
Sedimentation, Dam Safety and Hydropower: Issues, Impacts and Solutions

Greg Schellenberg, C. Richard Donnelly, Charles Holder, Marie-Helene Briand, and Rajib Ahsan, Hatch

1. Introduction

Global renewable energy production is steadily increasing to meet demands for clean and reliable energy. The International Hydropower Association (IHA) reports that renewables comprise 23% of the global electricity mix as of 2014, with 16% of the world's energy production coming from hydropower (IHA, 2015). With approximately 70 GW added in the last two years, global installed hydroelectric capacity currently exceeds 1,200 GW (IHA, 2015; IHA, 2016).

The International Commission on Large Dams (ICOLD) maintains a registry of over 58,000 dams larger than 15 metres in height and designates 9,595 of these as either solely or partially purposed for hydropower (ICOLD, 2016). These dams can store significant amounts of water. For example, ICOLD lists the 1,626 MW Kariba Dam in Africa (Figure 1) as having the largest reservoir volume in the world at over 180 km³ (ICOLD, 2016).



Figure 1 - The Kariba Dam and Reservoir

The safety of these dams, and protection of the public and the environment from an uncontrolled release of the water and sediments is critical to public acceptance of hydropower projects. In general, dams are remarkably robust. The expected useful life of a properly engineered and maintained dam can easily exceed 100 years (Kondolf, et al., 2014; ASCE, 1975). In fact, a number of ancient dams are still in existence; for example, a number of Iranian dams (Darius, Bahman, and Mizan dams) exceed 1,500 years in age and are still in place today (Angelakis, Mays, Koutsoyiannis, & Mamassis, 2012). The Lake Homs Dam in Syria, built in the 1300's BC, is distinguished as the oldest operational dam in the world (Chen S. , 2015).

Despite their general longevity, dam failures do occur. For example, in the spring of 1889, the largest dam failure incident in North American history took place. Following a period of heavy rains, the 22-m high South Fork dam, located just upstream of Johnstown, Pennsylvania, broke, releasing over 15 million cubic meters of water and debris into a narrow valley, killing more than 2,200 people. Over a century later, also following a period of unprecedented rainfall, Canada's most significant dam safety event took place during the devastating Saguenay floods of 1996. In this case, eight dams were overtopped. None of those failures involved large amounts of sediment release but the Saguenay failures caused significant bank erosion that had similar effects on the environment. Recent tailings dam failures in Brazil and British Columbia showed the significant immediate damage caused by sediment release.

The frequency of dam failure has been studied by many authors who have shown that the world-wide the potential for dam failure is in the order of 4×10^{-4} failures per dam year (Table 1).

Table 1 - Frequency of Dam Failure World-Wide (ICOLD, 1995)

Location	Reference	No. of Failures	Total Dam Years (thousands)	Failure Rate
USA	Gruner [55], [56]	33	71	5×10^{-4}
	Babb [57]	12	43	3×10^{-4}
	USCOLD [58]	74	113	7×10^{-4}
	Mark [59]	1	5	2×10^{-4}
World	Mark [59]	125	300	4×10^{-4}
	Middlebrooks [60] / Mark [59]	9	47	2×10^{-4}
Japan	Takase [62]	1046	30,000	4×10^{-5}
Spain	Gruner [55]	150	235	6×10^{-4}
World	Foster [61]	136	302	5×10^{-4}
Overall Average Dam Failure Rate				4×10^{-4}

In 1975, a study performed by ASCE/USCOLD showed that there were four general causes of dam failure as depicted in Figure 2.

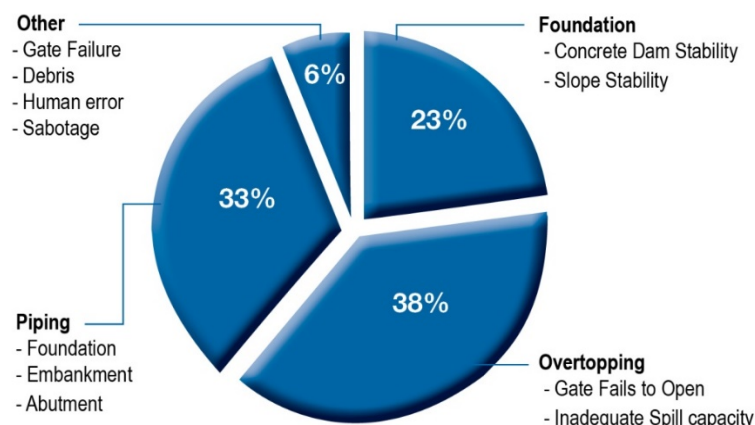


Figure 2 - Causes of dam failure (ASCE/USCOLD, 1975)

While no dam has ever failed as direct result of sedimentation issues, it does impact the safety of dams. Sedimentation can alter reservoir routing, complicate the management of seasonal flood inflow, reduce spillway discharge capacity, alter reservoir ice mat formation and increase loads on the dam and components of the dam such as gates.

In this paper, sedimentation issues, as they pertain to hydropower facilities and dam safety, are explored. This paper also introduces sedimentation management techniques and describes how they can be implemented to limit the impacts of sedimentation on hydropower. Selected case studies are presented to highlight issues and issue mitigation.

2. Background

The causes and processes for movement of sediment into reservoirs are well documented in available literature (Morris & Fan, 1998). Sedimentation is a processes of erosion, entrainment, transportation, deposition, and compaction of particulate materials [6, 7]. Sedimentation processes are relatively balanced in unregulated mature rivers that have stable catchments. However, immature rivers in volcanic or tectonically active regions can be very dynamic with sediment movement actively reshaping land forms and the river system. Similarly, changing land-use such as deforestation can result in rapidly altered sediment flow into rivers.

When a waterpower reservoir is created it causes a local decrease in river flow velocities that can initiate or accelerate the sedimentation process upstream of the dam. (Morris & Fan, 1998). Downstream, the reduction in sediment can cause dramatic changes to flood plains and deltas. As illustrated in Figure 3, sedimentation takes a typical form with progressively finer materials being deposited as the flows approach the dam.

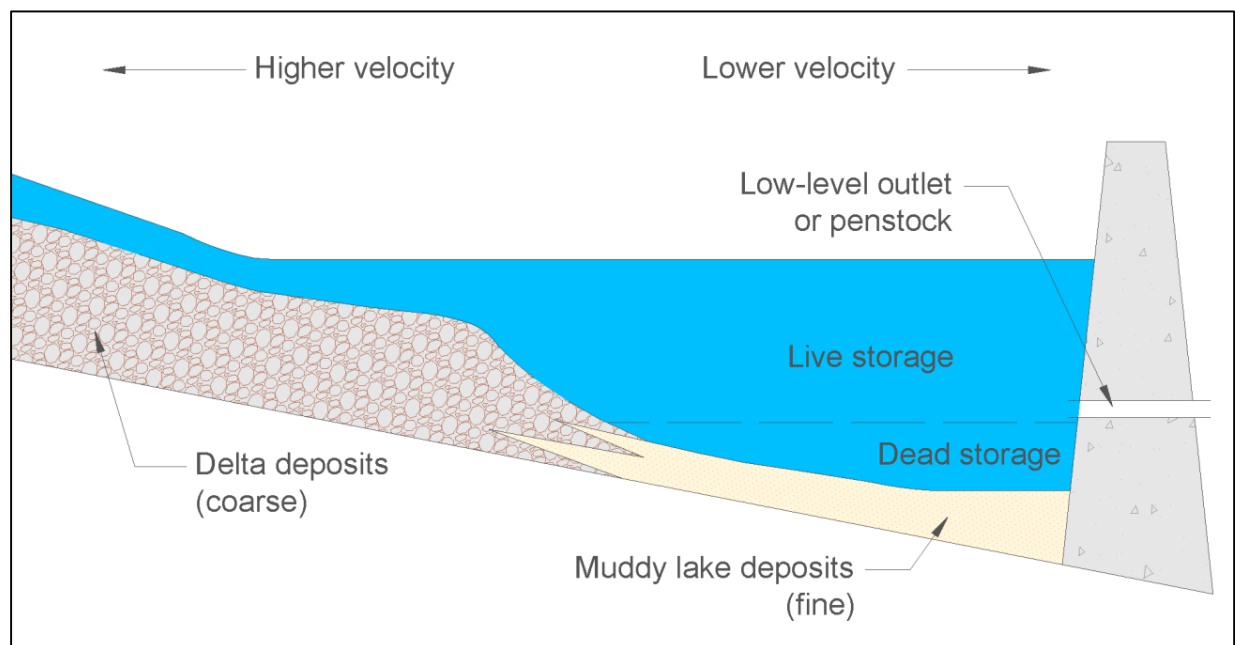


Figure 3 - Typical reservoir sediment profile, adapted from (Morris & Fan, 1998)

Morris, Annandale, & Hotchkiss (2008) describe three stages in a reservoir's life. The first stage is the *continuous sediment trapping* stage in which sediment accumulation occurs rapidly. In the case of the Dez Dam in Iran (**Error! Reference source not found.**) reservoir sedimentation is reported to have raised the reservoir bed elevation by about two meters per year over its 40 year lifetime (Steele, Izadjoo, Samadi-Boroujeni, & Galay, 2006).



Figure 4 - Dez Dam, Iran

During the second stage of the sedimentation process, *partial sediment balance*, occurs. During this stage the reservoir experiences a mixture of sediment deposition and removal, often with fine sediments reaching sediment balance but coarse sediments continuing to accumulate.

In the third and final stage *full sediment balance*, occurs with sediment inflow and outflow equal for all particle sizes. Complete sediment balance can only be reached if the incoming sediment load can be transferred downstream of the impoundment or otherwise removed from the reservoir.

Currently most reservoirs around the world are in the first stage of continuous sediment trapping. (Morris, Annandale, & Hotchkiss, 2008). However, due to the long expected lifespan of a waterpower facility, designs need to be based on achieving sediment balance.

As shown in Figure 5, developing regions of the world that stand to benefit most from production of hydroelectricity are often those that have the highest sediment yields (Grummer, 2009). Regions where there is a potential for large hydroelectric capacity and a substantial sediment yield can be expected to experience hydropower issues related to sedimentation (e.g. China, South America, Northern India). Areas with high sediment yield but currently insignificant hydroelectric capacity (e.g. southeast Africa and Central America) will need to consider sediment management techniques before developing hydropower facilities.

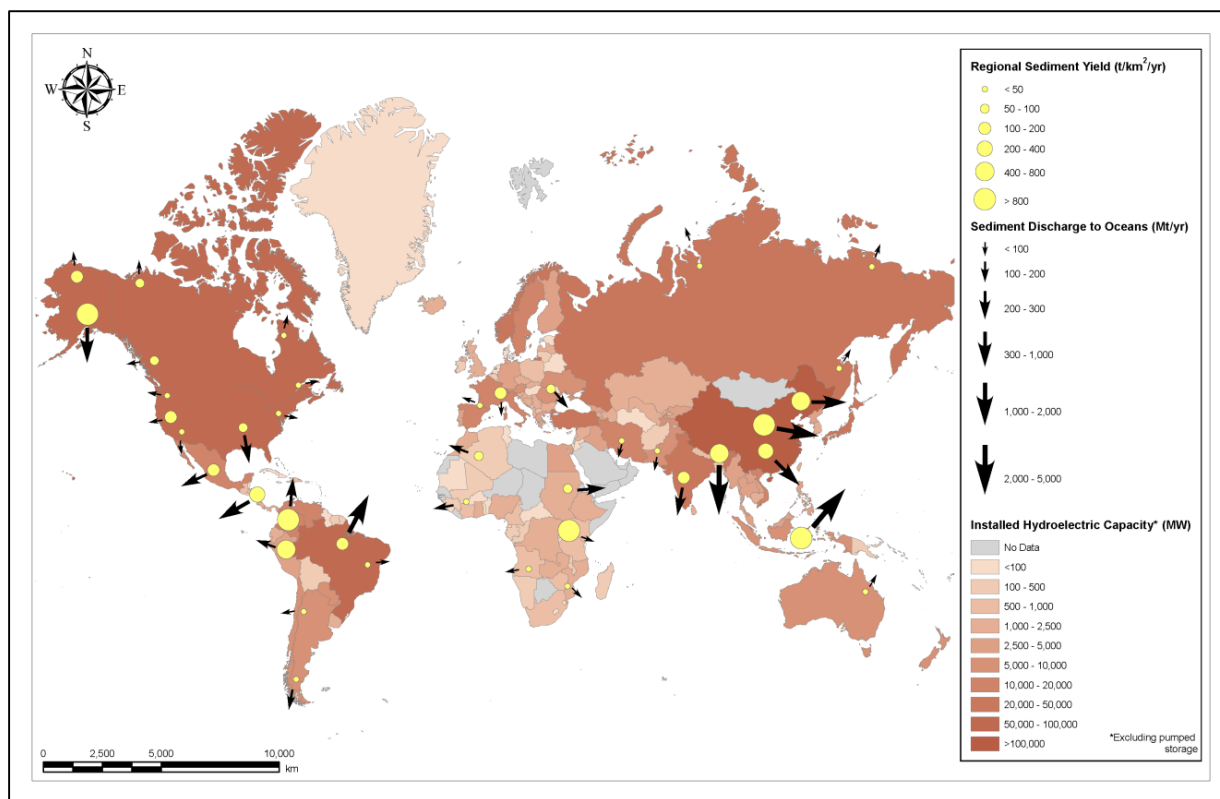


Figure 5 - Comparison of hydroelectric potential and sediment production by region*

**Installed capacity data from (IHA, 2015) and sediment yield data from (Milliman & Meade, 1983); figure adapted from (Milliman & Meade, 1983)*

3. Impacts of Sedimentation on Waterpower Facilities

3.1 Impacts on Generation

One of the main impacts of reservoir sedimentation on waterpower generation is the loss of storage. Globally, the total volume of water stored in reservoirs used for hydropower and other purposes around the world currently exceeds $6,800 \text{ km}^3$ (White, 2001). About 0.5 to 1% of this global reservoir volume is lost every year as a result of sedimentation (White, 2001; Morris, Annandale, & Hotchkiss, 2008). If these rates continue unabated half of the world's reservoir storage would be lost within the next 50 to 100 years. This is further illustrated in Figure 6 which shows that global per capita reservoir storage has been rapidly decreasing since its peak at around 1980 with a current per capita storage equivalent to levels that existed nearly 60 years ago.

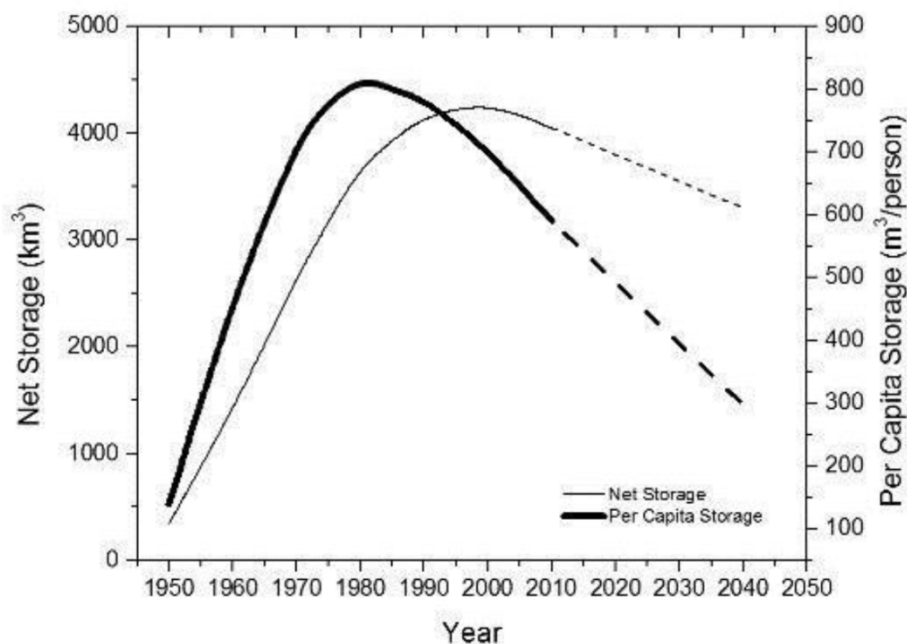


Figure 6 - Global reservoir storage volume (net and per capita) (Annandale, Morris, & Karki, 2016)

Without the ability to store water, waterpower facilities operate entirely as run-of-river plants with generation entirely dependent on seasonal flows. Flows that might not occur when energy is needed eliminating one of the key benefits that storage hydro provides over any other renewable power generation source (IHA, 2015). As an example of the impacts of sedimentation, infilling of the intake canals at the Inga I and II powerhouses in Congo have reduced generation capacity by approximately 30%. Dredging is performed regularly to attempt to mitigate the issues (InternationalRivers.org).



Figure 7 - The Inga Hydroelectric Project

In some cases, sediments discharged from an upstream dam in a cascade system can cause an increase the tail water level reducing power generation (Morris & Fan, 1998). Similar discharges along the system can affect the generation potential of all of the plants along the cascade system and could increase the possibility of powerhouse flooding. This then presents a potential for the loss of primary power supply sources and communication systems needed for spillway gate operation. While a remote possibility, this may need to be considered in a PFMA for a particular dam.

3.2 Impacts on Stability

Sediment loads on concrete dams or structural components such as spillway walls for normal load cases are commonly idealized as a static pressure defined by an at-rest soil pressure coefficient and the buoyant unit weight of soil. In North America, a commonly used criteria was published in the USBR design manuals for gravity, arch and other small dams (USBR, 1976). These manuals suggested silt be considered to be equivalent to a fluid weighing 85 pounds per cubic foot (pcf) for estimation of horizontal loads and to have a wet density of 120 pcf for vertical loads. The implication is that the wet density would reduce to a buoyant weight of 57.6 pcf that would be added to the water density of 62.4 pcf. The suggested lateral load implies a soil pressure coefficient of about 0.39 and an internal friction coefficient of about 37 degrees. However, available literature suggests that a wide range of internal friction angles apply to the various sediments that could accumulate in front of a dam. A wet, loose, silt or clayey sediment would likely have a much lower internal friction angle and, therefore, a higher at-rest pressure coefficient. On the other hand, a small reservoir on a mountainous stream that rapidly fills with coarse river bed material ranging in size up to large boulders could reasonably be considered to be filled with sediments that have a high internal friction angle. Sediment densities may also vary widely as has been well documented by Morris and Fan (1998). Consequently, a designer should expect that the lateral pressure on a concrete dam or a structural component might be significantly different than published criteria.

Published criteria do not mention any change to uplift under a concrete dam due to sediment. However, in principle, sediment could be either beneficial or detrimental. A fine silt or clay sediment might be expected to reduce seepage pressures under a dam in the same way as an engineered upstream blanket. Conversely, a fully liquidized sediment, i.e. one with the particles completely suspended, would transfer a higher pressure at the bottom of the reservoir that would increase piezometric pressures beneath the dam. In the case of a dam with a large turbid inflow forming a pool at the bottom of the reservoir, uplift would be expected to increase until enough particles had settled to form a blanket or seal the bedrock discontinuities. For a sediment completely liquefied by seismic activity, it might be assumed the same logic applies but it is likely that the sediments would return close to their original state rapidly resulting in a rapid dissipation of the higher pore pressure dissipates.

Given the huge uncertainty that still exists about pore pressure under a concrete dam due to earthquake loading when the dam might slightly lift and rock joints dilate, it seems questionable

to add higher uplift due to sediment liquefaction. For reservoirs with sediments that would not completely liquefy, there appears to be even less justification for an uplift increase.

Despite the limitations in the science, commonly used normal load case design criteria for silt loads appear to have been adequate to ensure the stability of structures. However, a review of published criteria suggests they omit plausible conditions that could reasonably be assumed to apply. For example, criteria often ignore the potential for an underwater sediment slope failure that could cause surface waves and, therefore, additional loadings, hydro-dynamic pressure waves and an inertial loading because of the dense fluidised soil-water mass moving downstream. Another phenomena commonly ignored in for normal loading conditions relates to the presence of turbidity currents that are known to occur in reservoirs with large sediment inflows during floods because the turbid water is slightly denser than rest of the reservoir. This implies the turbid 'fluid' has the potential to exert a higher pressure. Morris and Fan (1998) reported data published by the National Research Council of the USA (Washburn, 1928) that shows a turbid fluid with a sediment load of 100 mg/l could be about 6% heavier than clear water. As there is little published information on the impacts of turbid flows it is necessary for the criteria used to be based on observed conditions in the reservoir in question.

Submarine landslides are widely studied because of their potential to create tsunami waves but are commonly ignored for dams. In western Canada, the Fraser River deltaic sediment deposition in the Strait of Georgia has been identified as a potential hazard to local communities. The deltaic marine sediment deposition is fundamentally no different than reservoir sediment deltaic deposition. Dam designers need to be aware of the potential effect of underwater sediment slope failure on dams. While sediment slope failure could be caused by an earthquake, there seems no sound basis to rule out a sediment slope failure under normal loading conditions. The immediate result would be surface waves that propagate tsunami-like throughout the reservoir. However, a slope failure could also produce compression waves in the water body and has the potential to fluidise or to liquidise finer sediments laid down near the toe of the landslide. These underwater landslide effects and others might be trivial for many dams but, at least in some cases, the impacts could be significant. A key factor is the degree to which the steeply sloping deltaic sediment front has advanced into the reservoir. As the deposition extends downstream into the reservoir the potential for issues progressively increases. As such, the designer needs to provide explicit rationale for adoption or exclusion of underwater landslide phenomena as a potential loading case.

The design criteria adopted by engineers for seismic loads vary but a commonly adopted basis is to assume that the reservoir sediments fully liquidize, lose all shear strength, and exert a full dense fluid hydrostatic load based on the full buoyant weight of the sediment on the upstream face of a dam or concrete structure. While such complete liquefaction may be possible in an extreme case, in most cases that degree of fluidization is not possible. For example, even under very high seismic loading, a reservoir filled with coarse river bed material from a mountain stream would be unlikely to fully fluidize with a complete loss of shear strength. In some cases, designers have assumed that the fully fluidized dense-fluid contributes to hydro-dynamic pressure loading on a dam based on Westergaard's formula (Westergaard, 1931), ignoring the physical basis for its derivation. In fact, there is the more general question about the applicability of Westergaard's

formula for hydro-dynamic pressures, let alone if it should be applied to the liquidized sediments based on a saturated soil density.

The behaviour of reservoir sediments during earthquakes and their effect on a water retaining structure is, in general, poorly understood. A multi-disciplinary approach with close collaboration between geotechnical and structural engineers coupled with sufficient investigation of the reservoir sediment properties to assess their response to an earthquake is necessary to ensure the impacts have been adequately defined. Again, an explicit justification for the criteria adopted is an essential element in building a sound safety case for a dam

Researchers have investigated absorption of seismic energy by reservoir sediments and have concluded sediment saturation to be a major factor. Theoretical results suggest minimal system damping under dynamic loading when reservoir sediments are fully saturated, but significant reductions in acceleration when sediments are partially saturated (Bougacha & Tassoulas, 1991; Dominguez, Gallego, & Japon, 1997). For example, if the foundation is assumed to be rigid, hydrodynamic pressures decrease slightly at the base of the dam when sediments are fully saturated but increase when partially saturated (Bougacha & Tassoulas, 1991). The system's response to horizontal ground movement is also found to increase when sediments are partially saturated (Dominguez, Gallego, & Japon, 1997). Sediment thickness is also an important factor in considerations of dynamic loading, especially when sediment is partially saturated (Dominguez, Gallego, & Japon, 1997). Absorption of horizontal motion is minimal when the impounded sediment layer is thin, largely due to a relatively high modulus of elasticity and low attenuation coefficient of the sediment (Hatami, 1997). However, vibrational absorption increases as sediment continues to accumulate against the dam, again depending on sediment saturation (Gogoi & Maity, 2007). Other factors found to be important are sediment density, compressibility, and pore water pressure (Gogoi & Maity, 2007; Dominguez, Gallego, & Japon, 1997; Chen & Hung, 1993). This dependence on sediment properties makes a strong case for their measurement and inclusion (when appropriate) as part of the design loading conditions. (Bougacha & Tassoulas, 1991). The fundamental problem with the research at this point is that observations have been made under normal conditions. The same sediments that are assumed to absorb energy at the bottom of the reservoir could liquefy altering their effects. For this reason, the rationale for use of a reservoir bottom reflection coefficient for analysis of a dam must be logically linked to assessment of the concurrent reservoir sediment behaviour.

3.3 Impacts of Discharge Capability

Many dams may incorporate low-level outlets located close to the base of the dam to allow for drawdown of the reservoir in the event of a dam safety incident. Blockage of these outlets occurs as sediments fill up the reservoir's dead storage (Morris & Fan, 1998).

Liquefied sediment can also flow into and clog conduits or penstocks (Morris & Fan, 1998) directly, or indirectly impacting dam safety. For example, sediments can obstruct the outlets required to hold or lower the reservoir level or could cause a loss of the primary power supply needed for gate operation.

Reduction of the spillway capacity can also occur as a result of the loss of approach depth when the sediment front reaches the dam which has occurred at many hydro projects. Completely

infilled reservoirs can also lose much of the flood routing effects. A fully infilled reservoir becomes a delta filled valley with a gradient from the old upstream end of the reservoir towards the dam. The river will take a meandering course such that a flood wave cannot spread out to allow routing in the normal sense used for flood routing.

In colder climates, an infilled reservoir produces higher flow velocities that tend to prevent frazil ice settling upward into a stable ice cover that can cause frazil ice generation, potentially blocking flow discharge facilities and power intakes. At the Wilsey Dam in BC the whole tunnel penstock system froze solid due to ingestion of frazil ice. In this case the operator was forced to wait until the spring in order to clean out the ice with steam lances after closure of the intake gate(s) was affected.

3.4 Impacts on Equipment

Sediment can lead to significant damage to turbines and other mechanical equipment as a result of the break down of the oxide coating on the blades, leading to surface irregularities and, eventually, more serious material damage (Dorij & Ghomaschi, 2014). This reduces generation efficiency and increases risks of mechanical breakdown or failure. Sustained turbine erosion can lead to extended shutdown time for maintenance or replacement at large expense to the facility owner (Dorij & Ghomaschi, 2014). For example, the 60 MW Khimti I Hydropower Plant in Nepal (Figure 8) experiences a high concentration of incoming sediment, particularly during the monsoon season. While the plant features two sediment settling basins, they do not effectively reduce the volume of fine sediments that enter the facility resulting in significant erosion of the turbine components after only one year (6,000 hours) of operation (Thapa, Shrestha, Dhakal, & Thapa, 2004). It is estimated that this damage has resulted in a 1% loss in relative efficiency of the turbine (Thapa, Shrestha, Dhakal, & Thapa, 2004) coupled with the need for frequent maintenance and associated direct and shutdown costs.



Figure 8 - Khimti I Hydropower Plant, Nepal

The 43 MW Cahua plant in Peru (**Error! Reference source not found.**) has also experienced significant sediment erosion to its mechanical equipment due to large amounts of sediment consisting mostly of very hard quartz and feldspar (Neopane, 2010).



Figure 9 - Cahua Power Plant, Peru

(Neopane, 2010) identified a range of factors that determine rates of mechanical abrasion including sediment type, shape, angularity, hardness, and concentration as well as hydraulic and facility operation parameters such as flow rate and velocity, hydraulic head, turbulence, turbine rotation speed, sediment impingement angle, turbine material, and turbine operating procedures (Dorij & Ghomaschi, 2014) determined that impulse turbines such as the Pelton or Turgo styles are more susceptible to erosion issues than are reaction turbines such as the Francis, Kaplan, and Bulb varieties

Mechanical erosion can be prevented by either selecting appropriate metals to increase erosive resistance or by reducing the volume of fine sediment that reaches mechanical equipment in the first place or both (Thapa, Shrestha, Dhakal, & Thapa, 2004). Materials used commonly in sediment-prone hydropower plants are stainless steels that are heat treated for hardening and increased protection from abrasion (Dorij & Ghomaschi, 2014). Protecting mechanical equipment from sediment abrasion can also be achieved with hard surface coatings of ceramic paints or pastes or with hard facing alloys (Dorij & Ghomaschi, 2014). Recent research has shown improved resistance to sediment abrasion when tungsten carbide based composites are used as a surface coating (Dorij & Ghomaschi, 2014). Costs associated with abrasion protection can be high; the study on the Khimti I Hydropower Plant reports costs of \$25,000 US per runner for coating application and also notes that initial inspection of the applied coating has not shown significant improvement (Dorij & Ghomaschi, 2014).

3.5 Environmental Impacts

Given the high trapping efficiency of many hydropower facilities, there is certain to be some degree of sediment starvation downstream of the dam, resulting in potential ecological impacts downstream. In addition, dam construction can alter sediment regimes before the facility is even operational. Plant and animal species are sensitive to the alteration of the sediment regime created by alteration of both the sediment supply and the flow regime. (Morris, Annandale, & Hotchkiss, 2008; Ahmari, Ahsan, Penner, & Gonzalez, 2013). Increases in sediment concentration can create turbid waters with a smaller euphotic zone. This generally decreases plant productivity and can negatively impact various fish and bird species (Morris, Annandale, & Hotchkiss, 2008) and can cause abrasion of fish gills which may result in increased potential for disease or mortality. Turbidity increases can also cause visual impairment for predatory fish, affecting their feeding habits. Finally, sediment is a primary carrier of suspended pollutants such as nitrogen, phosphorous, and heavy metals (Ahmari, Ahsan, Penner, & Gonzalez, 2013).

Sedimentation and erosion have been of primary concern throughout the design and construction of Manitoba Hydro's 695 MW Keeyask Generating Station (Figure 10). Currently under construction on the Nelson River in northern Manitoba, Canada, this project has incorporated concerns of sedimentation and physical environment beginning at the earliest design stages. For example, a host of field measurements and numerical modelling exercises were carried out in order to determine the pre-impoundment sedimentation regime at the proposed forebay area in order to establish a baseline to which changes caused by the dam may be compared. This methodology will result in more appropriate development of mitigation strategies. Studies have also been carried out to estimate fill material losses during cofferdam construction and any resulting increases in Total Suspended Solids (TSS) concentration. Environmental regulations dictate that TSS increases during construction must be limited; Hatch has performed detailed analyses of the during-construction sediment regime at the Keeyask site under each of various stages of construction.



Figure 10 - Keeyask Generating Station, Canada

In some cases, the sediments accumulated behind a dam may have significant environmental effects if they were released as a result of a dam breach. As listed in Table 2, a number of dam

removal cases in which post- removal sediment transport resulted in significant long-term issues. Such issues would be magnified in the event of a dam breach event.

Table 2 - Examples of post- dam removal sediment transport issues (Donnelly, Nalder, Paroschy, & Phillips, 2001)

Dam	Date Removed	Height (feet)	Mitigation Techniques Attempted, Problems Reported
Woolen Mills, Wisconsin	1988	5.5	- Slow drawdown to allow low flow channel to form and seeding. Habitat improved 5 years after removal
Fort Edward, New York	1973	9.4	- 2600 m ³ (approx.) sediment dredged during removal. By 1976, over 470 000 m ³ of sediments dredged to maintain navigation, including 140 000 m ³ of PCB contaminated materials.
Sweasey, California	1970	16.8	- Reservoir lowered slowly to allow low flow channel to develop. Sediment transport problems for 2 years after removal
Nolichncky, Tennessee	1973	29	- Dam partially left in place to retain sediments. Significant sediment transport problems occurred over two year period.
Newaggo, Michigan	1969	20	- Removal produced a wave of sediment extending 5 miles downstream. 500 000 m ³ of sediment expected to move down river for 50 to 80 years.
Mussels, Pennsylvania	1992	9.4	- 760 000 m ³ of non-hazardous silt in the reservoir. Sediment mitigation involved staged drawdown and silt trap construction. 57 000 m ³ (est.) silt discharged after removal
Fulton, Wisconsin	1993	NR	- Sediment mitigation involved silt trap construction, dredging riverbank stabilization. Post removal sediment problems affected fish habitat for 5-km d/s. Expected to abate in 5 years.
Prairie Dells, Wisconsin	1991	18.3	- Sediment mitigation measures involved sediment trap construction and controlled drawdown over 2 years. Two years after removal, 30 000 m ³ of sediment excavated from trap. Ongoing turbid events have had negative impact on fishery. Expected to continue for 5 years.

4. Numerical modelling of sedimentation and sediment management strategies

It is clear that design of a hydropower facility should include some consideration of sedimentation and the impacts it may have. With advancements in sediment research and computational efficiency, numerical modelling has emerged as a viable option for hydromorphological simulation and optimization of reservoir operation and management. A variety of numerical tools are available for use in sediment and reservoir modelling. For example, the US Army Corps of Engineers' HEC-RAS model features a movable boundary sediment transport calculation module.

This model has been used successfully to simulate sedimentation processes and plan for hydropower development in northern Manitoba, Canada, for example (Kenny, Ahmari, Ahsan, & St. Laurent, 2014). MIKE 21, a two-dimensional hydrodynamic model, can also be used to simulate sedimentation processes. MIKE 21 was applied to study sediment deposition patterns at the Boegoeberg Dam in South Africa and was useful for simulating results of future flushing operations (Sawadogo & Basson, 2016). Bui and Rutschmann (Bui & Rutschmann, 2016) describe the three-part hydrodynamic, sediment transport, and physical habitat model "FAST"

that can be used effectively to simulate morphological processes and changes to fish habitat within alluvial rivers. FAST combines a two-dimensional hydrodynamic model with a semi-empirical sediment transport component to fully encapsulate the sediment-flow regime of a river. The FAST model was used in one study to predict hydromorphological conditions prior to constructing new hydropower facilities on the Nile River and to optimize sediment flushing procedures at these stations. This modelling study found that sedimentation is related to hydraulic retention time and that

Numerical modelling is a valuable tool for predicting reservoir sedimentation and the effectiveness of proposed sediment management techniques. However, like any numerical model, hydromorphological models require calibration data in order to confirm that simulation results are in agreement with reality.

5. Sediment Management Solutions

5.1 Dealing with Sedimentation Impacts

Recognizing the negative impacts of reservoir sedimentation, many dam operators incorporate some form of sediment management in the design of their facilities.

According to Morris, Annandale, & Hotchkiss (2008),

“The objective of sediment management is to manipulate the river-reservoir system to achieve sediment balance while retaining as much beneficial storage as possible and minimizing environmental impacts and socioeconomic costs”.

A sediment balance is achieved when the volume of sediment reaching a dam is equal to the volume of sediment that leaves it. Sediment management strategies can be classified into three general categories: (1) those that divert some of the sediment through or around the reservoir, (2) those that remove or rearrange sediment that has already been deposited, and (3) those that minimize the amount of sediment reaching the reservoir from upstream in the first place (Kondolf, et al., 2014). While some degree of sediment trapping is inevitable for most hydropower reservoirs situated in sediment-laden rivers, many dam operators have implemented sediment management techniques that result in complete or partial sediment balance during the life of the dam (Kondolf, et al., 2014).

5.2 Bypassing

On-stream sediment bypassing diverts part of the sediment-laden water around the reservoir and back into the river downstream of the dam. Bypassing is typically achieved using a weir that diverts river water during high flows when sediment concentrations are high. The diverted water, concentrated with sediment, flows through a diversion channel or tunnel before rejoining the river on the downstream side of the dam.

An off-stream reservoir can be used such that only the clear water is diverted over a bypass weir. However, an off-stream reservoir typically has a limited capacity with a capability of only excluding sediments carried by higher streamflows (Morris, Annandale, & Hotchkiss, 2008). It reduces both the amount of suspended sediment reaching the reservoir and bedload (Kondolf, et al., 2014). Other advantages of off-stream reservoirs include the fact that both the reservoir and the dam

itself are located away from the main river channel allowing for minimal disruption to aquatic species and habitat and eliminates the need for large on-stream spillways (Morris, Annandale, & Hotchkiss, 2008). However, off-stream reservoirs typically do not permit maximization of generation capacity, especially in areas that depend on high streamflows occurring over a short period of time (Morris, Annandale, & Hotchkiss, 2008).

Sediment bypassing works best in areas of high relief where the sediment-laden flows are carried efficiently through the diversion tunnel or channel. Bypassing is most cost-effective at dams that are located on the bend of a river; this allows for a relatively short diversion between the weir and the downstream side of the dam (Kondolf, et al., 2014).

5.3 Sluicing

A common method of sediment management is routing the inflows through the facility by means of a combination of dam infrastructure and hydrological management. Sediments that would otherwise be deposited behind a dam can be sluiced through gates designed to pass water at a velocity sufficient to maintain the sediments in suspension (Morris, Annandale, & Hotchkiss, 2008). This technique is known as *drawdown routing* or *sluicing* and involves lowering the reservoir water level before high streamflows carrying large volumes of sediment enter the reservoir upstream of the dam and allowing this volume of water and sediment to rapidly pass through the gates at a high velocity (Morris, Annandale, & Hotchkiss, 2008; Kondolf, et al., 2014). Methods of implementing drawdown routing depend on the hydrologic characteristics and reservoir size of a given facility. It will typically involve reservoir draw down in prior to an expected flood or during a flood with refill occurring during the receding limb of the flood hydrograph (Morris, Annandale, & Hotchkiss, 2008).

5.4 Dredging and flushing

The third most common method of sediment management is the removal or rearrangement of sediment that has already been deposited within a reservoir. Sediment removal can be further classified into two sub-categories: dredging and flushing. Dredging involves removing deposited sediment from underwater in order to recover storage volume within the reservoir (Morris, Annandale, & Hotchkiss, 2008).

Dredging is only a viable sediment management technique if it continues indefinitely; a dredged reservoir will continue to experience sedimentation so dredging will continue to be necessary (Morris, Annandale, & Hotchkiss, 2008). Problems with dredging arise when locations for depositing the excavated sediment become filled or are remote to the dam site. The cost of sediment dredging can also be significant: for example, dredging of six million cubic meters of sediment at the Loíza reservoir (Figure 11) in Puerto Rico in 1997 came at a total cost of \$10/m³ (Morris & Fan, 1998; Morris, Annandale, & Hotchkiss, 2008).



Figure 11 - Sediment Discharge from the Loiza Reservoir, Puerto Rico, during Hurricane Hortense

Tactical dredging is also used in some reservoirs to remove sediment from a specific area (i.e. near intakes) and depositing it either outside the reservoir or elsewhere within it (Morris, Annandale, & Hotchkiss, 2008). However, the reality of dredging also holds true for tactical dredging: continuous sediment deposition calls for continuous dredging.

Hydraulic flushing involves completely emptying the reservoir by opening bottom outlets and then allowing the incoming streamflow to scour deposited sediment and pass it through the structure (Morris, Annandale, & Hotchkiss, 2008; Kondolf, et al., 2014). The extent of the flushed area of the reservoir depends on how the sediment was deposited, but generally only a “core” of sediment along the original channel thalweg is flushed out while sediments on the sides of the reservoir remain in place (Morris, Annandale, & Hotchkiss, 2008).

An alternative method is *pressure flushing* where the reservoir is only partially drawn down before flushing occurs, causing a pressurized surge of water to scour the deposited sediments. However, pressure flushing mainly functions to redistribute coarse sediment from upstream closer to the dam. This can help alleviate impacts of the coarse sediment delta, but may not actually clear sediment entirely from the reservoir (Morris, Annandale, & Hotchkiss, 2008). Pressure flushing can also be considered a sediment *redistribution* or *focussing* method where deposited sediments are moved to a less compromising location within the reservoir.

There are various hydraulic techniques available to redistribute sediment in order to minimize localized problems. These may include the construction of reservoir channels or other features within the reservoir that can guide sediments towards a desired area, often being deeper parts of the reservoir that have yet to be sedimented. Tactical dredging can be incorporated in this technique as well (Morris, Annandale, & Hotchkiss, 2008).

5.5 Erosion control

A commonly recommended sediment management strategy is the reduction of incoming sediment from upstream through some form of erosion control. Many watersheds experience increased rates of erosion due to land use practices and other human impacts (Walling, 1999). Erosion control within the watershed of a hydropower dam would mitigate the impacts of sedimentation

by reducing the volume of sediment that is brought to the dam by the river. Morris and Fan (1998) state that there are only two methods of reducing the amount of sediment that enters a reservoir: either prevent erosion or trapping eroded sediment before it reaches the reservoir.

Sediment yield reduction techniques can be classified into three categories: *structural* or *mechanical* measures, *vegetative* or *agronomic* measures, and *operational* measures (Morris & Fan, 1998). Structural or mechanical measures include any method to decrease overland or channelized flow velocity, increase surface storage, and convey runoff downstream with a lower sediment load. Examples of such measures include terraces, conveyance channels, check dams, and sediment traps (Morris & Fan, 1998; Kondolf, et al., 2014). Vegetative erosion control measures take advantage of plants and their natural ability to limit soil erosion. They also include agricultural practices that minimize sediment yield from cropped areas. Operational erosion control measures are those that minimize erosion through planning, management, and organization. Examples include timing construction works such that the associated erosion is minimized or scheduling timber harvesting to coincide with favorable soil conditions (Morris & Fan, 1998).

Erosion management is perhaps the most widely recommended but the most poorly implemented sediment management technique (Morris, Annandale, & Hotchkiss, 2008). Reasons for this are largely socioeconomic in nature and center around the fact that land users may not see any direct benefits from controlling sediment yield (Morris, Annandale, & Hotchkiss, 2008).

5.6 Selection of Optimal Sedimentation Management Techniques.

Extensive study of sustainable sedimentation management practices has shown that the appropriate is a function of the reservoir life, expressed as the ratio of reservoir volume (CAP) to the mean annual sediment inflow to the reservoir (MAS) and retention time represented time as a function of the ratio of reservoir capacity (CAP) to the mean annual incoming flow to the reservoir (MAF).

As is illustrated in Figure 12, the selection of the optimal sediment management techniques can be estimated based on precedent experience and these factors.

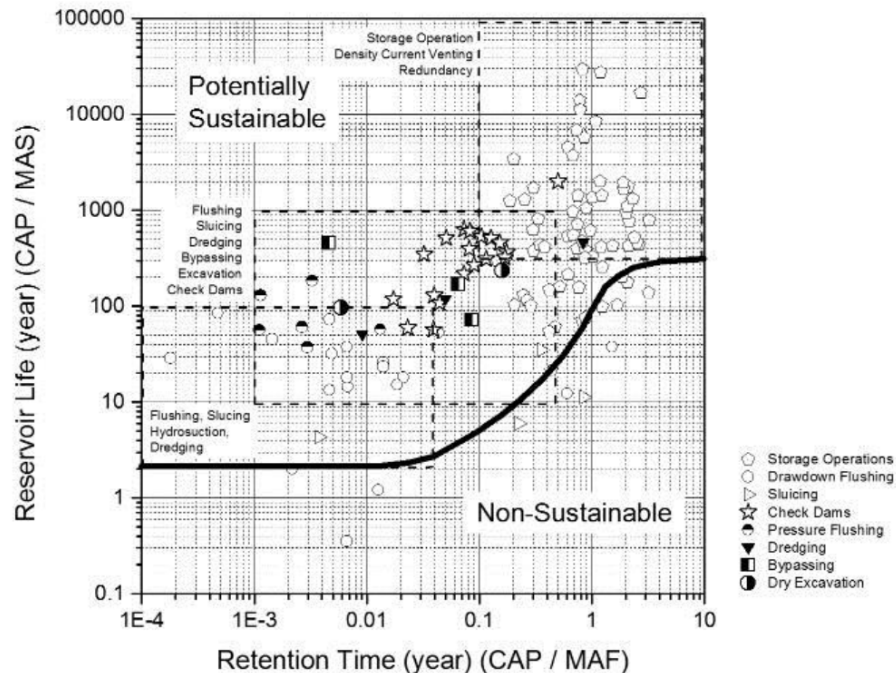


Figure 12 - Applicability of sediment management techniques in relation to reservoir life and retention time (Annandale, Morris, & Karki, 2016)

6. Case Studies

6.1 Forest Kerr, Canada

The 195 MW Forrest Kerr Hydroelectric Project in northwestern British Columbia, Canada was designed specifically with sedimentation in mind. The hydropower facility is located on the Iskut River that carries a large sediment load during the high flow season; average sediment load peaks at approximately 9,500 m³/day in July.



Figure 13 - Forrest Kerr Hydroelectric Project, Canada

Design of the facility headworks featured a 1:40 scale physical model that was used to test the initial layout for sediment and flow characteristics. Model results showed that the initial design

would become inundated with sediment very quickly when streamflows reached higher summer values. Therefore, designers began using the physical model to evaluate a range of alternatives for more effective sediment management. Modelling studies determined that sediment would be effectively managed by refining the approach channel dimensions and installing a box culvert along the channel invert to extract most of the sediment bedload. The culvert carries sediment downstream while the remaining flow is directed to an intermediate forebay through a desanding basin for settling and bypassing the finer, suspended sediments.

The example of the Forrest Kerr generating station showed that physical modelling, supplemented by CFD simulations were extremely valuable for determining a unique sediment management solution to a very complex problem (Sims, Murray, Alavi, & Hughes, 2013).

6.2 Dez Dam, Iran

Sedimentation has had a significant impact on the Dez Hydroelectric Power Project in southwestern Iran. This 520 MW facility, featuring a 203 m high concrete arch dam, has experienced an approximately 19% loss in reservoir storage in its 40 years of operation. Reservoir sedimentation has caused the bed elevation at the base of the dam to increase at a rate of approximately two meters per year. The reservoir bed is now within 12 meters of the power intakes and sediment may be drawn into the tunnels within a decade.

Sediment management strategies considered for the Dez Hydroelectric Power Project include watershed management, sediment flushing, tactical sediment dredging near the power intakes, and heightening the dam itself. These strategies were evaluated on the basis of technical and environmental issues, both capital and ongoing costs, power system benefits, the value of water, and on the impact each alternative would have on the “useful reservoir life”. The optimal solution preventing power intake sedimentation was determined to be sediment flushing, managed through powerhouse and spillway operation changes at the facility.

In addition to issues with intake sedimentation, over the 40 years of dam operation, sediment has deposited above the low level outlets. Sluicing of the sediments through the Howell-Bunger valves introduced a risk of damage. Therefore, a physical model was built to evaluate the option of replacing the Howell-Bunger valves with radial sluice gates. The results of this analysis showed that the downstream river reach could not tolerate the amount of scour associated with this modification. Therefore, the Howell-Bunger valves were re-designed with very hard, abrasion-resistant materials.

At this site, ongoing dredging of delta sediments and watershed management were found not to be a financially viable options but that dam heightening might be an effective strategy provided that structural implications could be satisfied (Steele, Izadjoo, Samadi-Boroujeni, & Galay, 2006).

6.3 Aswan High Dam, Egypt

The Aswan High Dam (AHD) on the Nile River in Egypt has a height of 111 m, impounds a reservoir with a total volume of 130 km³, and has an installed capacity of 2,100 MW (Abd-El Monsef, Smith, & Darwish, 2015).



Figure 14 - Aswan High Dam, Egypt

This dam has long been a source of controversy, largely due to the expected degree of sediment trapping by the AHD and corresponding starvation of sediment to the Nile River Delta further downstream (Abd-El Monsef, Smith, & Darwish, 2015). Now 46 years old, the AHD has indeed experienced significant sedimentation and the impacts of this sedimentation has been widely discussed.

Prior to construction of the AHD, the Nile River transported an average of 100×10^6 t/yr of sediment to the Nile River Delta in the Mediterranean Sea (Milliman & Meade, 1983). With a trapping efficiency of 99%, very little sediment now passes downstream of the AHD and reaches the Delta (Milliman & Meade, 1983; Abd-El Monsef, Smith, & Darwish, 2015). While the live storage capacity of the Lake Nasser/Nubia reservoir upstream of the AHD is not expected to be compromised for another 300-400 years (Smith, 1990), the downstream impacts of trapping 99% of incoming sediment on the Nile have been widely identified (Abd-El Monsef, Smith, & Darwish, 2015; Rashad & Ismail, 2000; Gu, Chen, & Salem, 2011; Stanley & Warne, 1993). Coastal erosion along the Mediterranean coast of Egypt has been ongoing for centuries, but the sediment trapping of the AHD has combined with sea-level rise and other factors to exacerbate coastal erosion problems (Abd-El Monsef, Smith, & Darwish, 2015). A variety of other environmental impacts have been attributed to hydropower in Egypt as well (Rashad & Ismail, 2000).

6.4 Three Gorges Project, China

Figure 5 highlights China as a country with both large hydroelectric capacity (the largest in the world with over 280,000 MW installed capacity) and high sediment yield. Kondolf et al. (2014) purports that China has responded by leading innovations in sediment management and successfully implementing a variety of techniques. Wang and Hu (2009) state that China has successfully implemented four main sediment management strategies: storing the clear and releasing the turbid, releasing turbidity currents, sediment flushing, and dredging.

The Three Gorges Project on the Yangtze River is the world's largest hydropower facility in terms of generation capacity at 22,500 MW.



Figure 15 - Three Gorges Dam, China

The dead storage portion of the Three Gorges reservoir (17 billion m³) is designed to be filled with sediment in approximately 120-150 years while the remaining 22 billion m³ is to be retained indefinitely for hydropower production, flood control, and inland navigation (Wang & Hu, 2009). The main sediment management technique used at Three Gorges to retain this degree of storage is strategic reservoir drawdown. Most of the annual sediment load in Chinese rivers is transported within 50-60% of the annual runoff during the June to September flood season (Wang & Hu, 2009). Operators at the Three Gorges Project draw down the reservoir during this season when the sediment load is the highest and retain clearer water in the rest of the year. This strategy is shown to be effective for reducing sediment impacts at both the Three Gorges Dam and the 400 MW Sanmenxia Reservoir (Wang & Hu, 2009).

7. Conclusions

Sedimentation affects hydropower production due to a loss of reservoir storage and/or damage to the mechanical components of the facility. Sediment deposited in reservoirs may also present additional and compounding structural load to a hydropower dam and may also become liquefied under dynamic loading from an earthquake. Methods of managing sediment at hydropower facilities fall under three general categories: those that divert sediment around or through the reservoir, those that remove deposited sediments, and those that minimize the amount of sediment reaching the facility in the first place. A variety of sediment management strategies have been used at facilities around the world, with many successful implementations documented.

Appropriate sediment management at hydropower facilities can be achieved through consideration of sediment concerns during all phases of the project, design, construction and operation.

8. References

- Abd-El Monsef, H., Smith, S., & Darwish, K. (2015). Impacts of the Aswan High Dam after 50 years. *Water Resources Management*, 29, 1873-1885.
- Ahmari, H., Ahsan, R., Penner, L., & Gonzalez, N. (2013). Assessment of erosion and sedimentation for hydropower projects on the Lower Neslon River, Manitoba. *Canadian Dam Association*. Montreal, QC: CDA.
- Angelakis, A., Mays, L., Koutsoyiannis, D., & Mamassis, N. (2012). *Evolution of Water Supply Through the Millennia*. London, UK: IWA Publishing.
- Annandale, G., Morris, G., & Karki, P. (2016). Sediment management at reservoirs and hydropower plants: New World Bank technical note. *Proceedings of the 84th ICOLD Meeting - International Symposium on "Appropriate technology to ensure propoer development, operation, and maintenance of dams in developing countries"* (pp. 4-1 - 4-9). Johannesburg, South Africa: ICOLD.
- ASCE. (1975). *Sedimentation Engineering*.
- ASCE/USCOLD. (1975). *Lessons from Dam Incidents, USA*. New York, N.Y.: Committee on Failures and Accidents to Large Dams of the U.S. Committee on Large Dams.
- Bougacha, S., & Tassoulas, J. (1991). Seismic response of gravity dams II: Effects of sediments. *Journal of Engineering Mechanics*, 117(8), 1839-1850.
- Bui, M., & Rutschmann, P. (2016). Numerical modelling for reservoir sedimentation management. *Proceedings of the Sixth International Conference on Water Resources and Hydropower Development in Asia*. Vientiane, Lao.
- Chen, B., & Hung, T. (1993). Dynamic pressure of water and sediment on rigid dam. *Journal of Mechanical Engineering*, 119(7), 1411-1433.
- Chen, S. (2015). *Hydraulic Structures*. Berlin Heidelberg: Springer-Verlag.
- Chopra, A., & Fenves, G. (1983). Effect of Reservoir Bottom Absorption on Earthquake Response of Concrete Gravity Dams. *Earthquake Engineering Sturctural Dynamics*, 11.
- Dominguez, J., Gallego, R., & Japon, B. (1997). Effects of porous sediments on seismic response of gravity dams. *Journal of Engineering Mechanics*, 117(8), 302-311.
- Donnelly, C., Nalder, N., Paroschy, N., & Phillips, M. (2001). Issues and controversies associated with dam removals. *Waterpower Conference*. Salt Lake City, Utah.
- Dorij, U., & Ghomaschi, R. (2014). Hydro turbine failure mechanisms: An overview. *Engineering Failure Analysis*, 44, 136-147.
- Ghanaat, Y., & Redpath, B. (1995). *Measurements of Reservoir-Bottom Reflection Coefficient at Seven Concrete Dam Sites*. US Army Corps of Engineers Experiment Station and the Bureau of Reclamation. Emeryville, CA: Quest Structures.
- Gogoi, I., & Maity, D. (2007). Influence of sediment layers on dynamic behavior of aged concrete dams. *Journal of Engineering Mechanics*, 133(4), 400-413.
- Graf, W., Wohl, E., Sinha, T., & Sabo, J. (2010). Sedimentation and sustainability of western American reservoirs. *Water Resources Research*, 46(W12535).
- Grummer, J. (2009). *Combating silt erosion in hydraulic turbines*. Retrieved May 16, 2016, from Hydro Review Worldwide: <http://www.hydroworld.com/articles/print/volume-17/issue-1/articles/combating-silt-erosion-in-hydraulic-turbines.html>
- Gu, J., Chen, Z., & Salem, A. (2011). Post-Aswan dam sedimentation rate of lagoons of the Nile Delta, Egypt. *Environmental Earth Sciences*, 64, 1807-1813.

-
- Hall, R., de Bejar, L., Sjostrom, K., & Matheu, E. (1998). Effect of Reservoir-Subbottom Energy Absorption on Hydrodynamic Forces on Dams. In N. Raufaste (Ed.), *Wind and Seismic Effects, Proceedings of the 30th Joint Meeting of the US-Japan Cooperative Program in Natural Resources Panel on Wind and Seismic Effects* (pp. 116-129). Building and Fire Research Laboratory, National Institute of Standards and Technology.
- Hatami, K. (1997). Effect of reservoir bottom on earthquake response of concrete dams. *Soil Dynamics and Earthquake Engineering*, 16, 407-415.
- ICOLD. (1995). *Bulletin 99 - Dam Failures - Statistical Analysis*.
- ICOLD. (2016). *Register of Dams - General Synthesis*. Retrieved April 25, 2016, from http://www.icold-cigb.org/GB/World_register/general_synthesis.asp
- IHA. (2015). *2015 Hydropower Status Report*. London, UK.
- IHA. (2016). *2016 Key Trends in Hydropower*. London, UK.
- InternationalRivers.org. (n.d.). *Inga 1 and Inga 2 Dams*. Retrieved June 10, 2016, from International Rivers.org: <https://www.internationalrivers.org/resources/inga-1-and-inga-2-dams-3616>
- Kenny, S., Ahmari, H., Ahsan, R., & St. Laurent, M. (2014). Assessment of impacts to the sedimentation environment for the Keeyask Generating Station Project using numerical modelling. *Proceedings of the 2014 Canadian Dam Association Conference*. Banff, Canada: CDA.
- Kondolf, G., Gao, Y., Annandale, G., Morris, G., Jiang, E., Zhang, J., et al. (2014). Sustainable sediment management in reservoirs and regulated rivers: Experiences from five continents. *Earth's Future*, 2, 256-280.
- Milliman, J., & Meade, R. (1983). World-wide delivery of river sediment to the oceans. *Journal of Geology*, 91(1), 1-21.
- Morris, G. L., & Fan, J. (1998). *Reservoir Sedimentation Manual*. New York: McGraw-Hill.
- Morris, G., Annandale, G., & Hotchkiss, R. (2008). Reservoir Sedimentation. In M. Garcia (Ed.), *Sedimentation Engineering: Processes, Measurements, Modeling, and Practice*. ASCE.
- Neopane, H. (2010). Sediment erosion in hydro turbines. *Ph.D Thesis*. Norwegian University of Science and Technology.
- Rashad, S., & Ismail, M. (2000). Environmental-impact assessment of hydro-power in Egypt. *Applied Energy*, 65(2000), 285-302.
- Sawadogo, O., & Basson, G. (2016). 2D hydrodynamic modelling of sediment deposition processes and flushing operation of Boegoeberg Dam, South Africa. *Proceedings of the 2016 ICOLD Conference*. Johannesburg, South Africa: ICOLD.
- Sims, N., Murray, D., Alavi, A., & Hughes, B. (2013). Crucial role of physical modeling in developing the configuration of the intake headwork structures. *Proceedings of the Hydrovision International Conference*. Denver, Colorado.
- Smith, S. (1990). A revised estimate of the life span of Lake Nasser. *Environmental Geology and Water Sciences*, 15, 123-129.
- Stanley, D., & Warne, A. (1993). Nile Delta: Recent geological evolution and human impact. *Science*, 260(5108), 628-634.
- Steele, R., Izadjoo, F., Samadi-Boroujeni, H., & Galay, V. (2006). Sedimentation issues in the Dez Dam reservoir. *Hatch H.G. Acres conference*.
- Thapa, B., Shrestha, R., Dhakal, P., & Thapa, B. (2004). Sediment in Nepalese hydropower projects. *Proceedings of the International Conference on the Great Himalayas: Climate, Health, Ecology, Management, and Conservation (2003)*.
- USBR. (1976). *Design of Gravity Dams*. Denver: United States Department of the Interior.

-
- USGS. (2006). *About liquefaction*. Retrieved May 17, 2016, from <http://geomaps.wr.usgs.gov/sfgeo/liquefaction/aboutliq.html>
- Walling, D. (1999). Linking land use, erosion and sediment yields in river basins. *Hydrobiologia*, 410, 223-240.
- Wang, Z., & Hu, C. (2009). Strategies for managing reservoir sedimentation. *International Journal of Sediment Research*, 24(2009), 369-384.
- Washburn, E. (1928). *International Critical Tables of Numerical Data, Physics, Chemistry and Technology*. New York: McGraw-Hill.
- Westergaard, H. (1931, November). Water Pressure on Dams during Earthquakes. *ASCE Transactions*, pp. 418-433.
- White, R. (2001). *Evacuation of sediments from reservoirs*. London, UK: Thomas Telford Publishing.