REVIEW OF SEDIMENT CONTROL MEASURES IN RESERVOIRS

M Z Qamar
Research Officer
M K Verma
Research Officer
A P Meshram
Research Assistant
M.K. Pawar
Chief Research Officer

Central Water and Power Research Station,

ABSTRACT

Silting of a reservoir is a natural process which starts once the river channel is dammed and ends when the reservoir is practically filled with sediments. Eventually, this process destroys the ability of the scheme to deliver the benefits for which it was built. It is an unavoidable process, that can not be stopped, but it can be controlled to some degree by means of certain practices, measures and works. These practices, measures and works which may be adopted to control the sediment entry and deposition in the reservoir and for removal of the accumulated sediment from the reservoir are highlighted in this paper.

INTRODUCTION

There are around 40,000 large reservoirs worldwide used for water supply, power generation, flood control etc. About one percent of the total storage volume is lost annually as a result of sedimentation and 300 to 400 dams would need to be constructed annually to maintain current total storage *(1)*. The life span of reservoirs is determined by the rate of sedimentation which gradually reduces storage capacity.

There are various options available for positively managing sedimentation in reservoirs. Namely minimizing sediment loads entering reservoirs by catchment conservation programmes, upstream trapping of sediments and bypassing of high sediment loads, minimizing deposition of sediments in reservoirs by sluicing and density current venting and removing accumulated sediments from reservoirs by hydraulic (reservoir flushing) and mechanical (dredging and digging) methods. All these methods can be used to extend the useful life of reservoirs. However, their technical, economical and environmental feasibility depend on a number of specific factors including:

- The availability of suitable engineering facilities at the dam to control water levels and outflows
- The availability of 'surplus' water and its value if used for other purposes
- The predictability of river flows, including seasonal variations
- The characteristics of the sediments entering and within, the reservoir
- The availability of disposal sites for dredged sediments
- The effects on the downstream reach of evacuating sediments through the dam
- The effects on the normal operation of the scheme and the financial and social consequences
- Institutional and political problems among the affected stake-holders.

SEDIMENT SOURCES

Sediment is fragmental material derived primarily from the physical and chemical disintegration of rocks from the earth’s crust. It is fragmental material transported by, suspended in or deposited by water or air. Such particles range in size from large boulders to colloidal size fragments and vary in shape from rounded to angular.

Once the sediment particles are detached, they may either be transported by gravity, wind, and water or by a combination of these agents. When the transporting agent is water the sediment is termed as “Fluvial Sediment” and the act of moving or removing the particles from their resting place is called erosion. The material is called alluvium if transported and deposited by streams, loess if transported and deposited by wind and glacial drift if it is transported and deposited by glaciers *(2)*. So main agents of soil erosion are water, wind and ice but some human activities like construction, mining or excavation add to the process, accelerating it in many situations. The factors affecting the erosion include the natural factors such as climate, topography, land use and geology and some man made activities such as agricultural activity, deforestation, urbanization, roads and highway construction and mining operation.

SILTING OF RESERVOIRS – CAUSES AND EFFECTS

The silting process is unavoidable and irreversible and can have multiple effects in the catchment, on the river system, on the environment and on the various engineering works in the adjacent areas. The silting process is reducing the storage capacity of the world’s reservoirs by more than 1% per year *(3)*. That is, on the global scale, about 50,000 Mm^3 of capacity is being lost to sediment every year. The general practice in India is to design a reservoir for a life of 100 years and the results of sedimentation studies indicate that the actual life of reservoirs will nearly coincide with design life. Available data suggest that large dams in India are silting at an average annual rate of about 0.5 percent. While this is a rather modest rate of storage loss, if it is unabated the twenty first century will witness the loss of over half India’s present reservoir capacity *(4)*.

CAUSES OF THE SILTING PROCESS

The silting process of reservoirs is determined by several Natural causes such as sediment transport in the river system (main river and tributaries), bank and shore erosion, bank and slope sliding and rare events (natural catastrophies such as exceptional floods, tectonic movements, huge mud / debris flows, and dam break) and it is strongly influenced in its time-space evolution by various anthropic activities and works such as intensive exploitation of forests without compensatory afforestation works, improper and uncontrolled forest clearing works aiming to extend the surface of agricultural land and others such as construction of roads and dams. The activities and works which reduce or slow down the silting process are regulation works in channel of the main river and tributaries, torrent and gully control works, soil conservation works (afforestation, grassing, vegetation screens) and land management, and partial trapping of coarse sediment by check dams. The main human activities and works in reservoir basin and at the dam wall, which can positively or negatively influence the silting process, is the operation of the reservoir. An inappropriate operation, especially during floods, can accelerate the sedimentation of reservoirs. On the contrary, flushing, sluicing and venting of turbidity currents are works which, partly at least, can decrease the silting rate and proportion of reservoir sedimentation.

EFFECTS OF RESERVOIR SILTING IN THE BASIN AND AT THE DAM

The silting process and formation of various sediment deposits in reservoirs could have serious effects within their basins, such as:

1) The reduction of useful and economic life of reservoirs by excessive, rapid or premature loss of storage capacity and the services that depend on it.
2) The reduction of hydro-power generation, water supply or discharge regulation capacity, where the reservoirs have been designed and completed to achieve these functions.
3) The silting, choking and blocking of bottom outlets and intakes, worsening the operation conditions for the hydro mechanical equipment at the dam.
4) The abrasion and damage of tunnels, galleries, guiding slots and rails of gates, turbines and other equipment at the dam and power station, due to the action of high velocity, sediment overloaded flows.
5) The additional lateral force on the dam wall exerted by deposited sediment.
6) The worsening of navigation conditions in the reservoir basin.

DEALING WITH SILTING AND DESILTING OF RESERVOIRS

There are many ways to deal with the problem of silting and desilting of the reservoirs which may be summarized as below (Figure 1):

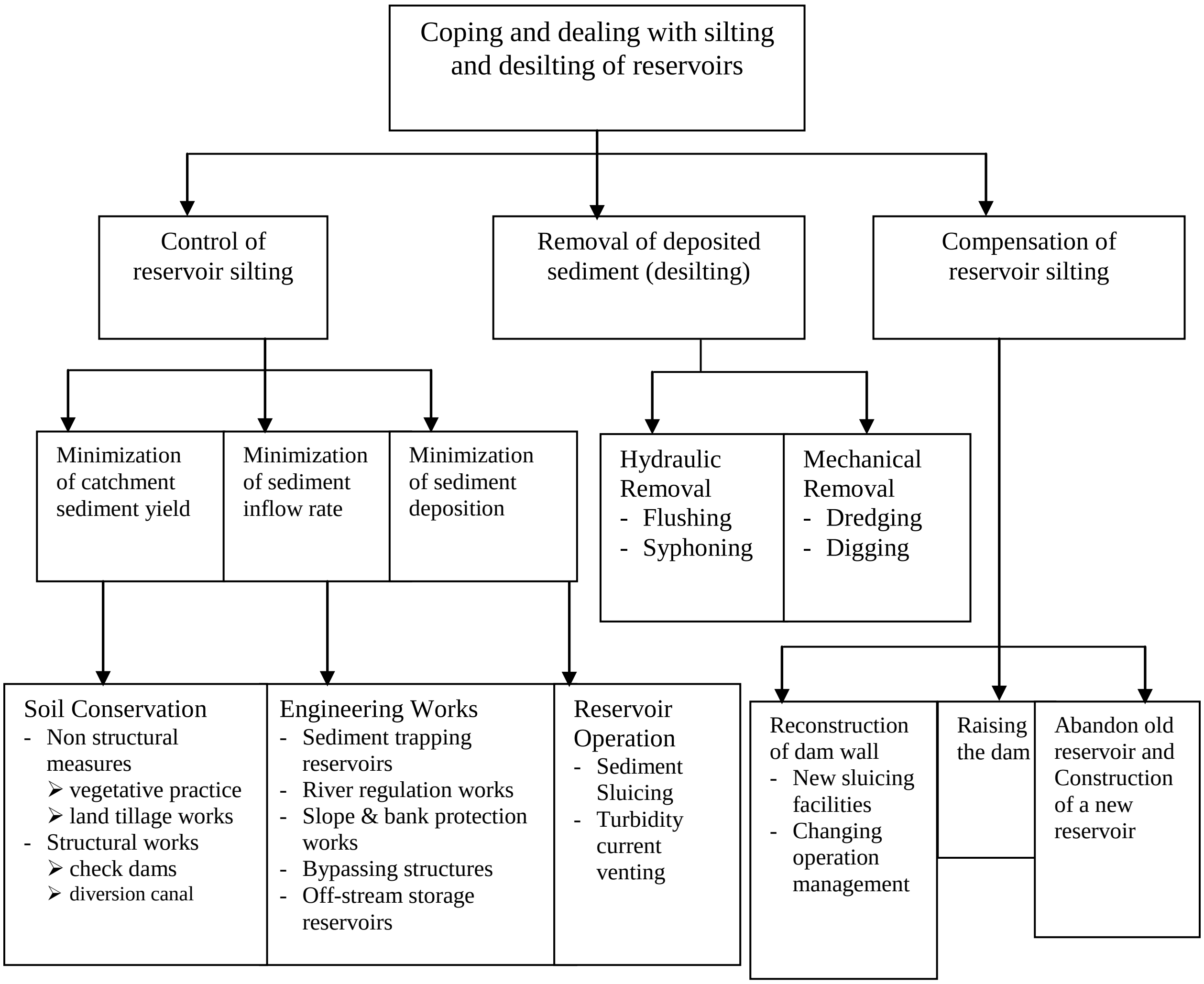

Figure 1: Schematic Diagram for sediment management in reservoirs

The measures, under the heading Control of Reservoir Silting and Removal of deposited sediment have been included in this paper.

CONTROL OF RESERVOIR SILTING

Controlling reservoir silting, both in its proportion and rate is a major objective of planning, design and operation engineers, with a view to preserve and extend, if and when possible, the useful lifespan of reservoirs, and to reduce the adverse effects to some reasonable levels. Controlling reservoir silting means the control of sediment deposition in a reservoir. It consists of various agricultural and engineering practices and works aiming:

a) To reduce/ minimize sediment yield of the catchment – soil conservation,
b) To reduce/ minimize sediment inflow rate into the reservoir –engineering works and
c) To reduce/ minimize sediment deposition within the basin – reservoir operation.

These practices, works and measures may be either independently or jointly applied in the river catchment, in the reservoir basin and at the dam site.

REDUCTION OF SEDIMENT YIELD OF CATCHMENTS

Reduction of sediment yield of river / reservoir catchment systems can be achieved by soil conservation practices that comprise a number of various non-structural and structural measures, works and actions in the catchment, such as proper vegetation and land tillage practices, small check dams for gully control and small diversion works for water supply to agriculture, that can be applied independently or in combination. In addition to serving other agricultural purposes, such soil conservation practices aim to reduce the amount of incoming sediments into a reservoir basin particularly when they are included in some carefully planned, long-term management programmes for catchments. These soil conservation practices are applicable both in the river and reservoir catchment, usually on a large scale and long term basis. Their direct but not immediate effect among others will be a reduction of sediment load carried by the river system into the reservoir basin.

REDUCTION OF SEDIMENT INFLOWS INTO RESERVOIR BASINS

Reduction or minimization to some degree of sediment amount that is transported by the river system and is brought into a reservoir basin can be achieved by exclusively engineering practices which include different types of hydraulic structures, such as:

(A) Sediment Trapping (Buffer) Reservoirs

Intercepting sediments in the upper reaches of the main river or its tributaries, upstream of the reservoir site, by silt or debris dams which create secondary buffer reservoirs, is one of the most important engineering practices in reducing the amount of the incoming sediments.

(B) River Regulation Works

When the upper river reaches (upstream of reservoirs) are regulated or channelized by making use of appropriate engineering practices and works, a significant reduction of sediment transport usually results in the river channel, and the river bed and banks are not supporting the process of silt transportation, and consequently, less aggressive incoming sediment-laden flows will enter the reservoir basin, and the silting process within the reservoir will be slowed down.

(C) Slope And Bank Protection Works

The main engineering measures include reducing the weight of the upper part of the sliding masses, adding weight to the toe of the masses to obtain a bank profile with a gentler slope, paving the slope with stone, buttress construction or anchorage of the sliding zones and runoff control and proper drainage.

(D) Sediment Bypassing Structures

Sediment bypassing schemes are very important and effective engineering practices in reducing the sedimentation rate of reservoirs and preserving their useful lifespan. They operate both during low-flows (for clear water storage), and high-flows (when sediment loaded floods are bypassed around a reservoir). When properly designed, sediment bypassing schemes are very effective from the technical point of view, although some difficulties could appear during their operation (entrance choking, concrete abrasion, filling with sediments and debris), increasing the maintenance cost of the entire scheme. Interesting cases and schemes in Switzerland, Japan, Italy, Austria, India and South Africa are reported in literature and some of them are given below:

Palagnedra Reservoir (Melezza River, Switzerland 1953), storage capacity of 5.5 Mm^3. In 1974, to divert the sediment laden flows from the head of the reservoir directly downstream, a 1760 m long bypassing gallery was constructed. The free flow capacity of this gallery is 225 m^3/s, at an active cross section of 30 m^2.

Miwa Reservoir (Mibu River, Japan 1959), a gross storage capacity of 29.95 Mm^3. In order to control the sedimentation of the reservoir, a very complex sediment interception and bypass scheme was designed and adopted including an upstream check dam for sediment storage, a separation dam and a 4.3 km long flood bypass tunnel of 7.5 m diameter, 300 m^3/s capacity.

Baira, reservoir (River Baira, India 1981), gross storage capacity of the reservoir is 3.76 Mm^3. A 5m x 7m high D shaped diversion tunnel was used for flushing of sediment from the reservoir.

Nathpa Jhakri *H.E. Project* (Himachal Pradesh on River Satluj) a diversion arrangement was proposed. The discharge capacity of the proposed diversion tunnel was 1000 m^3/s. Due to the diversion of the flow the velocity in the reservoir in the reach between dam and the inlet of the diversion tunnel was reduced considerably thus inducing the settlement of the suspended sediment. The settled sediment may be periodically removed from the reservoir through the under sluice spillways provided at the bottom of the dam *(5).*

The studies for this proposed diversion tunnel were conducted on a 1:60 G.S. scale model at Central Water & Power Research Station, Pune, mainly to determine the effect of diversion tunnel in reducing the entry of suspended sediment into the power intake. When the diversion tunnel is in operation it was observed that more part of the suspended sediment enters into the diversion tunnel as seen in Photo 1 and 2.

Due to the bifurcation of discharge, there is substantial reduction in the forward velocity in the reach between the dam and the intake of diversion tunnel. As such larger part of coarse and medium sediment settles in this reach and there is substantial reduction in the entry of suspended sediment into the power intake. It was observed that there would be reduction of about 27% to 69% in suspended sediment concentration of water entering into the power intake, depending upon the operating water level, discharge & gradation of suspended sediment entering into the reservoir.

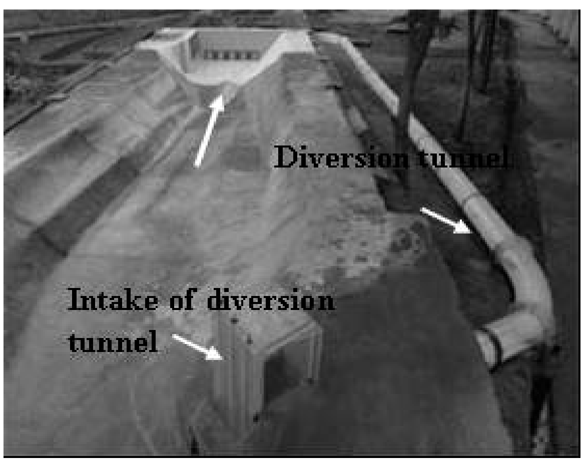

Photo 1
Part of reservoir alongwith dam,
power intake and the diversion tunnel

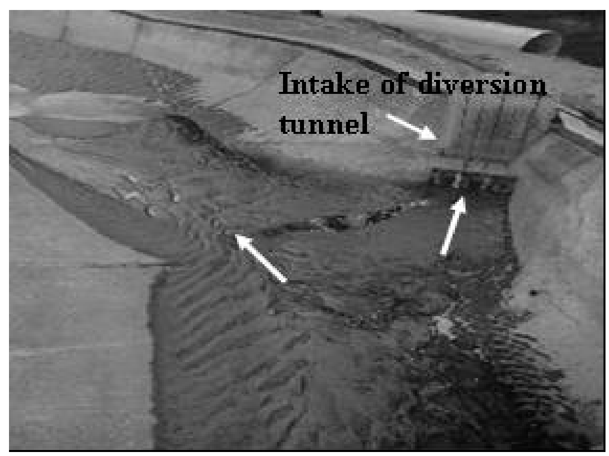

Photo 2
View showing the entry of
sediment in the diversion tunnel

On the other hand when the diversion tunnel is not in operation and the sluices are in operation it was observed that the concentration passing in the power intake and sluices are more or less same. This is due to higher velocities prevailing in the entire reach of the reservoir and the suspended sediment remains in suspension. This fact was verified by observing the velocities in the reservoir 60 m upstream of Power Intake and 60 m upstream of diversion tunnel for inlet discharge of 1200 m^3/s and water level of EL 1485 m and the average values of velocities are given below:

Conditions	Velocity at 60 m u/s of Diversion Tunnel (m/s)	Velocity at 60 m u/s of Power Intake (m/s)
Diversion Tunnel in operation and sluices closed	1.17	0.25
Sluices opened and Diversion Tunnel closed	1.31	0.84

From the above table it would be seen that when diversion tunnel is in operation the average velocity of 1.17 m/s prevailing in the reservoir upstream of diversion tunnel reduces to 0.25 m/s in the vicinity of power intake due to bifurcation of discharge. The coarse and medium sediment will settle in this region and fine particles remaining in suspension would find its way into the power intake. This phenomenon was also observed in the model. The deposition so occurred in front of intake is seen in the Photo 3.

On the other hand when the diversion tunnel is closed and sluices are in operation the average velocity of 1.3 m/s prevailed 60 m upstream of diversion tunnel reduces to 0.84 m/s in the vicinity of power intake. Such a high velocity would not permit settlement of medium and coarse part of suspended sediment and all the sediment would remain in suspension and finally enters into the power intake.

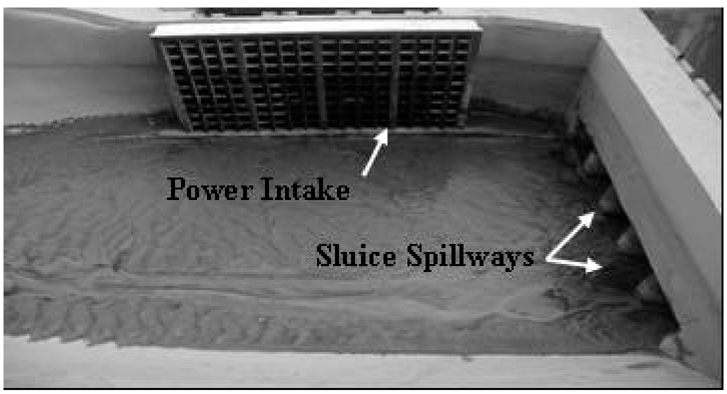

Photo 3: Deposition in front of intake due to bifurcation of discharge

REDUCTION OF SEDIMENT DEPOSITION IN RESERVOIRS

Reduction of sediment deposition in reservoirs by facilitating flood sediment-laden flows to pass through reservoirs, as quickly as possible, before settlement, deposition and consolidation of sediments is one of the most effective and economic ways to preserve the storage capacity of reservoirs and protect them against siltation. The sediment sluicing and the venting of turbidity currents are the two main techniques that can be classified as such methods and it must be underlined that both of them are hydraulic operational techniques and these are based on two fundamental principles, namely: a) It is better, easier and more economic to prevent silting from occurring than to cure, that is to remove the deposited sediments by any desilting operations afterwards, and b) It is very much easier to keep sediments in suspension than to erode them after settlement, especially when they are consolidated.

SEDIMENT SLUICING

Sediment sluicing at reservoirs is that operational technique whereby the incoming bulk sediments are kept in suspension and released through the dam mostly before they can settle down and be deposited on the bottom of reservoirs; only sediment-free water is stored to fill the reservoir capacity. Sediment sluicing is not a continuous –in-time operation, but it is limited to only a part of the year, normally during flood periods. It consists of successive operations of:

- Drawing the water level down, aiming to accelerate the flow and to facilitate and speed up the sediment passing through reservoir,
- Releasing as quickly as possible the sediment laden inflows through the fully-opened bottom outlets at the dam wall, and
- Raising the water level, aiming to refill the reservoir basin with relatively clear water, and to resume filling the storage capacity of reservoir for achieving its basic function.

VENTING OF DENSITY / TURBIDITY CURRENTS

Density current is defined as a gravity flow of turbid water through, under or over water of different density *(6)*. The density difference being a function of the differences in temperature, salt content or silt content of the two fluids. Turbidity currents occur when sediment laden water enters an impoundment, plunges beneath the clear water and travels downstream along the submerged thalweg (Figure- 2). The venting of density currents has long been considered an effective means of reducing the rate of reservoir silting, especially in impounding reservoirs. Obviously, the method is applicable only in reservoirs where and when such density/turbidity currents occur, and their high carrying capacity can be used to pass sediment through reservoirs. Once the density/turbidity currents have occurred in a reservoir, they start moving gravitationally along the basin, towards the dam site; when they reach the dam wall; they climb up the wall to a certain height, and then fall down and form a muddy pool at the dam heel. If the dam structure is provided with outlet works, a curtain/screen in front of the dam wall, or a syphon, then the density/turbidity currents can be effectively vented through.

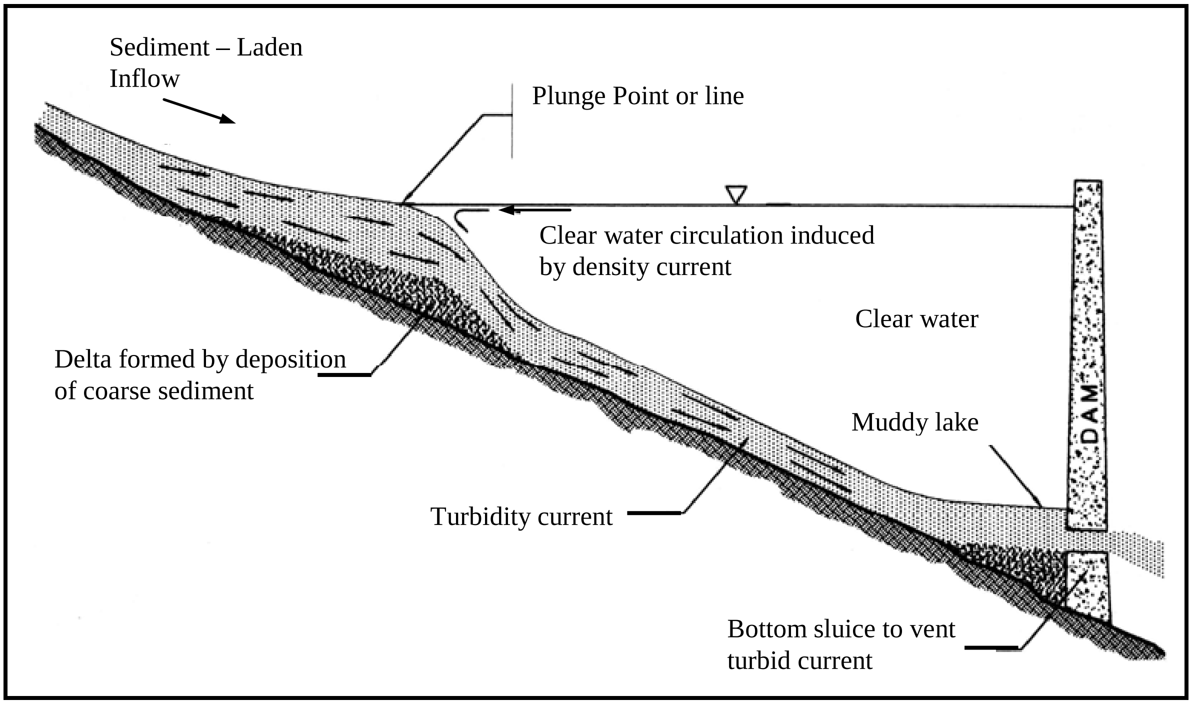

Figure 2: Venting of turbid density current through a reservoir *(4)*

DESILTING OF RESERVOIRS

In general, limited results have been achieved with most sediment control techniques used for existing reservoirs; better results are normally expected when such techniques are: a) Considered from the early design stages for new proposed reservoirs, b) Integrated into long-term watershed management projects, and c) Applied in combination with some desilting techniques and technologies for removing sediment from reservoir basins. Desilting of reservoirs is defined as that engineering practice which makes use of various sediment removal techniques and technologies, thereby aiming to restore, at least partially, the storage capacity lost due to the siltation process occurring in reservoir basins, and thus to prolong the useful lifespan of reservoirs for achieving their planned functions. These are of two types namely hydraulic (flushing and siphoning) and mechanical (excavation and dredging of sediments) techniques and technologies.

SEDIMENT FLUSHING

Sediment flushing of reservoirs is the operational technique whereby previously accumulated and deposited sediments in reservoirs are hydraulically eroded and removed by accelerated flows created when the (bottom or low-level) desilting outlets of the dam are opened, and/or the reservoir water levels are drawn down. It is applicable both for small and large reservoirs and has been employed in several countries to sustain the useful lifespan and storage capacity of reservoirs. When flushing is applied in natural and technically favourable conditions, it could be an effective technique to hydraulically remove large volumes of sediment from reservoirs.

Flushing is an efficient hydraulic sediment removal technique, but it is not widely utilized because (a) It requires a reservoir of a particular morphology (narrow and elongated basins, without branches), (b) It requires adequate sluicing facilities at the dam wall, which are not always available, especially at the old dams and (c) It involves large volumes of water to be used, which is unacceptable for reservoirs in arid and semi-arid regions. Basically, there are two types of flushing operations that can be utilized in removing sediment from reservoirs:

FLUSHING WITHOUT DRAWDOWN

Flushing operations without drawdown have only very local effects, as shown in Figure 3 and they are usually only applied to remove sediment deposited around the entrance of intakes, when wedge-shaped deposition in the reservoir basin has occurred. During such operations, the dam outlets are opened for a certain time and the water level in the reservoir is kept nearly constant. Sediment in the vicinity of the outlet openings is scoured and a flushing cone is created. In a very short period of time (minutes to hours) the flushing cone reaches its stable equilibrium state and no more sediment will be removed from it afterwards. Only clear water or water with a very low sediment concentration is released through the opening and the flushing operation has to practically cease.

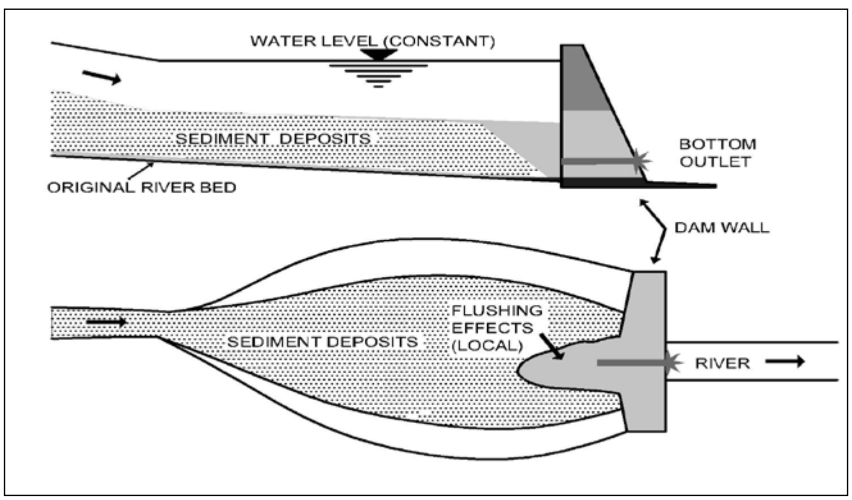

Figure 3: Flushing Operations without Drawdown

FLUSHING WITH DRAW-DOWN

Flushing operations with drawdown have more generalized effects, which extend both along and across the reservoir basin as shown in Figure 4. During such operations, the dam outlets are opened and the water levels in the reservoir are drawn down for certain periods of time. The drawdown can be either gradual when the sluice gates are gradually but incompletely opened and the flushing operation is fully controlled or quick when the gates are suddenly and completely opened and the flushing operation is totally uncontrolled. The efficiency of sediment flushing depends on the topographic position of the reservoir, the capacity of the outlet, the outlet elevation, the characteristics of the inflow sediment, the mode of operation, the time duration of flushing, the flushing discharge, etc.

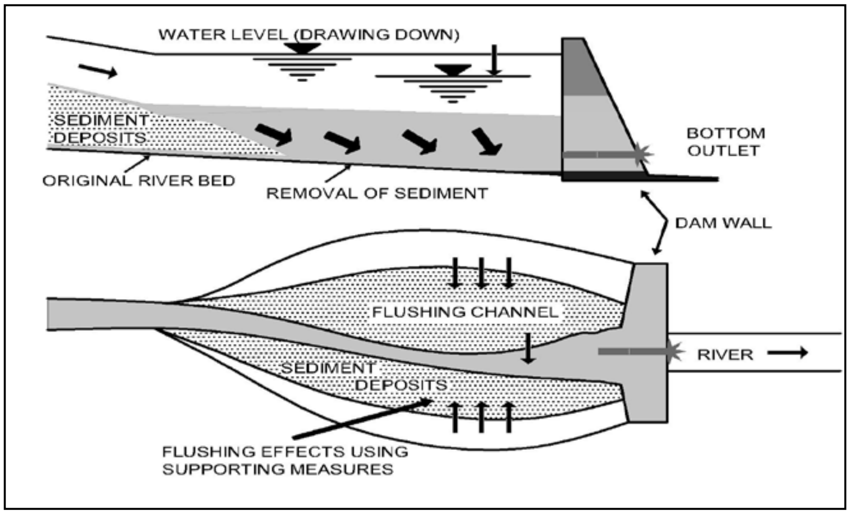

Figure 4: Flushing Operation with Drawing down of Water Level

CASE STUDY FOR SEDIMENT FLUSHING

The physical model studies for flushing of the sediment from reservoir for Kotlibhel H.E. Project, Stage IA (195 MW), Uttarakhand on River Bhagirathi were conducted at Central Water & Power Research Station, Khadakwasla, Pune. Studies were conducted in the model covering a river reach of 10 km upstream and 0.5 km downstream of dam axis, constructed to a geometrically similar scale of 1: 100 *(7)*. These studies were conducted for: (1) Assessing the layout and location of proposed intake mainly from sedimentation and flushing point of view and (2) Assessing the extent of flushing for different discharges and durations. The sedimentation profile obtained from mathematical model was used in these studies.

The flushing studies were carried out with flushing discharges of 500 m^3/s, 800 m^3/s and 1200 m^3/s after reproduction of siltation profiles with siltation level upto EL 532 m and upto EL 510 m. Studies for siltation profile with siltation level of EL 532 m with flushing discharge of 500 m^3/s and 800 m^3/s indicated that it is possible to flush out 1.25 M-cum and 1.76 M-cum respectively for 12 hours flushing duration. Studies for siltation profile with siltation level of EL 510 m indicated that sediment flushing quantities increases from 0.69 M-cum to 1.07 M-cum as flushing discharge increases from 500 m^3/s to 1200 m^3/s for 12 hours flushing duration. These studies indicated that the substantial quantities of the sediment could be flushed out and the reservoir capacity could be restored to the maximum extent. The layout of spillway with crest level EL 490.5 m would be efficient to flush out most of the in coming load. One flushing at above 500 m^3/s discharge during the month in rainy season is found to be suitable from the consideration of incoming annual sediment load of 0.695 M-cum/yr.

SEDIMENT SYPHONING

Sediment syphoning is the technique whereby previously accumulated and deposited sediment in reservoirs is hydraulically aspirated and removed by accelerated pressurized flows created by a special desilting unit, named a syphon-dredger or hydro-aspirator, which makes use of the upstream-downstream hydraulic head difference as the source of motive power.

DREDGING AND DIGGING

Removal of sediment previously accumulated and deposited in reservoirs, either in the wet condition, dredging, or in the dry condition, digging, is the most expensive method (in cost and long in time, involving secondary transportation and disposal problems) to recover, partly at least, the storage capacity lost due to sedimentation. Dredging and digging is to be resorted to only when alternative solutions are non-existent and the deposits removed can be used for beneficial purposes. Some coarse sediment dredged may be used as building/construction material.

CONCLUSION

The remedial measures presented in this paper can prolong the live reservoir capacity. Instead of adopting individual measures these may be adopted in combination for better results. Considering the alarming rates at which the reservoirs are being silted up, the sediment control practices, measures and works should be adopted at the planning stage itself as it is quite difficult to adopt them after the commissioning of the project.

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BRIEF PROFILE OF THE AUTHORS

(1) "**M.Z. Qamar**, graduated in Civil Engineering from Jamia Millia Islamia, New Delhi in 2001. Since 2004, he is working in Sediment Management Division of CW&PRS, Pune. His area of research is in the field of hydraulic model studies for desilting chamber, silt flushing conduits beyond desilting chamber and sediment control in reservoirs of hydro electric projects and some of them includes: Chamera –III, Parbati-III, Uri-II, Nathpa Jhakri, Punatsangchhu-I, Tapovan Vishnugad and Loharinag Pala H.E. Projects. He obtained his M. Tech degree in Water Resources Development from IIT, Roorkee in 2010 and presently he is working at CW&PRS, Pune as a Research Officer."

(2) "**M.K. Verma**, graduated in Civil Engineering from REC, Kurukshetra University, Kurukshetra in 1994. Since 1997, he is working in Sediment Management Division of CW&PRS, Pune. His area of research is in the field of hydraulic model studies for desilting chamber, silt flushing conduits beyond desilting chamber and sediment control in reservoirs of hydro electric projects and some of them includes: Tala, Dhauliganga, Sewa, Chamera- II & III, Teesta-V, Parbati- II & III, Uri-II, Nathpa Jhakri, Punatsangchhu-I, Tapovan Vishnugad and Loharinag Pala H.E. Projects. He obtained his M. Tech degree in Water Resources

Development from IIT, Roorkee in 2002 and presently he is working at CW&PRS, Pune as a Research Officer.”

(3) **“A.P. Meshram**, graduated in Civil Engineering from Pune University, Pune in 1998. Since 2002, he is working in Sediment Management Division of CW&PRS, Pune. His area of research is in the field of hydraulic model studies for desilting chamber, silt flushing conduits beyond desilting chamber and sediment control in reservoirs of hydro electric projects and some of them includes: Tala, Dhauliganga, Sewa, Chamera- II & III, Teesta-V, Parbati- II & III, Uri-II, Nathpa Jhakri, Punatsangchhu-I, Tapovan Vishnugad and Loharinag Pala H.E. Projects. He obtained his M.E. degree from Pune University, Pune in 2001 and presently he is working at CW&PRS, Pune as a Research Assistant.”

(4) **“M.K. Pawar**, graduated in Civil Engineering from Awadhesh Pratap Singh Vishwavidyalaya, Rewa, MP, in 1984. Since 1986, he is working in Sediment Management Division of CW&PRS, Pune. His area of research is in the field of hydraulic model studies for desilting chamber, silt flushing conduits beyond desilting chamber and sediment control in reservoirs of hydro electric projects and some of them includes: Tala, Dhauliganga, Sewa, Chamera- II & III, Teesta-V, Parbati- II & III, Uri-II, Nathpa Jhakri, Punatsangchhu-I, Tapovan Vishnugad and Loharinag Pala H.E. Projects. Presently he is working at CW&PRS, Pune as a Chief Research Officer.”