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Reservoir sedimentation management: A state-of-the-art review

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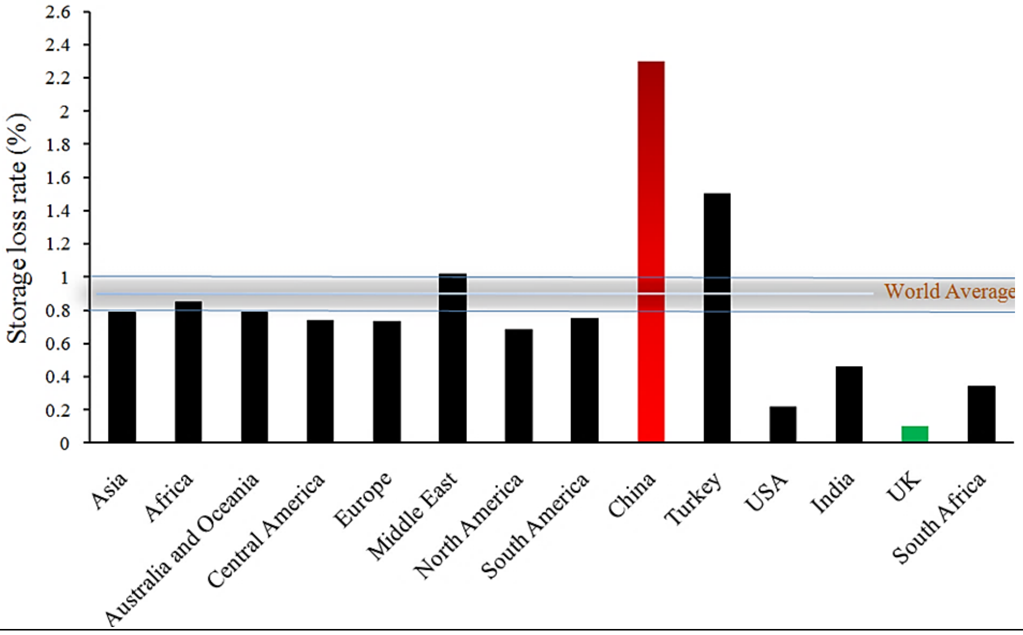
GRAPHICAL ABSTRACT



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ABSTRACT

Reservoir sedimentation is a serious challenge in many regions of the world and has severe consequences for water management, flood control, and generation of energy. The purpose of this paper is providing a valuable source of information on the reservoir sedimentation problem and reviewing the existing control strategies utilized globally against it. A wide range of sedimentation related problems were outlined. Different sediment management strategies were investigated with their main advantages and disadvantages. Special attention was devoted to the flushing technique as the most effective way of preserving the reservoirs' storage capacity. As the main novelty of this study, a series of innovative complementary methods to improve the efficiency of sediment removal during the flushing operation was introduced. Based on the analysis, each sediment management strategy may be advantageous under certain circumstances, and successful implementation of such strategies needs regular monitoring and comprehensive recognition of the effective factors. The use of initiative structural methods, including those cited in this article, although they improve the flushing efficiency, they may come with some limitations that should be considered in practice. It is strongly recommended that such structural methods be taken into account in the first phases of dams' design because they may influence the layout of dam structures. As conclusion, it was found that the progress is being made in successfully reducing and managing of sedimentation at reservoirs. New methods in combination with the flushing operation demonstrated significant performance in sediment removal from the reservoirs and restoring the corresponding storage. The study of this paper is recommended to interested researchers, dam owners, and water resources authorities.

1. Introduction

Dams are the largest hydraulic structures which provide important functions for the human societies. Construction of these huge structures across the rivers substantially alters the morphological equilibrium and the hydrodynamic of river system (Mulatu. 2012), and disrupts the transport of sediments, resulting in the reservoir sedimentation. The sedimentation process in a reservoir is a result of a complex interaction between the various sediment transport processes that prevail in the river and the surface soil erosion as well as the hydrodynamics of the reservoir (Dargahi. 2012). Today, the sedimentation, as one of the most important challenges for the long-term use of reservoirs, has caused

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several detrimental problems at both the upstream and downstream reaches of the dams. Accordingly, the management of reservoir sedimentation in order to ensure their sustainable use has drawn increasing attentions among the scientific community and the water resource authorities.

Sedimentation management can be accomplished by manipulating the river–reservoir system in a way that the sediment balance is achieved while retaining as much beneficial the reservoir storage as possible and minimizing the environmental impacts and the socio-economic costs (Morris et al. 2008). If it cannot be managed successfully, the reservoir gradually loses its storage capacity until the balance between the sediment outflow and inflow is again re-established, which, would occur after the reservoir has become filled up with the sediment. Therefore, the sedimentation management is very complex due to the influence of several non-linear and dynamic aspects, such as the ecological, the sociological and the economic factors (Boeriu et al. 2011). Although several valuable studies to combat the reservoir sedimentation problem are available, it is still the most serious technical problem faced by the dam industry and needs more attentions and further considerations.

This study aims at reviewing the reservoir sedimentation problem and the different mitigation strategies used over the world. The most innovative methods are highlighted with addressing their advantages, disadvantages and operational limitations. Special attention is devoted to the flushing technique as the most effective way of preserving the reservoirs storage capacity. New efforts for improving the efficiency of sediment removal from the dam reservoirs are reviewed. Finally, the most suitable strategies for controlling the rate of reservoir sedimentation and restoring the lost storage capacity are recommended.

2. Sedimentation related problems

Sedimentation includes the processes of erosion, transportation, deposition, and compaction of sediments (Chabalala et al. 2017). Reservoir sedimentation occurs when the sediments conveyed by river flow settle into a reservoir. A range of direct and indirect detrimental consequences of reservoir sedimentation at upstream, downstream and site of dam was reported by different researchers (more recently publications include Schleiss et al. 2016; Annandale et al. 2016; Rahmani et al. 2018; Huang et al. 2019; Kong et al. 2020; Morris 2020; Ren et al. 2021; Randle et al. 2021; Sedláček et al. 2022), among them, the findings of a number of selected researches are presented here.

De Araújo et al. (2006) in a case study assessed the impact of reservoir sedimentation on water availability for semi-arid regions and found that the water shortage risk almost doubled in less than 50 years. Kummu and Varis (2007) investigated the effects of sedimentation on the hydrology, sediment flux, and geomorphology of a hydropower dam at Lower Mekong Basin in China. The measurements demonstrated that at a distance of 660 km downstream from the dam, the annual sediment flux has been decreased more than halved. Fu et al. (2008) reported that the high rate of sedimentation in Manwan reservoir in China have had significant impacts on the downstream reaches. Wildi (2010) reviewed a range of potential hazards linked to the operation of dams and reservoirs. Chen et al. (2012) investigated the effect of construction of Xiaolangdi dam on the morphology of lower Yellow River during its first 10 year’s operation. They documented that the reservoir sedimentation caused a remarkable lifting of upstream river (up to 10 m) and significant reduction of river widths (up to 50%) and flow area (up to 50%). This declined the flood transporting capacities along the river by 42%-61% and consequently increased the flood disasters in North China. Besides, they reported that the river reaches downstream of the dam suffered a remarkable erosion after dam construction especially at the upper reach of the river downstream of the dam (upper 35% of length of the river). Armoring of downstream river bed material was also reported, so that, the surface bed materials in 2009 were approximately two times larger than 1999. Xie et al. (2015) investigated the influence of Three Gorges Dam on the downstream eco-hydrological characteristics and vegetation cover of East Dongting Lake, China. The results showed that after the construction of the dam, rates of both the vegetation cover and the lowering of minimum elevation of vegetation-covered area has increased rapidly. Furthermore, the monthly water level and the annual submergence duration decreased considerably. Andredaki et al. (2014) evaluated the impact of sedimentation on the coastal erosion of the Nestos River delta (in Greece) and the nearby shorelines and reported that construction of reservoirs system across the river have caused 83% reduction in the sediments supplied to delta and neighboring coast, constituted one of the main environmental challenges in this region. Mikhailov et al. (2015) revealed considerable changes in the delta of the Zambezi River (Mozambique) and its coastline after building of two large reservoirs of Kariba and Cahora Bassa. They pointed several problems occurred at the downstream of dams, for instance, reduction of sediments input to the river delta from 20 million to 0.75 million m^3/year. Heidarzadeh and Motieinejad (2017) concluded from a case study that the reservoir sedimentation may significantly deteriorate the water quality of reservoirs particularly for drinking and agricultural uses. Rahmani et al. (2018) examined the loss of storage capacity and the rate of sedimentation of 24 large reservoirs in the central U.S. Great Plains. They reported that since 2016, these reservoirs have lost near 17% of their initial capacity, with the maximum annual loss rate of 0.84%. Moges et al. (2018) investigated the rate of sedimentation at two dams in Ethiopia and its implications to watershed sediment yield. Huang et al. (2019) reviewed the unexpected sedimentation patterns at the downstream and upstream of the Three Gorges Reservoir in China. Morris (2020) classified the different strategies to combat reservoir sedimentation. He stated that this classification system can be employed as a checklist of measures to consider in assessing the sedimentation control alternatives for new and existing sediment-deposited reservoirs. In addition, Ren et al. (2021) investigated the sedimentation and its feedback to the control strategies at this dam. They claimed that the sedimentation has been significantly reduced by management strategies over 30 years. Sedláček et al. (2022) made a finer look at the sedimentation processes of two reservoirs at Czech Republic. They reported that the site-specific factors, unique to each reservoir, can affect the sediment distribution in reservoirs.

By summarizing the lessons learned from the existing experiences, it is found that the reservoirs sedimentation related problems can include one or more of the following 13 items:

i. Loss of water storage capacity (Alemu. 2016)
ii. Increasing risk of flooding of infrastructure and agricultural lands due to the rising of bed levels in the upstream reaches,
iii. Reduction of energy generation in hydropower dams (ICOLD 2012)
iv. Rising of ground water levels in backwater region,
v. Navigation impairment (Randle et al. 2021),
vi. Obstruction of outlet works or completely blocking of waterway and tunnels (Schleiss et al. 2016)
vii. Abrasion of hydraulic machinery and turbine blades which reduce the efficiency and increase the maintenance costs (Faghihirad et al. 2015)
viii. Lowering of the river-bed and instability of river-banks downstream of the dam site (Brandt. 2000; Kong et al. 2020),
ix. Earthquake hazard because of the sediment deposition behind the dam (Chen and Hung. 1993),
x. Shoreline erosion and landslides which can affect coastal morphology and estuaries (Andredaki et al. 2014),
xi. Deterioration of river morphology (Andjelkovic et al. 2017),
xii. Soil waterlogging or soil salinization (Randle et al. 2021),
xiii. Environmental and socio-economic implications (Juracek. 2015).

That is why Palmieri (1998) entitled the reservoir sedimentation as” the worst enemy for the productivity and longevity of existing dams”. Next section provides an overview of the sedimentation rate in different regions of the world.

3. Sedimentation rate

The International Commission on Large Dams, ICOLD (2012) reported that there are more than 55000 dams over the world with a total storage capacity of about 16120 km^3. Between 0.1 to 2.3 percent (in average 1 percent) of this storage capacity is lost annually due to sediment deposition within reservoirs (Mahmood 1987; White 2001; Schleiss 2013). Several studies revealed that the rate of sedimentation depends on the regional factors (climate, geomorphology, hydrologic system, …) and varies from one reservoir to the other (Annandale 2005; Al-Taiee 2007; Basson 2009; Roca 2012). Chanson (1998) reported that the main causes of rapid reservoir siltation in a few dams of Australia were the extreme climatic conditions, the rivers with high sediment load, the inappropriate soil conservation practices and the design mistakes. Dendy et al. (1973) determined the rate of sedimentation in 1105 U.S. reservoirs and reported an inverse relationship between the reservoir storage and the sedimentation rate.

Atkinson (1996) claimed that in the developing countries, where population pressures on vulnerable upstream ecosystems has led to high rates of soil erosion, the reservoir storage capacity is being diminished at much larger rates. As well, White and Bettes (1984) reported that the tropical and sub-tropical regions of the world often suffer more sedimentation related problems. Schleiss (2013) provided the rate of reservoir sedimentation in different regions of the world as illustrated by Fig. (1), which confirms the highest rate of sedimentation in arid regions. In Iran, the rate of reservoir storage reduction due to the sedimentation is less than 1% (0.55% ~ 0.75%) in average (Imanshoar et al. 2009).

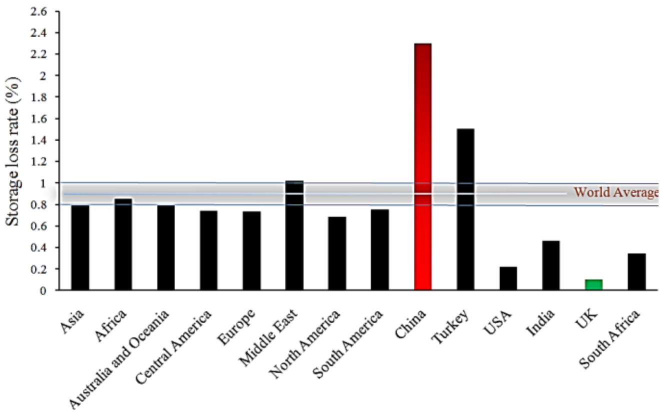

Fig. 1. Sedimentation rate in different regions of the world (Basson. 2009, Chaudhry and Rehman. 2012).

Morris (2003) and Boillat et al. (2003) revealed that, from 1995, the storage loss due to the reservoir sedimentation exceeded the storage added worldwide due to the construction of new dams. That is while the demand for new storage is escalated because of the high rate of population growth and the correspond water consumption, the irrigation and hydropower requirements. Since the construction of new dams faces a number of problems, the attentions have been turning to the sustainable use of reservoirs by control of reservoir sedimentation. Sedimentation problems are both hard and expensive to cure (Morris et al. 2008), but with appropriate management, these impacts can be significantly decreased. Over the years, many studies have been carried out and several management strategies have been proposed for dealing with the reservoir sedimentation. In the next section, a wide range of approaches for management of reservoir sedimentation are outlined.

4. Sediment management strategies

There are several techniques and methods available for managing, preserving and mitigating reservoir sedimentation problems (See Hotchkiss and Huang. 1995; Oehy. 2003; Basson. 2009; De Cesare et al. 2011) but not all of them are efficient, sustainable and affordable (Schleiss et al. 2008). Each technique or method can be used under particular circumstances and may be satisfactory by itself or in conjunction with others (Palmieri et al. 2003). The actual choice of the most convenient strategy will always be site specific and no standardization is possible because it is a complex process and depends on a large number of variables. Often a combination of methods, applied simultaneously or at the different points, may bring the most efficient results. Morris (1995) believes that an integrated approach which includes all feasible techniques is needed for balancing the sediment budget across reservoirs. Integrated sediment management consists of analysis of the sedimentation problem and employing of a range of sediment control strategies as suitable to the site (Schleiss et al. 2008). So, a sustainable sedimentation management strategy which encompasses the total fluvial sediment system, including the basin, river, reservoir, dam and downstream reaches should be taken into account (Sumi and Hirose. 2009).

In recent years, remarkable treatises have been published about the different sediment control and management strategies. Wang and Hu (2009) surveyed sedimentation mitigation strategies implemented in China and mentioned their advantages and disadvantages. Kondolof et al. (2014) conducted a comprehensive review on experiences from five continents in managing reservoir sedimentation. Podolak and Doyle (2015) analyzed the reservoir sedimentation and storage capacity in United States and pointed out the management requirements for the 21st century. Adeogun et al. (2018) conducted a cost analysis on a series of sediment control strategies for management of sedimentation at Jebba Hydropower reservoir, Nigeria, and concluded that the utilized sediment control scenarios are cost-effective and sustainable compared to the costs incurred in tackling the effect due to sedimentation. Morris (2020) classified the sedimentation management strategies into two groups of active strategies and adaptive strategies and documented that a combination of both approaches can represent the best overall response to the reservoir sedimentation. Adongo et al. (2020) assessed the reservoir sedimentation of 9 irrigation dams in northern Ghana and recommended some structural and non-structural methods to reduce the sedimentation rate. Basson et al. (2022) reported a drastic case of reservoir sedimentation at South Africa under a severe drought and recommended some mitigation measures to increase the storage capacity.

Despite these precious works on the sedimentation management strategies and the progresses that have been made in managing the sedimentation problem, there are still many reservoirs around the world that are experiencing sediment-related problems. Thus, more and wider knowledge is still needed to better understand and solve the sedimentation problem. Accordingly, this study aims to review different strategies utilized over the world for control and management of reservoir sedimentation. In this study, those strategies are divided into two categories of the common methods and the initiatives, as follow.

4.1. Common methods for control of reservoir sedimentation

i. A detailed survey of sedimentation management projects implemented over the world indicated that the common global strategies to control reservoir sedimentation can be grouped into four major themes: Reduction of sediment influx entering into the reservoir by Watershed Management Practices (WMPs). This can be achieved by soil conservation activities, reforestation in area suffering accelerated erosions, correction of landslides, terracing of steep slopes, construction of sediment traps and debris dams and so forth. A number of leading countries which successfully employed WMPs to manage the sedimentation are Indonesia, Japan, Morroco and France. Relevant experiences demonstrated that the main disadvantage of WMP is that, it is too expensive and time consuming. Although WMP is an ideal sustainable measure (Annandale 2005) but even when successful, it does not solve the sedimentation problem, just merely postpones it (Fan and Morris 1992).

ii. Establishment of hydraulic regime within reservoir which minimize deposition of sediments by reducing the trap efficiency of reservoir. This method was satisfactorily carried out in Switzerland, China, and Japan among others. Sediment routing (SR) is a technique that is used for this purpose. SR can be divided into sediment pass-through and sediment bypassing. Sediment pass-through is done by either increasing the flow velocity to pass sediment-laden flow without deposition (sluicing) or venting density currents. Sediment bypassing is accomplished either to divert sediment-laden flow around a reservoir (on-channel storage) or to divert water of low sediment concentration from the main channel to a reservoir located off it (off-channel storage). Japan and Switzerland, with several relevant projects, are the leading countries for sediment bypass tunnels. Examples of successful sediment by-pass projects are the Solis hydropower reservoir in Switzerland and the Miva dam in Japan. As well, the Cameguadua and San Francisco off-stream reservoirs in Colombia, are two examples which have operated successfully for many years.

iii. Removing the sediments that have already been deposited in the reservoir. Sediment flushing and sediment dredging are two techniques which are used to this purpose. Sediment flushing can be conducted in two ways of free flow flushing and pressure flushing. Also, sediment dredging can be divided into mechanical dredging (trucking or dry excavation) and hydraulic dredging (siphoning or hydro-suction removal system). In siphon or hydro-suction system, the motive force for conveying slurry through the pipeline is supplied by the head differential between the reservoir water level and the dam toe.

iv. Adaptive strategies including actions to combat sedimentation impacts without sediment manipulating (Morris 2015). They include allocation of additional storage volume by dam heightening or construction of new dams, improving reservoir operational efficiency, modification of intake and spillway structures, water loss control and conservation practices, utilizing more efficient irrigation systems, and ultimately, dam decommissioning. Of course, the dam decommissioning does not consider as a sediment management strategy; but it is an economical option if the useful life of the dam is finished (Tigrek and Aras. 2012; Niu and Shah. 2021). Examples for dam decommissioning are removing of San Clemente and Old Carmel River dams both in California at 2015 and 2016, respectively (Boughton et al. 2016).

Based on the worldwide experiences, some of the above-mentioned strategies may have technical limitations and/or environmental or economic consequences (DeNoyelles and Jakubauskas. 2008). A series of relevant limitations and disadvantages reported by the water resources authorities and the dam operators are presented in the next section.

4.1.1 Limitations of common sediment management strategies

Most of the sediment management strategies have drawbacks or undesirable effects. Among them, the WMPs are usually very expensive and time consuming, as well as, are not capable to recover already reduced reservoir storage (Sloff. 1991). Control of erosion alone cannot fulfill the sediment balance required to stabilize the reservoir storage volume and attain the sustainable use. Constructing auxiliary check dams or silt traps at the watershed upstream area may have a quicker effect but these will in turn fill with the sediment and so may not last long unless regularly managed, which again increases the costs. Reservoir dredging is not only costly but also not feasible for large and deep reservoirs. It may cost 15 to 100 times more than the original dam construction (DeNoyelles and Jakubauskas. 2008). Necessity for dewatering the reservoir and limited availability of sediment disposal sites may also cause difficulties. Excavating sediments from the reservoirs is also an expensive work which may require moving up to 100 times more material than the originally moved to construct the dam (DeNoyelles and Jakubauskas. 2008), indicates it will not be a generally applicable solution to the sedimentation problem. Increasing the height of dam to compensate for lost water storage is structurally not practical for many dams. Construction of new dams has environmental and social consequences, and needs high costs of construction and appropriate dam sites which currently may not be available. Sediment sluicing is similarly not able to remove consolidated cohesive sediment or pass part of the coarsest part of inflowing load. Venting the density currents (turbidity current) cannot pass more than 10 percent of annual sediment accumulation (Lai 1994). Sediment bypassing approach is not commonly used, because it requires special topographical and flow conditions.

A large number of researchers believe that among the different reservoir desiltation methods, the flushing operation is the most economic method to swiftly restore the reservoir storage capacity with acute deposition (Atkinson. 1996; Kantoush et al. 2010a). Atkinson (1996) claimed that “flushing offers the only means of recovering lost storage without incurring the expenditure of dredging or other mechanical means of removing sediment”. It has been successfully employed in several reservoirs having a wide range of physical sizes and proved to be an effective technique for restoring and maintaining the storage capacity of reservoirs (for example Unazuki dam in Japan). Hence, in the next section the flushing operation is addressed with particular focus.

4.1.2. Flushing operation

Flushing is a hydraulic method for scouring and transporting the previously deposited sediments in a reservoir by accelerated flows generated by quickly opening the low-level outlets of the dam (Boeriu et al. 2011). This measure can be employed either in the existing dams or the new dams (White 2001). Flushing can be implemented in two ways of pressurized flushing (or partial draw-down flushing) and free-flow flushing (or complete draw-down flushing). In pressurized flushing, the water is released through the bottom outlets while the reservoir water level is partially drawn down, usually to the minimum operating level. During the free-flow flushing, the water level is decreased to the level of dam sluice gates, the reservoir is emptied completely, and riverine condition establishes within the reservoir. A special case of flushing entitled sequential flushing occurs when a series of consecutive dams are flushed simultaneously, transporting scoured sediment from upstream reservoirs through the downstream reservoirs with minimal re-deposition (Morris 2015).

To assess the flushing feasibility of a reservoir, Atkinson (1996) along with Annandale (1987) and Paul and Dhillon (1988) developed a number of quantitative criteria such as sediment balance ratio (SBR), long term capacity ratio (LTCR), drawdown ratio (DDR), flushing width ratio (FWR) and top width ratio (TWR), as presented by Eqs. 1-5.

$$\mathrm{SBR}=\frac{\text{Sediment mass flushed annually}}{\text{Sediment mass deposited annually}} \tag{1}$$

$$\mathrm{LTCR}=\frac{\text{Reservoir Sustainable Capacity}}{\text{Reservoir Original Capacity}} \tag{2}$$

$$\mathrm{DDR}=1-\frac{\text{Flow depth for flushing water level}}{\text{Flow depth for the normal impounding level}} \tag{3}$$

$$\mathrm{FWR}=\frac{\text{Width of flushing channel}}{\text{Bottom width of reservoir}} \tag{4}$$

$$\mathrm{TWR}=\frac{\text{Top width of scoured valley}}{\text{Actual top width}} \tag{5}$$

A step-by-step description of how these ratios are calculated and their satisfaction range were presented by Atkinson (1996). Some researchers quantified the successfulness of flushing operation by flushing efficiency (FE) (Morris and Fan. 2010; Lai and Shen. 1996; Tolouei. 1989). The range of FE values for a number of dam reservoirs were presented by Fan (1995) and Morris and Fan (2010) for both cases of partial drawdown and free flow flushing. Many variables may affect on the flushing efficiency, generally from the literature, FE has a direct relationship with the size of bottom outlet, flushing discharge, flushing duration, flushing frequency, river bed elevation, river straightness, and the sediment particle roundness, and an inverse relationship with the reservoir length, width of valley, reservoir water level, elevation of bottom outlet, sediment size, and the consolidation rate of sediments. It has also been proved that the pressurized flushing is less effective than the free-flow flushing.

What needs to be considered is that, the pressurized flushing can only remove the sediments from a very limited area within the reservoir. Long narrow steep-sided reservoirs in valleys with a steep longitudinal slope are more suitable for flushing than short, wide, shallow reservoirs. The smaller the reservoir regarding to the annual flood volume, the greater the chance of successfully flushing. Low-level outlets must be close to the initial stream bed level and of sufficient hydraulic capacity [at least two times the mean annual flows are required] (White 2001).

Despite its low sediment removal efficiency, almost all the researchers confirmed the superiority of the flushing technique (if done correctly) to the other sediment desilting methods in both laboratory and field studies (Table 1).

Table 1. A number of reports confirming the success of flushing operation in restoring the reservoir storage capacity.

Experimental studies	Case studies
Lai and Shen. (1995)	Paul and Dhillon. (1988)
Fang and Cao. (1996)	Tolouei et al. (1993)
Scheuerlein et al. (2004)	Hassanzadeh. (1995)
Emamgholizadeh et al. (2006)	Atkinson. (1996)
Jugović et al. (2009)	Basson and Rooseboom. (1996)
Fathi-Moghadam et al. (2010)	Sen and Srivastava (1995)
Kantoush et al. (2010a)	White. (2001)
Emamgholizadeh and Fathi-Moghadam. (2014)	Morris and Fan. (2010);

Albeit, recently, worthy efforts were accomplished for improving the efficiency of sediment removal during the flushing operation, as addressed in the next section.

4.2. Initiatives for sedimentation management

During the recent years, new efforts were performed to improve the sedimentation management strategies in both laboratory and field scale. These, mostly, include thoughtful modifying the flow condition in the reservoir. Here, the most innovative methods are described in two division of combinatorial methods (CM) and independent methods (IM). Special attempts were devoted to the improving of sediment removal efficiency during the flushing operation.

4.2.1. localized vibrations to improve the flushing efficiency (CM)

Through a laboratory study, Dodaran et al. (2012) investigated the influence of localized vibrations at the deposited sediment layers on the efficiency of flushing operation. The results indicated that by employing the vibrating plates, a new hydraulic condition is established within the reservoir during the flushing operation. The results indicated that the volume and dimensions of the flushing cone are significantly influenced by the localized vibrations. They documented that the location of the vibrator than the dam axis and the frequency of vibration are the most influential factors affecting the dimensions of flushing cone; more the vibration frequency, larger the flushing cone dimensions. It was recommended that two vibrators located at the maximum flushing length and width removes the greatest volume of sediment and represent the optimum vibrator positions (Fig. 2).

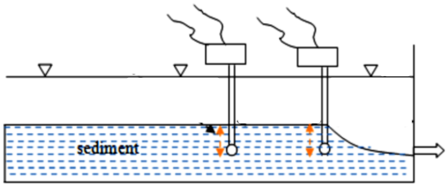

Fig. 2. Schematic of localized vibrations during the flushing operation (Dodaran et al. 2012).

4.2.2. Flushing combined with pile structure (CM)

With aim of strengthening the power of flushing flow passing through dam bottom outlet, a semi-confined pile group structure was designed and successfully tested by Madadi et al. (2016). They connected the proposed structure to the upstream edge of bottom outlet (Fig. 3) to increase the efficiency of sediment removal during the flushing operation. They documented that this structure could protect the bottom outlet from the blockage problems, as well. The process of sediment flushing in the presence of mentioned structure was influenced by two factors: 1) encountering the flow with piles (local scour) and 2) constricting the flow field due to the use of confining plate and vertical piles. Based on the experimental observations, they determined the best configuration of proposed structure, and documented that it can increase the amount of sediment removal up to 250% during the flushing operation. In addition, Beyvazpour et al. (2021) investigated the effect of installation a single pile (with different shapes) at the upstream of the reservoir bottom outlet to improve the pressurized flushing efficiency (Fig. 3). They reported that the single pile can also intensify the power of the vortices close to the bottom outlet and as a result, increase the efficiency of sediment removal during the flushing operation.

Fig. 3. Installation of piles behind the low-level outlet to improve the flushing efficiency; single pile (left), semi-confined pile group structure (right) (Madadi et al. 2016; Beyvazpour et al. 2021).

4.2.3. Flushing combined with vane structure (CM)

Beiramipour et al. (2021) employed a series of submerged vanes to facilitate the scouring of deposited sediments in the reservoirs during the pressurized flushing operation (Fig. 4). They stated that the submerged vanes act as an obstruction against the outflowing water through the low-level outlet and, accordingly increase the flow turbulence upstream the bottom outlet. They pointed out that the submerged vanes (if installed properly) can significantly increase the volume of evacuated sediments during the flushing operation. In addition, Naderi et al. (2022) installed a single plate (like that of submerged vane) at the upstream of the low-level outlet (Fig. 4) in order to enhance the sediment removal efficiency. They reported that this measure can extremely enhance the vortices, increase the outflow turbulence, and create the low-pressure zones, and as a result, increase the sediment removal efficiency by nearly 1450 % compared to the unequipped bottom outlet. Furthermore, Madadi et al. (2017) designed and successfully employed a new confined vane structure (Fig. 4) to remove more sediments from the reservoir during the flushing operation. They documented that this structure is very low cost but highly effective to increase sediment removal during flushing efficiency.

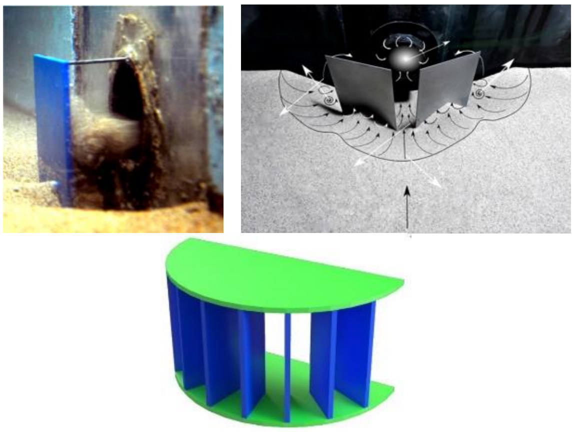

Fig. 4. Installation of vanes behind the bottom outlet to improve the flushing efficiency single vane (top-left) Double diverged vanes (top-right) schematic grouped vane (below) (Madadi et al. 2016; Beyvazpour et a. 2021; Naderi et al. 2022)

4.2.4. Flushing with projecting bottom outlet (CM)

To increase the efficiency of pressurized flushing, Madadi et al. (2017) proposed a new configuration for reservoir bottom outlet. In the proposed configuration, a projected semi-circular structure (PSC structure) was attached to the upstream edge of the outlet from one side, and was mounted on two columns which penetrate to a depth of sedimentary bed layer by piles, from the other side. They reported that by employing the projecting bottom outlet, the efficiency of sediment removal during the flushing operation increased significantly (up to 5.5 times) compared to the flushing via the typical (unequipped) bottom outlet. They mentioned several more advantages of PSC structure like its high structural stability and the interesting hydraulic features. This structure could successfully save the dams with high degree of outlet obstruction, when the level of deposited sediments reached to the upper edge of bottom outlet even up to three times of outlet diameter (Rajabipour. 2017). Furthermore, Haghjouei et al. (2021) proposed a dendritic bottomless extended structure (Fig. 5) to improve the pressurized flushing efficiency. They reported that such structure can remarkably increase the efficiency of sediment removal during the flushing operation. The proposed structure was able to flush sediments from three sides and avoid sediment blockage in the reservoirs' bottom outlets. It may be constructed in different configurations based on the dam in situ conditions. More recently, Paulo et al. (2021) proposed a new type of structure, called slotted pipe bottom outlet, to increase the sediment removal from the dam reservoirs when the flushing operation is accomplished. The proposed configuration of bottom outlet was composed of a horizontal pipe with an orifice at its end, and a number of slots parallel to its cross-section that is placed parallel to the axis of dam (Fig. 5). They documented the successful performance of such structure in evacuating the deposited sediments from the reservoirs.

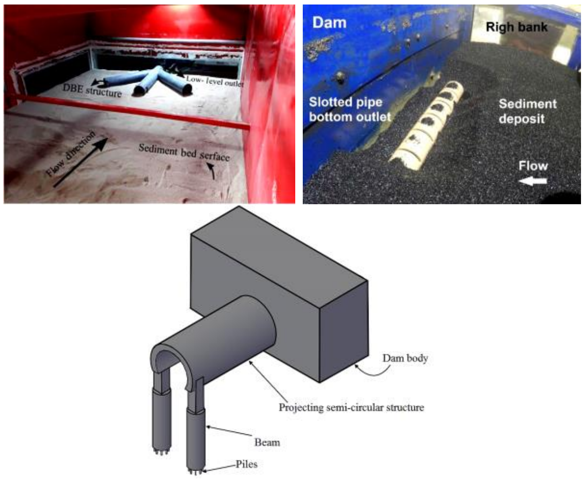

Fig. 5. New configuration for reservoir bottom outlet; dendritic bottomless extended structure (top-left), slotted pipe bottom outlet (top-right), schematic projected semi-circular outlet (below) (Madadi et al. 2017; Haghjouei et al. 2021; Paulo et al. 2021)

4.2.5. Submerged jet flow to improve flushing efficiency (CM)

Jet flow can pick up the sediments from the sedimentary bed, and in combination with the flushing operation, significantly scour them from the reservoir. Madadi et al. (2018) investigated the effect of the submerged single circular jet on the flushing efficiency on a laboratory scale (Fig. 6). They reported that the jet flow has a significant effect on the efficiency of sediment removal during the flushing operation. They determined the best position of jet nozzle to obtain the maximum efficiency.

Fig. 6. Submerged jet flow to improve flushing efficiency (Madadi et al. 2018).

In addition, by combining the idea introduced by Madadi et al. (2018) with the PSC structure proposed by Madadi et al. (2017), a new configuration was established for re-suspending and flushing the deposited sediments from the reservoir during the flushing operation. This was completely tested by Madadi et al. (2018). She reported that the new configuration has an impressive effect on the efficiency of flushing operation.

4.2.6. Jet-induced rotational flow establishment during flushing operation (CM)

Based on the idea proposed by Althaus et al. (2015, 2016), in an experimental study Abdipour et al. (2018) reported that generating a jet-induced artificial rotational flow field can avoid the settling of suspended sediments near the dam, enabling the release of suspended sediment through the bottom outlet. They reported that the amount of evacuated sediments by jets was almost doubled the amount of sediments released without the jets. Althaus et al. (2016) determined the optimal configuration of this system as four perpendicularly arranged jets which generates an axial mixer-like flow pattern.

4.3. Spiral flow-based machine for sediment removal (IM)

Spiral flow-based machine was firstly introduced by Zhang et al., (2011) for removing the sediments from the reservoirs. This machine was composed of three parts including the screw suction head, multi-axis bond, and swirl pipe. It works with the energy supplied by water head at the reservoir (without external energy requirement). Based on the reports, this machine has several advantages including the low energy consumption, low water loss, low operating costs, but the strong adaptability. It is capable to get out the high sediment concentration flows and transport them to a long distance.

4.4. Sediment focusing (IM)

The sediment focusing is an operation through which the sediments are rearranged tactically within the reservoir to solve localized problems such as impacts from delta deposition (Kantoush and Sumi. 2010). By this way, the bottom outlets of dams keep clear for a long time, therefore, it is an effective means of prolonging the useful life of a reservoir.

4.5. Sediment replenishment (IM)

Owing to the several detrimental effects of sediment deficit at the downstream reaches of dam, such as the bed armoring, bank erosion, lowering water table, destruction of aquatic and riparian habitats, and the oxygen stratification, the artificial sediment feeding to the downstream river was proposed to re-establishment of sediment balance along the river. This new method known as the sediment replenishment (also termed sediment augmentation or artificial sediment feeding) is an effective means of reservoir sedimentation management (Ock et al. 2013; Bertrand et al. 2013; Arnaud et al. 2015; Juez et al. 2016; Heckmann et al. 2017). In this method, the trapped coarse sediments at the upstream reach of the reservoir are periodically excavated/dredged and then transported to the river reaches just below the dam, so that the sediment is returned to the channel downstream by the natural or artificial floods (Kantoush and Sumi. 2010).

This method consists of four steps:

i. Mechanical extracting of the deposited sediment at the upstream of the reservoir
ii. Transporting the sediments to the downstream river channel by trucks
iii. Placing the coarse sediment with the specified way (pumping from ships, introduction from bank, recreation of artificial bed forms, etc.)
iv. Monitoring the downstream river hydraulic, morphology and environmental conditions

Kantoush et al. (2010) classified the effective factors that influence on the sediment replenishment into six categories:

i. Sediment properties (source, type, porosity, density, cohesion, size, percentage of fine sediment, etc)
ii. Flow characteristics (flood discharge, depth, velocity, frequency, erosion rate, etc.)
iii. Channel specifications (original bed morphology and slopes, bank vegetation, bed gradation and permeability, etc.)
iv. Replenishment features (sediment volume and geometry shape, location, arrangement, submergence, feeding frequency per year, feeding method, etc.)
iv. Monitoring characteristics (water quality, environmental investigations, riffles and pools survey, etc.)
v. Economic considerations (costs of excavation, treatment, transportation, feeding and monitoring, project benefits)

Sediment replenishment was successfully implemented in different reservoirs over the world (see Stähly et al. 2019; Katano et al. 2021) especially in Japanese large reservoirs (see Okano et al. 2004; Ock et al., 2019). A number of undertaken sediment replenishment projects in Japan includes Muro Dam (since 2006), Hinachi Dam (since 2008) Shorenji Dam (since 2009) and Nunome Dam (since 2004).

There are great studies in the literature about the sediment replenishment procedures and technical principles (Sumi et al. 2009; Miyagawa et al. 2017; Rachelly et al. 2021; Lin et al. 2021). The findings indicated that the effective volume ratio of sediment replenishment should be at least 30 to 40% of the annual deposited volume in reservoir (Kantoush et al. 2010). Furthermore, the sediment should be from coarse sand because the larger sediments are more useful for riverine systems than silt which may impact ecosystems by clogging, and causing heavy turbidity (Hartmann. 2009).

5. Conclusions

The purpose of this paper was providing a valuable source of information on the reservoir sedimentation problem and reviewing the existing control strategies utilized globally against it. A vast range of sedimentation-related problems occur downstream, upstream and site of dams were outlined. Different sediment management strategies were investigated with their main advantages and disadvantages. Based on the analysis, each sediment management strategy may be advantageous under certain circumstances, and the successful implementation of such strategies needs regular monitoring and comprehensive recognition of the effective factors such as watershed characteristics (geographic location, physiographic properties, land cover, climate condition,…), human activities, sediment properties, type of dam, reservoir geometry, economical value of water, geo-political aspects and ecological issues, among many others. Special attention was devoted to the flushing technique -as an effective method of reservoirs storage preserving- and new achievements from the laboratory and field studies for improving the efficiency of sediment removal during the flushing operation were presented.

It should be noted that the use of initiative structural methods, including those cited in this article, to improve the flushing efficiency may come with some limitations that should be considered in practice. It is strongly recommended that such structural methods be taken into account in the first phases of dams' design because they may influence the layout of dam structures. Also, using the numerical models, to simulate the flow and sediment around the such structures, can be useful tools for dam designers to choose the best option that is both hydraulically and economically appropriate. As conclusion, it was found that the progress is being made in successfully reducing and managing of sedimentation at reservoirs.

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