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Management Alternatives to Combat Reservoir Sedimentation

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Abstract

Many techniques are available to actively manage reservoir sedimentation, and an equally important suite of adaptive strategies are available for managing the impacts of sedimentation without manipulating the sediment. Successful reservoir management to combat the effects of sedimentation may employ a combination of active plus adaptive strategies. This paper describes both active and adaptive strategies to manage reservoir sedimentation, and may be useful as a checklist of options to consider in addressing a sedimentation problem. Widespread application of both active and adaptive strategies will be required to successfully address the growing sedimentation problem worldwide.

1 Introduction

Sedimentation reduces reservoir storage and the benefits derived therefrom. Sustainable reservoir management seeks to retard sedimentation and reduce its adverse impacts, and to ultimately achieve an equilibrium between sediment inflow and outflow that sustains storage capacity while maximizing project benefits.

Successful sedimentation management may employ a combination of strategies, which may change over time as sedimentation becomes more advanced. The classification of "active" management techniques presented by Morris (2014) has been modified and expanded in Figure 1 to include "adaptive" strategies which do not manipulate sediment, yet which are essential management options to address reservoir sedimentation. Both active and adaptive options should be considered as integral components of the management strategy, and a combination of both approaches can represent the best overall response.

2 Reduce Sediment Yield

Two types of strategies may be used to reduce sediment yield: control of either surface or channel erosion at its source, or trapping eroded sediment upstream of the reservoir.

Surface erosion. Soil surface erosion is initiated by raindrop impact which dislodges soil particles to initiate transport. Control of soil erosion generally focus on establishing and sustaining a protective vegetative cover. Leaves and vegetative detritus covering the soil intercept raindrops and protect the surface from direct impact. Organic material gives structure to the soil, providing both physical and chemical binding agents in the form or plant roots, mycorrhizal fungi threads and microorganisms. Plant material also provides food and habitat for burrowing fauna (earthworms, for example), which further improves soil structure, porosity and permeability. Through these vegetation-linked processes the soil develops a self-sustaining structure that resists erosion. Even if surface runoff is initiated the organic detritus on the soil surface, including grass stems, fallen leaves and twigs, creates small obstacles on the soil surface which impedes shallow surface flow and helps to trap sediment after it travels only a few centimeters.

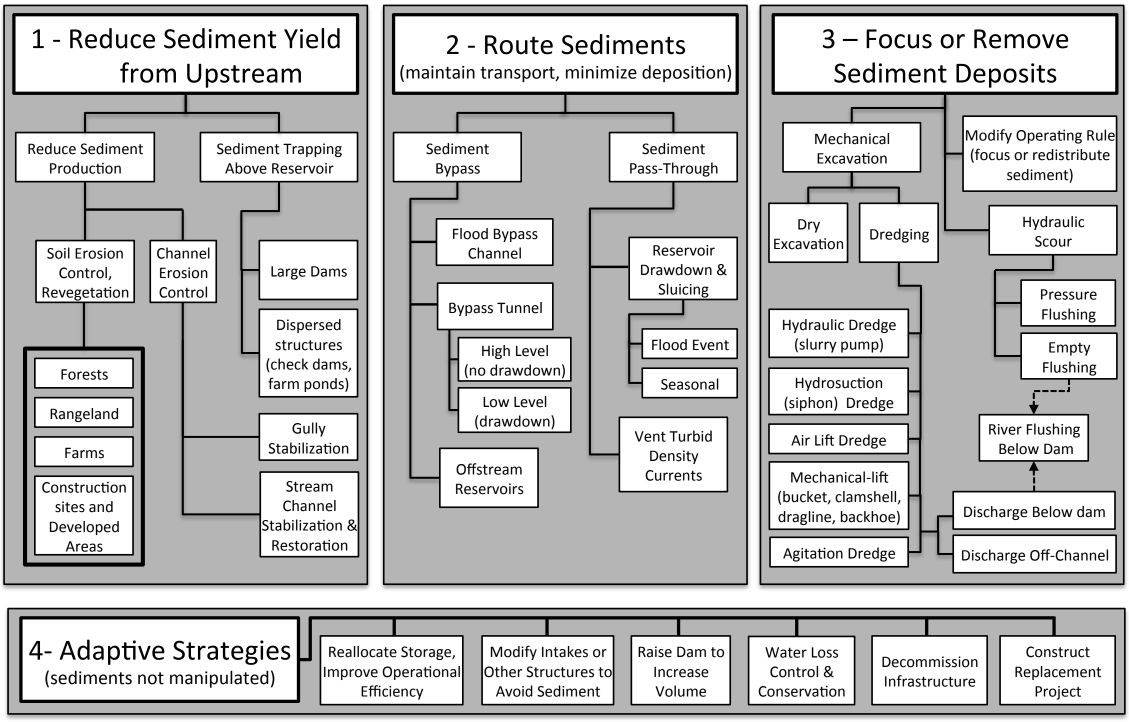

Figure 1: Classification system for sedimentation management outlining the four major types of activities that can be undertaken to combat sedimentation and its consequences.

Channel erosion. Once surface runoff flows coalesce to form channels the concentrated flow can be highly erosive. However, the bank erosion frequently apparent on the exterior of stream meanders only represents a significant source of sediment export when the channel is incising and widening. Bank erosion associated with the natural meandering of rivers, with an eroding bank on one side and a growing point bar on the opposite side, does not export significant sediment downstream as long as the river's longitudinal profile and cross-section do not change (the stream simply moves laterally across its floodplain, eroding one bank and filling the other). Prior to attempting channel erosion control it is important to distinguish between the natural meandering of a stable channel and accelerated erosion from a growing channel cross-section. Attempts to stabilize a naturally meandering stream of stable cross-section will not reduce sediment yield. On the other hand, gullies are an extreme case of channel incision and widening, frequently associated with intermittent flow.

Sediment trapping. Not all sediment that enters a channel will reach a downstream reservoir. Sediment trapping naturally occurs when a river overflows its channel and flows more slowly across its floodplain, depositing part of the sediment load. Large dams act as highly effective sediment traps, but a large number of small structures such as check dams and farm ponds can also be very effective in trapping sediment. For example, at least 2.6 million small farm ponds capture runoff from 21% of the total drainage area of the conterminous USA, representing 25% of total sheet and rill erosion (Renwick *et al*. 2005).

3 Route Sediments

Sediment routing techniques maintain inflowing sediment in motion, either passing sediment-laden floods around (bypass) or though (pass-through) the storage zone.

3.1 Sediment Bypass Strategies

Offstream reservoir. Offstream reservoir storage is constructed outside the natural river channel by impounding a side tributary having a small watershed or constructing the impoundment on an upland area. Clear water is diverted into the offstream reservoir by a river intake but large sediment-laden flows pass beyond the intake and are not diverted to storage. Offstream reservoirs have been used for municipal supply and as daily regulation storage for run-of-river hydropower. Although highly effective in reducing sedimentation, provision should be made for their eventual cleanout.

Sediment bypass tunnel. A sediment bypass tunnel (SBT) has its entrance upstream of the area to be protected from sedimentation and diverts either suspended sediment bed load sediment around the storage to discharge below the dam. They are sized to pass flood flows. Although outlet works at earthen dams often use tunnels through the abutments, these do not qualify as SBTs because they do not intercept sediment upstream of the storage zone. SBTs normally operate for extended or multiple periods each year, reducing environmental impact compared to the larger and more concentrated sediment releases characteristic of reservoir emptying and flushing using low level outlets at the dam.

SBT systems may be classed as either “high-level” or a “low-level” depending on the placement of the tunnel intake and whether it is required to draw down the reservoir to flush bed material through the tunnel. A high-level SBT system can flush bed material without reservoir drawdown, the low-level system cannot.

The entrance to a high-level SBT is installed at the upstream limit of the reservoir so that water and sediment can be bypassed around the impoundment without reservoir drawdown. The typical arrangement involves a low check dam to trap and divert sediment together with a bypass tunnel immediately upstream of the check trap dam (Figure 2A). At high flood flows the tunnel entrance will become submerged by backwater from the check dam and create orifice flow. The low velocity in front of the submerged SBT entrance will not transport coarse sediment into the tunnel, which now acts in a pressure flushing mode. When flow rate and water level diminish and free flow again occurs at the tunnel entrance, the higher velocity shallow flow will again transport coarse material into the tunnel. This sequence is illustrated in Figure 2(B).

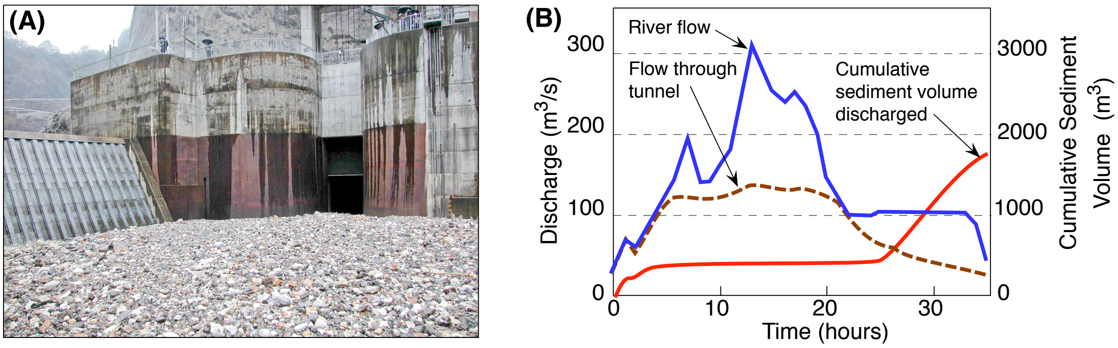

Figure 2: (A) Photo of the entrance to the bypass tunnel at Asahi pumped storage reservoir, Japan, with check dam on left. (B) Sediment bypass tunnel behavior at Asahi reservoir showing that bed material sediment is discharged only at lower rates of flood flow when the tunnel entrance is not submerged (after Fukuda *et al.* 2012).

The 30 Mm^3 multi-purpose Miwa dam in Japan (Umeda *et al.* 2004, I.E.A. 2006) provides an example of a high-level SBT designed for suspended sediment bypass. It uses the arrangement outlined in Figure 3 incorporating two separate upstream dams. A check dam traps bed load and suspended sand, which are removed mechanically, and further downstream a weir diverts flood flows and their suspended sediment into the SBT. This arrangement eliminates most of the abrasion damage in the tunnel and the trapped bed material can be excavated for use as construction material.

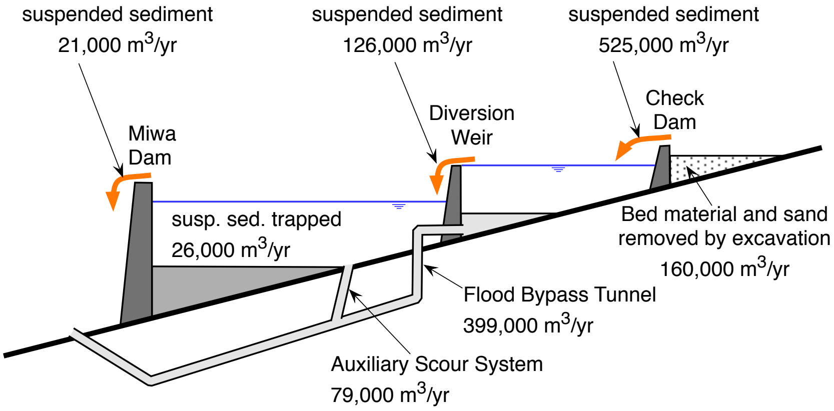

Figure 3: Sediment bypass arrangement for Miwa dam, Japan (after I.E.A. 2006)

In longer reservoirs a low-level SBT may be used with the tunnel entrance located below the normal pool elevation. The normally-submerged SBT can bypass suspended load, including turbidity currents, without reservoir drawdown, but to control the advancing delta the reservoir is drawn down for flushing. The flushing discharge may be passed through the SBT or through low level outlets at the dam.

An example of flushing through a SBT is the Solis hydropower reservoir in Switzerland where a retrofit STB system was designed to maintain storage volume for daily regulation. Bed load is directed into the tunnel entrance by a low guide wall, designed to emerge above the water surface only when the reservoir is drawn down to the SBT flushing level (Auel *et al* 2010).

At a run-of-river project under evaluation in Nepal a SBT is being considered to maximize the bypass of suspended sand, minimizing both sediment and hydraulic loading (maximize sedimentation efficiency) in the regulating storage volume between the SBT and the intake, and avoiding costly underground sedimentation basins for a design flow of 675 m^3/s. This operational strategy is shown in Table 1. The reservoir will be periodically flushed by opening high-capacity low-level gates at the dam.

Table 1: Operational Strategy, Suspended Sediment Bypass Tunnel at Run-of-River Hydropower Dam.

Inflow	Operation
Inflow < Design Flow	All inflow to power + environmental flow
Design Flow < Inflow < Flushing Flow	Inflow exceeding Design Power is bypassed
Inflow > Flushing Flow Threshold	Gates at dam opened for empty flushing of reservoir

3.2 Reservoir Drawdown and Sediment Sluicing

Temporary reservoir drawdown during events with high sediment inflow will reduce the residence time and enhance sediment discharge. Even in a shallow and nearly circular reservoir having poor geometry for sediment release, limited drawdown which reduces flood detention time can increase sediment discharge (Lee *et al.* 2013).

Sediment *sluicing* is a more aggressive drawdown technique implemented by reducing reservoir level in anticipation of a large flood event, and operating gates to create riverine flow conditions along the impounded reach to transport the inflowing flood and sediment through the reservoir. A high-velocity sluicing flow may also scour and release a portion of the previously deposited sediment. Drawdown sluicing can be performed on a seasonal basis, as practiced during the monsoon at some Himalayan hydropower reservoirs, or it may be event-based with reservoir operated guided by real-time reporting gages and hydrologic forecast models.

Because previously deposited sediment can be removed by both sluicing and flushing, in some cases the differentiation between these techniques may be ambiguous. The parameters in Table 2 may help to distinguish between the two processes.

Table 2: Differentiation Between Sluicing and Flushing.

Parameter	Sluicing	Flushing
Timing	Always coincides with natural flood flows	May not coincide with natural floods
Reservoir intakes	Can usually be operated during sluicing periods	Cannot operate (concentration too high, water level too low)
Outlet capacity	Can pass large floods with minimum backwater	Discharge may be limited by low level outlet capacity
Sediment discharge	Sediment Outflow ≈ Inflow	Sediment Outflow > Inflow
Erosion pattern	No retrogressive erosion	Retrogressive erosion may occur
Gate placement	Set and operated to achieve desired hydraulic profile during drawdown	Set gates at lowest possible level to maximize erosion in empty reservoir

Sluicing passes the natural hydrograph and its associated sediment through the reservoir with as little attenuation as possible, maintaining natural patterns of flow and sediment transport below the dam. This minimizes downstream environmental impacts. On the other hand, flushing can release very high sediment concentrations (e.g. 100,000 mg/l) and may require complex environmental mitigation measures. It is important that sites where sluicing is planned be properly designated to avoid being characterized as having the adverse downstream impacts normally associated with flushing.

3.3 Turbidity Current Venting

Turbid density currents are sediment-laden flows that plunge beneath the impounded water. Under favorable conditions they can travel along the submerged thalweg to the dam, where they either accumulate as a submerged “muddy lake” or are released (Figure 4). Turbidity currents usually transport fine sediment that can pass hydropower turbines with minimal abrasion. Although occurring frequently, turbidity currents do not always transport significant amounts of sediment to the dam. Bathymetric surveys revealing horizontal sediment beds extending upstream from the dam (Figure 4) indicate that large amounts of sediment are transported to the dam but are not being released.

Turbidity current forward motion is facilitated when the submerged current can flow along a defined channel, but as the submerged channel is infilled with sediment deposited by successive turbidity currents the reservoir thalweg becomes flat and wide. This causes the turbidity current to spread out, becoming wide and shallow with larger top and bottom surface areas. This increases frictional resistance, and also facilitates both sediment deposition plus dilution from above with clear water. Both processes lower the current’s density and velocity, allowing more sediment to deposit, and eventually causing the current to stall. Thus, turbidity currents which reach the dam by following the original river channel during the years following initial impoundment, may dissipate after the bottom configuration becomes flat as a result of sedimentation from multiple turbidity currents. Empty flushing can scour out and maintain a submerged channel which will help sustain turbidity current motion.

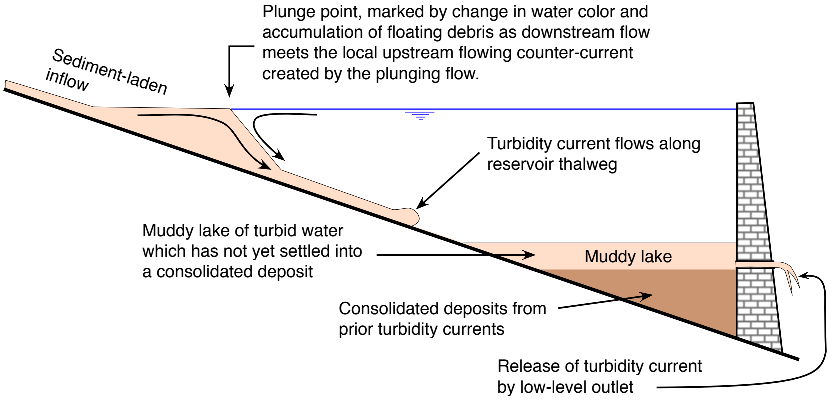

Figure 4: Passage of turbid density current through a reservoir, and the deposit of a horizontal bed of fine sediment due to sedimentation from the submerged muddy lake.

4 Focus, Redistribute or Remove Sediment Deposits

4.1 Focus or Redistribute Sediment

Reservoir delta profiles are influenced by the operating rule. When a reservoir is drawn down to a consistent minimum elevation each year the delta will establish a relatively stable profile and most inflowing sediment will be deposited on the delta face, which will advance as shown in Figure 5A. Sand in reservoir deltas is highly abrasive and cannot be allowed to encroach on a hydropower intake. To retard delta advance the reservoir's minimum operating level may be gradually raised, focusing delta deposition into the upper portion of the reservoir per Figure 5B. Conversely, a reservoir may be drawn down during floods to scour and move the delta deposits deeper into the impoundment, for example, to reduce backwater and upstream flood levels.

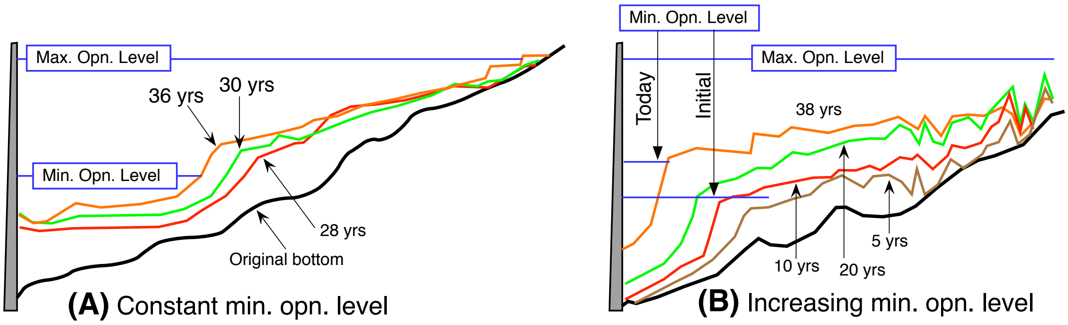

Figure 5: Advancement of reservoir delta: (A) with constant minimum operating level and (B) with an increasing minimum operating level.

4.2 Remove Sediment

Sediment may be mechanically excavated conventional excavation when the reservoir is drawn down and submerged deposits may be removed by dredging. Open excavation is commonly used to recover coarse sediment from the delta for commercial purposes. Construction of a check dam to trap coarse sediment into a zone to facilitate mechanical removal was previously shown for Miwa dam (Figure 3).

Dredging is generally the least costly and most feasible method of excavating large volumes of sediment from reservoirs as it does not require the reservoir to be emptied, and a slurry pipeline is a clean and quite method of transporting sediment (as compared to truck traffic). Permanent dredging may be feasible at hydropower sites which have less-costly self-supplied energy, an example being the Bajo Anchicayá hydropower reservoir in Colombia which has been maintained by continuous dredging since 1962.

Siphon or *hydrosuction* dredging is a special case of hydraulic dredging, in which the motive force for transporting slurry through the pipeline is provided by the head differential between the reservoir level and the foot of the dam. Since the maximum head available for slurry transport is limited by the dam height, operation of a hydrosuction dredge will typically be limited to within a kilometer or two of the dam.

4.3 Flushing

Pressure flushing occurs when a submerged low level outlet is opened to release sediment while the reservoir level is high. It will produce a localized scour cone immediately above the pressure flushing outlet. An intake located above this low-level flushing outlet can be maintained free of sediment, but this operation will not remove sediment beyond its immediate area of influence.

Empty flushing entails opening a low-level outlet to completely empty the reservoir to scour sediment deposits. Differences between sluicing and flushing have already been summarized in Table 2. Maximum flushing effectiveness is achieved by placing the outlet at the lowest level possible to maximize the erosional energy, and by using the highest discharge that can pass through the bottom outlet without backwater. For reservoirs in series, when the lower reservoir is empty a high-flow may be released from the upper reservoir to maximize downstream scour. *Sequential flushing* occurs when two or more reservoirs in series are flushed simultaneously, passing eroded sediment from upstream reservoirs through the downstream reservoirs with minimal redeposition.

While empty flushing may achieve a sediment balance for the fine fraction of the inflowing load, the coarse fraction may continue to accumulate in the reservoir. For example, Sumi *et al.* (2010) reported that flushing at the Unazuki dam in Japan removed 73% of the total sediment inflow but only 10% of the coarse sediment >2 mm. Thus, even with flushing a sediment balance may not be obtained across a reservoir.

4.4 River Flushing

Both empty flushing and dredging with the discharge of sediment below the dam will result in the release of high-concentration flow and the accumulation of sediment in the river channel with potentially adverse consequences to the environment, flood control, navigation etc. An essential consideration in these strategies is to provide sufficient clear water releases to flush the released sediment downstream in an acceptable manner.

5 ADAPTIVE STRATEGIES

Adaptive strategies are actions to combat sedimentation impacts which does not involve handling sediment. They may be used with or instead of active sediment management.

Reallocate storage and improve operational efficiency. Reservoir pools are normally established based on specific water levels, for example, the flood control pool that occupies the upper portion of a multi-purpose reservoir. Sedimentation does not affect all pools equally, and the higher pool(s) typically experience much less sedimentation than the lower pool(s) used for water supply. As a temporary remedial measure the pool limits may be moved to reallocate the storage loss in a more equitable manner.

If the operating rule remains unchanged all reservoir pools will suffer some decrease in benefits due to sedimentation. However, in many reservoirs operating rules were established >50 years ago, before the advent of real-time hydrologic monitoring and forecast tools. These tools make it possible to establish a buffer pool (within the flood control pool for example), which can be either filled for water supply or emptied for flood control, depending on existing and forecast hydrologic conditions. By making these improvements to the system's operational efficiency it may be possible to sustain benefits to all users for an interim period, despite sedimentation, and thereafter to partially mitigate storage loss impacts. Improvements in operational efficiency may be very inexpensive compared to any type of active sediment management.

Modify structures to avoid sediment. Sediment will eventually reach critical structures, such as intakes and spillways, and these structures may require modification to accommodate sediment encroachment.

Raise dam to increase volume. Storage may be increased by raising the dam, and even a relatively small increase in dam height can provide significant additional storage since the additional volume will be added to the top of the reservoir where surface area is greatest. The additional height may also be achieved constructing a higher dam downstream of the existing dam, which will then be submerged.

Water loss control and conservation. As water supply declines due to storage loss, it becomes increasingly important to use the available water more efficiently. This includes reduction of physical water losses as well as conservation by users (such as more efficient irrigation). It may also entail economic transitions into activities that are inherently more water efficient. Given the large differences in the economic benefits of water use among different activities, significant reductions in water use may have only modest economic consequences. For example, Hanak (2012) noted that, "*California's economy has become less reliant on water intensive activities. For instance, agriculture and related manufacturing account for nearly four-fifths of all business and residential water use—but make up just 2 percent of state GDP and 4 percent of all jobs*".

Decommission Infrastructure. A dam may be decommissioned when sedimentation renders it no longer economic to operate. For example, the 32 m San Clemente dam in California is currently being removed at a cost of $80 million due to obsolescence by sedimentation (www.sanclementedamremoval.org). Acceptable end-of-life strategies should be developed at any dam for which sustainable use is not considered feasible.

6 CONCLUSION

Reservoir storage is critical for sustaining our society. A variety of active and adaptive strategies exist to combat sedimentation, and these will need to be implemented on an increasingly widespread scale to sustain current living standards.

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