AUIQ Technical Engineering Science

Volume 1 | Issue 1 Article 8

2024

A Technical Review on Reservoir Sedimentation and their Mitigation Strategies

Sadique Khan
Civil and Environmental Engineering Department, King Fahd University of Petroleum & Minerals, Dhahran 31261, Saudi Arabia, sadiquekhan555@gmail.com

Recommended Citation
Khan, Sadique (2024) "A Technical Review on Reservoir Sedimentation and their Mitigation Strategies," *AUIQ Technical Engineering Science*: Vol. 1: Iss. 1, Article 8.
DOI: https://doi.org/10.70645/3078-3437.1007

AUIQ TECHNICAL ENGINEERING SCIENCE 2024;1:85–105

REVIEW

A Technical Review on Reservoir Sedimentation and their Mitigation Strategies

Sadique Khan

Civil and Environmental Engineering Department, King Fahd University of Petroleum & Minerals, Dhahran 31261, Saudi Arabia

ABSTRACT

Sedimentation in reservoirs is a critical concern of the 21st century which has affected the sustainability and functionality of water retaining structures. This technical review paper on reservoir sedimentation provides a comprehensive analysis of their causes, mechanisms, and their mitigation/control techniques. The paper starts with sedimentation in the reservoir at a global scale focusing on natural (Soil Erosion) and anthropogenic (man-made) factors such as deforestation, land clearing for agricultural purposes, and urbanization contributing to sedimentation in the reservoir. The origin of sediment is heavily influenced by topographical features, with origins located far-reach, mid-reach and near the reservoir. The sedimentation in reservoir had significant impacts which includes storage loss of reservoirs, degradation of aquatic habitat and soil pollution. A different physical process that is involved in reservoir sedimentation such as turbidity current, delta migration, climate change, and flow circulation are discussed in detail. Various mitigation strategies such as sediment yield reduction, routing of sediment through/ by reservoir, and removal of sediment by mechanical means are used in different parts of the world are presented. Case studies from different regions are selected to show the effectiveness of these strategies in real-world situations The success of sedimentation management strategies is dependent on site-specific factors such as topographical features, vegetative cover, climatic conditions, sediment properties and reservoir geometry. Among all the sedimentation management strategies discussed in the paper special attention is given to Flushing and Sluicing process while the growing implementation of bypass tunnels has also been observed in countries like China, Japan, and Switzerland. In later section paper also highlight the limitation of those strategy among which the efficiency of flushing process requires further investigation as future research. In addition, numerical modelling such as with RESCON 2 software can be used to understand the sediment flow behaviour near dams. In a later section, the paper also highlights the significance of integrated sediment management plans which involves collaboration between policymakers, engineers, scientists and local people. Sustainable land use practice like no till farming, vegetative cover to control soil erosion, routine monitoring of sediment deposition are main components of this approach. However, challenges always remains such as funding constraints, conflict among stakeholders, and uncertainties in due to climate change. Considering the scientific knowledge, engineering experts, stakeholder engagement, and effective and sustainable solutions are necessary to ensure the functionality, durability, and sustainability of reservoirs.

Keywords: Reservoir sedimentation, Causes of sedimentation, Mitigating reservoir sediments

1. Introduction

The increasing worldwide population needs sustainable water supply systems but the main obstacle to tackling these demands in water storage reservoirs is sedimentation [1]. Sedimentation is a phenomenon of erosion of solid surface and transportation of finer particles with river or valley water that get settled downstream of the reservoir due to low water velocity. It reduces the capacity storage of the reservoir as well as hinders river water flows. The durability of the hydraulic structure is also reduced due to sedimentation [2]. Sedimentation is a serious issue for the sustainability of hydraulic structures. The global

Received 25 May 2024; accepted 12 August 2024.
Available online 27 August 2024

E-mail address: sadiquekhan555@gmail.com (S. Khan).

https://doi.org/10.70645/3078-3437.1007

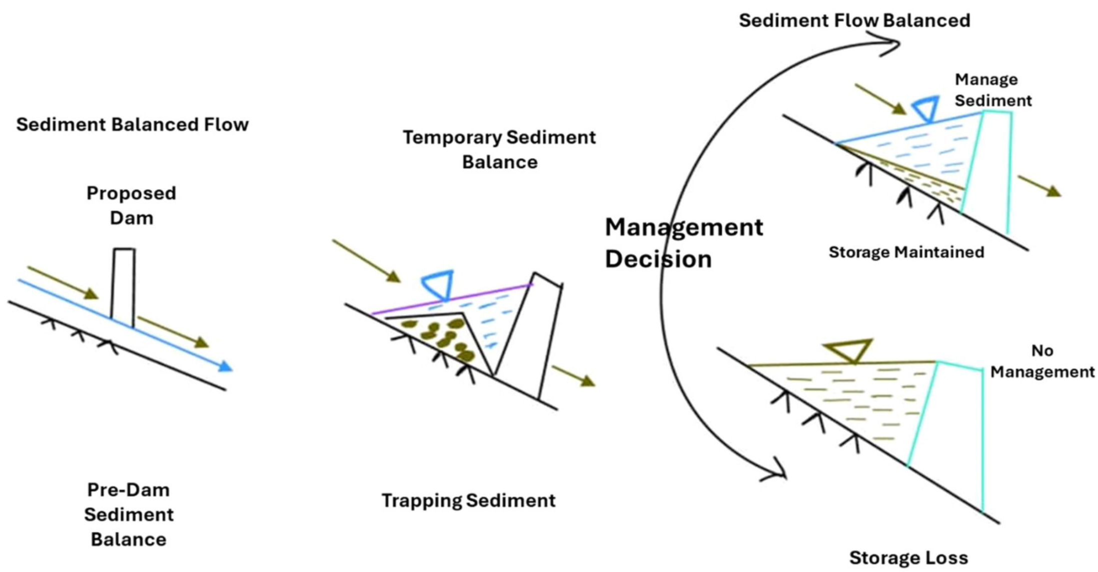


Fig. 1. Sediment equilibrium at pre- and post-impoundment is the total management decision.

storage capacity of the reservoir is estimated to be 6.1×10^{12} m^3 out of which 2×10^{12} m^3 is lost because of sedimentation problems which is approximately 32.8% of the worldwide storage capacity of the reservoir. Studies say that loss of storage capacity is approximately 0.5–1.0% per annum. It has been approximately calculated that half of the worldwide storage capacity of reservoirs will be lost by the end of the year 2050 [3]. Sedimentation causes groundwater level rise on the upstream side which results in flood, and vegetation loss downstream [3]. Ensuring the long-term sustainability of reservoirs is a management decision (Fig. 1). Designing dams or reservoirs without considering long-term management strategies related to sedimentation is not a sustainable process and engineering practice [4].

Let the total capacity of the reservoir is 30 million cubic meters and the dead storage to be maintained is 6 million cubic meters with average volume accumulation of sand is 0.15 million cubic meters per annum. After making calculations, the dead storage will be full of sediment in just ($6/0.15 = 40$) years and for total storage, it will take ($30/0.15 = 200$) years. Therefore, if proper management strategies are not applied after 200 years it will be nothing but just a reservoir full of sand and silt [2]. Study reveals that there are three different stages in a hydraulic structure life (1) Continuous and rapid accumulation of sediment, (2) Partial sediment equilibrium (fine sediments are in equilibrium and coarse sediment accumulates), (3) Full sediment balance (where inflow and outflow of sediment particle size are same or constant). It has been observed that in most parts of the world the reservoir is in continual stage of sedimentation [2].

Most civil engineering structures like buildings, highways, and other mechanical systems can be substituted or demolished and constructed again after they passed their durable life or become old. This approach does not fit dams or reservoirs when they become sedimented because they are huge structures and clearing huge dams from sedimentation is not a feasible option and it becomes an uneconomical approach. Site selection for new dams like geological, hydrological, and morphological physical are also a major concern while designing new dams [4]. In a book published it has been demonstrated the "Twentieth century had focused on building new dams while 21st century will focus on mitigation strategies to enhance and extend the life of existing reservoirs" and it will be most feasible if we start it today [5].

1.1. Research gaps

- Prediction of Sedimentation in the reservoir and its measurement

  Existing methods of sedimentation measurement in the reservoir need improvement to measure the sedimentation rate over time. Current models of sedimentation measurement do not account for all the variables which leads to discrepancies between actual and predetermined sedimentation rates. Introducing better tools for sediment accumulation monitoring in the reservoir will provide effective sedimentation management.

- Sediment management techniques
  More research is needed to develop sustainable sediment management techniques. Some of the current techniques like dredging, bypass tunnels, etc are not feasible and uneconomical.

- Effect of Sedimentation on Ecosystem
  Sedimentation in the reservoir affects the ecological system both upstream and downstream of the reservoir. These effects include groundwater depletion, risks of flood downstream, marine life, and vegetation loss. Considering the long-term ecological effects of sedimentation in reservoirs will help in designing better sediment management practices.

- Lifecycle Assessment of Reservoir
  Reservoir sedimentation results in the storage loss of reservoir which ultimately affects the sustainability of the reservoirs. It has been observed that less research has been done on lifecycle assessment of reservoirs, especially in the initial phase of design and planning of the reservoir. A lifecycle assessment must be done to ensure the durability and sustainability of reservoirs.

- Economic Analysis of different sediment management strategies
  A detailed economic analysis of different sediment management strategies is needed to understand the cost benefits associated with each sediment management strategy.

- Case Studies and Best Sediment Management Practices
  Different case studies on sediment management around the world give valuable insight into dealing with sedimentation in reservoirs. Identifying those practices and selecting the best practices will enhance the durability and sustainability of future projects.

- Policy and Regulatory Framework
  Further research is needed to improve the existing policies and regulations related to sedimentation in reservoirs. This can be achieved through proposing new frameworks or improving the existing policies.

1.2. Sedimentation: Global scale

The main causes of siltation in reservoirs are natural processes like erosion from water bodies, sediment from rivers, anthropogenic activities like urbanization, and heavy agricultural processes [6]. In a study, it has been found that in 1105 Dams in the United States which have a storage capacity less than $1.235 \times 104\ m^3$ the approximated sedimentation is 3.5% per year. The annual loss in storage is about 2.7% for the medium reservoir, and the average sedimentation rate was 1.5% [7]. Another study revealed that the Nizam Sagar Dam situated in Andhra Pradesh, India was designed for a sedimentation rate of 0.65 million cubic meters. While actual situation was different which represents 10.7 million metre cubic per annum. And finally, the reservoir lost its 70% capacity within 50 years [8].

In Central Europe, 19 reservoirs having a total storage capacity of 155.4 to 244.08 million meter cubic were sedimented fully at an average rate of 0.51% annually [9]. Further study on the Mediterranean basin shows that despite planned dead storage the storage capacity of the reservoir is decreased with an annual loss of 0.–0.5% in the northern region while 0.5–1% in the southern region and frequent losses in Maghreb and Spain [6]. Sedimentation in South African reservoirs is a challenging issue, and it has gained significant attention in the last two years because of urgent water-related issues within the country. Research indicates that in the year 2021, Africa had 163 dams all over the nation with a siltation rate of 25%. Of these siltation rates, sedimentation levels were 25–50% in 25 dams while two dams with 90% siltation rate. Sedimentation has significantly affected the major dam network in South Africa because of natural processes, less management, and anthropogenic activities [6]. In research, it has been demonstrated that in the Manwan reservoir in China, the siltation had affected downstream reaches [10].

Another study which is related to the Xiaolangdi dam, constructed on the Yellow River has affected morphological features within 10 years of its operation. A remarkable increase in water level (approximately 10m) has also been observed because of sedimentation. Frequent reduction in river width by nearly 50% as well as flow area by up to 50% has been observed which disturbs the transporting mechanism of the rivers and leads to flood disasters in Northern China [11].The construction of the Three Gorges Dam in China affected the East Dongting Lake China including its vegetation cover, hydrology, and Ecology. The construction of the dam has also resulted in low water levels and annual submergence duration [12]. A case study demonstrates that the sedimentation in a reservoir deteriorates water quality for drinking and agricultural purposes [13]. In the U.S., a study conducted on 24 reservoirs demonstrates that due to sedimentation the storage capacity has lost nearly 17% of its initial value with an annual average loss rate of 0.84% [14].

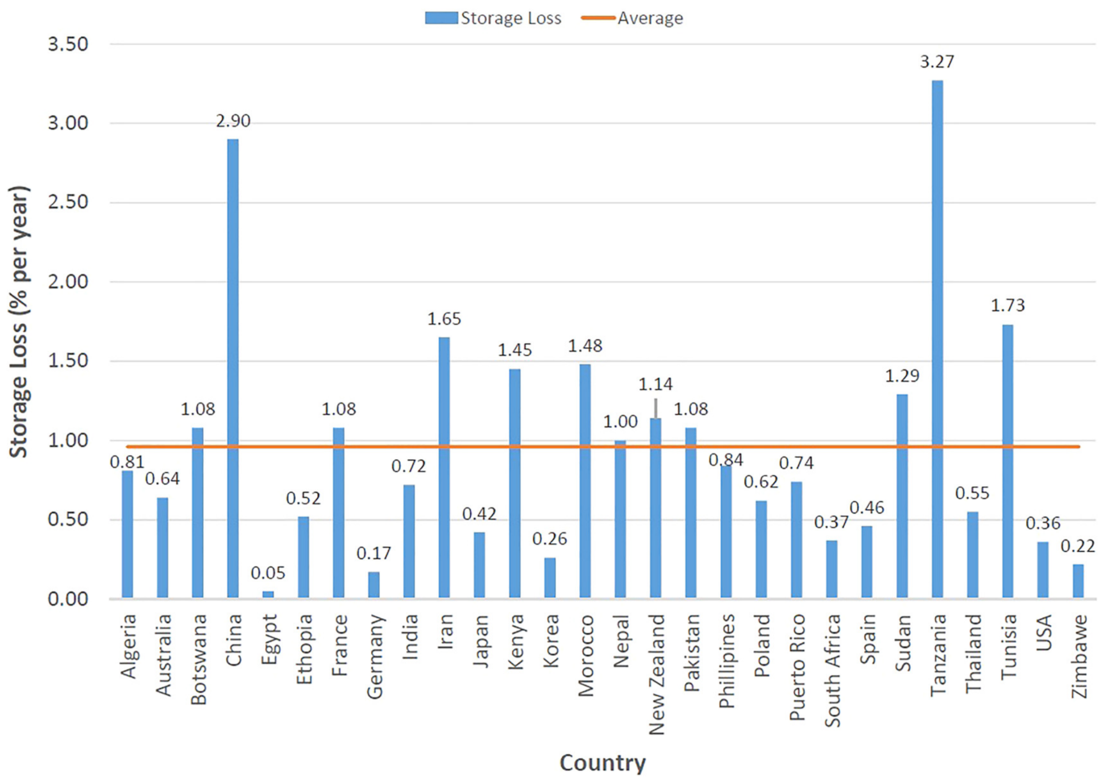


Fig. 2. Estimated annual loss due to sedimentation in large reservoirs in different countries globally adapted from [6].

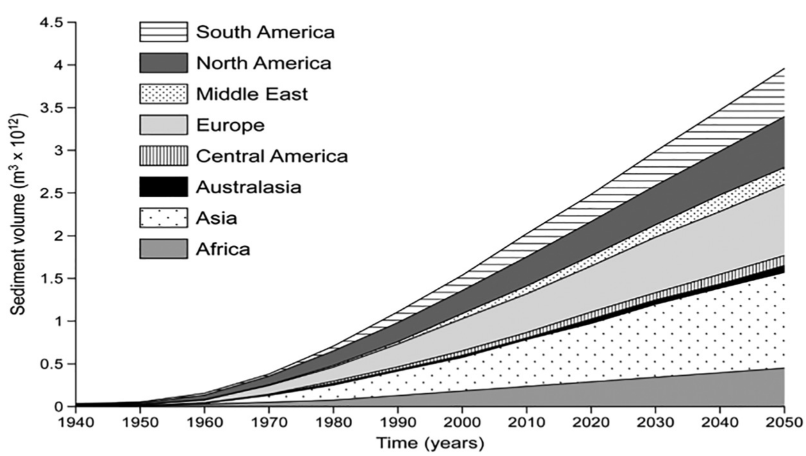


Fig. 3. Estimated and forecasted total amount of accumulated sediment globally from the year 1940–2050 [6].

1.3. Predictions of dam siltation at the global level

Different studies have been conducted and revealed that the global sedimentation rate is about 1% with frequent variations from country to country and it had reached up to 3.27% in Tanzania (Fig. 2). Estimated observations have documented that the future sedimentation by the year 2050 will reach 4000 billion cubic meters. Fig. 3 shows the amount of sediment accumulated in large reservoirs globally from 1940–2050 [6].

1.4. Causes of sedimentation

As discussed above, sedimentation occurs because of soil erosion but not alone, it's a complex process that can be categorized into two types-:

i. Natural Causes
ii. Anthropogenic or Human Causes

1.4.1. Natural causes

- Geomorphology
  The first natural cause is related to geomorphological features, which include patterns of land surface, location, size, and shape of hills, ridges, valleys, lakes, and rivers [2].

- Hydrogeology
  While second is related to Hydrogeology which determines whether groundwater is contributing to the reservoir or vice-versa [2].

- Geology
  Geology is also an important factor especially for dams as it interferes more with natural environments than other civil engineering structures [2].

- Nature of Soil
  The nature of soil explains the property of soil which is a major factor for erosion leading to siltation in the reservoir [2].

1.4.2. Anthropogenic causes

- Tillage Agricultural Practices
  The first cause is tillage activities on mountains and hilly areas leading to soil erosion because agricultural activities affect the top layer of soil [2].

- Overgrazing
  Secondly, overgrazing by animals also affects the top layer of soil which ultimately results in soil erosion [2].

- Mining Activities
  Mining activities which cause soil erosion because of high excavation and movement of machines and heavy equipment [2].

1.5. Research objectives

The objective of this term paper is to develop comprehensive strategies for mitigating sedimentation in reservoirs. This can be achieved by:

i. Thorough examination of sediment management techniques, like dredging methods, sediment bypass, sluicing, flushing, and watershed management practices which are aimed at reducing sediment input into reservoirs.
ii. Assessment of the effectiveness of those strategies, their advantages, and limitations.
iii. Effectiveness of these strategies in diverse geographic and hydrological contexts.

2. Physical processes involved in sedimentation

2.1. Route of sediments

The origin points of sediment as evaluated in literature are at far reach, mid-reach, and in the reservoir [15]. The far reach includes the sediments generated on steep slopes of hills and valleys and finally transported by the water in suspension form to the reservoir [16]. Mid erosion point includes gully, rill, and bank erosion of the streams [15]. In mid regions cascading mechanism takes place in which the size of sediment particles decreases because of abrasion and crushing of coarser particles [17]. Reservoirs situated near banks are more prone to subaerial and subaqueous landslides which is the main factor contributing to sedimentation Fig. 4(a) [18]. In different studies, the geomorphic stage of the reservoir is defined, and it has been concluded that the deposition of sediments in reservoirs is mostly associated with the size of particles or gradation. Fig. 4(b) the deposition of sediments in Turtmann Dam Switzerland, which shows gradation of coarse sediments upstream while fine sediments downstream [16].

Vegetation helps in combating reservoir sedimentation as it traps sediment particles by its root geometry. It can be implied as the main control technique to control erosion of soil by planting more vegetation near the banks of streams and constructing wetlands. It helps in reducing the formation of gullies and rills near the bank side of the stream and ultimately reduces landslides [19].

2.2. Delta migration

When river flow reaches to reservoir its velocity decreases which results in the settling of coarser particles and forms a delta in the upper region of the reservoir [20, 21]. Delta migration is the most common pattern of sedimentation deposition in reservoirs which is formed in three regions from upstream to downstream (top-set region, fore-set region, and bottom-set region) [22–24]

The gradation of sediment reduces downstream, as coarser particles are deposited in the top-set region quickly, while finer particles move with the bottom set by a phenomenon called turbidity currents. The profile of the top-set region is mostly flat while the fore-set region is defined by a large slope which varies according to sediment load composition. The slope point is called the pivot point, and it helps to move the sediment load downstream by a continuous load of sediments coming from the upstream side of the river or stream. The position of the sediment pivot point

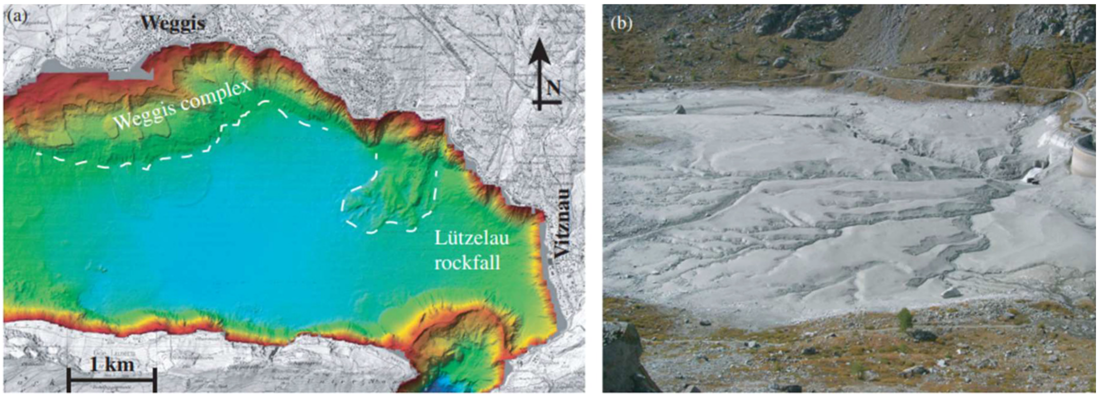


Fig. 4. (a) Vitznau basin of lake Lucerne where the Lützelau subaerial rockfall and the Weggis complex of subaqueous slides are represented (b) Sedimentation in Turtmann dam, Switzerland [15].

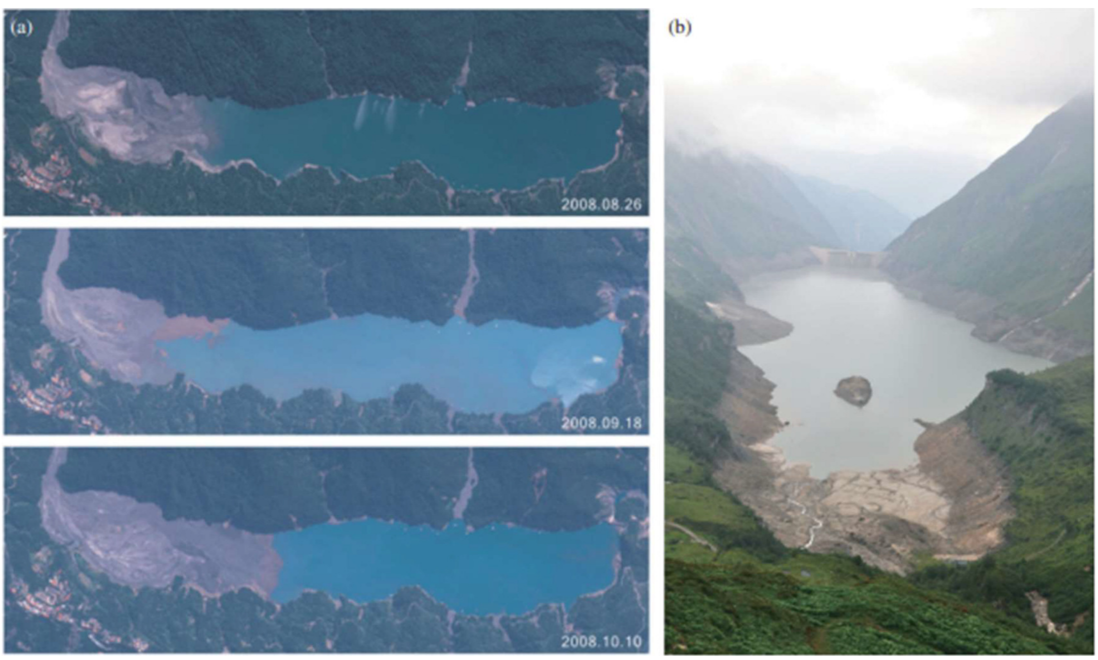


Fig. 5. (a) Delta migration of Gilbert-type into Wushe reservoir situated in central Taiwan; (b) Delta migration of Gilbert-type into the reservoir of Wasserfallboden, Austria [15].

is related to sediment particle size, the shape of the reservoir, the volume of accumulated sediment [25].

The origin of the delta depends on hydrology, morphology, and sediment characteristics but it changes drastically as observed in the case of the Wushe reservoir situated in the Choushui River in Taiwan Fig. 5(a). In only two months, the delta formed about 15% of the total length of the reservoir which is approximately 4.5 km. Fig. 5(b) is an example of Gilbert type delta into the reservoir of Wasserfallboden, Austria [15].

2.3. Turbidity current

The sediment remains in suspension due to turbulence produced in water media resulting in a phase mixture whose density is higher than ambient water. Turbidity current is the main cause of sediment transport in lakes and reservoirs along with debris and granular materials [15]. In several studies, the result demonstrates that in Alpine regions, the main cause of sedimentation in narrow reservoirs is turbidity current [26].

Fig. 6. Combination of factors like turbidity current, delta propagation, and sediment production from riverbanks causes sedimentation in Cachi reservoir, Costa Rica [33].

The severity of turbidity current depends on shear stress near the bed and turbulence intensity which keeps sediments in suspension form. The longevity of turbidity currents depends on discharge and the sediment concentration [15]. Turbidity currents are non-conservative currents because sediments are settled and deposited by the force of gravity. More sediments are generated mostly on slopes because the shear stress is sufficient near the bed region which causes flow to increase the concentration and make it more turbid [27, 28]. As soon as turbidity current reaches the reservoir it loses kinetic energy and is converted to potential energy which results in homogeneity in sediment concentration and starts settling at a vertical height near the face of the dam, this phenomenon is known as a return turbidity current [15]. A famous example of turbidity current whose magnitude is recorded was observed in Sanmenxia reservoir in which a 2-3m thick current was generated at a speed of 0.6 m/s over a length of 50 km and bed slope of 0.25% [15].

2.4. Flow circulation

The shape of dams is an important parameter that controls velocity distribution causing sedimentation, suspension of particles, and transport mechanism [29–31]. The efficiency of sedimentation management strategies depends on the geometry of the reservoir [32], which can be observed easily in the flushing operations of the Cachi, Costa Rica reservoir (Fig. 6) [33].

A water-retaining structure like groins, dead branches of trees, and river training structures creates a zone where the velocity of flow becomes very low which results in the formation of different sedimentation patterns and development habitats which have high ecological importance [15]. Groins and harbors act as sediment traps depending on the geometry of the reservoir [34]. In shallow zones covered with mangroves, sediment gets trapped, settles down, and barely enters flow because of low levels of turbulence. Obstruction occurs in flushing operations in shallow areas because of the presence of water hyacinth which traps the sediments [33]. Pumping operations between the lower and upper reservoirs creates turbulence and recirculation which causes a reduction in sediment settling and enhances the sediment transfer process between the two reservoirs [35].

2.5. Climate change

As demand for water increases every year, the storage capacity of water will also be expected to increase in the future. Reservoirs are very important structures built to store large amounts of water to mitigate the effects of climate change [15]. Small reservoirs are more susceptible to climate change because of

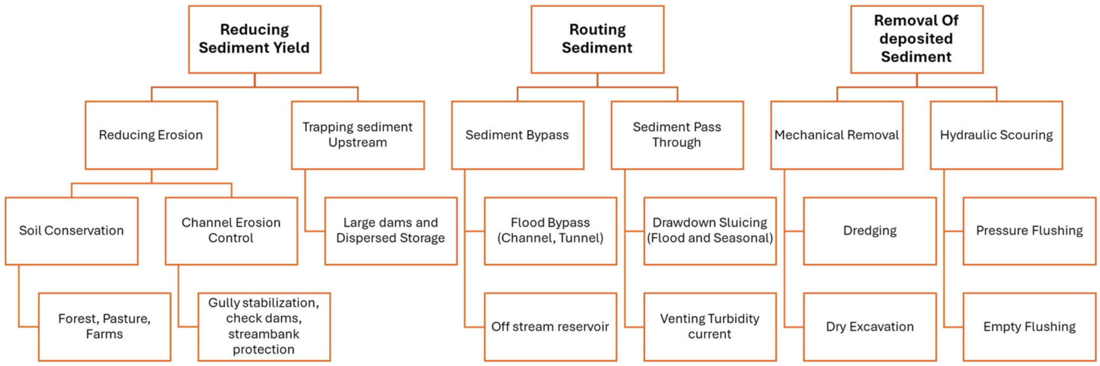


Fig. 7. Classification of management strategies against reservoir sedimentation.

their limited storage capacity to withstand long-term inflow variations [36]. In Alpine regions, because melting of glaciers which generates moraines, enhances sediment supply to the reservoir [15]. The effect of climate change on soil which is frozen at high altitudes on mountains increases the chances of erosion, ground subsidence, and landslides. High precipitation causes more soil erosion and failure of the riverbank [15].

3. Control/Mitigation strategies against reservoir sedimentation

Before the year 1950, there was no concept of sedimentation management in the planning phase of new reservoirs [37]. But it gained significant attention in late 1980 and by the end of the year 1990 publications on the influence of sediments have started coming in and researchers have tried to gain attention on sediment on water intakes and outflows. Reservoirs must be designed in such a way that they can operate and minimize the storage loss capacity. Mitigation methods can be employed before, after, or during the construction phase of the dam and they can be applied temporarily or continually. Effective techniques are mostly applied to remove sediment from the dam or around the dam (bypassing sediment) [15]. A study shows mitigation methods are adopted to minimize the sediment deposition and maximize bypass sediment through flow some methods use bottom sluices, and some are based on directly extracting sediment from the reservoir [38]. Usually, the measures to protect reservoirs against mitigation are divided into three classes (a) In river catchment i.e., upstream of the reservoir (b) In the reservoir (c) At the dam, and sometimes a combination of all these three [15]. There are several mitigation techniques applied globally to protect or conserve the reservoir against sedimentation but not all techniques are sustainable, efficient, and economical. Choosing a suitable technique is always site-specific because there is no standardization as it's a complex process that depends on a large number of variables [39].

3.1. Classified management strategies against reservoir sedimentation

To manage sedimentation problems in reservoirs, an equilibrium approach focuses on sediment inflow and outflow, impacts of sediment downstream, long-term storage, reducing hydropower issues, and minimal environmental impacts. The classification of management strategies can be grouped into 4 classes (Fig. 7) (1) Sediment generation from water streams (2) Routing of sediment-loaded flows around or bypass the reservoir (3) Removal of sediment to reduce deposition and (4) Adaptive strategies which focuses loss in capacity without taking into account the equilibrium approach [4]. This section will review methods adopted to mitigate reservoir sedimentation problems considering sustainability into account which enhances the reservoir life period, least impacts on downstream catchment, and increases the efficiency of hydropower.

Strategies to control reservoir sedimentation are area-specific and depend on the reservoir's technical conditions, hydrological conditions, financial availability, and environmental and optimal approach as suggested in the review employing both proactive and adaptive strategies will be a suitable approach. Both proactive and adaptive strategies are adopted when developing a reservoir for the long-term considering sustainability as well as including changes from near to future. A preliminary analysis is suggested which can be done by RESCON2 software to generate results [4].

3.2. Silting control in reservoir

After summarizing the different literature published on sedimentation control in reservoirs researchers have compiled the mitigation problems in the following different points.

(a) **Protection from sediments producing Far-reach upstream**.

After a complete survey on sedimentation management practices to control reservoir sedimentation around the world, it has been found that reducing sediment load to the reservoir by employing watershed management practices is most common among other categories [40]. It can be achieved by soil conservation mechanisms which include afforestation, planting more trees or vegetation to provide cover to soil vulnerable to erosion, slope stabilization, crop rotation [15]. Many countries have adopted watershed management practices which include Indonesia, Morocco, Japan, and France. The main drawback of watershed management practices is that it is too expensive and time-consuming [39].

(b) **Production of sediment at Mid-reach**

It includes protection of stream bank from failure, formation of rills and gullies, decreasing residual load by constructing sand & gravel settling basins, check dams, and transverse sills [15].

(c) **Sediment protection In-reservoir production**

It includes the protection of stream banks and slopes using hard or soft solutions (vegetation cover or eco-friendly slope stabilization) [15].

(d) **To establish a hydraulic regime in the reservoir**

It reduces the accumulation of sediments by reducing the capture or trap efficiency of the dam. This method has been successfully carried out in Switzerland, Japan, China, and other countries. One of the common techniques is sediment routing which can be divided as sediment passes through or bypasses. Passthrough is achieved by increased velocity of flow (loaded with sediment) without sluicing or density currents. Bypassing is done to divert sediment-loaded flow around the reservoir or divert the sediment-loaded flow of low sediment concentrations from the main channel to a nearby reservoir. Switzerland and Japan are the most common countries using bypass tunnels. One successful bypass tunnel project is the Solis hydropower reservoir in Switzerland and the Miwa dam in Japan [39].

(e) **Removal of Sediments**

This technique primarily focuses on the removal of sediments from the reservoir. Two common methods including flushing and dredging are used in this process. Sediment flushing can be divided into free flow and pressure flushing while sediment dredging can be done in two ways which are mechanical dredging (dry excavation) and hydraulic dredging (technique based on hydro suction) [39].

(f) **Adaptive strategies**

Allocation of more dead storage volume by increasing dam height, constructing new dams, improvement in reservoir operation efficiency, changes in intake and spillways structures, conservative practices, more effective irrigation systems, and finally dam decommissioning [40]. Dam decommissioning is not a useful approach that can be categorized under sediment management but if the life period of the dam is over it will be an economical option [40]. A common example of dam decommissioning is the San Clemente and Old Carmel dams in California [41].

3.3. Reduction in sediment yield

3.3.1. Reduce erosion

It is an approximation that 1/3rd of agricultural land was lost because of soil erosion late twentieth century. With a 0.43% loss in crop production annually European Union is suffering from severe erosion of 12 million hectares of agricultural areas [4]. In a country where Industrialized agricultural practices are common, no-tillage farming is useful as it protects against soil disturbance as well as maximizes the protection of soil by vegetation and mulch. Tillage farming has some other benefits which include an increase in the water-holding capacity of the soil, enhanced biological activity, and soil organic content, and less erosion when compared to common tilled fields. A blog posted by the U.S. Agricultural Department which promotes no-tillage agricultural activities gained the attention of farmers as the benefits include less fuel expense and low time on tractors [42]. In a study, that analyzed data for Central Oklahoma, USA, between the years 1943-1948 and 2004-07 from a sediment gauging point above Fort Cobb. The reduction in sediment yield had been achieved by 86% (760-108t/km^2/year), which is a result of watershed management practices started in the 1950s. In China, sediment yield decline has also been observed on a large scale in the Yellow River Basin [43, 44].

3.3.2. Trapping of upstream sediments

Small-on farm structures are a suitable approach to trap sediments and prevent soil from erosion, it also retains water in farm structures [45]. Taking an example, In the USA alone 2.6 million small ponds have been constructed which trap runoff from 21% of the total drainage area which ultimately represents 25% of total soil erosion [46]. Check dams can be considered suitable sustainable land use management strategies if they provide stability against erosion and vegetative cover. In China, there are large numbers of check dams constructed on the Yellow River including warping structures to restrict gully erosion and provide fertile farm fields. Warping dams are built in such a way that it protects against erosion of soil with the main aim of conversion of gully floors into productive farmland [4]. Because of steep slopes, weak sedimentary profile, occurrence of earthquakes frequently, landslides, and heavy rainfall, Taiwan experiences the highest sedimentation problems globally. One example of the Shihmen dam which was constructed in the year 1963 to supply water to Taipei has an initial gross capacity of 309Mm^3. But typhoon Gloria hit during the first year of its operation and accumulated 19.5 Mm^3 of sediment into the reservoir. Because of this catastrophic occurrence of typhoons 120 check dams were constructed in watersheds to decrease sediment production. However, these check dams provide minimal storage capacity for sediment inflow and fill up completely. Again, a typhoon hit in the year 2004 and accumulated 28.9 Mm^3 of sediment and by the end of the year 2007 the dams had lost 38% of their original volume capacity [4].

3.4. Routing sediments

High Temporal Variation in sediment-laden water is a general characteristic of river streams globally [4]. An example of high temporal variation is the 1993 heavy rainfall in Nepal resulted in the release of around 85 Mm^3 of sediment accumulated in the

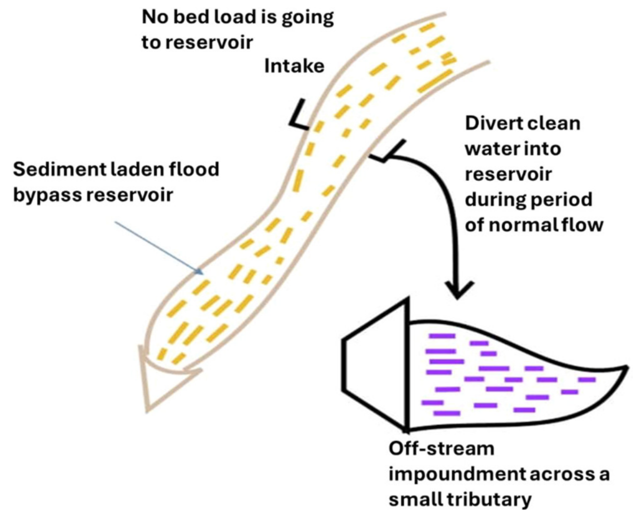


Fig. 8. Sketch representing off-stream reservoir for sedimentation control.

Kulekhani reservoir which ultimately creates a loss in storage capacity which is equivalent to 100 year of sediment accumulation in normal rainfall conditions. It takes almost 3 years after the event, the sediment generation returned to their normal levels [47, 48]. Similarly, another example of the Caonillas reservoir in Puerto Rico because of hurricanes which resulted in 55 Mm^3 loss in storage capacity which was estimated to be equivalent to 50 years of normal sediment accumulation [49].

The sediment routing concept focuses on minimal sediment accumulation by either bypassing the sediment-loaded flows around the reservoir or passing through the storage zones. Overall, it can be summarized as storing clear water and diverting/releasing the muddy water flows. This concept is very suitable where frequent or extreme sedimentation problems occur. Five common strategies applied to sediment control by routing are shown in Table 1 Below [4].

3.4.1. Off-stream reservoir

Off-channel is built outside mainstream constructing small intake structures to divert the clear water to the storage zone. Clear water is turned into off stream

Table 1. Sediment routing techniques for separating clear and muddy water [4].

Strategy	Management strategy
Sediment Bypass:	
(a) Off-stream Reservoir	Divert clean water (normal flows) into storage
(b) Flood Bypass	Divert muddy water (flood flows) around storage
Sediment Pass-Through:	
(c) Vent Turbid Density Currents	Vertical separation of clear and muddy flows
(d) Drawdown Sluicing	Timewise separation of clear and muddy flows
(e) Compartmented Reservoir	Horizontal separation of clear and muddy flows

Table 2. Examples of sediment bypass tunnels around the World [53].

Country	Reservoir/Dam name	SBT commission	Dam commission	Discharge [m^3/s]	Length [m]	Slope [%]	Reservoir volume [106 m^3]	Catchment [km^2]
Swiss	Pfaffensprung	1922	1922	220	282	3.0	0.15	390
Swiss	Serra	1952	1952	40	425	1.6	0.18	34
Swiss	Runcahez	1962	1961	110	572	1.4	0.48	50
Swiss	Ual da Mulin	1962	1962	145	268	4.3	0.06	25
Swiss	Val d'Ambra	1967	1965	85	512	2.0	0.4	24
Swiss	Egschi	1976	1949	50	360	2.6	0.4	108
Swiss	Palagnedra	1978	1952	220	1,760	2.0	4.26	140
Swiss	Rempen	1986	1924	80	450	4.0	0.5	43
Swiss	Hintersand	2001		38	1050	1.2	0.11	35
Swiss	Solis	2012	1986	170	968	1.9	4.1	900
Japan	Karasuhara/ Tachigahata	1905	1905		333 (channel) 139 (tunnel)	1.3	1.24	19
Japan	Nunobiki	1908	1900	39	258	1.3	0.76	10
Japan	Asahi	1998	1978	140	2,384	2.9	15.47	39
Japan	Miwa	2004	1959	300	4,300	1.0	29.95	311
Japan	Matsukawa	2016	1974	200	1,417	4.0	7.4	60
Japan	Koshibu	2016	1969	370	3,982	2.0	58.0	288
Taiwan	Nanhua	Presume. 2018	1994	1000	1287	1.85	144.0	108
Taiwan	Shimen	In planning	1964	600	3702	2.89	310	760
Taiwan	Tsengwen (also Zengwen)	2017	1973	995	1235	5.32	N.A	481
Pakistan	Patrind	2017	2017	650	140	1.12	6.0	2400
France	Rizzanese	2012	2012	100	133	6.9	1.2	N.A

channel with the help of gravity and the pumping process while sediment-loaded flow will bypass. Off-stream reservoirs serve different purposes like water supply and regulation of river run storage and hydropower generation. This method is highly efficient in sediment reduction. Two examples of streams built in Puerto Rico, Rio Fajardo & Rio Blanco which approximately reduced 90% of the sediment-loaded flows [50]. A schematic view of the Off-stream reservoir is shown in Fig. 8 [4].

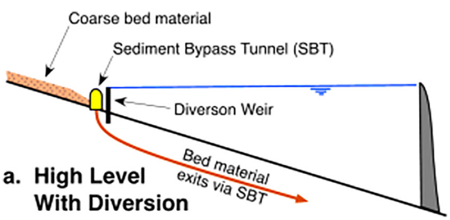
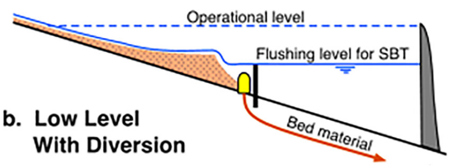
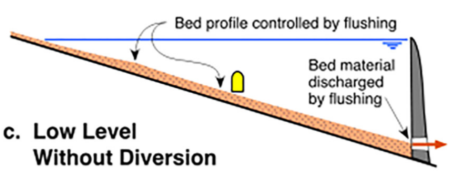
Off-channel provides many benefits other than sedimentation control, such as coarser particles left in the river stream instead of going to the reservoir thereby enhancing the geomorphic and ecological conditions downstream [4]. Knellpoort Reservoir in South Africa is a good example of an off-channel reservoir that solves pre-existing sedimentation problems. In Welbedacht municipal water supply reservoir was built on the Caledon River to prevent sedimentation by the flushing process. However, the outlet work was placed too high, and less flushing time reduced flushing efficiency because of that reservoir lost its 86% capacity in the first 20 years of its operation [51]. Again in 1989 Knellpoort off-channel was built 15km upstream as an alternative to storage capacity and reduced sedimentation. River water is sent to the reservoir by pumping mechanisms and sent via a canal which is facilitated by the desilting basin [51].

3.4.2. Sediment bypassing

This technique is used to divert the incoming sediment-loaded flow around the reservoir to prevent it from entering the reservoir. A weir is constructed upstream to divert sediment-loaded flow into a bypass tunnel which finally releases this sediment-loaded water to the river stream downstream. Weir diverts flow when a high load of sediment concentration is coming to the reservoir but as soon as concentrations of sediment decrease, water is permitted to the reservoir [52]. The perfect geometry for constructing sediment bypass structures where the river takes a sharp turn, which makes the gradient steeper which helps in gravity flow, and the shortest path for the bypass tunnel is achieved [52]. However, there are very less bypass tunnels constructed with only 30 examples globally [4]. Japan and Switzerland are at the top list for constructing bypass tunnels, In Japan [52]. The main feature of 21 sediment bypass tunnels which 10 are in Switzerland, 6 in Japan, 3 in Taiwan, and one each in France and Pakistan, Table 2 [53].

The oldest bypass tunnel was built in Japan on a municipal water supply reservoir (Nunobiki Dam) which is situated near Kobe city and was built after the dam was completed in the year 1900. This bypass tunnel diverted sediment-loaded water for 100 years as demonstrated in a study [52]. Pfaffensprung

Table 3. The different arrangement system of installing sediment bypass tunnels to reservoir [4].

The case scenario	Release strategy	Divert bed load	Drawdown below min level	Bed load/Delta
	Sluice gate and suspended load Via Bypass Tunnel	Yes	No requirement for a bypass	Bed Load Intercept above the reservoir
	Drawdown for bed flushing and suspended load release through the sediment bypass tunnel	Yes	Depends on design	Delta diverted through a diversion weir
	Low-level outlet and suspended load through sluicing by SBT	No	No requirement for bypass	Both delta and bed load are managed by excavation

sediment bypass tunnel was the first bypass tunnel built in 1922 and is described as a Swiss method of sedimentation control [4].

Bypass tunnels are mostly built for supercritical flow whose maximum velocity range is 10 to 15 m/s. The most used configuration is type-A which diverts sediments coming from upstream of the reservoir by using weir diversion. When the weir is submerged it acts as a wall and allows the surface to flow into the reservoir while water with heavily loaded sediment is transferred to the tunnel [4]. Table 3 represents the case scenario of different types of building sediment bypass tunnels and their preferred arrangement.

The entrance of the sediment bypass tunnel of type-A built at Asahi Reservoir in Japan is shown in Fig. 9(a) which shows the entrance point of the tunnel located upstream of the weir. When high flow occurs, the entrance of the tunnel is fully submerged by water received from check dams and it forms orifice flow. Full submergence which creates low velocity ahead of the bypass tunnel entrance will prevent coarser particles from entering the tunnel. But as soon as the water level decreases and free flow occurs at the entrance of the tunnel, shallow flow with high velocity again transfers coarser material into the tunnel [4]. This is shown in Fig. 9(b).

The second configuration presented as type B, built a bypass entrance downstream at a lower level which ultimately reduces tunnel length. In this type, the reservoir must be drawn down to stabilize delta sediments through the tunnel and protect the delta from reaching downstream and overtopping the normally submerged weir. Solis hydropower in Switzerland is an example of a type-B sediment bypass tunnel with a diversion weir [4]. The limitation of bypass tunnel is abrasion of the tunnel floor because of coarse bed load, and gravel. Miwa Dam (Japan) has a total capacity of 30 Mm^3 and uses a type-A diversion weir which removes coarse bed material through a bypass tunnel by preventing sediment with the help of a check dam on the upstream side [54]. Fig. 10 will explain the bypass tunnel arrangement at Miwa Dam Japan.

The third Configuration of bypass uses no weir at the upstream side, and it releases the sediment upstream by different means. This configuration is based on flushing by turbidity current generated in the reservoir [55]. Type-C configuration example can be seen in Nepal where a reservoir is used for hydropower generation. This type of configuration creates a head pond upstream of the reservoir which acts as a sedimentation basin upstream. The schematic view is illustrated in Fig. 11. The bypass tunnel of the C-configuration passes all the flow, exceeding the turbine design flow capacity. Nepali mountainous river is a canyon and narrow in shape which gives a good advantage of flushing the

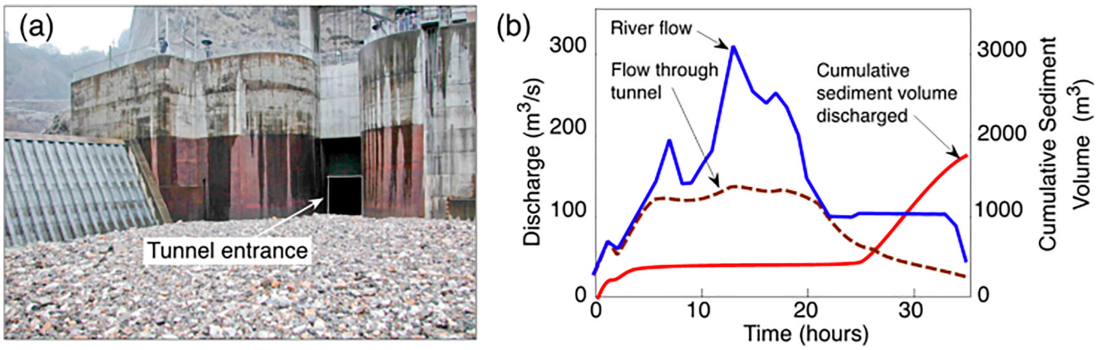


Fig. 9. (a) Entrance point of bypass tunnel at Asahi reservoir, Japan having diversion weir left side (b) Sediment bypass behavior indicates discharge of bed material at lower flows when the tunnel mouth is not submerged, resulting in scouring velocities across [4].

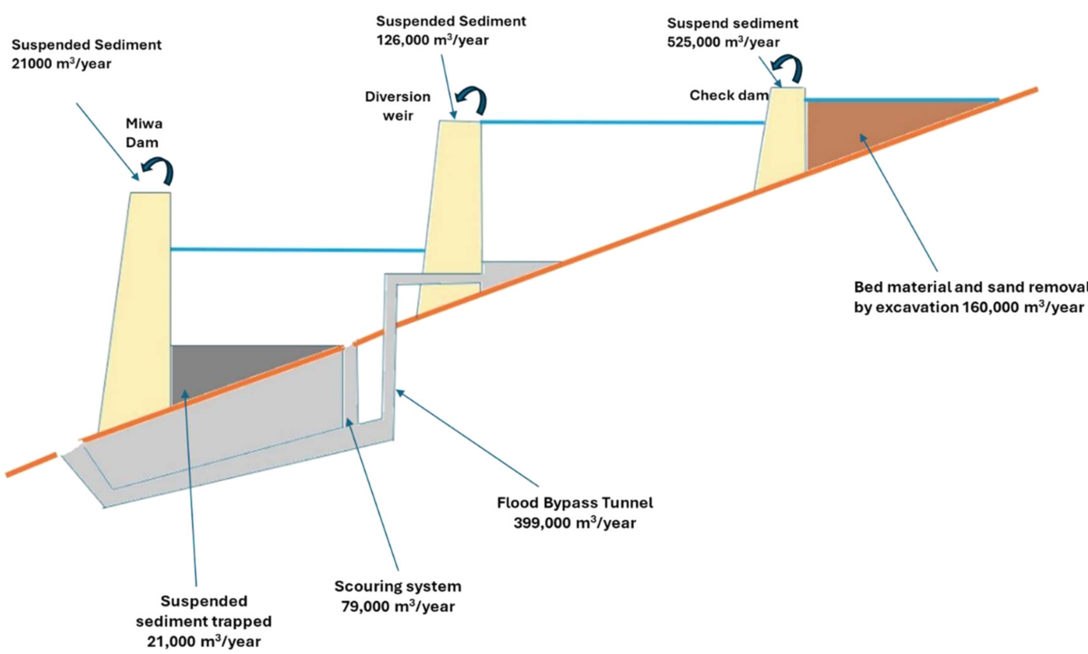


Fig. 10. Bypass tunnel arrangement at Miwa Dam, Japan.

sediment upstream of the reservoir by outlet structures [4].

3.4.3. Venting turbidity density currents

Turbidity density current is generated in the dam when a high sediment-loaded concentration of water is separated by a lower density of water and flows along the reservoir without mixing. Turbidity current will dissipate when the bed surface of the reservoir is uneven which causes turbulence in the water. In most of the reservoir's turbidity current is the main mechanism of sediment removal through the dam by practice termed venting [11]. Fig. 12 this technique is most feasible in large reservoirs where other tech-

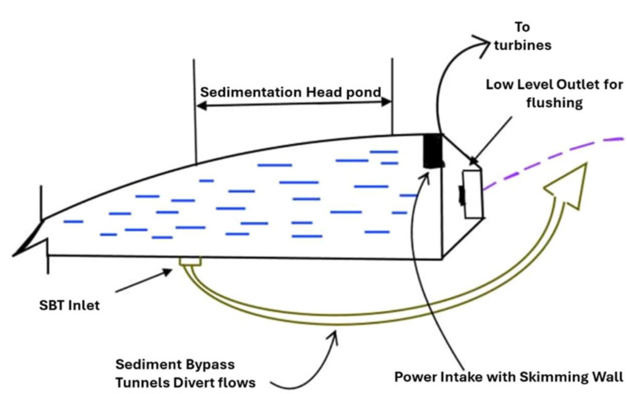


Fig. 11. Schematic of type C-configuration in Nepali reservoir.

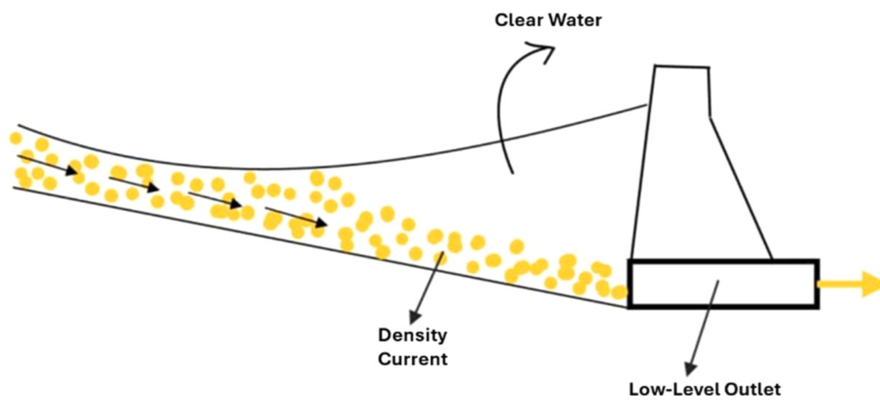


Fig. 12. Sketch of turbidity venting current.

niques do not work. The main concern for sediment removal through this process is that the reservoir has a significant velocity which causes the sediment to be in suspension and travel downstream easily [5]. This process becomes more significant during the season of floods, in which sediment is delivered downstream by natural means. Sanmenxia and Xiaolandi reservoir uses this process to remove the sediment along with the flushing technique [5].

The turbidity current mechanism is based on the configuration type-c MENTIONED above. Turbidity current releases fine sediment which passes the hydropower turbines with very little abrasion allowing their discharge to the downstream side. Releasing the sediment through hydropower turbines is very beneficial as it helps to reduce the loss of storage capacity and maximize the availability of volume to accumulate more coarser sediments [4].

3.4.4. Sluicing (By Reservoir Drawdown)

Sluicing is the process of discharging the high flow coming to the reservoir during periods of extreme events and floods. It aims to release the incoming sediment-laden water downstream which minimizes the sedimentation. In this way, some past deposited sediment also gets scoured and transported through the dam downstream, but the main objective is to reduce the chances of incoming sediment accumulation [56]. Sluicing can be done by lowering the water table in the reservoir so that when high flow reaches the reservoir, can be released easily. Large capacity outlet structures are required to release the large flow coming to the reservoir, in the meantime maintaining low water levels and sufficient velocity and transport capacity. The structures can be kept at the bottom of the reservoir, tall crest gates can be used for this process [52].

In China, there is a saying regarding sluicing "Store clear water and release muddy water". Three Gorges Dam is designed in such a way that during seasonal rainfall it maintains the required drawdown to pass the high sediment-laden and at the same time mobilize the sediment deposited in the past. Sluicing can be very effective in long and narrow reservoirs. At the same time, it is also effective in small reservoirs with deep high-capacity low-level outlets [57]. Sluicing focuses on the release of muddy water and at the same time, this process does not produce high suspended sediment concentration which is linked to the emptying and flushing of the reservoir. Even in this case, when sluicing scours the already deposited sediments the peak sediment concentration because of large flow is still less than flushing. Considering all these benefits this process is considered to be an environmentally friendly technique [52].

3.5. Removal of sediments from the reservoir

3.5.1. Flushing process

The flushing method of removing sediment is based on scouring and removing the accumulated sediment in the reservoir using accelerated flows which is produced by smooth and quick opening of the low-level outlets of the dam [58]. This method is done in three ways which involve Pressure flushing (partial drawdown of the reservoir), Free flow flushing (complete drawdown of the reservoir or emptying the reservoir), and Turbidity density current [4, 39]. Pressure flushing aims to release the water through low-level outlets and water is drawn partially to the minimum pool level. Free flow flushing is the process of emptying the reservoir either partially or in most cases fully up to the sluice gate level. Flushing of dams in series is a special case of removing the sediments from the reservoir by flushing dams in series which scoured the accumulated sediments from upstream to downstream side with minimal sediment deposition [59].

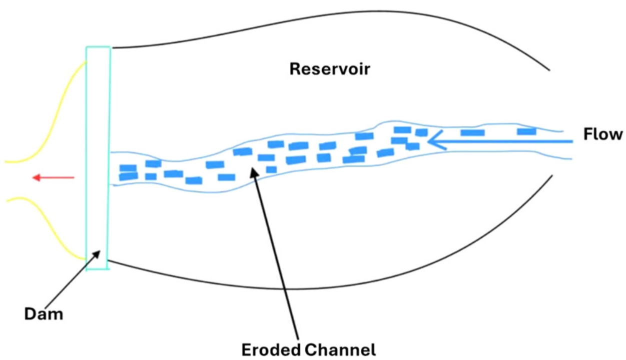


Fig. 13. Sketch of drawdown flushing in an eroded channel.

Table 4. Successful flushing operation in different countries.

Dam	Location	References
Unazuki & Dashidaira	Japan	[61–63]
Sanmenxia	China	[64, 65]
Cachi	Costa Rica	[66]
Gennisiat	France	[67]
Gavins's point	South Dakota, Nebraska	[68]

3.5.2. Drawdown flushing

Drawdown flushing aims to empty the reservoir fully using low-level outlet gates /sluice gates. The best flushing can be achieved by developing river flow situations upstream of the reservoir, which is influenced by narrow valleys having steep slopes, steep longitudinal slopes, discharge in the river maintained to threshold limit to mobilize the sediments and transport it downstream and installing low-level outlet gates [5]. This technique is feasible in small reservoirs and rivers with heavy seasonal flow patterns [59]. Flushing in flood season has greater advantages because of high discharge availability, and more energy which causes high erosion so that incoming sediments as well as sediment deposited in the past released downstream of the reservoir [5]. The schematic view of drawdown flushing can be seen in Fig. 13 [60].

The literature review studies indicated some of the successful flushing operations in various countries such as Unazuki & Dashi Daira dam "Japan" [61–63], Sanmenxia dam "China" [64, 65], Cachi dam "Costa Rica" [66], Gennisiat dam "France" [67] and Gavins point dam " South Dakota Nebraska" [68] are mentioned in Table 4.

In the study, certain measures have been established for the flushing operation which include steep longitudinal slope, High flow erosive velocity, and narrow valleys having steep banks. Low-level outlets to pass large flows, strong seasonal flow patterns [5, 69]. In literature, different factors are suggested that need to be considered for flushing operations such as the Capacity of the reservoir, mean annual runoff, and mean annual sediment inflow for successful flushing the ratio of reservoir capacity to mean annual runoff is not greater than 4% [69, 70].

Different environmental concerns can arise especially when flooding is done in a non-flood season which keeps sediment left in the bed of the downstream channel. Ecologically important basins will fill with sediment, gravel, and cobbles. Fine sediment beneath the cobbles, clogs the bed which disturbs the recharge of groundwater, and eggs of species, as well as clogging the void spaces in between stone which serves as habitat for aquatic invertebrates and larval fish [71]. Flushing of sediment-loaded water is avoided through powerhouses because it results in the abrasion of turbines [52]. In general, frequent flushing has less impact downstream as sediment delivery is needed downstream for river health and more often in small channels. Opening of gates gradually and at fixed times such as during high flows (rainy season or snow melt), possess less impact downstream [72].

Sometimes flushing and sluicing are combined such as during seasonal duration in which the pool is emptied and low-level outlets are opened before the rainy season starts which allows high flows to pass through the reservoir empty and carry the deposited as well as incoming sediments from upstream. This approach is used in Chinese reservoirs on the Sanmenxia dam in which the Yellow River is kept empty for 2 months at the beginning of the rainy season which allows sediment-loaded flows to transport the sediment accumulated during the last year and the incoming sediment from the upstream during that period [65].

3.5.3. Dredging of sediment

Dredging is a technique to excavate the sediment deposited below the water in the reservoir. It can be categorized into two types (i) Mechanical dredging which uses a backhoe, clamshell, and dragline, which places the excavated sediment into the truck for further transport for its disposal (ii) Hydraulic dredging which transports sediment through the slurry pipeline into downstream near to the dam or sometimes for dewatering. The dewatered sediment can be used for further uses such as in the case of Lake Spring Field (USA) where these dewatered sediments are used in farmland [5]. Hydraulic dredging is preferred as compared to mechanical dredging. The mechanism of hydraulic dredging is siphoned or hydraulic dredge which uses the difference in water head between the reservoir water surface and the discharge point near the dam which works as slurry transport. One primary concern in the slurry pipeline is friction losses which hinder it to use within few kilometres of the dam [52].

In China, a hydraulic suction machine is used to stir the sediment in the reservoir using hydraulic and

Table 5. Case studies related to reservoir sedimentation and their mitigation strategies.

Dam	Location	Strategy of Mitigation	References
Dashidaira	Kurobe River, Japan	Sluicing and Flushing	[73–75]
Nunobiki	Japan	Check dams and Sediment bypass tunnels	[53, 75–77]
Asahi	Japan	Sediment bypass tunnels	[75]
Fort Cobb Reservoir	Central Oklahoma USA	Soil conservation practices	[43, 44]
Shihmen reservoir	Taiwan	Check Dams	[78]
Knell Port Reservoir	South Africa	Off Storage reservoir	[51]
Pfaffensprung	Switzerland	Bypass tunnels	[79]
Solis Hydropower reservoir	Switzerland	Bypass tunnel and diversion weir	[80, 81]
Zengwen Reservoir	Taiwan	Turbidity current	[4]
Cogsweel reservoir	California	Dredging	[5]
Jansanpei Reservoir	Taiwan	Flushing and increasing the height of the dam	[82]
Three Gorges Dam	China	Store clear water and release muddy water	[3]

mechanical power, and then the sediment with high concentrations is discharged downstream by using a siphon. Mechanical dredging can be used when the reservoir is empty [52]. It uses scrapers, dump trucks, and other mechanical equipment. Mechanical dredging is less costly, but it requires a full drawdown of the reservoir. It suits best those reservoirs which are kept empty for part of the year such as flood control reservoirs. One example of Mechanical dredging is the Cogswell reservoir on the river San Gabriel (California) which was dredged between the years 1994 and 96 and 2.4 Mm^3 sediment was removed and transported to the disposal site with an associated cost of 5.6 dollars/m^3 [5].

3.6. Case studies

This section presents different case studies globally focusing on mitigation control measures for reservoir sedimentation. In every case study, the techniques used to control the sedimentation in the reservoir are highlighted such as sluicing, flushing, bypass tunnels, watershed management, and mechanical removal. These techniques will help to combat the reservoir sedimentation to enhance its durability and efficiency. This section presents an overview of different and effective sediment management approaches considering geographical context followed by references to ensure the accuracy and relevancy of the data provided. Some of the case studies as an example across different parts of the world are shown below in Table 5.

4. Literature review assessment

Reservoir Sedimentation poses difficult challenges to the sustainability and functioning process of dams and hydraulic structures globally. Sedimentation in the reservoir is caused by erosion of the soil surface leading to the removal of finer particles of soil and transported it with the water reaching upstream of the reservoir. One of the major concerns related to reservoir sedimentation is the loss of the storage capacity of the reservoir. There are other causes of reservoir sedimentation as well discussed in the literature such as deterioration of water quality and less durability of structures. This paper presents a detailed analysis of reservoir sedimentation mechanisms, causes, and their mitigation strategies highlighting the importance of sustainable sedimentation management in reservoirs. In literature analysis, this paper highlighted the causes of sedimentation such as natural and anthropogenic. Both causes include soil erosion, deforestation, agricultural land expansion, and urbanization. In the introduction, the paper presents the sedimentation rate at the global level by analyzing different literature on reservoir sedimentation and the storage loss capacity of the reservoir. A study referenced in the paper which is related to Nizam Sagar Dam (Andhra Pradesh), India revealed that the dam had lost 70% of its original capacity within 50 years of its operation (Varady 1984).

Similarly, there are several studies which have been done on sedimentation including Central Europe, Mediterranean Basin, South Africa, and China as presented in the literature. One of the studies says that the Three Gorges Dam in China affected the vegetation cover, hydrological pattern, and ecological concern at East Dong Ting Lake [12]. Deterioration of water quality has also been observed because of reservoir sedimentation [13]. In the United States, 24 reservoirs had lost their storage capacity by approximately 17% of their original value with an annual average rate loss of 0.84% [14]. Physical processes which are involved in sedimentation are explained and discussed in detail in the literature. These processes include sediment routing, delta migration, flow circulation, and turbidity currents. Climate change has become an important concern leading to erosion of soil and reservoir sedimentation. The effect of climate change leads to increased temperature and erratic rainfall, melting of frozen soil on hillsides, ground subsidence, and landslides [19].

The core of the paper is evaluating the different mitigation strategies in reservoir sedimentation. These strategies are divided into 4 groups. The first category includes sediment yield reduction which can be achieved by introducing watershed management practices which include afforestation, and construction of check dams. Countries that have successfully adopted sediment reduction yield practices are the USA, China, and Taiwan as presented in the literature. The second category focuses on Routing Sediment to off-stream reservoirs, through sediment bypass tunnels and venting turbidity currents. This sediment strategy aims to reduce the sediment by either passing it through the dam or by diverting it to stream channels such as bypass tunnels and turbidity currents. The Solis Hydropower reservoir and Miwa dam in Japan had successfully adopted the sediment bypass tunnels. Several different countries have successfully adopted bypass tunnels as presented in the literature Table 2. The third category of mitigation focuses on Sluicing and flushing. The purpose of sluicing is to release the sediment-laden water through the dam using an outlet gate (reservoir drawdown), while flushing is adopted during the rainy season when high flow reaches the reservoir. The high velocity associated with rainwater releases the sediment load coming to the reservoir as well as the sediment deposited previously because of the high erosive nature of water. Both of these methods were successfully employed in the Three Gorges Dam in China and several Japanese Dams. Finally, the fourth category of sediment control in reservoirs is sediment removal which includes dredging, flushing, and drawdown of the reservoir. Dredging is done in two ways, mechanical dredging, and hydraulic dredging. Countries like China and the USA have adopted this sediment control technique. The primary concerns related to this technology are high cost and environmental harm (the sediment carried through hydraulic dredging must be disposed of safely).

5. Future recommendation

5.1. Avoiding sediment by selecting the best site

Site selection is very important for the reservoir to control the reservoir sedimentation. Taking sustainability into account, the selection of a site can be made in such a way that it can adopt temporal and spatial changes. As an example, sedimentation can be reduced by giving priority to river channels having low sediment-laden water. A site with steep slopes is preferable as it passes the sediment easily through the dam.

5.2. Consideration of future sediment management plan in dam design

The long-term equilibrium profile i.e., the incoming and outgoing sediment must be calculated during the design phase of the dam using sediment transport models. Gates must be implemented for the long-term release of water through the dam. The location of the gate is site-specific, but it can be set as low so that it produces sufficient hydraulic capacity for long-term sediment removal. For flushing in low flow period gate must be placed at a lower level while for sluicing it needs more water to withdraw so the gate for sluicing is placed at a higher level. Placing radial gates is a good option at the bottom of the dam.

5.3. Flushing dams in series

Sediment transport through the reservoir in series is adopted when a river crosses the territorial boundaries. Conflicts between upstream and downstream users give poor results as they operate independently. Hence establishing the dam in series, it is very necessary to share real-time data and coordinate with the authorities to evaluate the efficiency of the process and to transport the sediment easily. Long-term availability and accurate hydrological as well as sediment data are necessary to evaluate the impacts of sediment. A survey of the dam is very essential for analyzing the suspended sediment, monitoring sediment downstream, and sediment which is accumulated by flushing.

5.4. Behaviour of coarse and fine sediment

Transporting behaviour, trapping ability, and downstream impacts of fine and coarse sediment are different, and provision is made to assess them separately. In the majority of reservoirs, gravels are trapped with 100% efficiency, causing gravel deficiency downstream of reservoirs and it's very hard to transport them by sluicing or flushing except in small reservoirs. Sluicing and flushing are adopted for the removal of fine sediments. So, it is recommended that the quality of sediment coming to the reservoir is assessed properly before designing the dam.

5.5. Social, economic and environmental impacts of sedimentation

As discussed above sedimentation not only disturbs storage space of dams but also disturbs infrastructure and the environment. An example of Aswan Dam which had reduced the flow of sediment downstream to the river Nile by 98% [83]. This had reduced the Nile Delta to 125–175 metre/year. Another Example of Mississippi river delta which is also suffering from erosion because of many dams in the way and lock around the river [83]. Among 33 major wide deltas Globally 24 are shrinking presently because of sedimentation in the reservoir. These Coastal areas are more prone to heavy flooding because of erosion in coastal regions and will result in sea level rise by an expected value of 0.46m by the end of year 2100 due to climate change [52].

It is true that sedimentation results in shallow storage capacity loss but can also cause other problems [4]. In a study, the primary consequences due to sedimentation are aggradation of upstream and deterioration of downstream channels. Secondary and tertiary problems include flooding, rise in groundwater tables, crop failure upstream, channel instability, loss of access to diversion works, bridge piers and abutments, and geomorphological disturbance downstream [84]. The total removal of sedimentation is indeed neither possible nor viable, but it can be controlled by adopting preventative measures to alleviate the storage capacity loss of reservoir due to sedimentation [52]. Reservoirs storage spaces are dual in nature i.e., exhaustible as well as renewable resource. If the reservoir is designed by motive to fill with sediment in future, then the reservoirs are said to be exhaustible resources while reservoirs which are designed by considering the preventative measures against sedimentation are categorised in renewable resources. Both of these facts proved that the reservoir storage space prevention is a management decision either they consider sedimentation management approach or not [36].

According to Hotelling Rule, cost-benefit analysis is continued to assign a correct value for reservoir sedimentation management approach to preserve the storage space of reservoir which says for maximum output for current and future generations the cost of exhaustible resources must increase at proper interest rate to increase the current value of reservoir in future [85]. Good reservoir locations are limited in number, and many are in operation, so reservoir storage space must be considered as exhaustible resource in those condition where sedimentation management is not implemented. While if the reservoir sedimentation management is induced into the design, operation and management of reservoir the storage space are considered as renewable resource. However, the economic analysis for reservoir sedimentation control is heavily dependent on the decision whether the reservoir is considered as exhaustible of renewable resource [86].

6. Conclusion

In conclusion, sustainable management of water is a serious concern of the 21^{st} century and in the coming decades hence, reservoir sedimentation poses significant challenges to sustainable water management of water resources globally. In this paper, we have explored the detailed review of sedimentation mechanisms in the reservoir which includes the natural erosion process and anthropogenic activities such as deforestation, clearing land for agriculture, and urbanization. Sediment origin is at far reach, mid-reach, and near the reservoir depending on the topographical features. The different impact of sedimentation including loss of storage capacity, impact on aquatic bodies, and soil pollution is discussed. Fortunately, we had discussed the mitigation strategies to control the sedimentation in the reservoir. These strategies including bypass tunnels, dredging, flushing, and sluicing are explained in detail with their advantages and disadvantages. Each sediment management strategies discussed have their advantages and disadvantages. Based on the analysis each management strategy becomes successful when monitored timely and implemented based on geographic location, physical features, vegetative cover and climatic condition, anthropogenic activities, sediment properties, geometry of reservoir, geopolitical aspects, ecological concern, etc. Special attention was given to the flushing and sluicing processes. While in recent decades bypass tunnels have also been implemented in many countries like China, Japan, Switzerland, and many more.

One limitation is flushing efficiency should be considered for future directions. Also, numerical models can be used to simulate the flow and sediment behaviour near the dam. Numerical modelling is the best approach for engineers to choose the best option that is economical and hydraulically accepted. RESCON 2 software has been mentioned in the literature to analyze sedimentation behaviour in preliminary design, but the result must be carefully identified as sediment management is a complex and site-specific process. Furthermore, it is a fact that successful reservoir sedimentation management can be achieved by collaborating with policymakers, engineers, scientists, and local communities. On the other hand, sustainable land use practices, preventive measures against soil erosion, and routine monitoring of sediment accumulation are also needed for sedimentation management. There are always some challenges that remain with sedimentation management such as funding issues, conflicts between policymakers, and uncertainty due to climate change which needs to be considered. Using advanced technology coupled with increased awareness of management programs poses opportunities to develop more effective and sustainable solutions. By combining scientific knowledge, engineering expertise, and stakeholder engagement, we can work towards protecting the integrity and functionality of reservoirs for future generations.

Conflict of interest

The authors declare no conflict of interest to any party.

References

1. M. W. George, R. H. Hotchkiss, and R. Huffaker, "Reservoir sustainability and sediment management," *J Water Resour Plan Manag*, vol. 143, no. 3, 2017, doi: 10.1061/(asce)wr.1943-5452.0000720.
2. C. A. Obialor, O. C. Okeke, A. A. Onunkwo, V. I. Fagorite, and N. N. Ehujuo, "Reservoir sedimentation: causes, effects and mitigation," *International Journal of Advanced Academic Research*, vol. 5, no. 10, pp. 92–109, 2019.
3. S. Ren, B. Zhang, W.-J. Wang, Y. Yuan, and C. Guo, "Sedimentation and its response to management strategies of the Three Gorges Reservoir, Yangtze River, China," *Catena (Amst)*, vol. 199, p. 105096, 2021, doi: 10.1016/j.catena.2020.105096.
4. G. L. Morris, "Classification of management alternatives to combat reservoir sedimentation," *Water (Switzerland)*, vol. 12, no. 3, Mar. 2020, doi: 10.3390/w12030861.
5. G. L. Morris and J. Fan, "Reservoir Sedimentation Handbook," McGraw-Hill Book Co, 1998.
6. S. Mohafid, L. Stour, and A. Agoumi, "Multidimensional valorization of sediments trapped by dams for sustainable and integrated water resources management," *Multidisciplinary Science Journal*, vol. 6, no. 8, Aug. 2024, doi: 10.31893/multiscience.2024146.
7. F. M. Dendy, W. A. Champion, and R. B. Wilson, "Reservoir sedimentation surveys in the United States," *Geophysical Monograph Series*, vol. 17, pp. 349–357, 1973.
8. R. G. Varady, "The State of India's Environment, 1982: A Citizens' Report. By the Centre For Science and Environment. New Delhi: Centre for Science and Environment, 1982. vii + 192 pp. Charts, Maps, Photographs. $25. (Distributed in North America by the Council on Interna," *J Asian Stud*, vol. 43, no. 3, pp. 563–564, 1984.
9. M. G. Louis, "Summary: sedimentation of reservoirs," *Man Made Lakes, their Problems and Environmental Effects*. American Geophysical Union, Washington DC, p. 343, 1973.
10. K. D. Fu, D. M. He, and X. X. Lu, "Sedimentation in the Manwan reservoir in the Upper Mekong and its downstream impacts," *Quaternary International*, vol. 186, no. 1, pp. 91–99, Aug. 2008, doi: 10.1016/j.quaint.2007.09.041.
11. J. Chen, W. Zhou, and C. Qiang, "Reservoir sedimentation and transformation of morphology in the lower yellow river during 10 year's initial operation of the Xiaolangdi reservoir," *J Hydrodynam B*, vol. 24, no. 6, pp. 914–924, 2012.
12. Y. Xie, T. Yue, C. Xin-sheng, L. Feng, and D. Zheng-miao, "The impact of Three Gorges Dam on the downstream eco-hydrological environment and vegetation distribution of East Dongting Lake," *Ecohydrology*, vol. 8, no. 4, pp. 738–746, 2015.
13. N. Heidarzadeh and O. Motiey Nejad, "Evaluating sedimentation effect on reservoirs water quality: a case study, Shahriyar reservoir," *International Journal of Environmental Science and Technology*, vol. 14, no. 12, pp. 2623–2636, 2017, doi: 10.1007/s13762-017-1317-z.
14. V. Rahmani et al., "Examining storage capacity loss and sedimentation rate of large reservoirs in the central U.S. great plains," *Water (Basel)*, vol. 10, no. 2, p. 190, 2018, doi: 10.3390/w10020190.
15. A. J. Schleiss, M. J. Franca, C. Juez, and G. De Cesare, "Reservoir sedimentation," *Journal of Hydraulic Research*, vol. 54, no. 6, pp. 595–614, 2016, doi: 10.1080/00221686.2016.1225320.
16. R. P. C. Morgan, *Soil erosion and conservation*. John Wiley & Sons, 2009.
17. T. P. Burt and R. J. Allison, "Sediment cascades in the environment: an integrated approach," 2010, Wiley. doi: 10.1002/9780470682876.ch1.
18. J. Imran, G. Parker, J. Locat, and H. Lee, "1D Numerical model of muddy subaqueous and subaerial debris flows," *Journal of Hydraulic Engineering*, vol. 127, no. 11, pp. 959–968, 2001, doi: 10.1061/(asce)0733-9429(2001)127:11(959).
19. A. J. Schleiss, M. J. Franca, C. Juez, and G. De Cesare, "Reservoir sedimentation," *Journal of Hydraulic Research*, vol. 54, no. 6, pp. 595–614, Nov. 2016, doi: 10.1080/00221686.2016.1225320.
20. J. Fan and G. L. Morris, "Reservoir sedimentation. I: delta and density current deposits," *Journal of Hydraulic Engineering*, vol. 118, no. 3, pp. 354–369, 1992, doi: 10.1061/(asce)0733-9429(1992)118:3(354).
21. W. H. Graf and M. S. Altinakar, *Fluvial hydraulics: flow and transport processes in channels of simple geometry*, vol. 42. Wiley New York, 1998.
22. J. Fan and G. L. Morris, "Reservoir sedimentation. II: reservoir desiltation and long-term storage capacity," *Journal of Hydraulic Engineering*, vol. 118, no. 3, pp. 370–384, 1992, doi: 10.1061/(asce)0733-9429(1992)118:3(370).
23. S. Kostic and G. Parker, "Progradational sand-mud deltas in lakes and reservoirs. Part 1. Theory and numerical modeling," *Journal of Hydraulic Research*, vol. 41, no. 2, pp. 127–140, 2003, doi: 10.1080/00221680309499956.
24. C. J. Sloff, "Sedimentation in reservoirs.," 1998.
25. E. L. Matyas and L. Rothenburg, "Characteristics of sediment profiles in reservoirs," *J Hydrol (Amst)*, vol. 87, no. 1–2, pp. 33–44, 1986, doi: 10.1016/0022-1694(86)90113-7.
26. C. Oehy and A. Schleiss, "Effects of obstacles and jets on reservoir sedimentation due to turbidity currents," 2003.
27. G. Parker, Y. Fukushima, and H. M. Pantin, "Self-accelerating turbidity currents," *J Fluid Mech*, vol. 171, no. 1, p. 145, 1986, doi: 10.1017/s0022112086001404.
28. G. Parker, M. Garcia, Y. Fukushima, and W. Yu, "Experiments on turbidity currents over an erodible bed," *Journal of Hydraulic Research*, vol. 25, no. 1, pp. 123–147, 1987, doi: 10.1080/00221688709499292.
29. S. A. Kantoush, E. Bollaert, and A. J. Schleiss, "Experimental and numerical modelling of sedimentation in a rectangular shallow basin," *International Journal of Sediment Research*, vol. 23, no. 3, pp. 212–232, 2008, doi: 10.1016/s1001-6279(08)60020-7.

30. S. A. Kantoush, G. De Cesare, J. L. Boillat, and A. J. Schleiss, "Flow field investigation in a rectangular shallow reservoir using UVP, LSPIV and numerical modelling," *Flow Measurement and Instrumentation*, vol. 19, no. 3–4, pp. 139–144, 2008, doi: 10.1016/j.flowmeasinst.2007.09.005.
31. P. A. Tarela and A. N. Menéndez, "A model to predict reservoir sedimentation," *Lakes & Reservoirs: Science, Policy and Management for Sustainable Use*, vol. 4, no. 3–4, pp. 121–133, 1999, doi: 10.1046/j.1440-1770.1999.00087.x.
32. N. R. B. Olsen, "Two-dimensional numerical modelling of flushing processes in water reservoirs," *Journal of Hydraulic Research*, vol. 37, no. 1, pp. 3–16, 1999, doi: 10.1080/00221689909498529.
33. M. B. Jansson and A. Rodríguez, "Sedimentological studies in the Cachí Reservoir, Costa Rica. Sediment inflow, reservoir sedimentation, and effects of flushing," *UNGI Rapport*, vol. 81, 1992.
34. S. Hartmann, H. Knoblauch, H. Badura, G. De Cesare, C. Steinich, and J. Schneider, "ALPRESERV-Sustainable Sediment Management in Alpine Reservoirs considering ecological and economical aspects: Pilot Actions and Database," 2008.
35. M. Müller, G. De Cesare, and A. J. Schleiss, "Continuous long-term observation of suspended sediment transport between two pumped-storage reservoirs," *Journal of Hydraulic Engineering*, vol. 140, no. 5, 2014, doi: 10.1061/(asce)hy.1943-7900.0000866.
36. G. Annandale, "Sustainable water supply, climate change and reservoir sedimentation management: technical and economic viability," 2014, CRC Press. doi: 10.1201/b17397-3.
37. G. De Cesare and R. Lafitte, "Outline of the historical development regarding reservoir sedimentation," in *32nd IAHR Congress, Harmonizing the Demands of Art and Nature in Hydraulics*, 2007.
38. E. Leonard, "Methods of computing sedimentation in lakes and reservoirs: a contribution to the International Hydrological Programme, IHP-II Project," *Arctic and Alpine Research*, vol. 18, no. 2, p. 246, 1986, doi: 10.2307/1551145.
39. M. R. Madadi, "How to cite: M.R. Madadi, Reservoir sedimentation management: a state-of-the-art review Reservoir sedimentation management: A state-of-the-art review," 2022.
40. Y. Niu and F. A. Shah, "Economics of optimal reservoir capacity determination, sediment management, and dam decommissioning," *Water Resour Res*, vol. 57, no. 7, p. e2020WR028198, 2021.
41. D. A. Boughton et al., "Removing a dam and re-routing a river: will expected benefits for steelhead be realized in Carmel River, California," 2016.
42. E. Creech, "Saving money, time and soil: the economics of no-till farming," *USDA Conservation blog, November*, vol. 30, 2017.
43. P. Rustomji, X. P. Zhang, P. B. Hairsine, L. Zhang, and J. Zhao, "River sediment load and concentration responses to changes in hydrology and catchment management in the Loess Plateau region of China," *Water Resour Res*, vol. 44, no. 7, 2008, doi: 10.1029/2007wr006656.
44. S. Wang et al., "Reduced sediment transport in the Yellow River due to anthropogenic changes," *Nat Geosci*, vol. 9, no. 1, pp. 38–41, 2015, doi: 10.1038/ngeo2602.
45. M. Mekonnen, S. D. Keesstra, L. Stroosnijder, J. E. M. Baartman, and J. Maroulis, "Soil conservation through sediment trapping: a review," *Land Degradation & Development*, vol. 26, no. 6, pp. 544–556, 2014, doi: 10.1002/ldr.2308.
46. W. H. Renwick, S. V Smith, J. D. Bartley, and R. W. Buddemeier, "The role of impoundments in the sediment budget of the conterminous United States," *Geomorphology*, vol. 71, no. 1–2, pp. 99–111, 2005, doi: 10.1016/j.geomorph.2004.01.010.
47. H. S. Shrestha, "Sedimentation and sediment handling in Himalayan reservoirs," 2012.
48. D. P. Sangroula, "Sedimentation and sustainability of the Kulekhani Reservoir: A Himalayan case," 2013.
49. "Sedimentation survey of Lago Caonillas, Puerto Rico, February 2000," US Geological Survey, 2001. doi: 10.3133/wri014043.
50. G. L. Morris, "Offstream reservoirs for sustainable water supply in Puerto Rico," in Am. Water Resource Assn., Summer Specialty Conf, 2010.
51. J. W. L. De Villiers and G. R. Basson, "Modelling of long-term sedimentation at Welbedacht Reservoir, South Africa," *Journal of the South African Institution of Civil Engineering= Joernaal van die Suid-Afrikaanse Instituut van Siviele Ingenieurswese*, vol. 49, no. 4, pp. 10–18, 2007.
52. G. M. Kondolf et al., "Sustainable sediment management in reservoirs and regulated rivers: experiences from five continents," *Earths Future*, vol. 2, no. 5, pp. 256–280, 2014, doi: 10.1002/2013ef000184.
53. C. Auel, "Sediment Bypassing–A Sustainable And Eco-Friendly Strategy Against Reservoir Sedimentation," in *Twenty-Sixth International Congress on Large Dams/Vingt-Sixième Congrès International des Grands Barrages*, CRC Press, 2018, p. I_192-I_212.
54. C. Onda, T. Sumi, and T. Asahi, "Planning and analysis of sedimentation countermeasures in hydropower dams considering properties of reservoir sedimentation," *Journal of Disaster Research*, vol. 13, no. 4, pp. 702–708, 2018, doi: 10.20965/jdr.2018.p0702.
55. Y. G. Lai, J. Huang, and K. Wu, "Reservoir turbidity current modeling with a two-dimensional layer-averaged model," *Journal of Hydraulic Engineering*, vol. 141, no. 12, 2015, doi: 10.1061/(asce)hy.1943-7900.0001041.
56. K. Bhattacharyya and V. P. Singh, *Reservoir Sedimentation: Assessment and Environmental Controls*. CRC Press, 2019.
57. Z. Wang and C. Hu, "Strategies for managing reservoir sedimentation," *International Journal of Sediment Research*, vol. 24, no. 4, pp. 369–384, 2009, doi: 10.1016/s1001-6279(10)60011-x.
58. P. Boeriu, D. Roelvink, C. A. Mulatu, C. N. Thilakasiri, A. Moldovanu, and M. Margaritescu, "Modeling the flushing process of reservoirs," in *Proceedings of International Conference on Innovations, Recent Trends and Challenges in Mechatronics, Mechanical Engineering and New High-Tech Products Development*, 2011.
59. R. White, *Evacuation of sediments from reservoirs*. Thomas Telford Publishing, 2001. doi: 10.1680/eosfr.29538.
60. Y. G. Lai, J. Huang, and B. P. Greimann, "Hydraulic flushing of sediment in reservoirs: best practices of numerical modeling," *Fluids*, vol. 9, no. 2, p. 38, 2024, doi: 10.3390/fluids9020038.
61. T. Kokubo, "Prediction methods and actual results on flushing of accumulated deposits from Dashidaira reservoir," in *19th ICOLD Congress, Florence*, 1997, 1997.
62. J. Liu, S. Minami, H. Otsuki, B. Liu, and K. Ashida, "Environmental impacts of coordinated sediment flushing," *Journal of Hydraulic Research*, vol. 42, no. 5, pp. 461–472, 2004, doi: 10.1080/00221686.2004.9641216.
63. T. Sumi, "Historical perspective and challenges on sediment flushing in the Kurobe River, Japan," 2018, CRC Press. doi: 10.1201/9780429020940-1.
64. Z. Wan, "The function of bottom sluice gates of gorge-shaped powerstation," *J. Sediment. Res*, vol. 4, pp. 64–72, 1986.

65. G. Wang, B. Wu, and Z. Wang, “Sedimentation problems and management strategies of Sanmenxia Reservoir, Yellow River, China,” *Water Resour Res*, vol. 41, no. 9, 2005, doi: 10.1029/2004wr003919.
66. M. B. Jansson and U. Erlingsson, “Measurement and quantification of a sedimentation budget for a reservoir with regular flushing,” *Regulated Rivers: Research & Management*, vol. 16, no. 3, pp. 279–306, 2000, doi: 10.1002/(sici)1099-1646(200005/06)16:3 < 279::aid-rrr586 > 3.3.co;2-j.
67. L. Thareau, Y. Giuliani, C. Jimenez, and E. Doutriaux, “Gestion sédimentaire du Rhône suisse: Implications pour la retenue de Genissiat,” *Congrès du Rhône «Du Léman à Fort l’Ecluse, quelle gestion pour le futur*, 2006.
68. A. H. N. Jungkyu, C. T. Yang, D. B. Pridal, and J. I. Remus, “Numerical modeling of sediment flushing from Lewis and Clark lake,” *International Journal of Sediment Research*, vol. 28, no. 2, pp. 182–193, 2013.
69. T. Sumi, “Evaluation of efficiency of reservoir sediment flushing in Kurobe river,” in *Proceedings of the 4th International Conference on Scour and Erosion*, Tokyo, Japan, 2008, pp. 5–7.
70. “Sediment bypass tunnels to mitigate reservoir sedimentation and restore sediment continuity,” 2014, CRC Press. doi: 10.1201/b17397-30.
71. G. M. Kondolf and W. V Matthews, “Management of coarse sediment in regulated rivers of California,” 1991.
72. T. Sumi, S. Nakamura, and K. Hayashi, “The effect of sediment flushing and environmental mitigation measures in the Kurobe River,” in *23rd ICOLD Congress*, 2009.
73. J. Liu, S. Minami, H. Otsuki, B. Liu, and K. Ashida, “Prediction of concerted sediment flushing,” *Journal of Hydraulic Engineering*, vol. 130, no. 11, pp. 1089–1096, 2004, doi: 10.1061/(asce)0733-9429(2004)130:11(1089).
74. S. Minami et al., “Coordinated sediment flushing and effect verification of fine sediment discharge operation in Kurobe river,” in *Proceedings of the ICOLD Conference*, Kyoto, Japan, 2012, pp. 6–8.
75. C. Auel, S. A. Kantoush, and T. Sumi, “Positive effects of reservoir sedimentation management on reservoir life: examples from Japan,” 2016.
76. T. Sumi, M. Okano, and Y. Takata, “Quantitative evaluation of a bypass tunnel to prevent reservoir sedimentation,” *Journal of Japan Society of Civil Engineers, Advances in River Engineering*, vol. 10, pp. 197–202, 2004.
77. 角 哲 也, “Comprehensive reservoir sedimentation counter measures in Japan,” *VAW-ETH Mitteilungen*, vol. 232, pp. 1–20, 2015.
78. H. Wang and G. M. Kondolf, “Upstream sediment-control dams: five decades of experience in the rapidly eroding Dahan river Basin, Taiwan,” *JAWRA Journal of the American Water Resources Association*, vol. 50, no. 3, pp. 735–747, 2013, doi: 10.1111/jawr.12141.
79. O. Reed, “Swiss methods of avoiding silt deposits in reservoirs,” *Eng. News Rec*, vol. 8, pp. 289–290, 1931.
80. C. Auel, T. Berchtold, and R. M. Boes, “Sediment management in the Solis reservoir using a bypass tunnel,” 2010.
81. C. Oertli and C. Auel, “Solis sediment bypass tunnel: first operation experiences,” 2015.
82. J. Hwang, “The study and planning of reservoir desilting in Taiwan,” *Water Int*, vol. 10, no. 1, pp. 7–13, 1985, doi: 10.1080/02508068508686288.
83. M. Schwartz, *Encyclopedia of coastal science*. Springer Science & Business Media, 2006.
84. R. H. Hotchkiss and F. H. Bollman, “Socioeconomic analysis of reservoir sedimentation,” in *Energy and Water: Sustainable Development*, ASCE, 1997, pp. 78–83.
85. R. M. Solow, “The economics of resources or the resources of economics,” *Discounting and Environmental Policy*, pp. 9781315199818–17, 2018.
86. G. W. Annadale, T. J. Randle, E. J. Langendoen, and R. H. Hotchkiss, “Reservoir sedimentation management: A sustainable development challenge.” [Online]. Available: https://iahr.oss-accelerate.aliyuncs.com/library/HydroLink/HydroLink2018_03_Reservoir_Sedimentation.pdf.