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Key Points:
- Reservoirs trap sediment, losing storage capacity
- Downstream reaches can become sediment starved
- Many dams can be designed/operated to pass sediment

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Sustainable sediment management in reservoirs and regulated rivers: Experiences from five continents

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Abstract By trapping sediment in reservoirs, dams interrupt the continuity of sediment transport through rivers, resulting in loss of reservoir storage and reduced usable life, and depriving downstream reaches of sediments essential for channel form and aquatic habitats. With the acceleration of new dam construction globally, these impacts are increasingly widespread. There are proven techniques to pass sediment through or around reservoirs, to preserve reservoir capacity and to minimize downstream impacts, but they are not applied in many situations where they would be effective. This paper summarizes collective experience from five continents in managing reservoir sediments and mitigating downstream sediment starvation. Where geometry is favorable it is often possible to bypass sediment around the reservoir, which avoids reservoir sedimentation and supplies sediment to downstream reaches with rates and timing similar to pre-dam conditions. Sluicing (or drawdown routing) permits sediment to be transported through the reservoir rapidly to avoid sedimentation during high flows; it requires relatively large capacity outlets. Drawdown flushing involves scouring and re-suspending sediment deposited in the reservoir and transporting it downstream through low-level gates in the dam; it works best in narrow reservoirs with steep longitudinal gradients and with flow velocities maintained above the threshold to transport sediment. Turbidity currents can often be vented through the dam, with the advantage that the reservoir need not be drawn down to pass sediment. In planning dams, we recommend that these sediment management approaches be utilized where possible to sustain reservoir capacity and minimize environmental impacts of dams.

1. Introduction

1.1. Reduced Sediment Loads Downstream of Dams

Dams interrupt the continuity of sediment transport through rivers systems, causing sediment to accumulate within the reservoir itself (impairing reservoir operation and decreasing storage) and depriving downstream reaches of sediments essential to maintain channel form and to support the riparian ecosystem. The most common discourse on sediment problems has been that of increased erosion and sediment loads from poor land use and expansion of human impacts into previously undisturbed areas [*Walling*, 1999]. However, most river systems around the world actually show *decreased* sediment loads, because of trapping by upstream dams [*Walling and Fang*, 2003]. Estimates of sediment that reached the ocean (or at least deltas) under pre-human-disturbance conditions have been in the range of roughly 15–20 billion tons per year (Bty^{-1}) [*Walling*, 2006]. Of this amount, *Syvitski et al*. [2005] estimated that catchment-level human disturbances have increased the erosion of sediment from uplands and its delivery to rivers by about 2.3 Bty^{-1}, but that the *net* effect has been a reduction in sediment loads of rivers by an estimated 1.4 billion tons due to sediment trapping in reservoirs. *Vorosmarty et al*. [2003] extrapolated estimates from 633 large reservoirs to over 44,000 smaller reservoirs and concluded that more than 53% of the global sediment flux in regulated basins is potentially trapped in reservoirs, or 28% of all river basins, for a total trapping of 4–5 Bty^{-1}.

No matter what estimate is used, sediment trapping by reservoirs is now of primary global importance. This has significant consequences, both for the channels downstream, and for the sustainability of the reservoirs and thus future water supplies. There is increasing evidence of channel erosion and ecosystem impacts resulting from sediment starvation downstream of dams, often termed *hungry water* [*Kondolf*, 1997; *Draut et al*., 2011; *Grams et al*., 2007; *Ma et al.*, 2012; *Schmidt and Wilcock*, 2008; *Singer*, 2010]. Coastal areas that rely on riverine sediment supply are especially vulnerable to impacts of reduced sediment supply [*Vorosmarty et al.*, 2003], such as sand-starved beaches that have narrowed or disappeared, accelerating erosion of coastal cliffs [*Inman*, 1985; *Gaillot and Piégay*, 1999] and deltas [*Syvitski et al.*, 2009]. The Mississippi River Delta has lost over 4800 km^2 [*Coastal Protection and Restoration Authority of Louisiana* (*CPRA*), 2012] due largely to reduced sediment supply from trapping in upstream reservoirs [*Meade and Parker*, 1985; *Meade and Moody*, 2010]. Of the world's 33 major deltas, 24 are sinking, largely from human causes including reduced sediment supply; in combination with an assumed 0.46 m rise in sea level by 2100, this would lead to a 50% increase in flooding, with profound consequences for coastal populations [*Chen et al*., 2012]. Actual sea level rise will not be uniform across the globe because of isostatic and gravity effects associated with melting ice caps [*Milne*, 2008].

1.2. Coarse vs. Fine Sediment

It is useful to distinguish between coarse and fine sediments, both in their role in river systems and their susceptibility to being trapped by reservoirs. Coarse sediment (gravel and sand) can be viewed as forming the "architecture" of most riverbeds, as the material that constitutes the channel bed, bars, and often banks. Moreover, many geomorphic features that serve as important habitats, such as riffles, are composed of coarse sediments (gravels, cobbles). Downstream of dams, reduced supply of coarse sediment has resulted in channel incision and consequent effects on bridges and other infrastructure, and degradation of aquatic habitat quality, including loss of gravels needed by spawning salmon [*Kondolf*, 1995].

Fine-grained sediment (silt and clay) is important for the structure of some riverine forms, such as vertically accreted floodplains and estuarine mud flats, but it also plays important roles distinct from coarse sediment, such as a source of turbidity, and its role in transporting nutrients and contaminants adsorbed onto clay particles. Anthropically increased loads of fine sediment (e.g., from land disturbance) can cause problems of increased turbidity in the water column and sedimentation in river channels, estuaries, and harbors [*Owens et al*., 2005], and deposition of fine-grained sediment in streambed gravels can affect salmon spawning habitat [*Kondolf*, 2000] and aquatic habitats generally [*Wood and Armitage*, 1997]. Loss of a river's natural fine-grained sediment load can have a range of negative impacts, as the native species in a river are, by definition, adapted to the natural conditions. Construction of Glenn Canyon Dam dramatically reduced turbidity and summer water temperatures in the downstream reaches, providing excellent habitat for exotic rainbow trout but nearly extirpating the native fish species [*Schmidt et al.*, 1998], and because outmigrating juvenile salmon can avoid predators in turbid water better than in clear waters [*Gregory and Levings*, 1998]. Artificially clear releases below New Don Pedro Dam on the Tuolumne River, California, have likely contributed to observed high predation rates on juvenile salmon [*EA Engineering, Science, and Technology* (*EA*), 1992].

Nutrients are often associated with fine sediments, and along with trapping of fine sediments, nutrient trapping by dams can have significant ecosystem impacts downstream. After construction of Three Gorges Dam (and other dams upstream), suspended sediment loads decreased in the Middle Yangtze River by 91%, total phosphorous decreased by 77%, and particulate phosphorous by 83% annually [*Zhou et al.*, 2013]. As phosphorous is the limiting nutrient for bioactivity in the river, its reduction implies a likely reduction in primary productivity of the river and coastal region downstream.

Because gravel moves through river channels as bed load, it is virtually certain to be trapped by dams. Dams typically have trap efficiencies of 100% for gravel, with only small dams on steep channel capable of passing bed load. (However, once any dam has completely filled with sediment, bed load can presumably pass over the structure.) Because sand can be transported as either bed load or suspended load, depending on turbulence of the flow, its trapping efficiencies are variable. Sand can pass many smaller dams on steep streams with turbulent flow, but typically not large reservoirs. Silt and clay are always transported as suspended load, and are often termed washload, i.e., suspended load finer than sand that can pass through the natural river network (and small dams without significant storage) mostly without being deposited. Large reservoirs with protracted residence times can trap even washload [*Morris and Fan*, 1998]. The percentage of suspended sediment trapped by a reservoir increases with residence time, and generally increases with the ratio of total reservoir storage to inflow, as estimated by the widely used Brune curve [*Morris and Fan*, 1998].

1.3. Loss of Reservoir Capacity

Sediment trapped behind dams reduces reservoir capacity, and in some high-profile cases, reservoirs have already filled with sediment, not only impairing functions and/or rendering useless the dam infrastructure, but posing safety hazards as well [e.g., *US Bureau of Reclamation*, 2006; *California State Coastal Conservancy*, 2007; *Wang and Kondolf*, 2014]. *Sumi et al.* [2004] reported that global gross storage capacity was about 6000 km^3 and annual reservoir sedimentation rates about 31 km^3 (0.52%), such that (ignoring new storage created after that date), global reservoir storage capacity would be half lost by 2100. *Annandale* [2013] estimated that global net reservoir storage has been declining from its peak of 4200 km^3 in 1995 because rates of sedimentation exceed rates of new storage construction. With increasing demands for water storage, and fewer feasible and economically justifiable sites available for new reservoirs, loss of capacity in our existing reservoirs threatens the sustainability of water supply [*Annandale*, 2013]. Thus, we can think of the sediments accumulating in reservoirs (with negative consequences there) as "resources out of place," because these same sediments are desperately needed by the downstream river system to maintain its morphology and ecology, as well as replenishing vital land at the coast.

1.4. The Imperative to Sustainably Manage Sediment

The impetus to develop alternatives to carbon-based energy sources has renewed support for hydroelectric power projects globally [e.g., *the World Bank*, 2009], with new hydropower projects mostly in the developing world, many financed by outside investors. For example, in the Mekong River basin, largely undeveloped before 1990, 140 dams are built, under construction, or planned [*Grumbine and Xu*, 2011]. An assessment of pre-dam sediment yields by geomorphic province and systematic analysis of sediment trapping by planned dams (accounting for changes in trap efficiency over time and for multiple dams in a given sub-catchment) indicates that full build of the 140 dams as planned would result in a 96% reduction in sediment load to the Mekong Delta, i.e., once erodible sediment stored in channel bed and banks was exhausted, the Delta would receive only 4% of its natural sediment load (G. M. Kondolf et al., Dams on the Mekong: cumulative sediment starvation, submitted to *Water Resources Research*, 2013). With such profound change to the river's sediment load, the ongoing subsidence and land loss in the Mekong Delta are likely to accelerate.

Trapping of sediment by dams is not inevitable, at least not by all dams. Some dams can be designed to pass sediment, either through the dam or around the reservoir, using a range of proven techniques, each applicable to a range of conditions. However, sediment management approaches are not used in many reservoirs where they could be. It may be that dam developers and operators are not aware of the range of potential management approaches, nor that they have been demonstrated to be effective (and under what conditions different methods are appropriate). Thus, collectively we are missing opportunities to sustain reservoir functions into the future, and to minimize downstream impacts of sediment starvation. With large numbers of new dams planned for Asia, Africa, and South America, it is timely that lessons learned from successful reservoir sediment management be used to inform planning and design of new dams, and to establish policies and design standards for sustainable reservoir design and management.

At the Fifth International Yellow River Forum in September 2012, reservoir sediment management experts from abroad joined Chinese experts for two fruitful days of presentations and discussion to exchange collective experience in sustainably managing sediment in reservoirs and addressing problems of downstream sediment starvation. Because of the extremely high sediment loads of the Yellow River, China has innovated more than most other countries in sediment management, and has a rich experiential base upon which to draw. Likewise, good examples of successful sediment management can be studied from other Asian countries, Europe, North and South America, Africa, and the Middle East. This document summarizes key points from the collective experience of the expert group and reflections on approaches to sustainably managing sediment in and through reservoirs. It builds upon prior work [e.g., *Morris and Fan*, 1998] through its incorporation of more recent and diverse experience in managing sediments in reservoirs, and through its synthesis of the subject in a more concise form. We begin with a review of approaches to sustainable sediment management and examples of successful application drawn from the experience of our participants and the published literature. From this base of experience, we present general principles for managing sediment, and conclude with implications for dam planning, design, and operation.

There is a wide range of sediment management techniques to preserve reservoir capacity and pass sediment downstream, many of which represent ways to achieve the goals expressed by the Chinese expression, "Store the clear water and release the muddy." Many of them have been successfully employed in reservoirs in a range of settings, as described by *Morris and Fan* [1998], *Annandale* [2011], *Sumi et al.* [2012], and *Wang and Hu* [2009]. Although terminology differs somewhat, the reservoir sediment management classifications of *Morris and Fan* [1998] and *Kantoush and Sumi* [2010] both distinguish among three broad categories: (1) methods to route sediment through or around the reservoir, (2) methods to remove sediments accumulated in the reservoir to regain capacity, and (3) approaches to minimize the amount of sediment arriving to reservoirs from upstream (e.g., Figure 1). The first two methods maintain reservoir capacity and provide sediment to downstream reaches, but the third category (reducing sediment delivery from upstream) addresses only the reservoir capacity issue, not downstream sediment starvation. We begin describing methods in the first two categories (that pass sediment through or around the reservoir, minimizing sediment accumulation in the reservoir and supplying some sediment to downstream reaches), then address strategies to reduce sediment supply from the upstream catchment (which do not address downstream sediment starvation), and finally strategies to mechanically add sediment to river channels downstream of dams (which do not address reservoir capacity sustainability).

2. Reservoir Sediment Management Strategies

This section reviews reservoir sediment management strategies that both prolong reservoir life and benefit downstream reaches by mitigating the sediment starvation that results from sediment trapping. Some of the terms for sediment management have been used in different ways by various authors (e.g., "sluicing" and "flushing" are often assigned confusing meanings), so we endeavor to clearly indicate how we define the various terms.

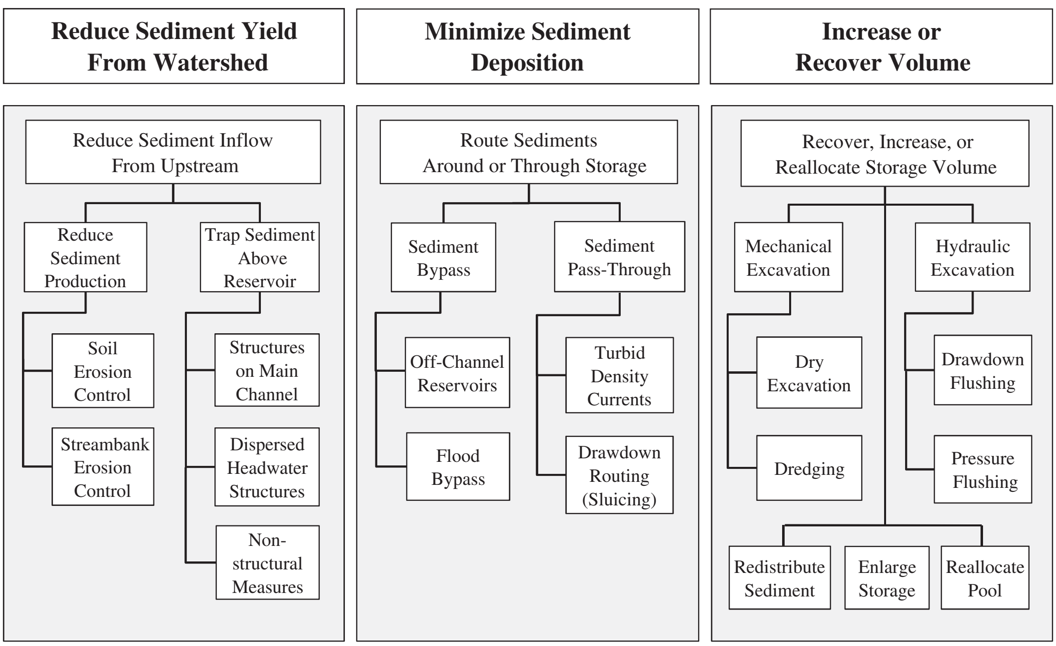

Figure 1. Classification of strategies for sediment management from the perspective of sustaining reservoir capacity.

2.1. Sediment Bypassing and Off-Channel Reservoir Storage

Sediment bypassing diverts part of the incoming sediment-laden waters around the reservoir, so that they never enter the reservoir at all. Typically, the sediment-laden waters are diverted at a weir upstream of the reservoir into a high-capacity tunnel or diversion channel, which conveys the sediment-laden waters downstream of the dam, where they rejoin the river (Figure 2). Normally the weir diverts during high flows, when sediment loads are high, but once sediment concentrations fall, water is allowed into the reservoir. (A variant of this approach may involve the use of a bypass that diverts sediment-laden waters already in a reservoir.)

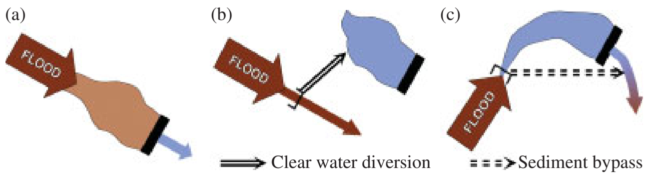

Figure 2. (a) Conventional reservoir, which traps incoming sediment, contrasted to alternative configurations for bypass of sediment-laden flood flows around the storage pool: (b) bypass off-stream storage, wherein a diversion dam in the river diverts water to the off-channel reservoir during times of clear flow but does not divert when suspended sediment concentrations are high, and (c) a sediment bypass channel or tunnel, which during times of high water and high sediment concentrations, diverts flow from the river upstream of the reservoir, passing it around the reservoir and into the downstream channel.

The ideal geometry for sediment bypass is one where the river makes a sharp turn between the point of sediment collection and the point of sediment reintroduction to minimize the length of the conveyance device and take advantage of the relatively steeper gradient for gravity flow (Figure 2c). Where that ideal condition does not exist, the technique is most practical where the reservoir is relatively short, as there must be sufficient gradient to drive the transport of sediment through the diversion tunnel or diversion channel. At Nagle Dam in South Africa, the river takes a sharp bend at the reservoir, providing an ideal "short cut" for the bypass, with steep slopes [*Annandale*, 1987].

Overall, Japan and Switzerland are the leading countries for sediment bypass tunnels: in Japan, three are in operation and two under construction; in Switzerland, six are in operation [*Vischer et al.*, 1997; *Auel et al.*, 2010] (Table 1). The oldest sediment bypass tunnel in Japan was installed at the municipal water supply reservoir Nunobiki dam near Kobe city 8 years after completion of the dam in 1900. This bypass scheme has successfully diverted coarse sediment for more than 100 years as described by *Sumi et al*. [2004]. At the Miwa and Asahi dams in Japan, the rivers are sufficiently steep that a straight tunnel has adequate gradient to carry most sediment load downstream of the dam [*Sumi et al.*, 2004; *Suzuki*, 2009; *Sumi et al.*, 2012]. Miwa Dam (on the Mibu River, in the Tenryu River basin) was built in 1959 with 30 million m^3 (Mm^3) storage capacity. Subsequent deposition of 20 Mm^3 of sediment has prompted expensive sediment removal efforts. To prolong the reservoir's life, a 4.3-km-long sediment bypass tunnel and diversion weir at the upstream end of the reservoir were constructed in 2005 (Figure 3). The dam and diversion tunnel operate such that during the rising limb of a flood, sediment-laden flows are diverted into the bypass tunnel, but the tunnel inlet is closed on the falling limb of the flood so the clear waters can be stored (Figure 4) (assuming the commonly observed hysteresis curve of higher sediment concentrations on the rising limb). The system is successfully routing sediment downstream, the efficiency being a function of the magnitude of the flood and the timing of the operation, and with no impacts detected on the downstream ecology in the 7 years after the scheme's inception [*Sumi et al.*, 2012]. Asahi Dam on the Shingu River was built in 1978; sedimentation problems motivated the 1998 construction of a sediment bypass with a 13.5-m high diversion weir and 2350-m long tunnel. By 2006, sediment bypassing through the tunnel had avoided a cumulative 750,000 m^3 of sediment deposition [*Mitsuzumi et al*., 2009].

In Taiwan, the sediment-plagued Shihmen Reservoir on the Dahan River, will be retrofit with a sediment bypass, taking advantage of the sharp river bend at the reservoir [*Wang and Kondolf*, 2014; *Water Resources Agency* (*WRA*), 2010). Sediment bypasses are expensive because of the cost of the tunnel, but have many advantages, in passing sediment without entering the reservoir, and without interfering with reservoir operation. In case of coarse sediment bypassing, an anti-abrasion design for tunnel bottom surface is essential for minimizing long-term operation costs, as described by *Visher et al.* [1997] and *Sumi et al.* [2004].

Table 1. Characteristics of Successful Sediment Bypass Tunnels in Japan and Switzerland

Name of Dam	Country	Date Constr	Tunnel Shape	Tunnel Cross Section (BxH) (m)	Tunnel Length (m)	General Slope (%)	Design Q ($m^3 s^{-1}$)	Design Velocity (ms^{-1})	Annual Operation Frequency (days/a)
Nunobiki	JP	1908	Archway	2.9 × 2.9	258	1.3	39	7	—
Asahi	JP	1998	Archway	3.8 × 3.8	2350	2.9	140	12	13
Miwa	JP	2004	Horseshoe	2r = 7.8	4300	1	300	10	2–3
Matsukawa	JP	2015	Archway	5.2 × 5.2	1417	4	200	15	—
Koshibu	JP	2016	Horseshoe	2r = 7.9	3982	2	370	9	—
Egshi	CH	1976	Circular	R = 2.8	360	2.6	74	10	10
Palagnedra	CH	1974	Circular	2r = 6.2	1800	2	110	13	2–5
Pffaffensprung	CH	1922	Horseshoe	A = 21 m^2	280	3	220	14	ca. 200
Rempen	CH	1983	Horseshoe	3.5 × 3.3	450	4	80	12	1–5
Runcahez	CH	1961	Archway	3.8 × 4.5	572	1.4	110	9	4
Solis	CH	2012	Archway	4.4 × 4.68	968	1.8	170	11	1–10

Notes: CH = Switzerland, JP = Japan, Q = discharge.

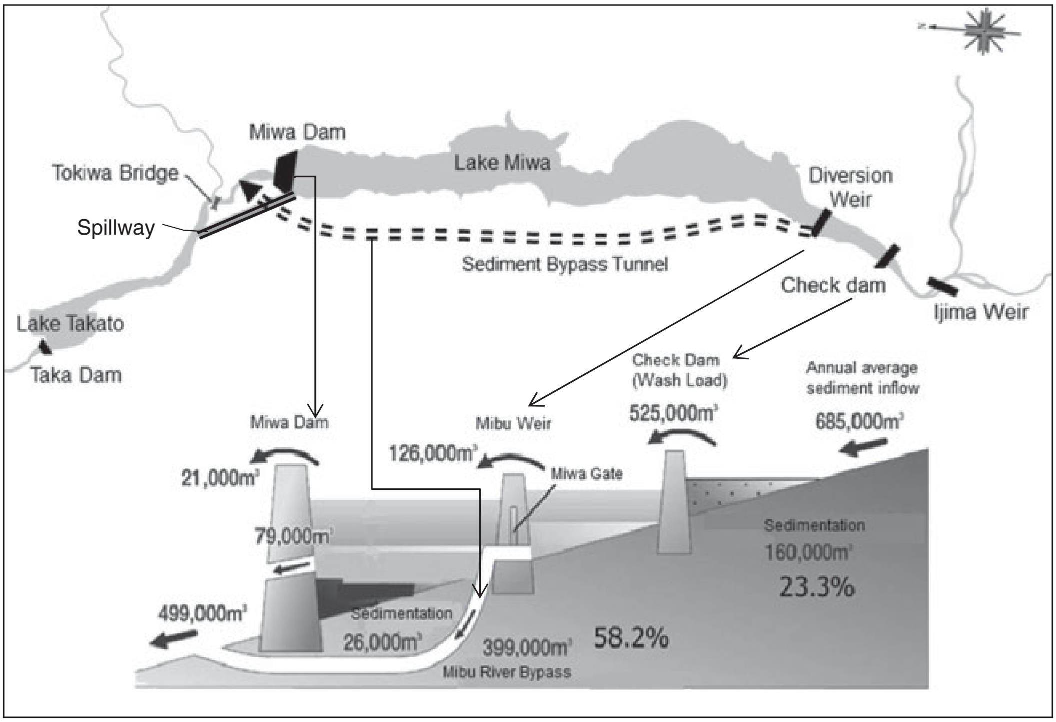

Figure 3. Diagram of sediment bypass system for Miwa Dam, Mibu River, Japan. A check dam traps coarse sediment, and a diversion weir diverts flows with high suspended sediment concentrations into a bypass tunnel.

An alternate approach to sediment bypass is to build off-channel reservoir storage, such that the diversions from the weir are clear-water diversions, while sediment-laden water is left in the river to pass downstream (Figure 2b) [*Morris and Fan*, 1998]. Similar to sediment bypass, there needs to be sufficient gradient to drive flow through diversion channels or tunnels to the off-channel storage feature. One advantage of this approach is that all bed load can be excluded from the reservoir. Simulations using daily data from streamflow and sediment gages in Puerto Rico indicate that it is possible to exclude between 90% and 95% of the total sediment load from an off-stream reservoir, thereby prolonging reservoir life by a factor

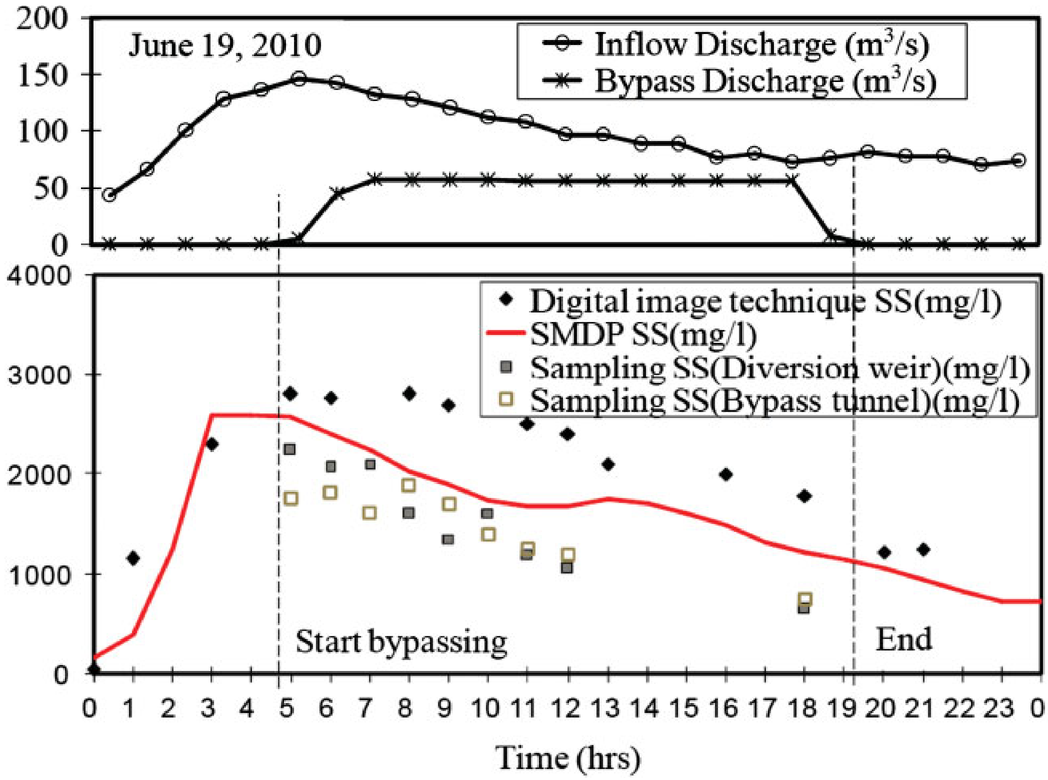

Figure 4. Sediment bypass at Miwa Dam June 19, 2010: (a) hydrographs for inflow into the reservoir and for flow through the bypass tunnel, and (b) suspended sediment concentrations (mg/l) at the diversion weir and in the bypass tunnel. [Modified from *Kantoush et al.*, 2011]

of more than ten as compared with an on-channel reservoir on the same river [*Morris*, 2010]. The intake structure can be designed to present a much smaller impediment to the migration of fish species than a dam, and downstream river morphology is maintained because sediment load and flows capable of transporting sediment are not impaired. The rate at which water can be diverted to the off-channel storage reservoir is limited to the capacity of the diversion channel, so this approach is less suited to flashy streams in semi-arid zones where water flow is concentrated in floods. Under appropriate hydrologic conditions, even a diversion of relatively modest capacity may result in firm yields close to those achieved by an on-channel reservoir.

Off-channel storage could be more widely used than has been the case. In run-of-river hydropower projects, turbines run at full capacity during the wet season when streamflow exceeds the plant's design capacity. During the dry season, an off-channel reservoir can provide a small live storage volume, to store inflow over a 24-h period for delivery to turbines during the hours of peak demand. For example, the recently designed San José project in the Andes Mountains of Bolivia is fed by eight intakes, has 125 MW capacity with 600 m of gross head, and requires a 0.35 Mm^3 regulating reservoir to provide 6 h of peak power (Figure 5). Off-channel storage was ideal to provide peaking power at this site, because vertical canyon walls made site access difficult for construction of a main stem dam, and the high load of large bed material (up to 1 m diameter) presented an unfavorable situation for sediment management. Coarse sediment (>0.15 mm) will be removed by desanders prior to entering the regulating reservoir, and finer sediment trapped in the pool will need to be excavated after several years.

The Cameguadua and San Francisco off-stream reservoirs in the Cauca River basin near Manizales, Colombia, have operated successfully for many years. These two reservoirs have a total installed capacity of 197 MW at five power stations; they are fed by seven intakes, and accumulated fine sediment is removed by dredging.

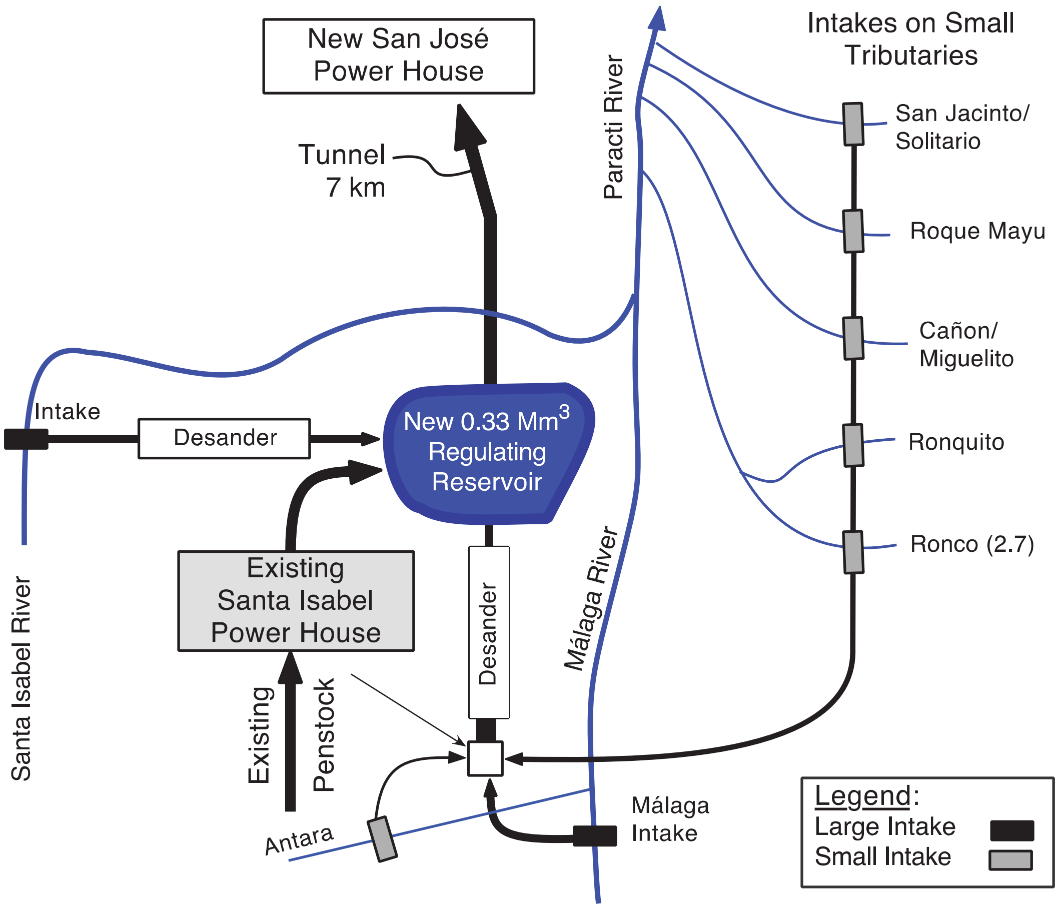

Figure 5. Schematic layout of 125 MW San José hydroelectric project, Paractia River, Bolivia, incorporating an off-stream regulating reservoir for pondage and desanders to remove the coarse sediment abundant in the streams.

2.2. Sediment Sluicing

Drawdown routing, or *sluicing* [*ICOLD*, 1999], involves discharging high flows through the dam during periods of high inflows to the reservoir, with the objective of permitting sediment to be transported through the reservoir as rapidly as possible while minimizing sedimentation. Some previously deposited sediment may be scoured and transported, but the principal objective is to reduce trapping of incoming sediment rather than to remove previously deposited sediment. One advantage of this approach is that deposition in the reservoir is minimized and the sediment continues to be transported downstream during the flood season when sediment is naturally discharged by the river. Finer sediments are more effectively transported through the reservoir than coarse sediments.

Sluicing is performed by lowering the reservoir pool prior to high-discharge sediment-laden floods (Figure 6). This approach requires relatively large capacity outlets on the dam to discharge large flows while maintaining low water levels and the required velocities and transport capacity. These outlets need not be at the very bottom of the dam, and at some sites with smaller storage volumes, tall crest gates can be used for this purpose.

A drawdown and sluicing strategy may be employed at reservoirs of all sizes, but the duration of sluicing depends on the watershed size and the time scale of flood events.

For dams of small watersheds with rapidly rising floods, the reservoir may be drawn down only for a period of hours. In other cases, such as dam sites with small storage volumes for daily regulation (pondage), the reservoir may be held at a low level during the entire flood season to maximize sediment pass through while continuing to produce power and using a desander to protect hydro-mechanical equipment from

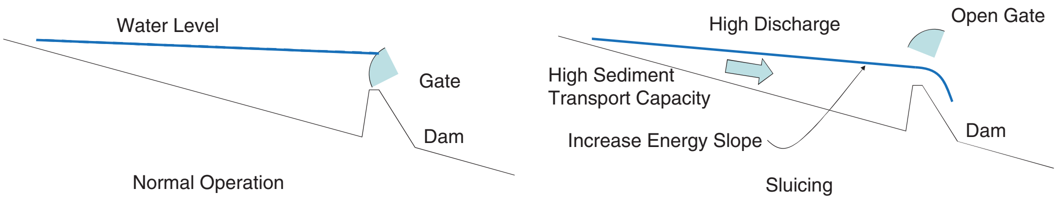

Figure 6. Schematic representation of sluicing operations.

the abrasive sediment that is mobilized by sediment sluicing. In storage reservoirs on large rivers the reservoir may be held at a low level for a period of many weeks at the beginning of the flood season and filled with late-season flows.

By virtue of passing the rising limb of the flood, which generally contains higher sediment concentration than the falling limb of the flood hydrograph, sluicing is consistent with the Chinese strategy to, "release the muddy flow and store the clear water" [*Wang and Hu*, 2009]. In China, sluicing has most-famously been implemented at the Three Gorges dam where prolonged seasonal drawdown during the early part of the flood season is designed to maximize flow velocity and sustain sediment transport through the reservoir, and also mobilize some of the previously deposited sediment. The reservoir level is raised later in the season to fill storage for sustaining releases during the low-flow season (Figure 7). The objective is to sustain the natural patterns of flood and sediment discharge along the river, while producing power and assisting navigation. This strategy to stabilize reservoir capacity is best suited to narrow reservoirs. The Three Gorges Reservoir, e.g., is about 600-km long but does not exceed 1.5 km in width, and it has a high-discharge capacity at the dam.

Reservoirs trap less sediment when the flood-detention period is reduced, and a change in the reservoir operating rules to minimize flood-detention time, especially on the rising limb, can reduce sediment trapping at a very low operational cost. While sluicing operates most effectively in long narrow reservoirs, benefits can also be achieved in storage reservoirs having other configurations. For example, the John Redmond reservoir in Kansas (USA) has a nearly circular configuration, a large flood control pool, and a small water conservation pool. Analysis of historical operations during 48 flood events plus modeling showed that a measurable increase in sediment throughput could be achieved by making relatively minor changes to the operating rule, while still maintaining downstream flood control targets [*Lee and Foster*,

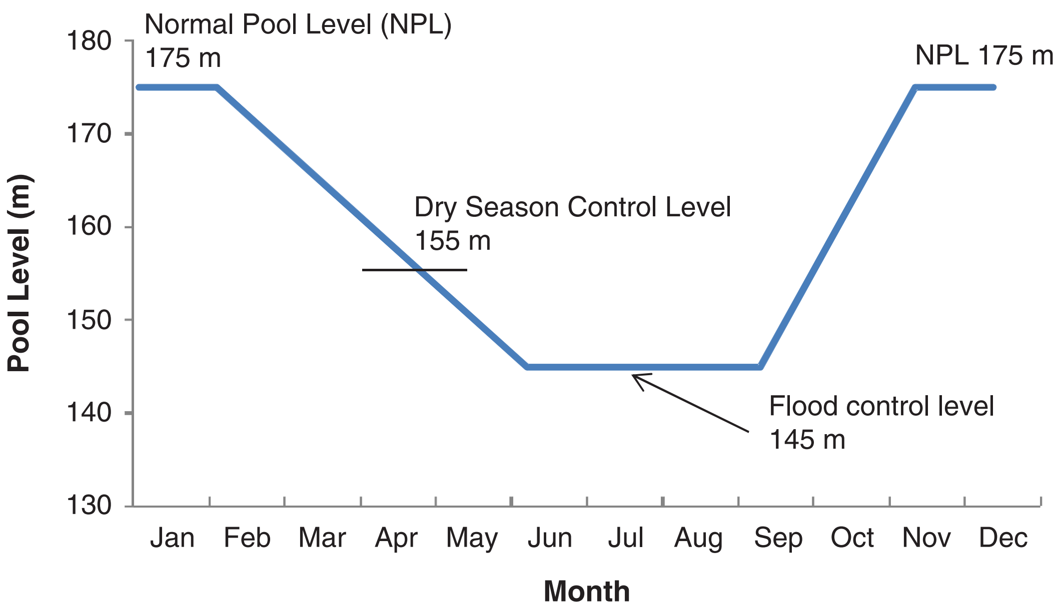

Figure 7. Seasonal pool operation at Three Gorges Reservoir. [Redrawn from *Zhou*, 2007]

2013]. Compared to the conventional reservoir operation, "the altered scenario purposefully minimized reservoir elevation and residence time through larger, more rapid releases of water after periods of high inflows," resulting in measurably decreased trap efficiency [*Lee and Foster*, 2013:1437]. This reduction in sediment trapping efficiency is achieved without any structural modifications, by simply including a sediment management objective in the reservoir operating rule.

2.3. Drawdown Flushing

In contrast to *sluicing*, whose aim is to pass sediment without allowing it to deposit, drawdown *flushing* focuses on scouring and re-suspending deposited sediment and transporting it downstream. It involves the complete emptying of the reservoir through low-level gates that are large enough to freely pass the flushing discharge through the dam without upstream impounding, so that the free surface of the water is at or below the gate soffit (Figure 8). While flushing can be undertaken in reservoirs having any configuration, because the flushing channel will typically not be wider than the original streambed, flushing will recover and maintain a substantial fraction of the original reservoir storage only in reservoirs that are long and narrow.

Figure 8. Schematic representation of drawdown flushing.

The best scenario for flushing is to establish river-like flow conditions through the reservoir upstream of the dam, which is favored by the following conditions: narrow valleys with steep sides; steep longitudinal slopes; river discharge maintained above the threshold to mobilize and transport sediment; and low-level gates installed in the dam [*Morris and Fan*, 1998]. Flushing is best adapted to small reservoirs, and on rivers with strongly seasonal flow patterns [*White*, 2001].

Flushing differs from sluicing in two key respects [*Morris and Fan*, 1998]. First, as discussed above, flushing focuses on the removal of previously deposited sediments, instead of passing incoming sediments through the dam. Secondly, (and consequent to the first) is that the timing of sediment release to the downstream channel may be different from that of the sediment inflow into the reservoir, and the difference is greatest if flushing is conducted during the nonflood season. Flushing can release large amounts of fine sediment to the downstream channel during periods of relatively low flow, when the river is unlikely to have sufficient energy to transport the sediment downstream. The accumulation of sand and finer sediment on the bed can have substantial impacts on the river ecology, and if the deposits are sufficiently large it can also impact the channel's capacity to convey floodwaters. Flushing during the flood season also has the advantage of having greater discharges available, with more erosive energy, and incoming sediment can also be carried through the dam as well as the sediment being eroded and resuspended from reservoir deposits [*Morris and Fan*, 1998].

Flushing has been successfully implemented in many dams globally, such as: Unazuki and Dashidaira dams in Japan [*Kokubo et al.*, 1997; *Liu et al.*, 2004; *Sumi and Kanazawa*, 2006], Sanmenxia dam in China [*Wan*, 1986; *Wang et al.*, 2005], Cachi Dam in Costa Rica [*Jansson and Erlingsson*, 2000], and Genissiat Dam on the Rhône River in France [*Thareau et al*., 2006], and recommended as the only sediment management measure feasible in terms of public acceptance and cost for Gavins Point dam on the Missouri River [*US Army Corps of Engineers*, 2002].

For flushing to be successful, the ratio of reservoir storage to mean annual flow should not exceed 4%, because with larger storage the reservoir cannot be easily drawn down *Sumi* [2008] (Figure 9). Because flushing flows need to pass through the low-level outlet without appreciable backwater, it may not be feasible to use large floods which exceed low-level gate capacity as flushing events.

Sediment deposited from flushing can have significant environmental impacts, especially if flushing is carried out during nonflood season and sediments remain on the bed of the downstream channel. Ecologically important pools can fill with sediment, gravel, and cobble riffles can be buried in finer sediment,

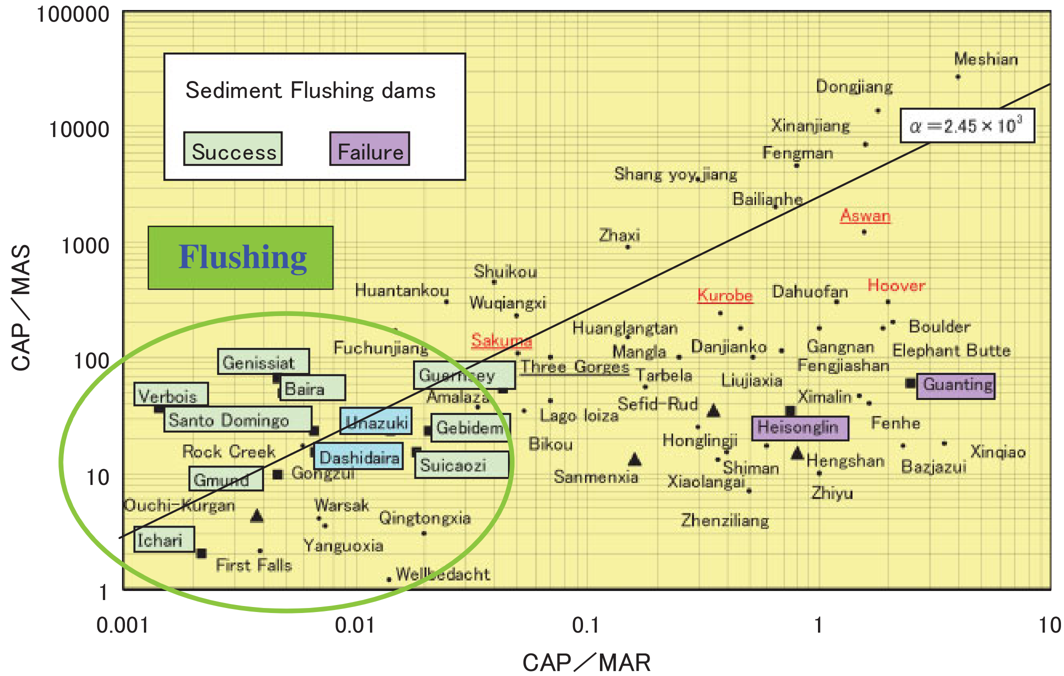

Figure 9. Plot of flushing projects from diverse environments showing that successful cases are characterized by impoundment ratios of 0.4 or less. That is, reservoir storage capacity divided by mean annual runoff (inflow to the reservoir) should be less than 0.4.

and fine sediment can clog the bed, thereby eliminating surface-groundwater exchanges, smothering eggs, and clogging the void spaces between stones used as habitat by aquatic invertebrates and larval fish. Even a small release of sediment (i.e., a small fraction of the river's natural annual sediment budget) during the river's base-flow period can have large impacts because the sediment cannot be transported downstream. On the Kern River, California, sand was flushed from a small diversion dam during base flow in 1986 in anticipation it would be transported away the next winter. However, a series of dry years followed, and the flushed sand remained on the bed for several years because the river did not experience a sufficiently large flow to transport it away [*Kondolf and Matthews*, 1993].

As a general rule, flushing sediment-laden water through the power house is not recommended because it can cause abrasion of the turbines. Sand in particular will quickly destroy turbines. The Zhengzhou workshop presentations included reports of some cases in which fine sediments were successfully passed through powerhouses, but any such flushing scenario must be carefully monitored so that the penstocks can be shut off before sand is mobilized. However, as experienced at Nathpa Jhakri, India, even silt with a high-quartz content (70%–80%) can destroy turbines within months. It is therefore important to assess the mineral content of sediment and susceptibility of the hydro-mechanical equipment to damage, and to stop power production when the reservoir level drops to the point that abrasive sediment may be eroded from the reservoir delta and carried into the power intake.

The main challenges are to sustain the largest possible reservoir storage volume over the long term under drawdown flushing operations, while minimizing adverse downstream environmental impacts as described by *Gerster and Rey* [1994] and *Staub* [2000]. There is a trade-off between frequent flushing with its frequent power losses and less frequent flushing operations. Generally, more frequent flushing (e.g., annually) has less downstream impacts because it delivers sediment to the downstream channel, where it is needed for river health, more often and in small pulses. This reduces the potential for sediment pulses to overwhelm the river's transport capacity and aggrade the channel. Opening of the gates gradually and at appropriate times such as high flows (e.g., the rainy season or snowmelt season) will lessen the impacts of change in sediment concentration on the downstream environment [*Sumi et al.*, 2009]. Another consideration is consolidation of cohesive sediments. With time, cohesive sediments can "set up" and develop a hardened surface that requires heavy equipment to break up and push into the flushing current. Regular

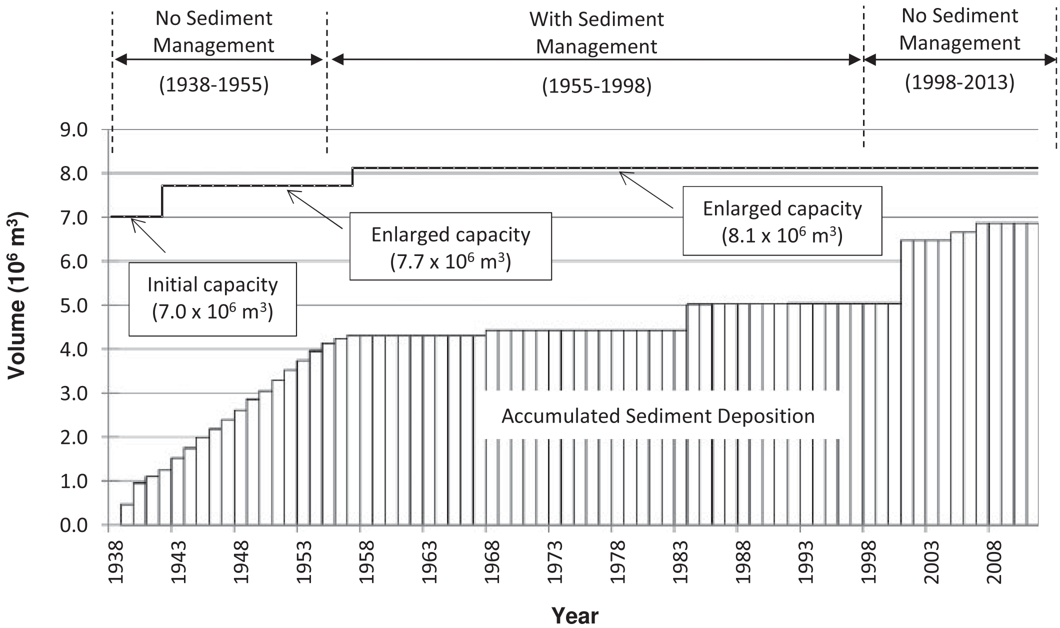

Figure 10. Deposition within Jen-San-Pei reservoir in Taiwan, 1938 to present. Prior to 1955, no sediment management was conducted and the reservoir filled rapidly, but beginning 1955 seasonal drawdown and sediment passing maintained reservoir capacity. From 1998 to 2012, the pass-through operations were stopped, allowing sediment to accumulate. Pass-through operation was resumed in 2013. [Modified from *Huang*, 1994 and extended to present using data from Water Resources Agency of Taiwan]

reservoir flushing can reduce or interrupt consolidation of cohesive sediments and aid in fine sediment removal. It is particularly important to be able to release a flow of clear water after flushing to mobilize sediment and carry it further downstream. This may be in the form of a natural flood hydrograph, or an additional release from the dam with the reservoir at a higher level so that sediment is no longer being scoured.

Flushing will not solve all sedimentation problems. Not only is there the limitation imposed by the limited width of the flushing channel with respect to the overall width of the reservoir, but there is also the problem posed by the limited hydraulic energy that can be generated with flushing. Thus, flushing discharges may efficiently remove fine sediments, but coarse sediments transported into the reservoir by large floods will continue to accumulate without being removed by lower discharge flushing flows. In Cachi Reservoir (Costa Rica) and Hengshan Reservoir (China), coarse-grained deltas are prograding downstream toward the dam despite regular sediment flushing [*Morris and Fan*, 1998].

In some cases there is no clear-cut transition point between reservoir drawdown for sluicing and for flushing, since drawdown for sluicing can scour and mobilize deposits, just a flushing does. Flushing and sluicing may be combined in a seasonal reservoir operation, wherein the pool is emptied and outlet gates are opened at the beginning of the rainy season to allow high flows to pass through the empty reservoir, carrying their incoming sediment as well as eroding stored sediment. This approach is employed in some Chinese reservoirs. For example, the Sanmenxia dam on China's Yellow River remains empty for over 2 months during the first part of each flood season, allowing sediment-laden floods to flush out sediment deposited during the previous year, and also allowing sediment-laden floods to pass through the reservoir [*Wang et al.*, 2005].

Seasonal operation has also been used at the Jensanpei Reservoir in southern Taiwan, which was built in 1938 to supply water to a sugar mill, which operated only part of the year [*Huang*, 1994]. Through the early 1950s, the reservoir was rapidly filling with sediment, and lost 4.3 Mm^3 of its original 7 Mm^3 capacity (Figure 10), but beginning in 1955, the dam was operated to pass sediment through a seasonal drawdown approach. The reservoir would be drawn completely down and the outlets left open for the first 2.5 months of the rainy season (Figure 11). During this time, inflowing floods could transport most of their sediment through the reservoir without depositing it, and they could also scour sediment

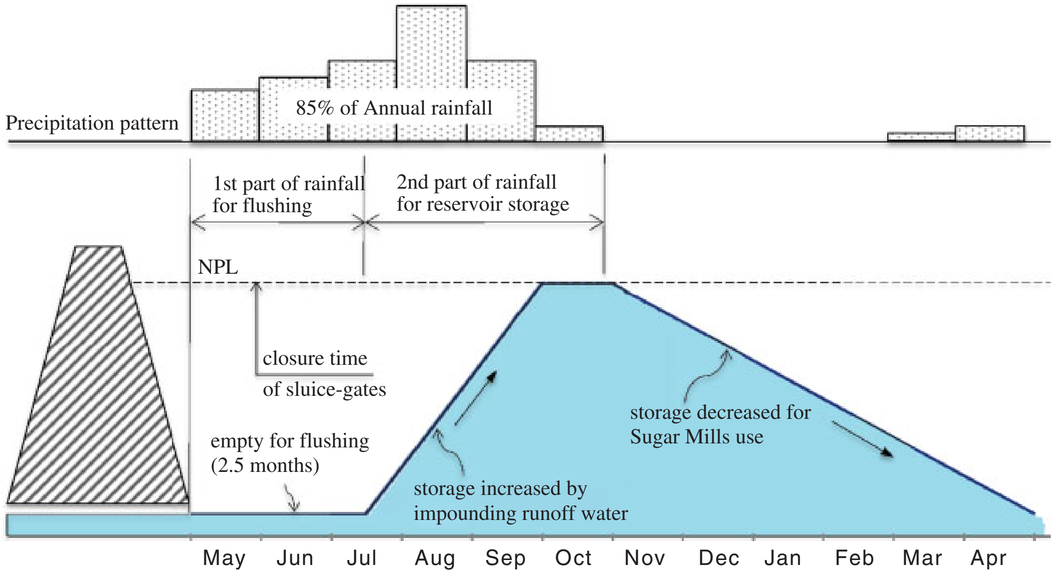

Figure 11. Seasonal operation of Jen-San-Pei reservoir in Taiwan to pass sediment. The reservoir was drawn completely down and the outlets left open for the first 2.5 months of the rainy season, to allow inflowing high flows to transport their sediment through the reservoir and scour sediment already deposited. Midway through the rainy season, the outlet gates were closed, so the reservoir could impound water to process sugar cane, harvested from November to April. [Redrawn from *Huang*, 1994]

already deposited. Midway through the rainy season, the outlet gates were closed, and the reservoir began impounding water for processing sugar cane, which is harvested between November and April. However, by the late 1990s, because of economic changes, the sugar mill was no longer used, and the site around the reservoir was developed for tourism. For tourism, the drawn-down reservoir was considered unattractive, and the seasonal drawdown operation was abandoned from 1998. As a result, sediment began to accumulate in the reservoir until 2013, when the operators resumed seasonal drawdown and sediment pass through after finishing repairs to the sluice gate, which had become nonfunctional due to the sedimentation and lack of maintenance for the years without drawdown (Figure 10). The dam was also raised twice (in 1942 and 1957) to increase reservoir capacity from the original 7 Mm^3 to 8.1 Mm^3, but the benefit of this was minor compared to the benefit of seasonal sediment pass through. Jensanpei is an example of a combination of sluicing (allowing inflowing floods during the first half of the rainy season to pass through the reservoir without depositing their sediment loads) and flushing (scouring sediment deposited). It worked because the reservoir could be drawn down seasonally without affecting its functions.

2.4. Flushing Sediment for Dams in Series

In flushing sediment through a series of dams, simultaneous flushing can be accomplished by releasing the flushing pulse first from the upstream reservoir. Just before that pulse reaches the next downstream reservoir, its lower level gates are also opened to pass the sediment. After finishing the sediment flush, the reservoirs are refilled and clear water released from upper level gates to flush the downstream channel of deposited sediment.

A notable example of management of dams in series is the operation of 19 dams on the Rhône from the Swiss border to the Mediterranean Sea, whose operation is coordinated by the Compagnie Nationale du Rhône with two dams upstream in Switzerland. Except for Genissiat Dam on the Upper Rhône, all are run-of-the-river dams that operate by short-circuiting the "old river" with a straight canal, leaving abandoned meander bends with greatly reduced flows, some of which have been the loci of ecological restoration efforts [*Stroffek et al.*, 1996]. With availability of storage in Lake Geneva, sediment is managed in reservoirs and channels of the Upper Rhône by flushing, such that the opening of gates is coordinated from dam to dam as a pulse moves downstream. However, on the Lower Rhône, storage is lacking, and while it would theoretically be possible to coordinate flushing with high tributary inflows, disruptions to

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navigation must be arranged a year in advance, so flushing is not attempted, and instead, sediment is removed mechanically [*Compagnie National du Rhône*, 2010].

"Environmentally friendly flushing" from Genissiat Dam limits the potential impacts of flushing on downstream aquatic life, water supply intakes, and restored side-channel habitats. This approach is of particular interest because this flushing is conducted under extremely strict restrictions on turbidity and suspended sediment concentrations, not to exceed 5 g/l on average over the entire operation and not to exceed 15 g/l over any 15-min period [*Thareau et al.*, 2006]. The dam is equipped with outlets at three levels: a bottom gate, an outlet halfway up the dam, and a surface spillway. Concentrations are controlled by mixing waters with high sediment concentrations from the bottom of the water column with enough "cleaner" water from higher in the water column (normally via the mid-level outlet) to stay within the required concentrations. Genissiat Dam receives high sediment loads from Verbois Dam upstream, which is flushed to avoid sedimentation and consequent backwater that could flood parts of urban Geneva. In four decades of flushing every 3 years, an estimated 23 million tons of sediment could have deposited in the reservoir, but only 4.5 million tons have actually deposited. The operation is costly to the Compagnie National du Rhône, which engages a staff of about 400 over approximately 10 days, at a cost of about €1.4 million (based on the 2003 flushing, [*Thareau et al.*, 2006]). Nevertheless, to remove an equivalent volume (1.8 million tons in 2003) by dredging would have been far more costly.

On the Kurobe River, Japan, Dashidaira and Unazuki dams are operated in coordination, with high runoff triggering flushing of the upstream dam and sluicing through the downstream dam [*Kokubo et al.*, 1997; *Liu et al.*, 2004; *Sumi and Kanazawa*, 2006] (Figure 12). The basic sequence of operations is to draw down the reservoir water level, maintaining a free-flow state over several hours (the duration being determined by the amount of sediment to be flushed), and then allowing the reservoir water level to recover. In July 2006, a free-flow condition was continued for 12 h to flush out an estimated 240,000 m^3 of deposited sediment (Figure 13). The flushing/sluicing operation is followed by release of a clear-water "rinsing" flow to remove accumulated sediment from the channel downstream.

2.5. Pressure Flushing

This technique is a variant on drawdown flushing: rather than drawing the reservoir down so that it is acting like a river in carrying its sediment load, pressure flushing works only to remove sediment directly upstream of the dam to keep intakes operational. The reservoir level is not lowered, but outlets are opened to remove sediments a short distance upstream of the outlet, creating a cone-shaped area of

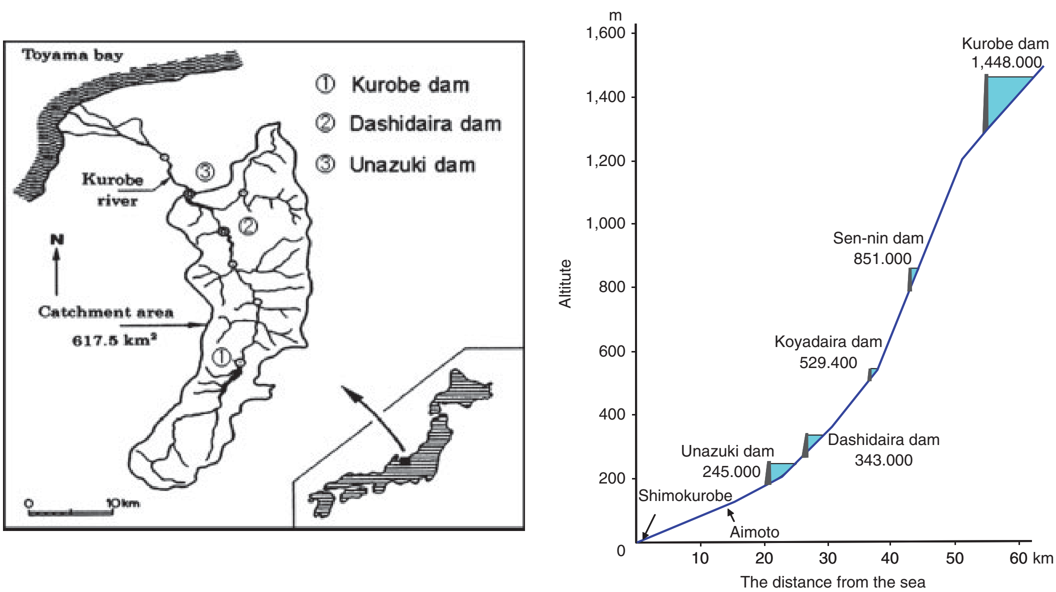

Figure 12. Kurobe River, Japan. Map of drainage basin and location of major reservoirs (a), and longitudinal profile showing all reservoirs (b).

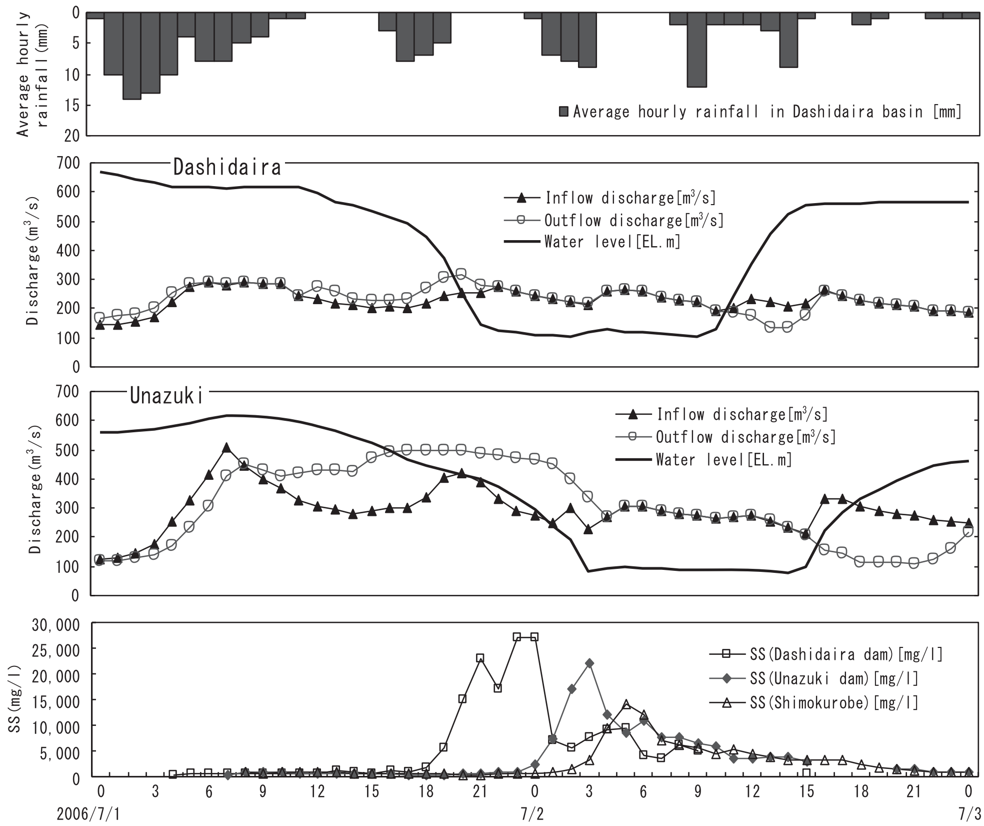

Figure 13. Coordinated flushing on reservoirs in the Kurobe River, Japan, 1–3 July 2006. Precipitation (a), inflow and outflow hydrographs and reservoir stage for Dashidaira (b) and Unazuki (c) dams, and resultant suspended sediment concentrations (d).

scour just upstream of the outlet, the scour hole being created in a fraction of the time it would take to refill [*Ullmann*, 1970]. *Shen et al.* [1993] developed an empirical formula for the dimensions of the flushing "cone" as a function of hydraulic and sediment variables, which could inform design of the dam outlets [*Lai and Shen*, 1996]. However, the scale of sediment removal by this technique is much smaller than with drawdown flushing. Rather, pressure flushing serves to reduce sediment concentrations to the intake and thereby reduce abrasion of hydraulic structures by sediment [*Lai and Shen*, 1996]. To maintain or restore reservoir capacity, pressure flushing is not an effective technique.

2.6. Turbidity Current Venting

Turbidity (or "density") currents are important in the transport and deposition of sediment in reservoirs worldwide. Turbidity currents form when inflowing water with high sediment concentrations forms a distinct, higher density current that flows along the bottom of the reservoir toward the dam without mixing with the overlying, lower density waters. If the bed of the reservoir is highly irregular, with protruding features that would break up the flows and cause turbulence, turbidity currents may not sustain themselves. However, turbidity currents occur in many reservoirs, and it is often possible to allow this dense, sediment-laden water to pass through outlets in the dam, a practice referred to as "venting" of turbidity currents (Figure 14). This can be undertaken as a sediment management technique, even at large reservoirs where other techniques, such as reservoir drawdown, are not feasible. Some dams have been able to pass half of the inflowing sediment load by venting turbidity currents, but the technique is possible only in cases where the turbidity current has sufficient velocity and turbulence to maintain particles in suspension and the current can travel all the way to the dam as a distinct flow, where it can then be passed downstream [*Morris and Fan*, 1998].

Facilities for the venting of turbidity currents should be provided at every project where turbidity currents are anticipated to convey substantial amounts of sediment to the dam. Advantages of turbidity

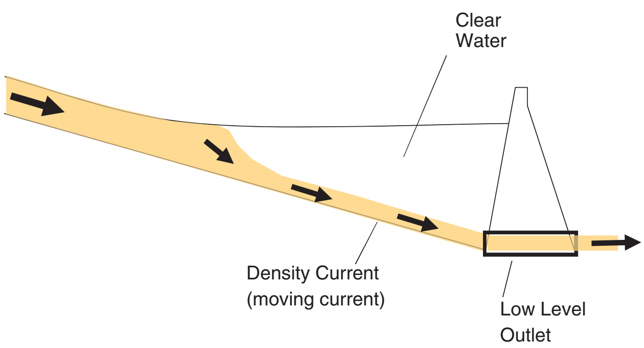

Figure 14. Schematic representation of density current venting.

current venting are that it delivers suspended sediment to downstream reaches during the floods when the sediment would naturally be delivered, and that it does not require reservoir drawdown or otherwise significantly impact reservoir operations.

Both Sanmenxia and Xiaolangdi Reservoirs on the Yellow River vent turbidity currents, along with flushing to discharge sediments, and the Yellow River Institute of Hydraulic Research has developed a new formula to predict the formation of plunge point for density currents, which can help in selection of optimal dam sites for density current venting, and criteria for design and operation of reservoirs to create effective density currents. With installation of a curtain (typically a sheet of geotextile hanging vertically from the water surface, suspended from flotation tanks and secured in place by a cable and anchor system, extending partway down the water column to force flow underneath), it may be possible to vent density currents at higher outlets on the dam, avoiding problems of clogging low-level outlets.

2.7. Dredging and Mechanical Removal of Accumulated Sediments

Accumulated sediments can be removed by suction using hydraulic pumps on barges with intakes. If cohesive sediments have "set up," cutter heads may be required to break up the cohesive sediments. Dredging is expensive, so is most often used to remove sediment from specific areas near dam intakes. If there is sufficient hydrostatic head over the dam, it can create suction at the upstream end of the discharge pipe to remove sediment and carry it over the dam as a siphon. This hydrosuction is typically limited to reservoirs less than 3 km in length, and to low elevations, where the greater atmospheric pressure facilitates the function of the siphon. In China, hydraulic suction machinery is commonly used to stir the sediment within the reservoir with hydraulic and mechanical power, then to discharge the highly concentrated sediment-laden water out of the reservoir through siphons by the help of water head difference between upstream and downstream of the dam.

If a reservoir is completely drawn down, mechanical removal can be employed using scrapers, dump trucks, and other heavy equipment to remove accumulated sediments. While still costly, mechanical removal is commonly less expensive than hydraulic dredging, and can remove coarser sediments, but it requires the reservoir to be drawn down far enough to expose coarse sediment. Mechanical removal is best adapted to reservoirs that remain dry for parts of the year such as flood control reservoirs. Cogswell Reservoir on the San Gabriel River, California, was mechanically dredged in 1994–1996, with 2.4 Mm^3 removed and taken to a nearby upland disposal site, at a cost of \$5.60/m^3 (or \$6.47/m^3 if planning and permitting are included) [*Morris and Fan*, 1998]. Another 2.55 Mm^3 has been identified as requiring excavation following a 2009 wildfire that increased erosion in the catchment [*Los Angeles County Department of Public Works* (*LACDPW*), 2012].

3. Upstream Sediment Management Approaches

Various approaches have been employed to reduce the amount of sediment entering the reservoir from upstream. These methods do not mitigate downstream sediment starvation effects, only sediment accumulation in reservoirs.

3.1. Catchment Erosion Control

Various attempts have been made to reduce sediment inflow into the reservoirs through changes in land use, notably reforestation and altering agricultural practices to emphasize contour plowing and other erosion control approaches. While these methods offer a number of benefits, such as maintaining soil productivity for food security, increasing infiltration, and reducing storm runoff, their benefits in reducing sediment inflow to reservoirs have not been clearly demonstrated [*Annandale*, 2011]. San Francisco-based Pacific Gas & Electric Company invested in watershed restoration and erosion control projects in the catchment above their dams on the North Fork Feather River for some years until concluding that, other benefits aside, they could not justify the cost in terms of reduced maintenance or greater generation at their facilities [*Kondolf and Matthews*, 1993].

3.2. Checkdams

Checkdams, often called by their Japanese name, *sabo* dams, can reduce sediment yield to a downstream reservoir in two ways. The first is by inducing deposition of debris flows and reducing the rate of hillslope erosion [*Takahara and Matsumura*, 2008; *Mizuyama*, 2008; *Cheng et al.*, 2007]. Small checkdams locally reduce the channel gradient and thereby induce deposition of debris flows and fluvially transported sediment, because stream energy is dissipated in the check dams, reducing the gradient in between. The checkdams also direct the main flow of water through the channel centerline, to reduce the tendency for the channel to undercut the side slopes. Successful applications of this technology have been reported in the Duozhao Ravine, Jiangjia River basin, southwestern China [*Zeng et al*., 2009] and the Loess Plateau of China [*Ministry of Water Resource of P.R. China* (*CMWR*), 2003].

The second way checkdams reduce sediment yield to downstream reservoirs is by trapping sediment before it reaches the downstream reservoir. The cumulative volume of sediment trapped in small check dams is usually trivial, so larger check dams have also been built explicitly to store sediment before it reaches a larger reservoir downstream. The obvious problem with this approach is that the check dams fill with sediment, and in high sediment-yield river basins this can occur quickly, creating a new set of problems, with multiple sediment-filled reservoirs, all potentially unstable and costly to maintain.

Multiple checkdams to intercept sediment above the Saignon Dam in southern France were deemed a "failure" by *Chanson* [2004] because both checkdams and reservoir had filled within 2 years of construction. Likewise *Ran et al.* [2004] found that nearly all checkdams built in four Yellow River tributaries had filled with sediment within 25 years, but concluded they had been successful in reducing sediment delivery to the downstream reservoir, if only temporarily. *Sukatja and Soewarno* [2011] reported that the Sengguruh Reservoir (East Java) lost 93% of its initial 21 Mm^3 capacity in 16 years, despite annual dredging and five checkdams built upstream, all of which were completely full within a decade. Eight additional checkdams were then proposed for the upstream channel, with a combined capacity of 6.9 Mm^3, equivalent to about 2 years average sediment inflow into Sengguruh Reservoir.

The construction of Shihmen Reservoir in 1963 on the Dahan River, Taiwan, was accompanied by construction of over 120 checkdams upstream to reduce sediment delivery to the reservoir. By 2007, 38% of Shihmen Reservoir's initial capacity of 290 Mm^3 had been lost to sedimentation, and virtually all of the checkdams' cumulative capacity of 35.7 Mm^3 (equivalent to about 12% of the reservoir's initial capacity) had filled with sediment [*Wang and Kondolf*, 2014]. Three large checkdams accounted for 86% of the total checkdam capacity, and one of these checkdams, Barlin Dam (capacity 10.5 Mm^3), failed in 2007, releasing most of its sediment in a massive downstream wave of water and sediment (Figure 15). The Taiwan Water Resources Agency is now conducting modeling studies to design a sediment bypass around Shihmen Reservoir, which promises to provide a more sustainable way to manage the high sediment loads [*Wang and Kondolf*, 2014]. Despite the extent of (and large investment in) checkdams in the Dahan River basin and elsewhere, the experiences reported in the literature illustrate that the benefits from checkdam storage upstream of larger reservoirs are temporary at best, and the sediment-filled checkdams become new hazards throughout the landscape.

3.3. Sediment Traps

Low dams located just upstream of reservoirs can function as traps for (mostly coarse) sediment. These should be designed for easy access by heavy equipment, so the trapped material can be easily excavated and either used for commercial aggregate or trucked to the downstream river channel for sediment augmentation, as done in Japan [*Kantoush and Sumi*, 2010]. The Alameda County Public Works Agency (California) built a sediment trap upstream of Cull Canyon reservoir on San Lorenzo Creek in 1981. It effectively trapped sediment during high flows in the 1990s, and 4500 m^3 was excavated and stockpiled as

Figure 15. Sequential photographs looking at Barlin Dam, showing the dam (a) prior to filling with sediment (October 2002), (b) after filling with sediment (September 2005), and (c) after failure (September 2007). (Photographs courtesy of Taiwan Water Resources Agency, reprinted by permission.)

a source of aggregate for county projects [T. Hinderlie, Alameda County Public Works Agency, personal communication 2013].

3.4. Warping

Warping involves diverting sediment-laden water onto agricultural land to permit deposition of suspended sediments, to improve soil fertility. A traditional English term, warping was conducted in English lowlands through the nineteenth century [*Creyke*, 1845; *Williams*, 1970], but the technique has also been implemented for two millennia on highly sediment-laden rivers of the Loess Plateau of China (with suspended sediment concentrations typically exceeding 200g/l), yielding not only the traditional benefits to agricultural land, but now also serving the function of reducing sediment loads to reservoirs downstream, such as Heisonglin [*Morris and Fan*, 1998; *Zhang et al.*, 1976].

4. Sediment Augmentation Downstream of Dams

To compensate for the lack of sediment supply downstream of dams, sediment may be added to the channel, an approach termed sediment augmentation or sediment replenishment (Figure 16). Most commonly, the sediment added is gravel and sand, and in rivers with important fish species and other sensitive ecological resources, there are often prohibitions on increasing turbidity, which restrict the addition of finer sediments. Most examples to date are from the US, Japan, and Europe, and the majority have been for habitat restoration. In most cases, the sediments added are obtained from gravel quarries in the floodplain or other such sources, but in some cases (such as the Middle American River at Ralston Afterbay and several dams in Japan), the sediments are taken from the reservoir delta deposits or sediment traps built at the upstream end of the reservoir [*Jones and Stokes*, 2003; *Kantoush and Sumi*, 2010].

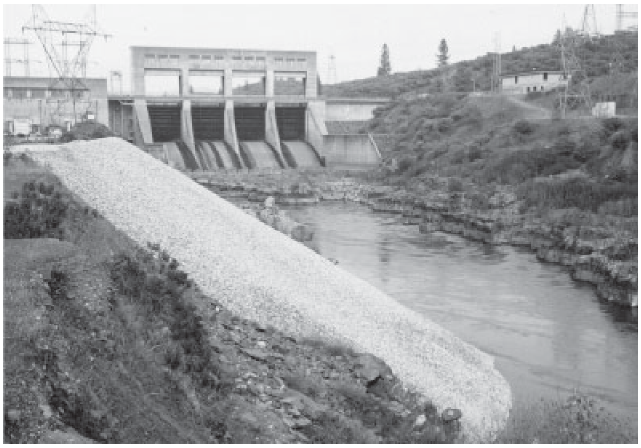

Figure 16. Gravel augmentation via high-flow stockpile on the Sacramento River, below Keswick dam (photo by *Kondolf*, 1990).

The largest ongoing sediment augmentation project is on the Rhine below the Barrage Iffezheim, where an average of 170,000 m^3 of coarse sediment is added to the channel annually, to prevent channel incision and consequent damage to infrastructure such as bridges, pipeline crossings, and embankments [*Kuhl*, 1992]. However, most projects are undertaken to restore aquatic habitat, especially for fish. Sediment augmentation can be implemented by placing sediment directly in the flowing river (high-flow direct injection), but is more commonly done as a gravel deposit along the margins of the river, where it can be mobilized by high flows (e.g., in-channel or point-bar stockpiles) [*Ock et al.*, 2013]. Past sediment augmentation for habitat has often involved building forms from gravel (e.g. riffle construction). Where the upstream dam controls flows so much that scouring is rare, these projects can be successful in creating habitat [e.g., *Wheaton et al.*, 2004; *Merz and Chan*, 2005], but such projects have promptly washed out in high flows on other rivers [e.g., *Kondolf et al.*, 1996]. Increasingly, gravel augmentation projects are designed to restore some part of the river's gravel load below the dam, so that the river itself can transport and redistribute the gravel in natural bars and riffles, which have high habitat value [*Gaeuman*, 2013].

5. General Principles Drawn From Collective Experience in Reservoir Sediment Management

With reference to the Brundtland Commision's [*United Nations* (*UN*), 1987] definition of sustainable development, that is, to meet the needs of the present without compromising the ability to meet the needs of future generations, we recommend that all dams be designed and operated so that they continue to provide benefits to future generations. The geologic and hydrologic settings (as well as operational requirements) of reservoirs vary widely, and thus no one approach is suitable for all sites. Nonetheless, the expert group agreed on a set of principles that have broad applicability. We first present a set of general principles, followed by more specific guidance for siting, design, and operation.

5.1. All Dam Proposals Should Address Sedimentation

Sediment trapping by dams creates problems for dam operation, reduces dam and reservoir lifetime, and causes downstream sediment starvation. We recommend that sedimentation be explicitly addressed in planning and design documents for all proposed dams, including quantification of upstream sediment yield to the reservoir, and with projections of reservoir sedimentation rates into the future for the conventional design approach as well as management based on more sustainable principles. Rivers vary widely in their sediment loads, and the load carried by the river should be explicitly acknowledged in planning documents. Planning and design documents should indicate how reservoir sedimentation will be managed in the long term to contribute to sustainable development.

While it is sometimes possible to retrofit concrete dams with additional low-level outlets for sediment flushing, as done for Sanmenxia reservoir, it is generally not possible to retrofit compacted earthen dams, and in any event, retrofitting is much more expensive than incorporating such outlets in the initial design and construction, and may impair the stability of the dam. Thus, it is always better to take sediment into account in the initial planning phases, and to incorporate appropriate features at the outset.

5.2. Plan Over Sufficiently Large Temporal and Spatial Scales

In planning dams, reservoir sustainability and downstream impacts should be analyzed over a sufficiently long temporal scale (300 years or more) to capture long-term impacts, and a spatial scale much larger than the reservoir and its immediate environs should be adopted. The upstream river basin should be analyzed for its sediment production, with respect to additional dams, and other changes. Downstream impacts to the river sediment balance should be an integral part of the analysis of proposed dams, and extending downstream far enough to incorporate the limit of impacts, including the coastal zone where appropriate.

As many large rivers cross international boundaries, there can be important transboundary dimensions to sediment management. As discussed in Section 2.4, flushing of Verbois Dam on the Rhône River in Switzerland is coordinated with flushing of the Genissiat Dam downstream in France, in a successful example of cross-border coordination. In the Mekong River basin, the Lancang River, the upper reaches of the Mekong in China, formerly supplied 50% of the river's total sediment load, but dams being constructed on this upper reach will trap 83% of the natural sediment load from the upper basin, with potentially significant consequences for lower basin countries (Kondolf et al., submitted manuscript, 2013). The Douro River flows from Spain into Portugal, and multiple dams in both Spain and Portugal have cut off sediment supply to downstream reaches, contributing (along with instream sand mining) to the sediment starvation that led to collapse of the Entre Os Rios bridge in 2001, killing 59 [*Sousa and Bastos*, 2013]. Such transboundary impacts are typically not anticipated when dams are planned, nor mitigated.

5.3. Adopt a Life-Cycle Management Approach to Design and Operation

For purposes of dam design and operation we recommend adoption of a life-cycle management approach in lieu of a design life approach. Planning and economic studies for reservoirs are commonly based on a design life of only 50 years [*Morris and Fan*, 1998], which effectively makes it difficult to manage sedimentation problems during and after that period. A 50-year design life is the economic norm, because all costs and benefits are usually calculated to represent present values. The costs are then compared to the benefits using a market-based discount rate. Because any benefits farther than 50 years in the future, when reduced to a present value, are extremely low, additional capital costs to manage sedimentation well into future generations are not "economically justified." This means, e.g., that most dams do not have large, low-level outlets that could be used to manage sediment both during a traditional design life and well beyond. To the extent that sedimentation has been considered, it has most commonly been addressed by provision of a sediment storage pool within the reservoir's dead storage, commonly designed to accommodate 100 years worth of sedimentation [*Morris and Fan*, 1998]. However, with adequate maintenance and management of sedimentation, the usable life of a reservoir can be extended for a much longer period [*Palmieri et al*., 2003].

5.4. The Dual Nature of Reservoir Storage Space

Renewable resources are used at a rate that is smaller than their rate of regeneration, thus they are "renewed." *Exhaustible resources* are used at a rate greater than the rate of their regeneration, and are often considered to have fixed quantities, which can be "exhausted" by use. How should we classify reservoir storage space, as exhaustible or renewable? In reservoirs that are (by design) allowed to fill with sediment, reservoir capacity is properly classified as an *exhaustible resource*. Alternatively, in reservoirs managed to prevent or minimize storage loss from sedimentation, reservoir capacity can be viewed as a *renewable resource* [*Annandale*, 2013]. This fact means that the nature of reservoir storage space depends on a developer's decision to either implement reservoir sedimentation management approaches or not. A decision not to implement reservoir sedimentation management approaches means that reservoir storage space, once lost to sedimentation, is no longer available for use by future generations.

If traditional cost–benefit analysis practice is to be continued, assigning the correct value to implementation of reservoir sedimentation management approaches to preserve reservoir storage space requires application of the Hotelling Rule, which says that for the maximum good of current and future generations, the price of exhaustible resources should increase at the rate of interest, to maximize the value of the resource stock over time [*Solow*, 1974]. Hotelling was responding to the problem of natural resources that were priced "too cheap for the good of future generations, that … are being selfishly exploited at too rapid a rate" [*Hotelling*, 1931]. Given that good reservoir sites are limited and many already used, reservoir storage space should be viewed as an exhaustible resource in cases where reservoir sedimentation management is not implemented. However, if reservoir sedimentation management is incorporated as an integral part of the design, operation, and management of a dam and reservoir, the reservoir storage space can be viewed as a renewable resource. The decision as to whether reservoir sedimentation management should be implemented or not, i.e., whether the reservoir is viewed as an exhaustible or a renewable resource, has significant implications for the economic analysis of dam and reservoir projects [*Annandale*, 2013]. Thus, sustainable development of dams and their reservoirs requires close attention to either preventing sediment deposition or removing deposited sediment from reservoirs.

There are reasons to consider alternatives to the traditional cost-benefit approach when considering reservoir sedimentation. Issues such as climate change, reforestation, and the safe storage of nuclear waste all have very long time horizons. Published procedures exist that offer different approaches to discounting, such as hyperbolic and exponential discounting, declining discount rates, and intergenerational discounting [*Johnson and Hope*, 2012], all of which deal with very long time horizons.

5.5. Distinguish Between Behavior of Fine and Coarse Sediment

Both suspended and bed load sediments are important to river systems. Not only do reservoirs trap different grain sizes with different efficiencies. It is important to understand downstream sediment impacts and to plan for them. As discussed in Section 1.2, the transport characteristics, trapping potential, and downstream impacts of fine and coarse sediment are quite distinct, and should be considered separately. For example, gravels are trapped with 100% efficiency in most reservoirs, commonly leading to gravel deficits downstream, and it is rare that gravels can be sluiced or flushed except in small reservoirs. Sluicing and flushing work best with finer grained sediments, which in any event, are usually the vast majority of sediment. In all cases, it is essential that the caliber of sediment coming into a reservoir be known to effectively design for it.

6. Specific Recommendations

The expert group offered a number of points that often arise in sediment management. These can be viewed as specific examples under the broader recommendation that dam planning, siting, design, and operation be undertaken in the context of a longer term and larger spatial scale perspective.

6.1. Avoid Sediment Problems Through Dam Siting

Decisions about siting reservoirs largely determine future reservoir performance. To date, dams have typically been sited based principally on engineering, economic, and often political considerations, commonly on land already owned by the dam proponent or otherwise convenient for the purpose. For sustainability, siting decisions should account for the larger spatial and temporal context. For example, sediment problems can be minimized by giving preference to river channels with lower sediment loads (e.g., in less erodible areas, and perhaps higher in the catchment) and to sites where sediment passing is more feasible (e.g., steep gorges instead of low-gradient reaches). For a given level of hydroelectric generation within a river basin, it may be possible to minimize impacts by concentrating dams in a smaller number of rivers (preferably with naturally low sediment yields), allowing other rivers to flow freely, contributing sediment to downstream reaches and supporting habitat. This sort of "triage" is often difficult to implement politically.

The effect of reservoir siting on the severity of reservoir sedimentation problems is illustrated by difference between the two principal water supply reservoirs for Taipei, Taiwan: Shihmen and Fetsui Reservoirs. As noted above, Shihmen Reservoir has been plagued by sedimentation, losing 38% of its capacity since its construction in 1963. *WRA* (2011) estimated an average of 3.53 Mm^3 of sediment flows into Shihmen Reservoir annually, compared to 0.95 Mm^3 estimated to flow into Fetsui Reservoir, implying that the Fetsui site is better suited from the perspective of reservoir sustainability.

6.2. Anticipating Future Sediment Management in Dam Design

The long-term equilibrium profile, i.e., the river bed profile through the reservoir after anticipated sedimentation has occurred to reach equilibrium between incoming sediment and outgoing sediment through the dam or bypass, should be calculated in advance for every project, drawing upon hydraulic and sediment transport models. Gates should be placed and sized with respect to the requirement to achieve the desired long-term profile. There is no standard location for the proper placement of gates, because this will depend on the situation at each dam, but in general gates should be set low enough and with sufficient hydraulic capacity to establish the desired equilibrium profile and support the type of sediment management operation identified for long-term use. For example, if flushing is to be performed during a low-flow period, the gates may be smaller and placed very low in the dam section, while gates for drawdown sluicing will have much greater hydraulic capacity and will probably be set at a higher level. In many cases, an array of large radial gates at the bottom of the dam may be the best option. Their high initial capital costs are likely to be offset by the longer economic lifetime of the reservoir.

Although the need for a new outlet tunnel or new gates may not be manifest until some future point when sedimentation has advanced to the point that a new operational rule is required, such future needs should be anticipated during initial design and the dam designed to accommodate such future requirements. It is preferable to install the needed gates at the outset for the integrity of the dam and so that they are more likely to be operated when needed to pass sediment.

The location and configuration of intakes should take into consideration the long-term equilibrium sediment profile and the ability to naturally scour sediment away from the area of the intake to sustain water deliveries despite sedimentation.

6.3. The Larger Context

Dams in a series should be operated in concert to achieve management of sediment transport along the river system, even where the river cross territorial boundaries. Poor results and conflicts between upstream and downstream dams will result if dams are operated independently. Therefore, when a series of dams are developed along any river, particular attention should be given to establishing the appropriate coordination and data-sharing among the parties, including both the historical and real-time monitoring data required to determine the efficiency of the operation and to identify means to improve the operation and pass sediment.

The availability of long-term, accurate hydrologic and sediment data are essential for the purpose of design and for analyzing impacts. This should include, at a minimum, reservoir sedimentation surveys, where possible suspended sediment sampling, and monitoring of reaches downstream likely to be affected by sediment starvation, flushed sediments, etc. Ironically, a glance at the dates of reservoir sedimentation surveys [*Ackerman et al.*, 2009] suggests that reservoir sedimentation surveys have become less frequent in the US since the 1940s, despite improved technology, and in many river basins, such as the Sado River basin in Portugal, no sediment surveys have ever been conducted, despite the presence of dams on all the river's tributaries. Sediment management designs and impact analysis cannot be any better than the data on which they are based. Thus, data collection efforts should be emphasized, as well as data-sharing among agencies and political jurisdictions.

Operational flexibility to flush sediment while minimizing impacts on power system costs or reliability is easier to achieve in larger grid systems where the fraction of power generated by the reservoir relative to the total mix of generators is relatively modest. Therefore regional integration of power grids may enable improved sediment management operations.

7. Conclusions

Sediment trapping by dams has consequences for the reservoir and for the downstream channels and, in some cases, coastal zones. As sediment accumulates behind dams, it can impair reservoir functions and ultimately reduce or eliminate storage capacity, threatening the sustainability of water supply and hydroelectric generation. Good dam sites are limited, so reservoir storage capacity should be viewed under the Hotelling Rule as an exhaustible resource if a conscious design decision is made to allow a reservoir to fill with sediment, and, consequently, reservoir storage capacity should be valued more highly than it is presently in dam planning. Today many dams are planned and built without any consideration of sedimentation, or at best, the reservoir is designed to store anticipated sediment loads for 50–100 years before its functions are impaired. Yet in many cases, dams can be designed to pass much of their sediment load, and in this case, reservoir storage capacity can be viewed as a renewal resources, with much more positive implications for the future sustainability of water supply and hydroelectric generation. Based on the broad experience of our assembled expert group, we recommend that dams be planned and designed for sediment management, where possible by passing sediment through or around the reservoirs.

Choices in the siting, design, and operation of dams determine their ability to pass sediment. Siting decisions are irreversible, and to retrofit dams after they are built with sediment passage facilities such as discharge gates is expensive at best and impossible at worst. Therefore, the most important consideration in sediment management through reservoirs is getting it right from the start. This principle implies that existing plans for dams not yet built should be urgently and fundamentally revisited to consider a full range of sediment passage options. Even for existing dams, an assessment of options to improve sediment management is desirable and recommended.

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