this value at Sefidrud site was about 22% which was contributed to the consolidated deposit). This volume of water should be taken into account while studying water resources planning as well as during operation period of the project, as conservation water right.

4. REFERENCES

1. Fan J. and Jiang R. (1980). On methods for the de-siltation of reservoirs. International seminar of experts on reservoir de-siltation, Tunisia.
2. Murthy BN. (1968). Capacity survey of storage reservoirs. Publication No. 8, CBIP, New Delhi, India.
3. Rooseboom A. (1975). Sediment transport in rivers and reservoirs. D. Engineering dissertation, university of Pretoria.
4. Tolouie E. (1989). Reservoir sedimentation and de-siltation. A thesis presented to the faculty of engineering, university of Birmingham, UK.
5. Xia M. (1983). Sediment problems in design and operation of medium and small size reservoirs. Science press, Beijing, China.
6. Zhang Q. and Long Y. (1981). Sediment problems of Sanmenxia Reservoir. Proceeding international symposium on river sedimentation, Beijing, China.
7. Zhang R. and Qian N. (1985). Reservoir sedimentation. International research and training center on erosion and sedimentation. Beijing, China.