


Mechanisms of bedload sediment transport in reservoirs and associated mitigation techniques: A review

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ABSTRACT

Sediment transport in reservoirs, particularly bedload transportation, affects reservoirs capacity, aquatic habitat integrity, and longevity. Sedimentation of reservoirs is one of the main environmental problems and decreases their capacity, land productivity, and hydraulic structures' life, such as dams, due to sedimentation. Many factors control the incipient and continued bedload transport in a reservoir. These include the following: flow velocity, water depth, sediment size and density, bed slope, and the presence of cohesive forces. The flow of bedload takes place when the shear stress exerted by the flowing water is higher than the critical shear stress required for the movement of sediment particles from the substrate. Reservoir morphology is an important factor that determines the flow pattern and sediment deposition areas. Several techniques have been used in the reduction of sedimentation reservoirs. These have been discussed in this review.

Keywords: sedimentation mitigation, sediment bypass tunnels, environmental problem, reservoir capacity, sediment deposition zones and trap efficiency.

RESERVOIRS SEDIMENTATION

With the global population on the rise, the need for a sustainable water supply system is growing. However, despite this urgent requirement, the global capacity for water storage is steadily decreasing due to reservoir sedimentation, water scarcity, and a few global environmental problems.[1]. Gravity causes bedload deposits to occur in the upstream area of the reservoirs, and a decrease in water flow and velocity results in a loss of water storage volume [2] the sediment volume in reservoirs in the USA amounts to approximately 25×10^5 million cubic meters, with nearly one-third of reservoir volumes lost in 2023 [3]. Sedimentation problems will make the reservoir lose 0.5–1% of its total volume every

year. This problem is greater than the excess capacity that comes from the construction of new reservoirs [4]. Sediment deposition in reservoirs threatens the hydropower systems by obstructing inlet and outlet structures. This accumulation can result in decreased efficiency and increased maintenance expenses for hydraulic machinery due to abrasion. Furthermore, suspended sediment has been observed to clog cooling circuits near turbines, which directly extract water from the reservoir [5]. Changes in morphology have negative consequences on riverine ecosystems due to water quality and loss of aquatic and riparian habitats [6]. The small reservoirs can be controlled by sluicing or flushing sediment through large low-level outlets during floods or the rainy season, and sedimentation refers to two primary

causes: natural causes and anthropogenic causes. Sediment accumulation affects the dam’s stability by increasing the load on the dam body [7]. Reservoir sedimentation damages turbine blades by causing erosion and the formation of oxide coatings. If erosion continues, it may require lengthier shutdowns for maintenance or blade replacement [8]. The heavy particles in weight settle near the reservoir entrance within the delta formation, while lighter particles are transported a longer distance and deposited near the dam barrier, thus creating a muddy pool [9]. Delta typically contains sand; delta deposits can be scoured and transported deeper into the reservoir, accelerating their advance toward the dam and intake. As the reservoir draws down at a similar level every year, the particle deposition continually deposits on the face delta with little vertical growth. In contrast, when the minimum drawdown level is gradually increased over time, it can slow down the forward movement of the delta and result in vertical growth instead [10]. The rate at which storage is lost over time due to sedimentation depends on the reservoir’s initial storage capacity and a certain loss rate:

$$C_t = \text{Max}(0, C_0 - \frac{Lr}{100} C_0 t) \quad (1)$$

where: C_t is the storage at time t (year), C_0 is the initial reservoir capacity at the time of construction (m^3) and Lr is an annual loss rate (% of reservoir capacity) [11]. Table 1. presents regional average sedimentation rates (percent per year) and the projected dates when 80% of hydropower storage and 70% of other-use storage would be lost to sediment, for each region [5].

Siltation is a minor problem for the dams, but it could reduce their lifespan by half in just a few decades. But for more than 10% of huge or small

dams, it might become a big concern in just a few years or decades. The world has roughly 50,000 big dams, which hold about 7000 km^3 of water. Every year, rivers around the world get about 40,000 km^3 of water. The amount of sediment stored each year may now be more than 0.6% of the overall 1500 km^3 storage capacity of multifunctional reservoirs. Most of it is in the planned dead storage areas of hydroelectric projects [12]. The sedimentation rate for reservoirs larger than $1.24 \times 10^9 m^3$ in storage capacity was only 0.16 percent per year, with an average rate of 0.11 percent annually [13]. According to 19 reservoirs in Central Europe, with storage capacities ranging from 1.48×10^5 to $2.26 \times 10^8 m^3$, they revealed that they experienced depletion due to sedimentation at an average rate of 0.51 percent per year [14]. Also, in Ghana the average annual sediment load and sediment inflow into the reservoirs fluctuated between 3159 and 12,850 milligrams per liter and between 1594 and 355,017 cubic meters per year, respectively. The best method of sedimentation reduction is to practice the vegetation method and use the screen at the dam entrance [15]. To achieve reservoir sustainability, it is essential to prevent sedimentation in the reservoirs and maintain their storage function [4]. Figure 1. shows the impression about the related sedimentation process and its problems in reservoirs. A number of technologies and practices of sediment management have been developed and utilized. These methods can be classified as illustrated in Figure 2.

Prediction of soil erosion is the most important point in managing rivers and reservoirs, as well as sedimentation issues. In India, soil erosion averages 0.16 tons per kilometer annually, with 10% of it settling in the reservoirs and 29% being transferred to the sea [18]. The following mathematical equations are used to estimate the soil erosion loss [19]:

Table 1. Sedimentation risk ratio on the dams

Region	Average sedimentation rate%/year	Hydropower dams:80%	Other used dams: 70%
Africa	0.85	2100	2090
Asia	0.79	2035	2025
Australia & Oceans	0.94	2070	2080
Central America	0.74	2060	2040
Europe	0.73	2080	2060
Middle East	1.02	2060	2030
North America	0.68	2060	2070
South America	0.75	2080	2060

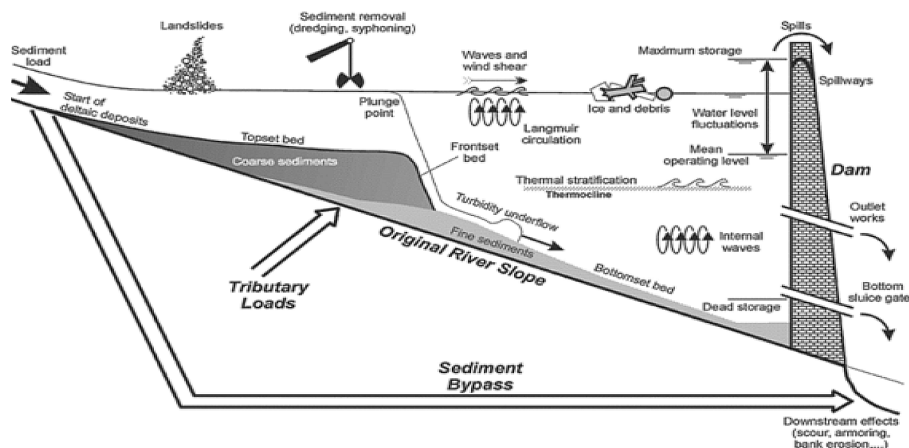


Figure 1. Schematic sketch of typical physical processes of sedimentation in a reservoir [16]

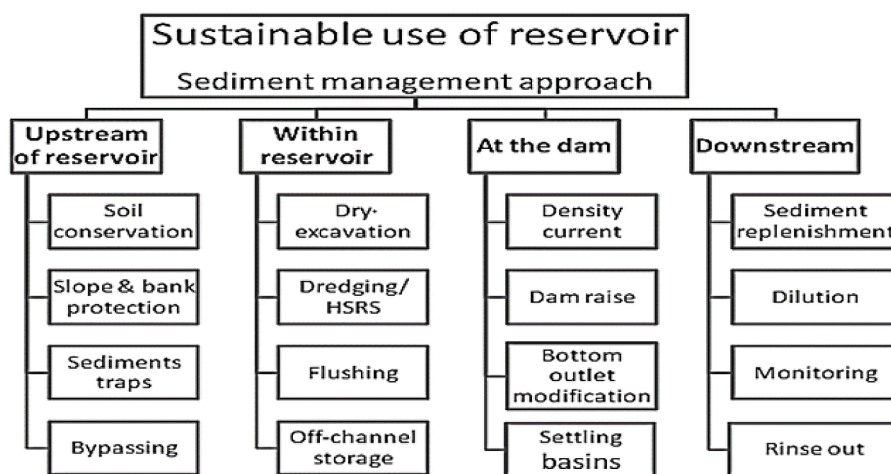


Figure 2. Inventory of measures for sediment management [17]

$$A = C'' \cdot S^{1.4} \cdot L^{0.6} \tag{2}$$

$$A = C'' \cdot S^{1.4} \cdot L^{0.6} \cdot P \tag{3}$$

$$A = R \cdot K \cdot L \cdot S \cdot C \cdot P \tag{4}$$

where: C'' is constant, S is the slope steepness factor, L is the slope length factor, P is the conservation factor, R is the rainfall erosivity factor, K is the soil erodibility factor, C is a cover management factor and A is soil loss per unit area in the unit time.

Estimation reservoir sedimentation rate

The rate of sedimentation in reservoirs changes depending on parameters like the type of soil, the type of land cover, disturbances (like landslides and wildfires), contributing areas, and hydroclimatic conditions. Collecting the required information on the sedimentation rate is an important step

for the sustainability of water resource management in future studies [20]. Different methods and techniques are used to estimate the sedimentation rate in reservoirs. The most direct measurement is through periodic lake bathymetry surveys, which survey two storage volumes for the same dams at two different times [21]. An empirical equation such as the modified universal soil loss equation and the monovarietal rating curve is used widely to observe the sedimentation rate. Using satellites and remote sensing to figure out how much sediment is trapped in a reservoir is a more advanced method. New technologies combine land surface models with real-world models to show how sedimentation changes over time and space [22–24]. Brune (1953) came up with the idea of trap efficiency as a way to figure out how much silt is in a reservoir. This method depends on the relationship between the trap efficiency and reservoir capacity inflow (C/I) ratio. Brune (1953) developed a curve

illustrating trap efficiency in response to the reservoir capacity-inflow ratio, employing data from 44 reservoirs in the USA, grounded in the original equation [25]:

$$Te = 1 - \frac{0.5}{\sqrt{\Delta\tau\Gamma}} \tag{5}$$

where: Te is a trap efficiency (% in decimal units). $\Delta\tau\Gamma$ is the local residence time change in years.

$$\Delta\tau\Gamma = \frac{\sum_{i=1}^n Vi}{I} \tag{6}$$

where: V is a storage capacity of reservoir in km^3 , I is an inflow volume km^3/day . Also, the following equations below were developed, Te is one of the main properties of reservoir estimation. Trap efficiency has been derived below [26, 27]:

$$Te = -22 + \frac{119.6 C/I}{0.012+1.02C/I} \tag{7}$$

$$Te = \frac{Vi - Vo}{Vi} \times 100\% \tag{8}$$

$$Te = 100 \times \left[\frac{K}{0.012+1.02K} \right] \tag{9}$$

$$Te = \frac{\left(\frac{C}{I}\right)}{0.00013+0.01 \times \left(\frac{C}{I}\right) + 0.000016 \times \sqrt{\left(\frac{C}{I}\right)}} \tag{10}$$

$$Te = I - \frac{1}{(1+K\frac{C}{A})} \tag{11}$$

where: C is the reservoir capacity, I is the inflow volume, K is the coefficient which varies from 0.046 to 1.0 and value of K is a 0.1 is recommended for average conditions, and values of K is 1.0, 0.1 and 0.046 may be used for coarse, medium and fine sediments, respectively and A is the area of the catchment above the reservoir.

Brune plotted Te against the reservoir C/I ratio (Figure 3) is a graph plotted by Brune has three curves consisting of one median and two envelop curves [28].

It was mentioned that an artificial neural network (ANN) was utilized to estimate reservoir sedimentation volume using a 32-year dataset from the Gobind Sagar Reservoir on the Satluj River in India. This river, which is close to the Himalayas and often has landslides and slips, could hold about $9,867.84 \times 10^6$ tons of sediment. The appropriate ANN model, employing the sigmoid activation function and RP as a learning rule, was determined through trial and error. Annual input parameters, including rainfall (Ra), capacity (Ct), and inflow (Ia), were used to estimate the output storage volume (Sv). For model development, 70% of available data was randomly selected, with the remaining 30% used for testing. SPSS 11.5 software was employed for this purpose. This equation below has been derived:

$$Sv = (-0.006 \times Ct) + (0.113 \times Ra) + (0.003 \times Ia) + 36.672 \tag{12}$$

Martellotta et al. [29] studied using a DJI Matrice 300 RTK drone with ZENMUSE L1 LiDAR technology as another way to estimate the silting volume increment of the Camastra reservoir. The given dead volume was compared to the previously obtained silting volume. The survey covered six areas, for which more than 1500 frames were obtained with a resolution of 20 MP and then processed to generate 2D and 3D views. GPS surveys and GMS modes were used alongside the drone survey. This equation below was derived for estimation:

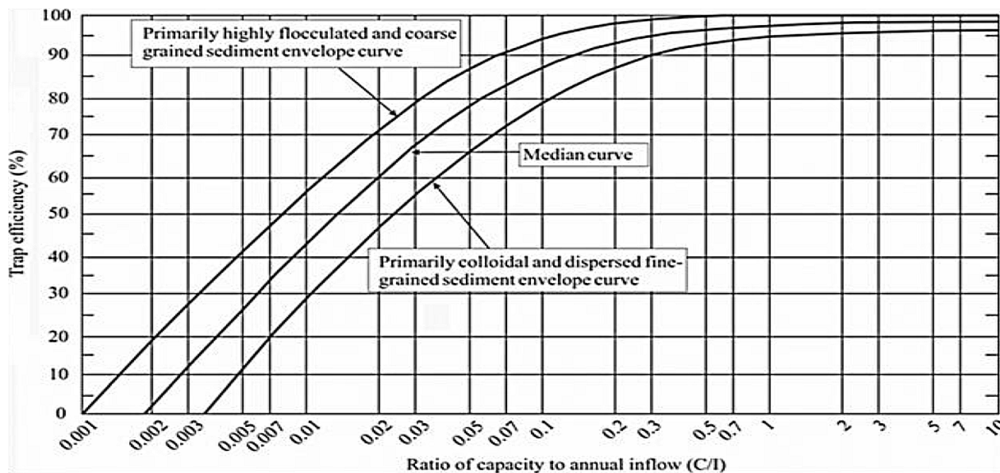


Figure 3. Brune’s curve for estimating sediment trapping efficiency

$$V_s = V_\infty \left\{ 1 - e^{-\left(\frac{t}{\tau_0}\right)^\sigma} \right\} \quad (13)$$

where: V_s (m^3) is the silting volume, V_∞ (m^3) is the maximum reservoir capacity, t (years) is the number of years of prediction, starting from the date of commissioning of the dam, σ is the measure of the level of complexity of the sedimentation process, and τ_0 (years) is the characteristic time interval for filling the reservoir.

The volume of silt carried out from the survey was $17.7 \times 10^6 m^3$, and the silting value up to 2022 of $18.65 \times 10^6 m^3$ of land deposited increases annually.

Reservoir sediment replenishment

Sustainable use of reservoirs faces significant challenges due to sedimentation, which reduces storage capacity. This paper reviews the feasibility of sediment flushing, covering factors such as water availability, cost, timing, reservoir geometry, sediment properties, outlet design, and downstream impacts; it emphasizes the need for careful planning and evaluation. To fix the problems that sediment deficiency downstream of dams causes, like bed armoring, bank erosion, a lower water table, habitat destruction, and oxygen stratification, a method called sediment replenishment, also known as sediment augmentation or artificial sediment feeding, has been suggested. This technique aims to restore sediment balance in rivers downstream of dams and is effective in managing reservoir sedimentation [30–32]. In this method, large amounts

of sediment are extracted out of the reservoir and moved to the river area just downstream of the dam on a regular basis. From there, the sediments are directed downstream through either natural or man-made channels [33]. Japan is one of the current leaders in SR (sediment replenishment) applications, with nearly 25% of its dams resorting to sediment excavation and a growing use of downstream replenishment [34]. Lack of a sediment layer in the downstream dam causes problems in morphological, hydrological, and ecological aspects. Sediment deficit is not only an environmental issue but also a socio-economic problem [33]. Figure 4 shows the management strategies for the sediment replenishment factor and summarize previous studies that have solved this problem.

The sediment replenishment can effectively restore the macroinvertebrate community structure downstream of a dam over time by increasing sediment deposition [35]. Sediment replenishment can restore the macroinvertebrate community structure downstream of a dam, indicating ecological recovery, and it has been confirmed in the Sarine River in Switzerland [36]. Numerous implementation strategies have changed in response to accessibility, costs, release flow regimes, and accessible places. principal goals, bedload sediment can be added to the channel bed by following different techniques [37], In-channel bed stockpiling, an old method since 1970, is widely used for supplying riffles or pool tails by spawning gravels within low-flow channels but may increase turbidity downstream. High-flow stockpile: the method is placing the gravel particles along the riverbank to be distributed in the riverbed during high-flow conditions [38,

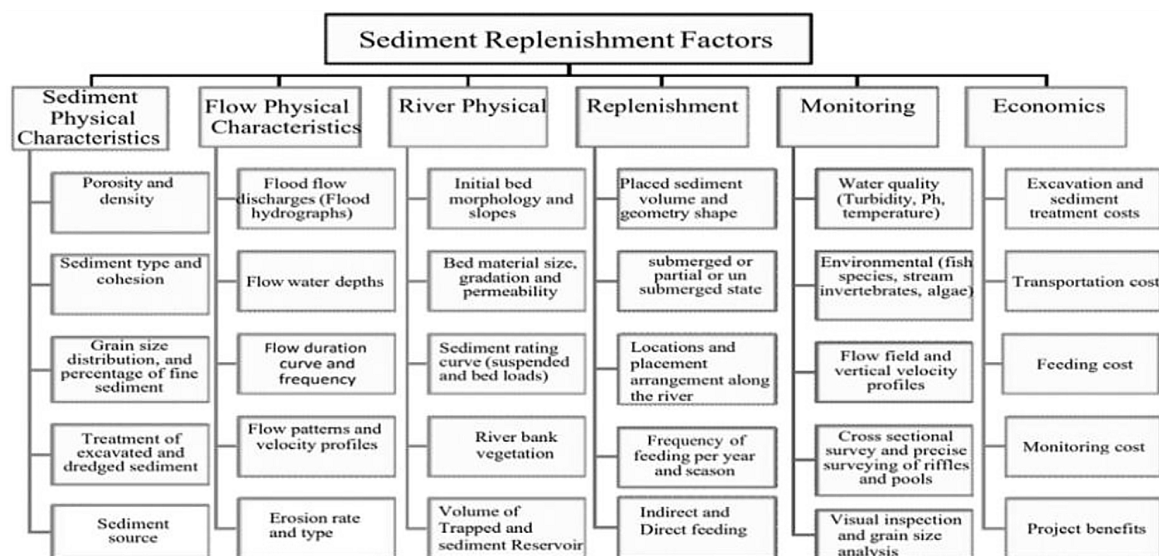


Figure 4. Main groups of sediment replenishment characteristics and managing factors [33]

39]. Sediment augmentation includes local, multi-reach, and river-segment-wide approaches; the point-bar stockpile method enhances a point bar by introducing coarse sediment based on site-specific low-flow and bank full channel dimensions of the reaches. The evolution of bedforms downstream is significantly influenced by the geometrical configuration of the replenishment volume. Parallel configurations lead to a wider spread of material across the channel [40]. Alternating configurations can be useful for producing sediment clusters and keeping material in the channel for a long time. For all configurations and volumes, the transported material moved in a longitudinal direction and tended to settle at a distance no greater than twice the length of the refill. The percentage of sediment replenishment that stays the same (PD). The weight measurements show how much gravel was taken out of the flume (PD%). For a successful replenishment, the reach that needs to be restored must have a high persistence value.

$$PD = \left(1 - \frac{M_{washout} (kg)}{M_{placed\ Sediment}(kg)}\right) \times 100 \quad (14)$$

where: *PD* is expressing how much of the replenished gravel remains in the reach after a disturbance, based on weight measurements.

Simultaneous placement of multiple replenishment volumes enhances erosion and redistribution of the added material, thereby prolonging the interval before the next replenishment campaign is required [33]. Figure 5. Shows the

different techniques for sediment replenishment along the rivers.

For building a point bar, coarse sediment can be added using the point bar stockpiling technique, which therefore requires a site with appropriate geomorphic and logistical conditions. Alternatively, the high-flow direct injection method places the sediment directly into the channel during a high-discharge event to promote immediate entrainment and downstream redistribution. However, excessive sediment replenishment leads to imbalance in the river system and increasing suspended concentration [42]. However excessive sediment replenishment leads to imbalance in river system, and increasing suspended concentration [43]. For enhancing replenishment efficiency, the replenished sediment volume should be sized to match the river’s annual sediment deficit. Berm erosion is promoted by placing stockpiles so they are well submerged during high flows, although the optimal trench geometry cannot be determined reliably without site-specific hydraulic and morphodynamical modelling. Beyond placement design, operational decisions at the dam are a primary control on performance; therefore, sluicing should be carried out as often as practicable to improve recovery of the downstream sediment balance.

EFFECT OF SEDIMENTATION ON THE ECOLOGICAL SYSTEM

Sedimentation significantly impacts ecological systems in diverse environments, ranging from freshwater rivers and lakes to marine coastal

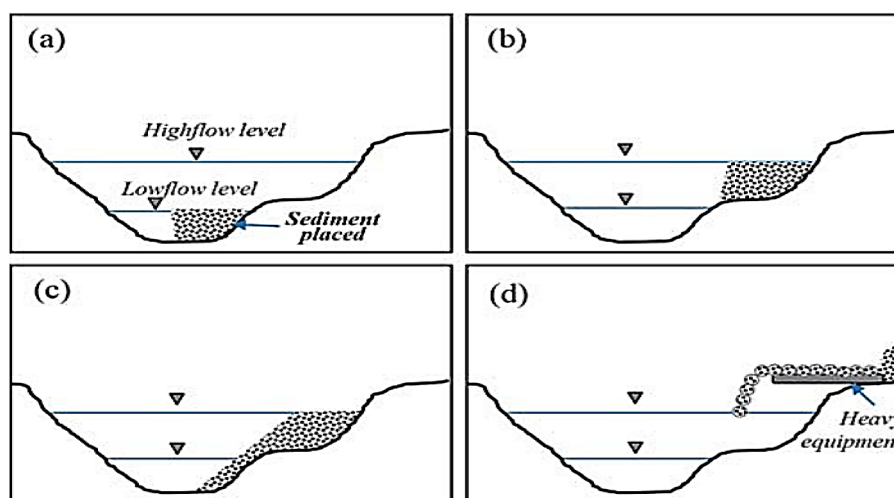


Figure 5. Different techniques for sediment replenishments(a) in channel bed stock pile, (b) high flow stockpile, (c) point bar stock pile, (d) high-flow direct injection [41]

regions. Reid et al. 2011 [44] conducted an experiment on stream and estuary ecosystems, demonstrating that interconnected ecosystems can be adversely impacted by the same stressor, exemplified by the transfer of excess fine sediment from streams to estuaries. It was expected that benthic macroinvertebrate communities would respond differently to sedimentation in streams and estuaries due to variations in the physical environment and species trait representation between systems. To compare these responses, fine terrigenous sediment was added at the same time to replicated plots in stream-run habitats and the nearby estuary. Adding sediment to streams made invertebrate populations smaller after one week, but there were no changes in taxon richness or community structure that were consistent, and densities had returned to normal after another week. Conversely, the addition of sediment to estuarine sites resulted in significant reductions in invertebrate densities and alterations in community structure, which persisted at the innermost sites 16 days post-addition. In both systems, sedimentation effects were only noticeable for some of the common taxa, and biological traits did not help predict the effects. When making predictions about how changes in land use that may increase sedimentation will affect things, we should consider how they might have worse effects in estuaries. Due to the relevance of sedimentation to ecosystems and humans, various methods to determine sedimentation rate have been developed and used depending on conditions such as data accessibility, measurement purpose, and budget and time available [45]. Sedimentary ecosystems cover most of the ocean bases, making them the most extensive ecosystem on Earth in terms of area [46]. The sedimentation may have

significant impacts on the alternating stages of an organism’s life cycle as well as the relative abundance and composition of macroalgal assemblages. Researchers have described only a small number of the micro-, meio-, and macroscopic benthic organisms that live in and on sediments, and they have conducted only a few studies to estimate the total number of species and biogeographic patterns. There is enough data on a few species to indicate that sedimentary organisms have a major effect on important ecological processes. Finely suspended sediment or deposited sediment affects fish in many ways. The characteristics of sediment that affect fish have been shown in Table 2. Suspended and settled sediments can reduce dissolved oxygen in the surrounding water, which in turn lowers fish tolerance to the harmful effects of suspended particles. In addition, elevated turbidity can modify surface-water heat dynamics; because warmer water has a lower oxygen solubility, dissolved oxygen may decline further during turbid periods, particularly in slow-flowing or stratified systems. Particles of sediment smaller than 63 μm are the most chemically active. They become bioavailable and have the ability to influence ecological processes because of their significant attraction for soluble metals, organic pollutants, and nutrients that may be deposited [47–49]. The suffocation of spawning habitat caused by sedimentation by particles will mostly affect species that spawn on or in the bed substrate. Given their immobility, the particular substrate and hydraulic conditions selected for spawning, and their immobility, eggs occupy the most limited niche of any stage of fish life; sediment transportation can negatively impact incubated salmonid eggs and juvenile stages. Excessively large grains (large cobble) or armor layers prevent salmonids

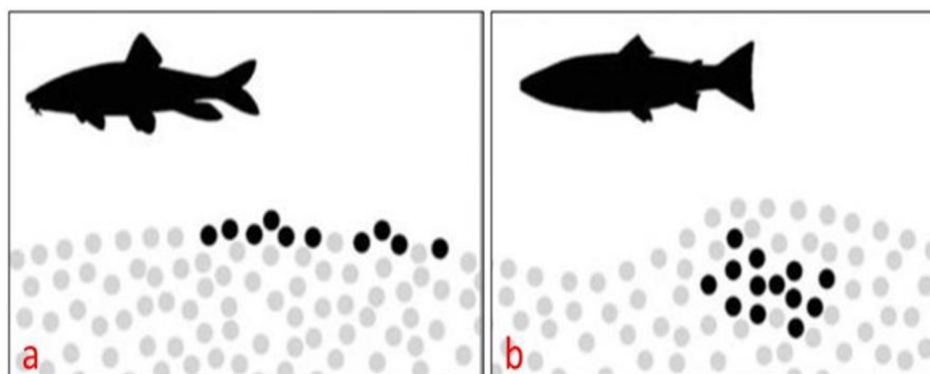


Figure 6. (a) Egg development on the substrata surface (breams), (b) fish that bury eggs in spawning pits in the gravel bottoms (salmons) [50]

Table 2. Characteristics that influence the effects of fine sediment on freshwater fish

Factor	Effect
Source of sediment (natural, agricultural, urban, etc.)	Determines the physical and biogeochemical characteristics of the sediment (e.g., Sediment Oxygen Demand (SOD)) and the temporal dynamics of inputs to rivers
Temperature	Influences reactivity of biogeochemical processes, fitness of individual especially if close to lethal limit
Angularity of particles	Influences abrasion effects on soft/sensitive tissues (e.g. gills)
Size of particles	Blocks micropores in egg chorion, influences rate of sedimentation and reactivity and content of contaminants through surface area and associated substrates
Sediment oxygen demand	Competes for oxygen demanded by incubating larvae
Organic matter composition and source	Determines SOD, influences bacterial communities on sediment, influences sedimentation processes
Toxicity (associated pollutants)	Can result in lethal levels particularly at incubation stage
Concentration of particles	Influences rate of sedimentation, turbidity, and abrasion
Resulting turbidity	Influences light, ability to forage and feed (visual feeders)
Duration of exposure	Can result in fatalities if prolonged, and result in changes to fish populations. May result in adaptation over long periods of time
Frequency of exposure	Can result in fatalities if prolonged, and result in changes to fish populations. May result in adaptation over long periods of time
Natural background concentration/turbidity	Determines tolerance levels of fish populations to fine sediment pressures
Availability and access to refugia	Provides opportunity to escape sediment pressure particularly if pressure is of short exposure
Species/genotype of fish	Determines tolerance levels to fine sediment pressures
Life stage of fish	Determines nature of impact and sensitivity to sediment pressure
Time of occurrence (relative to life history stage)	Influences impact—e.g. high risk during immobile larval stages
Fitness/health of individual	Determines tolerance threshold and ability to move away from pressure
Presence of other stressors/pressures	Influences tolerance thresholds/behavior and/or presence of refugia

from redd building; high percentages of small grains (fine gravel, sand, silt, and clay) do not allow successful reproduction due to reduced permeability and, consequently, insufficient supply of water and oxygen (Figure 7). Figure 6 shows the sedimentation layer’s importance for fish egg development; some fish bury eggs inside the gravel layer spaces.

In the abrasion process, increased loads of fine sediment led to higher suspended particle concentrations and faster deposition rates. Because of being prone to abrasion from flow particles, invertebrates may become dislodged or face damage to their body parts. The most adverse effect is probably produced by larger particles, especially sand, moving through saltation or as bedload; in

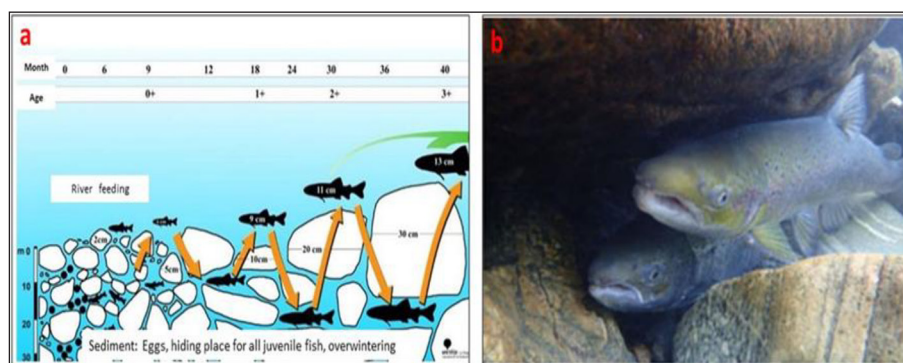


Figure 7. (a) Habitat use of Atlantic Salmon and brown trout juveniles in relation to grain size distribution in Norwegian salmonid rivers, (b) Adult Atlantic salmon of approx. 100 cm in length seeking shelter in the river bottom of the boulder-dominated cascade river Nordøla in Western Norway

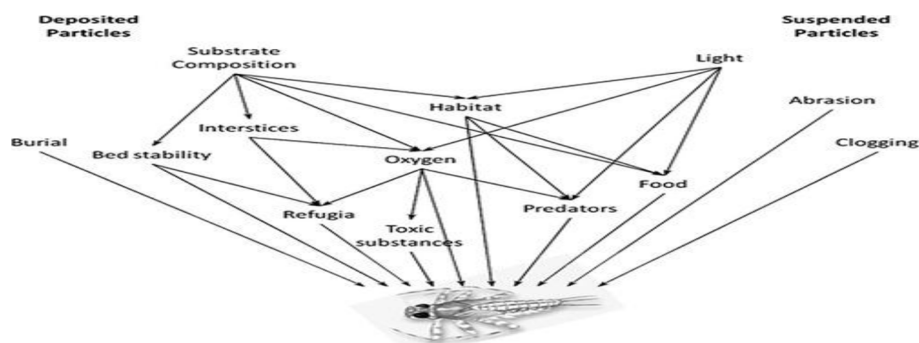


Figure 8. Direct and indirect mechanisms by which fine sediments impact upon macro-invertebrates, Impacts are caused by both suspended and deposited particles. Arrows show interacting effects and impacts on macro-invertebrates at the individual, species and community levels (collectively represented here as a mayfly larvae) [53]

studies, saltating sand resulted in catastrophic drift that was not observed when sand was deposited. High-velocity, smaller particles may cause damage. Most prone to harm are exposed body components such as the gills and filter-feeding system. Behavioral responses to protect sensitive structures from abrasion can ensue, such as retraction of filter combs, although such behavior disrupts normal functioning. For instance, when suspended sediment loads are high, *Brachycentrus* transition from filtering to grazing, most likely due to abrasion. When fine sediments settle on riverbeds, they can change the chemical environment in significant ways. As water penetrates the substrate less, the gradients of oxygen and other dissolved substances become greater. When organisms can't escape from their negative effects, they may move to areas with less velocity or utilize time fixing and cleaning their damaged structures. A lot of organic matter can make microbes work harder, which can lower oxygen levels and cause an accumulation of harmful substances like manganese, ferrous iron, and ammonium ions. While the increasing presence of particulate organic matter may advantage certain invertebrate species, it can also disturb the overall balance of the ecosystem [51, 52]. In Figure 8, it can be detected how the fine sediments (deposited and suspended particles) influence the aquatic invertebrate in several interlocking processes: direct processes (abrasion, clogging, and burial) and indirect habitat modifications (sediment composition, pore spaces, bed stability, refugia, oxygen, and light) that in turn affect habitat, prey, predators, toxicants, and survival/condition of the invertebrate.

Furthermore, deposit feeders may benefit from enhanced retention of organic matter on the riverbed; however, any increase in quantity may be

mitigated by a decline in nutritional quality. A significant amount of the material consists of accessible inorganic substances. Similarly, the nutritional value of periphyton (the film of interconnected bacteria, fungi, algae, organic materials, and silt on stone surfaces) may decline as the proportion of inorganic material in the layer increases. Periphyton quality can continue to decline due to the influence of turbidity on algal proliferation. Floating sediment limits the penetration of light to the riverbed, thereby impeding algal growth, and consequently, the nutritional quality of periphyton is lower. The decline in periphyton food quality may adversely affect invertebrate scrapers, such as snails, that depend on this resource [54, 55]. The detrimental impact of sediments with a high organic component is considerable, as their breakdown reduces oxygen levels in water. Excess silt decreases the flow velocities of interstitial and hyporheic zones, hindering natural waste removal necessary for embryo development. Suspended solids harm fish species like perch and roaches by affecting the deposition of eggs on macrophytes, where silt may adhere to the eggs, disrupting oxygen and carbon dioxide exchange. Fine sediment can also exert sublethal effects on fish fry, including delaying emergence by trapping fry in interstitial pores. Researchers have identified a relation between fine sediment (less than 0.850 mm) and fry survival, indicating a decline in survival of up to 3.4% for each 1% increase in fine sediment [56–58].

Impounding structures can hold both nutrients and sediments because many nutrients are attached to sediment particles. When levels of nutrients, especially phosphates and nitrates, become too high, the ecosystem upstream can change as plants and other organisms grow too much. If sediment isn't managed well, eutrophication and the spread

of organisms may occur more quickly, which might adversely affect the performance of the reservoir. At the same time, these nutrients may not reach areas downstream, which could disrupt the nutrient balance in ecosystems. Sediments can also bind or break down pollutants, making them less available to living things. However, if contaminated sediments accumulate in a reservoir, the toxins stored there can be hazardous to valleys downstream [59]. Fine sediment significantly influences the transport and destiny of several agricultural and industrial pollutants [60, 61]. Sponges form crucial parts of benthic ecosystems globally. As sessile suspension feeders, they will possibly be affected by changes in sediment depth. The roles herein include bioerosion that occurs on calcium carbonate substrates, filtering high water amounts, and acting as a significant linkage between benthic and pelagic ecosystems [62]. Sponges are suspension feeders that primarily acquire food and nutrients by filtering the water column, with many tropical species also depending on photosynthetic symbionts. They predominantly feed on particles smaller than 5 micrometers, particularly cyanobacteria and heterotrophic bacteria. Sedimentation in water areas has negative consequences on sponges. Sediments can negatively impact sponges by (1) direct ingestion of fine particles that clog filtering systems and affect physiology, and (2) scouring of surfaces by larger sediment particles

[63]; (3) by increasing turbidity and reducing light penetration, which will impact phototrophic species; and (4) by preventing the access of settling larvae to appropriate substrates when covered by deposited material [64, 65]. The biodiversity and abundance of sponges are significantly affected by sediment patterns, with sponge assemblages often exhibiting lower diversity and abundance in situations with high sedimentation. The direct and indirect impact of sediment on sponges can be mentioned in Table 3.

DIFFERENT TECHNIQUES TO MITIGATE SEDIMENTATION IN RESERVOIR

To preserve or restore the capacity of the original reservoir, required measures include (i) preventing sediment flow, (ii) directing sediment coming through controlled routing, and (iii) removing the accumulated sediment after accumulation. Since gravel river channels move as a bed load, it is almost always trapped by the dams, usually with 100% trapping efficiency for gravel except for small dams on steep channels capable of passing the bed load. Silt and clay are transported as suspended loads (often referred to as washing), usually passing through natural river networks and small dams, which occurs without significant storage with minimal sedimentation. Sand, however,

Table 3. Summary of the impacts of settled and suspended on different aspects of sponge [68]

Impact	Settled sediment	Suspended sediment
Filtering apparatus & pumping	<ul style="list-style-type: none"> – Clogging – Reduction or complete arrests in pumping activity 	<ul style="list-style-type: none"> – Clogging – Reduction or complete arrests in pumping activity – Some sponges exhibit ability to recover when sediment is gone
Respiration	<ul style="list-style-type: none"> – Not known 	<ul style="list-style-type: none"> – Reduction due to decrease in pumping to reduce ingestion of sediment – Elevation possibly due to initiation of sediment clearing mechanisms, causing increased metabolic demand
Feeding	<ul style="list-style-type: none"> – Reduction in feeding efficiency following burial by sediment 	<ul style="list-style-type: none"> – Reduction in feeding efficiency
Reproduction	<ul style="list-style-type: none"> – Reduction in spermatocytes and oocytes 	<ul style="list-style-type: none"> – Reduction in proportion of reproducing individuals – Reduction in female to male ratio – Oocyte size and reproductive index reduced. – Reduction in spermatocytes and oocytes
Growth	<ul style="list-style-type: none"> – Growth reduction due to energy expenditure on sediment removal mechanisms 	<ul style="list-style-type: none"> – Weight loss due to reduction in symbiont derived nutrients – Less pronounced negative effects in species with heterotrophic feeding strategies
Sponge symbionts	<ul style="list-style-type: none"> – Cyanobacterial loss in buried tissues – Chlorophyll a concentration reduction 	<ul style="list-style-type: none"> – Higher phototrophic sponge abundance at less turbid offshore sites
Larvae	<ul style="list-style-type: none"> – Not known 	<ul style="list-style-type: none"> – Not known
Juveniles	<ul style="list-style-type: none"> – Increased mortality 	<ul style="list-style-type: none"> – Increased mortality
Abundance & diversity	<ul style="list-style-type: none"> – Variation between studies; reports of increases and decreases in abundance and diversity 	<ul style="list-style-type: none"> – Variation between studies; reports of increases and decreases in abundance and diversity

Table 4. Cases on sediment transportation and replenishment process

References	Study area	Factors of sediment transport and negative consequences	Sediment transportation rate assessment	Annual mean volume of sediment replenishment (m ³)
[69]	Langat River, Selangor	Seasonal flow changes affect transport; median particle size (d ₅₀): 0.415 mm (high-flow), 0.101 mm (low-flow).	$Tj = \sum_1^n Gb$ $Gb = \frac{Wi}{(T \times hs)} \times b$ $Gs = 0.5 \gamma_s \times v^2 \times \left[\frac{d_{50}}{g(\frac{\gamma_s}{\gamma} - 1)} \right]^{0.5} \left[\frac{\tau_0}{(\gamma_s - \gamma)d_{50}} \right]^{1.5}$ $X = \frac{Ggr \times s \times ds}{D \times (\frac{ds}{\tau})^n}$	437–2,144 truckloads (25-ton trucks).
[70]	Saint-Sauveur Dam	Floodgate operations cause coarse sediment deposition; downstream incision (3 m post-dam).	$Qs = \rho \times \sqrt{g(s-1)} \times (D_{84})^3 \times 14 \tau_{84}^2 \times 2.5 [1 + (\tau_m / \tau_{84})^4]$	~25,450 m ³ gravel added; 22,650 m ³ from lateral erosion.
[71]	Futase Dam, Japan	Algal biomass declines when Dcri > 2 mm; bed material shifts harm ecosystems.	$\tau = \rho \left(\frac{ku}{\ln(10h/D_{84})} \right)$ $Dcri = \left(\frac{\tau}{0.045 R_s \times g \times D_{50}^{0.6}} \right)^{2.5}$	5,000–15,000 m ³ placed ~0.2 km downstream annually.
[72]	Mosul Dam	Tigris River supplies sediment; reservoir capacity reduced by accumulation (d ₅₀ = 12.4 mm).	Sediment ration curve for Mosul dam reservoir was used for 25 years Mosul dam operating. $TE_{Brune} = 100 \left[1 - \frac{1}{1 + 50 \left(\frac{C}{\tau} \right)} \right]$ $TE_{deny} = 100 [0.97^{0.19 \log(C/\tau)}]$ $TE_{ward} = 100 \left[1 - \frac{0.05}{\sqrt{\Delta t}} \right]$	Not quantified; focus on long-term capacity loss.

can be transported as a bed load or suspended load, depending on the flow disturbance. While small dams on the steep, turbulent currents can allow some sand to pass, large reservoirs usually retain it [73]. The vegetation significantly mitigates reservoir sedimentation by capturing sediment particles through its root system. It serves as a principal erosion control strategy by enhancing vegetative cover adjacent to the streambank and establishing wetlands. This method mitigates soil erosion, reduces the development of gullies and rills along streambanks, and ultimately lowers the risk of landslides [30, 74]. For mitigating the sedimentation problem, study in the delta process is crucial. When the river reaches the reservoir, the water velocity decreases, and heavy particles settle and create the delta migration. Fine particles were moved by the water flow, which created the current turbidity. Delta migration is formed in three regions from upstream to downstream (topset region, foreset region, and bottomset region [75]. To mitigate the sediment accumulation in the reservoir, it is crucial to reduce sediment levels at the source or in the rivers. The sediment particles may originate in the far and middle reaches of the catchment and in the reservoir. However, if the same sediment particles are released, they can cause clogging and reduce the flow in the channel [76].

Sediment bypass tunnels (SBT)

The sediment bypass tunnels are an effective technique for mitigating or preventing reservoir

sedimentation. The bypass tunnels are effective in preventing both bed load sedimentation and suspended sedimentation by evacuating sediments from the reservoir region during floods. The use of sediment bypass tunnels, however, is very limited across the globe owing to high costs. The bypass tunnels are generally designed for supercritical flows, which are not more than 10–15 m/s [73]. The morphology and ecology of the downstream regions should be regularly monitored to optimize the operation of sediment bypass tunnels (SBT). This monitoring is not only important to ensure the efficiency of sediment but also to assess the impact on local organisms and flora. Sediment bypass is commonly done through the tunnel, or occasionally an open channel may be used. Both suspended load and bedload can be transferred. The tunnel is produced in the dam body. However, some problems, like sediment accumulation, clogging, channel abrasion, river morphology issues, and water quality problems, have occurred. Two primary intake locations are usually available. The most common is on the head (a) of the reservoir, but another viable option is located at the bottom, near the dam (b) [77], as shown in Figure 9.

For the proper working of the sediment bypass system, it is necessary to predict and monitor not only the rating curve of flow but also the sediment concentration of the arriving water. In the sediment bypass of Nunobiki Dam, a diversion of 1.11 m³/s has been developed, and sediment inflow per day in ca. 100 years can be calculated by the following stream power equation.

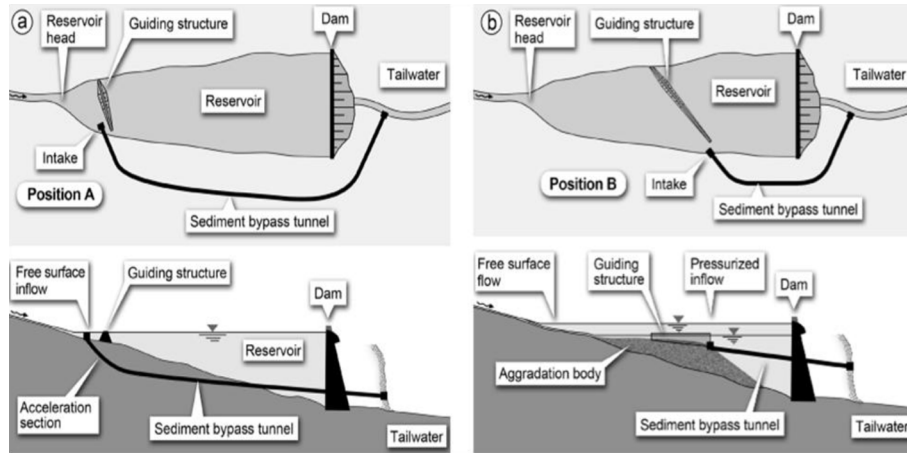


Figure 9. Sediment bypass intake is usually positioned on the head of the reservoir (a), but an alternative location is close to the dam (b) [78]

$$D = \alpha (A.R.I)^\beta \quad (15)$$

where: D is sediment yield during a flood event (m^3), A is catchment area (km^2), R is daily rainfall (mm), I is average riverbed slope in 200 m upstream from the calculating point α , and β are constants.

The slope of the tunnel invert must be sufficiently inclined to resist deposited sediment, but it must not be too inclined to slow down the flow of water and prevent abrasion. Levees of existing SBTs have slopes ranging from 1% to 4%. The cross-sectional shape of the bypass tunnel is generally in the form of an archway section, commonly referred to as hood sections, but in a horseshoe section. A gate is typically installed for the tunnel bypass, which opens to accommodate the maximum water depth, and the following parameters will be considered for their values: The uniform flow velocity is 9 to 15 m/s, and it is feasible for uniform flow velocity at the outlet point. If the Froude number is greater than 1, flow is supercritical. At the end of the acceleration section, velocity and height varied between 12 and 20 m/s. Asahi Dam, built in 1998 in Japan, has a hood-shaped sediment bypass and operates 13 times annually with a design discharge of 140 m^3/s . The Pfaffensprung sediment bypass functions 200 days a year, discharging sediment at a rate of 220 m^3/s [79]. Prediction of bedload flow sedimentation is an essential step in sediment bypass modeling. Einstein [80] carried out a theoretical analysis of bed load and derived a set of equations implicitly defined from the process of bed load transportation.

$$q_s = 11.2 \rho_s \frac{(\theta - 0.03)^{4.5}}{\theta^3} \cdot \sqrt{(s - 1) \cdot g D^3} \quad (16)$$

Smart and Yaggi (1983) equation for slopes of $0.0004 \leq S \leq 0.2$ follows:

$$q_s = \frac{4 \cdot \rho_s \cdot R_h \cdot U}{(s - 1)} \cdot \left(\frac{D_{90}}{D_{30}}\right)^{0.2} \cdot Se \cdot \left(1 - \frac{\theta_c}{\theta}\right) \quad (17)$$

where: R_h is hydraulic radius (m), U is mean flow velocity (m/s), Se is energy slope (-), and D_{90} and D_{30} (m) are diameters in which 90 % and 30 % of particles are smaller, respectively. The impact of the term $(D_{90}/D_{30})^{0.2}$ is low, so that it is replaced with a factor 1.05 [81]. The last equation published by Cheng [82] for $0.0013 \leq S \leq 0.19$ reads:

$$q_s = 13 \cdot \rho_s \cdot \theta^{1.5} \cdot \exp\left(\frac{0.05}{\theta^{1.5}}\right) \sqrt{(s - 1) g D^3} \quad (18)$$

Reservoir operation and sediment outflow have an impact on the effectiveness of sediment bypass. Is determined by dividing the volume of inflowing sediment by the volume of bypassed sediment. This construction is often made of stones and concrete. The materials include steel lining, granite pavement, cast-basalt tiles, and high-performance concrete [83]. To reduce erosion on the other river's banks, the angle between the tunnel's center and the river's thalweg should be minimal. The tunnel is designed such that it transports water at an 80% level from the tunnel height. The design of the sediment bypass at Asahi Dam aimed to flush the bedload and suspended load. A tunnel was designed with the objective of achieving two circumstances: first, the turbidity in peak flow should be prolonged. The peak flow was 200 m^3/s , whereas in the other concept,

Table 5. Hydraulic parameters of sediment bypass in Switzerland and Japan

SBT	Q (m³/s)	Maximum (V) (m/s)	(V) at outlet section (m/s)	Uniform (V) (m/s)	Froud number
Pfaffensprung	220	17	5	14	2.4
Egschi	50	12	10	10	2.0
Runcahez	110	20	10	9	1.4
Palagnedra	220	19	13	13	2.4
Rempen	80	14	12	12	2.8
Solis	170	13	11	11	1.7
Nunobiki	39	Not given	7	7	1.4
Asahi	120	12	12	12	2.2
Miwa	300	Not given	10	10	1.7

it flushed the entire bedload from the upstream side when the peak flow reached 660 m³/s, corresponding to the design for the 50-year flood at the sediment bypass, because it's the maximum flow in the design for the sediment bypass, or when it reached 1,200 m³/s, corresponding to the 100-year flood at Asahi Dam, since it is the flood design at Asahi Dam. Its capacity was set at 140 m³/s [84]. A weir built upstream diverts the sediment-rich flow into a bypass tunnel, which then releases the water back into the river downstream. When the sediment concentrations are low, the weir allows the water to enter the reservoir [85]. The sediment bypass system can be expensive due to the cost of construction of the tunnel, but it provides significant benefits, such as allowing the sediment to pass without entering the reservoir and disrupting its operation. To ignite the thick sediment, it is important to incorporate an anti-abrasion design for the lower surface of the tunnel to reduce long-term operating expenses (Table 5).

Sediment bypass and abrasion problem

Abrasion is a wear process that leads to material loss from solid surfaces as a result of impacts from metallic particles. It includes kinetic energy

from vertical impacts (deformation wear) and horizontal friction (cutting wear), whereas sliding and rolling do not contribute to abrasion. A significant issue in sediment bypass tunnels, such as the hydro-abraded inverted tunnel, arises from the combination and transport of large sediment volumes under high flow velocities. The degree of abrasion correlates with geological conditions in the catchment area, where high quartz content and larger average grain diameters intensify abrasion within the tunnel. A specific case of Swiss bypass tunnel abrasion has been categorized according to geological conditions and grain diameter, as discussed by Auel [86] (Table 6).

The presence of granites in the area upstream of the Asahi Dam was indicated. Moreover, the granite boulders have been deposited along the riverbed. The average size of the bed materials at the bypass intake was 50 mm. The maximum size was 300 mm. It was assumed that the size of the sediment passed through the tunnel. The formula can calculate the volume of the abrasion.

$$V = C_1 \times E_t + C_2 \times W_t \tag{19}$$

where: V is the volume of the abrasion(m³), C_1 is coefficient of damage by impact (m²/N), coefficient of abrasion to friction (m²/N).

Table 6. Geologic parameters of sediment bypass tunnels in Switzerland

No	Name	Geology	Quartz content	Grain diameter dm/d ₉₀ (cm)	Abrasion damage
1	Pfaffensprung	Granite	High	25/270	Major
2	Egschi	Grison's schist	Low	10/30	Mean
3	Runcahez	Gneiss	High	23/50	High
4	Palagnedra	Gneiss	High	7.4/16	High
5	Rempen	Flysh/Nagelfluh	Low	6/20	Low
6	Solis	Grison's schist	Low	6/15	Low-Mean

E_i is kinetic energy of gravel acting on the channel bed. ($N \times m$), and W_i is the total work done by abrasive force ($N \times m$), and the mean annual thickness abrasion for concrete steel were estimated at 40 to 50 mm/year and 0.2 mm/year, respectively [87].

The abrasion caused by the impact force due to the angle of impact and the speed of water pressure on the surface area are very essential factors. In geopolymer concrete, the abrasion loss due to longer curing time is low when it comes to the surface area, as geopolymer concrete is more durable than traditional concrete. The abrasion resistance depends on the physical properties, such as porosity and types of aggregates, along with the mechanics properties, as explained in [88].

Higher flow velocities and turbulence produce greater levels of energy, meaning that faster flow velocities work to enhance the abrasive effect on concrete, causing more erosion. A bigger solid particle, characterized by its angularity, has an enhanced abrasive effect as compared to the smaller solid particle, as explained by Dandapat and Deb [89]. Debris flow moves at a high velocity, which makes it very hazardous, and it includes water, mud, rocks, sand, and soil, as well as other matter like tree branches. Debris flow has several elements that include the flow mass, which has large solid particles; the snout; and the saltation front, which has saltating solid particles. These components appear in a specific order, following the direction of the debris flow. When the solid particles contact or touch the mortar surface, micro-cracks are formed and weaknesses occur. Then, the saltating particles force the aggregate away, which gives way to the stripping of the particles that form the aggregate [90, 91]. Figure

10 shows a good representation of the process of the removal of coarse particles. In the abrasion process, the mortar matrix undergoes mechanical wear and subsequently loses fine aggregates while exposing the coarse aggregates. Ultra-high-performance concrete (UHPC) and high-performance concrete (HPC) are forceful and durable, and they are better able to resist impact and abrasion. UHPC is characterized by a dense microstructure that minimizes water permeability and erosion susceptibility. Its advanced cement-based composition, enhanced with silica fume and fiber reinforcement, contributes to its effectiveness as an abrasion material. Additionally, UHPC demonstrates exceptional durability, significantly reducing chloride ion diffusion compared to conventional concrete, making it highly suitable for harsh hydraulic applications [92–94].

Grass and planting to mitigate sediment transport in the river and channel

Vegetation-based mitigation strategies, including grass planting and riparian vegetation restoration, are increasingly recognized as effective nature-based solutions to manage sediment transport [96–98]. Plants influence sediment dynamics by altering hydraulic conditions, reducing flow velocity, and stabilizing soil through root reinforcement [99]. This paper synthesizes recent findings on the role of grasses and planted vegetation in sediment control, comparing them with earlier studies and highlighting advancements in methodologies, effectiveness, and implementation challenges [100–102]. Vegetation interacts with sediment in multiple ways, influencing its entrainment, transport, and deposition. For example, plant roots bind soil particles, reducing their likelihood of being eroded, while foliage

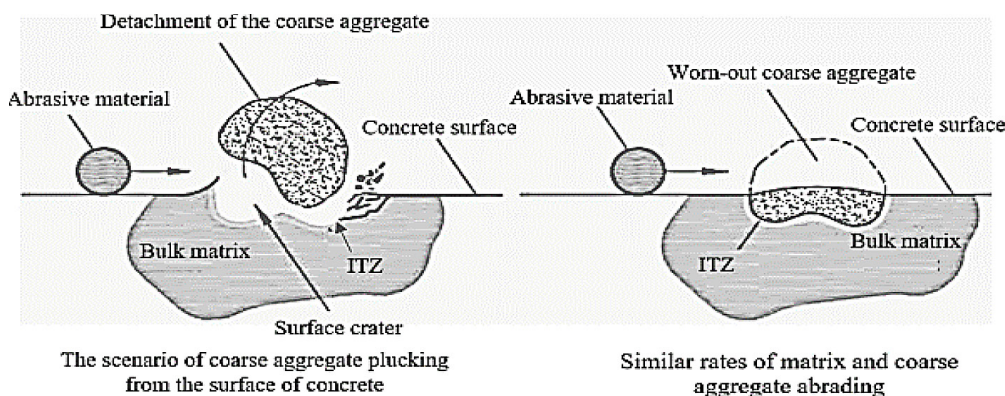


Figure 10. Mechanisms of aggregate detachment and aggregate abrasion at the surface of concrete showing the roles of the abrasive action and the ITZ and surrounding concrete material [95]

slows water flow, promoting sediment deposition [103–106]. Additionally, submerged vegetation increases hydraulic roughness, further limiting sediment transport downstream [107]. Recent field and flume studies confirm that vegetation reduces flow velocity, increases hydraulic roughness, and facilitates sediment retention. Grass roots in particular have been shown to improve soil cohesion significantly, minimizing erosion during high-flow events.

Vegetation provides local flow resistance by reducing velocity, since it enhances drag, while concurrently reducing the availability of shear stress for transport and erosion [108]. Vegetation can treat the water area environment. The vegetation in Putrajaya wetland can eliminate 82.11% of total nitrogen, where bacteria convert nitrate into harmless nitrogen gas, 70.73% of nitrate-nitrogen, and 84.32% of phosphate. Compared the disparities among USA wetland complexes, which diminished peak flows and annual total suspended solids (TSS) by over 90%, alongside a drop in $\text{NO}_3\text{-N}$ outflow to zero [109]. Figure 11 shows the important role of vegetation in trapping sediment in wetland areas. The presence of vegetation causes the suspended particles to settle due to decreasing water velocity. Vegetation path and physical shape can influence the sediment transportation rate. The bed load transport from emergent vegetation by experiment was studied by [110]; the study demonstrates that stem drag significantly influences bed shear stress, elucidating the correlation between bed shear stress (τ) and bed load rate (q_s) as illustrated:

$$q_s = 0.017(\tau)1.05 \quad (20)$$

The effectiveness of different vegetation types in sediment transport can be compared based on their structural and functional characteristics. Vegetation stabilizes riverbanks by improving soil moisture retention and reducing fluvial disturbance, which together affect the flow regime and influence the river’s energy and sediment transport capacity [112]. Compared to bare banks, banks with plants have more total kinetic energy (TKE). The TKE values are lower in the middle of the channel and higher near the wall. Near the vegetated wall, turbulence was much less anisotropic than it was in the middle of the rivers. Vegetation decreases the variation in the drag coefficient. The maximum velocity occurs at 65% of the water depth from the bed (or 35% below the surface) for vegetated banks [113]. Despite their advantages, vegetation-based strategies for sediment control face several challenges [114]. One major challenge is establishment time, as young plants offer limited erosion control before their root systems develop. Seasonal variations also impact effectiveness, with growth cycles affecting how well vegetation can stabilize sediment. Flood resilience is another critical issue, as extreme floods may uproot vegetation, reducing its stabilizing benefits [115, 116]. Additionally, optimal planting configurations must be carefully considered; overly dense vegetation may obstruct flow, while sparse coverage may not effectively trap sediment (Table 8, 9).

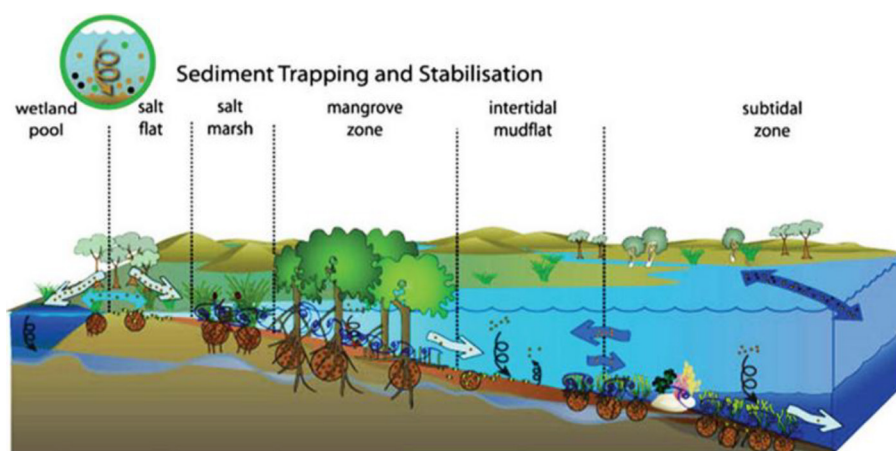


Figure 11. The wetland zone, the present of vegetation is sparse, but has the important role for trapping sediment. Vegetation decreases the suspended particles and allow to settle the particles. River vegetation facilitates sediment deposition by enhancing drag forces, sheltering flows, and providing surfaces for trapping and stability (Table 7) [111]

Table 7. Effects of vegetation on sediment transport

Vegetation type	Sediment trapping efficiency	Erosion resistance	Flow reduction effect	Best use case
Grasses	High	High	Moderate	Streambanks, channels
Shrubs	Moderate	Moderate	High	Riparian buffers, slopes
Trees	Variable	Very High	Very High	Large riverbanks, erosion-prone areas
Aquatic plants	High	Low	Variable	Wetlands, Slow-moving Streams

Bedload dredging and sediment siphoning in reservoirs

Two primary mitigation strategies have emerged: bedload dredging, involving mechanical or hydraulic sediment removal, and sediment siphoning, which utilizes hydraulic gradients for passive transport [122]. This review synthesizes their mechanisms, comparative efficacy, environmental impacts, and recent innovations to guide context-specific sediment management.

Bedload dredging

Bedload dredging employs mechanical (e.g., grab dredgers) or hydraulic (e.g., suction pumps) methods to excavate sediments, particularly near dam intakes or foundations [123]. Sediment dredging has successfully eliminated accumulated nutrients (nitrogen, phosphorus) and contaminants (heavy metals, persistent organic pollutants), which would otherwise

remain sequestered in bottom sediments and potentially leach into the water over extended periods. Dredging in agricultural drainage ditches can eliminate 33–66% of phosphorus found in sediments [124]. Advanced techniques include jet-assisted dredging – fluidizes fine sediments into turbidity currents during floods, achieving moderate removal rates in Chinese reservoirs [125]. Eco-friendly dredging – combined with Delft3D modeling in Indian reservoirs (Kundah Palam, Pillur) to minimize operational disruption [123]. Automated dredging – uses geospatial monitoring for precise residual management, though requiring extensive sediment characterization [126]. This technique has two main advantages: Targeted removal of coarse or contaminated sediments [127]. Material reuse – dredged sediments can be repurposed for agriculture or construction [123]. Additionally, this technique faces several challenges, including high costs – fuel, labor, and maintenance expenses

Table 8. Different vegetations types and their influence on bedload transportation

Vegetation type	Key effects on sediment transport	Citation
Grasses	Reduce flow velocity and trap sediments; less efficient than shrubs and trees due to lower stem density	[117]
Shrubs	Effective in wind-driven sediment transport reduction; morphological diversity may reduce effectiveness.	[118]
Trees	Increase flow resistance and promote sediment deposition; deep root systems stabilize soil.	[119]
Aquatic Plants	Emergent plants reduce bed shear stress; submerged plants stabilize the bed and reduce resuspension.	[120, 121]

Table 9. Challenges and solutions in vegetation-based sediment control

Challenge	Impact	Proposed solution
Establishment time	Young plants offer limited erosion control	Use fast-growing species or pre-grown plants
Seasonal variability	Growth cycles impact effectiveness	Select resilient, multi-seasonal species
Flood resilience	Extreme floods may uproot vegetation	Combine vegetation with engineered reinforcements
Optimal planting density	Too dense: flow obstruction; too sparse: reduced sediment trapping	Use mixed-density plantings for optimal effectiveness

[128]. Ecological disruption – elevated turbidity and benthic habitat destruction [129]. Inefficiency in cohesive sediments – high shear strength (>20 kPa) in Indonesia’s Bengawan Solo River demanded high-capacity dredgers [130]. After sediments with high levels of pollutants or too many nutrients are removed, bottom habitats, benthic organisms, aquatic plants, and fish may grow back, which will improve biodiversity and the function of the ecosystem. While dredging can reduce internal nutrient/pollutant load, it can also alter water physicochemical properties (pH, dissolved oxygen, redox potential, transparency, temperature), disturb sediment-water interactions, release nutrients and heavy metals, and disrupt aquatic communities. Annual dredging volume in Europe (sediments dredged in European harbors, rivers, etc.) is 300 million m³/year [131].

Sediment siphoning

Sediment siphoning exploits hydraulic head differences to transport sediments through pipelines. Key design parameters include: pipe diameter (D) and inlet submergence (C/D)

– optimal efficiency at C/D = 0 and Froude numbers > 5.8 [122]. Inlet geometry – wedge-shaped (60°) or swinging inlets improve cohesive sediment removal by 110% [132]. Burrowing-type pipes – deployed in Japanese reservoirs to address blockages [133]. The technique advantage includes: energy efficiency – gravity-driven operation reduces fuel dependency [134]. Low turbidity – minimal plume generation compared to dredging [135]. Cost-effectiveness – Sudan’s Roseries Reservoir saved \$2 million annually [127]. The limitation of this technique is Site specificity: This technique requires a sufficient hydraulic head. Clogging risks – coarse sediments (>2 mm) impede flow. Bedload dredging excels in removing coarse/contaminated sediments but incurs high costs and ecological impacts. Sediment siphoning offers a low-energy alternative for fine sediments but is constrained by site hydraulics. Integrated approaches, leveraging real-time monitoring and hybrid systems, represent the future of sustainable sediment management (Tables 10–12).

Table 10. Operational and environmental trade-offs for bedload dredging and sediment siphoning

Criterion	Bedload dredging	Sediment siphoning
Energy use	High (fuel-powered)	Low (gravity-driven)
Cost	High operational/maintenance	Moderate initial investment
Depth adaptability	Effective in shallow and deep zones	Limited by hydraulic gradient
Ecological impact	High turbidity, habitat disruption	Low disturbance, minimal biota impact
Sediment type	Coarse/contaminated	Fine/loose non-cohesive

Table 11. Pros and cons of bedload dredging vs. sediment siphoning

Criterion	Bedload dredging	Sediment siphoning
Mechanism	Mechanical/hydraulic excavation	Hydraulic suction
Energy use	High (fuel-dependent)	Low (gravity-driven)
Operational depth	Flexible (shallow to deep)	Limited by hydraulic head
Ecological impact	High turbidity, habitat disruption	Low turbidity, minimal disturbance
Cost efficiency	High operational costs	Lower long-term costs
Sediment applicability	Coarse/contaminated	Fine/cohesive

Table 12. Mechanism-to-impact matrix

Method	Turbidity	Storage recovery	Flow regime	Cost
Bedload dredging	High	High (temporary)	Disrupted	High
Sediment siphoning	Low	Moderate (sustainable)	Maintained	Moderate

CONCLUSIONS

Sedimentation in the reservoir poses a major issue in the sustainable management of water resources around the globe in the 21st century and the coming centuries. The scope of the study includes the in-depth study of sedimentation in the reservoir due to natural erosion processes and human-made processes like cutting down trees for deforestation, land clearance for agricultural purposes, and further due to the increase in urbanization. The causes of sedimentation depend on topographical elements and occur in the river's far reach, mid-reach, and in the vicinity of the reservoir. The different impacts of sedimentation have been discussed. The positive aspect is that we have deliberated upon different techniques to reduce sedimentation in the reservoir. The different techniques, like bypass tunnels, dredging methods, flush operations, and sluicing operations, have been described thoroughly in the study along with their advantages and disadvantages. Each of the sediment management techniques described above has its own set of advantages and disadvantages. The key to obtaining a successful outcome in every sediment management technique is to observe and implement them in accordance with their geographical position, physical properties, plant growth, climatic factors, anthropogenic factors, sediment characteristics, reservoir shape, and ecological parameters. Particular attention was given to the flushing and sluicing process. Bypass tunnels have been created in many countries around the world in the past decades, including China, Japan, and Switzerland. Moreover, the success of sedimentation at sedimentation reservoirs can also be achieved through collective action. In addition to that, land usage, erosion, and sedimentation monitoring have significant importance in sedimentation management. Despite all the progress, there are still many challenges in sedimentation management, which include limited funding, conflict among politicians, and the uncertainties caused by climate change. Combining modern technological advancements with increased knowledge of management programs would open an opportunity to develop more productive solutions. Many spheres of science have provided powerful opportunities for various programs with respect to sedimentation management..

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