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Master Thesis

In the Master Program 'Water Management and Environmental Engineering'

Various Hydro-Power Plant Sites and their relations with Erosion Transport and Deposition in the Reservoirs

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Abstract

This master thesis, a preliminary research and limited to some extent as it tries to cover the huge periphery of soil erosion, sediment yield and sedimentation transportation of a reservoir. It will help the readers to take prior consideration for assessing the soil erosion and sedimentation management in the reservoir.

Large numbers of research works have been done on soil erosion, sediment yield and sedimentation in various reservoirs and all research works to guide us to understand the practical importance of the sedimentation problem. However, it remains unexplored in different aspects. Research on erosion process, sedimentation as well as their modeling approaches is still ongoing. Models that are capable to correlate both erosion and sedimentation at the basin scale have not been explored for the reservoir.

Different approaches may be developed to predict the effect of future climate change on sedimentation of the reservoir. Relationships between upstream and downstream of a reservoir can be established by studying the complex phenomena of soil erosion, sediment yield, and sedimentation of a reservoir. Research on water quality impact of sediments on water availability is also expected.

Within the described framework the following five objectives are addressed in this thesis:

1. Presenting most update researches on soil erosion, transportation, and deposition of sediment in the reservoir
2. Presenting various hydropower plants with their condition and circumstances of sediment control and management will help to have a proper future decision on any similar issue.
3. Investigating a variety of sediment management strategies have been used around the world, with many successful implementations documented
4. Analysising of many different issues due to sediments erosion, transport, and deposition. Analyse the result and give recommendations.
5. Discussing and highlights the need for appropriate sediment management at hydropower facilities and shows how this can be achieved through consideration of sediment concerns from the earliest design phase through to construction and operation.

Artificial water storage, originated by the construction of dams, is essential for the sustainable health and welfare of civilizations since it supplies water for human consumption, irrigation, and energy production. Furthermore, dam reservoirs are used for recreation, navigation and they provide safety in the downstream valleys against extreme flood events and droughts. All reservoirs are subjected to sedimentation which, without adequate prevention and mitigation counter-measures, threatens their sustainability. As well as the evident loss of storage capacity, the adequate and safe operation of water intakes and bottom outlets belonging to the vital outlet structures can be affected by the deposition of sediments in the reservoir. This Vision Paper first addresses the state-of-the-art and the main scientific advances in terms of prevention and mitigation measures against sedimentation in reservoirs. Then, the main research challenges, which result from the assessment of what are the remaining open questions, are pointed out. The emerging research methodologies to study sedimentation processes are also discussed.

Acknowledgment

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Chapter 1

Introduction

1.1 Aim of the study

The headline under this title is (everyone can read and understand the content even with no previous knowledge about sedimentation).

This master thesis seeks to generate an awareness of sedimentation problems, outlining practical strategies for their identification, analysis, and management. Basic concepts and tools are presented which, when applied in an integrated manner, can achieve what we will term sustainable sediment management in reservoirs.

This handbook (as I consider) introduces the overall concept of sustainable sediment management with the goal of converting today's sedimentation reservoirs into resources that will benefit future generations as well as our own. Whereas the twentieth century focused on the construction of new dams, the twenty-first century will necessarily focus on combating sedimentation to extend the life of existing infrastructure. This task will be greatly facilitated if we start today.

This master thesis designed to give a good overview for the engineers, managers, students, and people with no background about sediments management. It's designed to be easy to follow and with no deep details to be discussed. Using pictures and tables and some statistical data.

Presenting various hydropower plants with their condition and circumstances of sediment control and management will help to have a proper future decision on any similar issue.

1.2 Study Methodology

- Data were collected through investigations and correspondence with the various Site Managers, Researchers, Engineers, Media Department, Hydropower plants Technicians, also through the internet (Websites, Electronic books, Articles, Magazines), hard copies books wherefore no data were measured or observed.
- Depending on my previous practical experiences in dams and reservoirs field almost (10 years), the materials were chosen carefully a wearing of any complexity of data and formulas.

1.3 Outline of the Master Thesis

This master thesis core designed into 11 different case studies, each case studies present and discuss a specific strategy for sediment control management. Some chapters include their own conclusions.

Erosion, transport, and deposition of sediment are a chine of processes that related of each other therefore understanding the management strategy of sediment will help the readers to better understanding of these processes and simulated (as possible) with any other hydropower project sites in everywhere.

These three processes are strongly bonded with each other and therefore they relate to suitable remedies for sediment control and management.

What I present in this master thesis a different hydropower plants with different locations and circumstancing … these locations are organized and present according to the applied sediment management strategies.

Some of the location used more than one strategy (in case of one is not enough).

Before starting in every case study there is a brief introduction to the sediment management strategy regarding the presented case study. This introduction will give a good tool to start understanding the strategy by covering the theoretic part.

The presented case study in every chapter will help the readers for better understanding the strategy and how it applied as a part of the practical side. Both the theoretical and practical part work together to express the integrated approach of sediment erosion, transportation, and deposition in the reservoir which is the title of this Master Thesis.

The information and data presented according to Sediment management strategies as the management activities to address reservoir sedimentation may be classified into four broad types of methodologies:

1. Reducing sediment inflow from the upstream will be present and discussed in the chapter (2&3)
2. Passing sediment through or around the impoundment to minimize sediment trapping will be present and discussed in the chapter (4, 5, 6, 7).
3. Redistributing or removing sediment deposits will be present and discussed in the chapter (8,9,10,11)
4. Adapting to sedimentation will be present and discussed in the chapter (12)

For readers who have (no or limited) background about sediment, I highly recommend checking the appendix of the chapter (1), it presents the fundamental sedimentation knowledge and will make a better understanding for other chapters and their strategies clearly.

1.4 Introduction to the thesis topic

Reservoirs created by dams constitute an important element for providing water to the increasing world population. However, as the river enters the impoundment, the flow velocities decrease and the sediment carrying capacity drops, causing the sediment to deposit. Thus, the storage volume of the reservoir is being lost. It has been estimated that about 1% of the total storage capacity of all reservoirs in the world is lost every year due to sedimentation (Mahmood, 1987; White, 2001). Apart from that, sediment deposited at the upstream end of reservoirs may also increase flooding probability. The interrupted flow of sediment, particularly in combination with regulated water outflow, has a significant impact on the sediment balance and river morphology of the river reach downstream, as well as its ecological properties. It has been suggested that sediment deposition in the reservoirs is one of the principal problems hindering the sustainable use of surface waters resources developed presently or in the future (Wang et al, 2005).

The majority of existing dams and other impounding structures continuously trap sediment and have no specific provisions for sustained long-term use. The lifespan of their storage capacity was frequently designed to be less than 100 years (Morris and Fan, 1997), and in practice sometimes reached much shorter duration. Sediment management can also be realized outside the reservoir, by reducing sediment inflow either by soil erosion control, upstream sediment trapping or sediment bypass (White, 2001). Any of these solutions will however either consume a proportion of water which will then not be available for reservoir's intended purposes, lower the reservoir levels during the operation, or move the problem to other areas.

From the viewpoint of the dam and reservoir management, there are typically two main concerns regarding sediment. The first is, as mentioned above, the gradual loss of storage volume, which results in reduced capability to provide water for irrigation, hydropower production, and other uses, as well as to intercept floods and regulate the flow. The other is associated with the threat that the sediment represents for the dam structure. If the sediment deposits approach the structure too closely, they may block the outlets or even compromise the safety of the dam. The sediment passing through the turbines causes abrasion of mechanical equipment, decreasing its power generating efficiency and ultimately loss of production time during its repair.

Sediment dynamics in the reservoir is greatly affected by the reservoir operation. Most of the sediment load arrives at reservoirs during the high flow events. Keeping the water levels high or filling the reservoir during these events causes most of the incoming sediment to deposit while keeping the levels low transports more of the inflowing load and may even lead to erosion of the previously deposited sediment. Understanding the driving forces behind the sediment deposition and their consequences is therefore of high importance in reservoir management.

The sedimentation management strategies are outlined in the figure (1) below, which may be used as a checklist for ensuring that all strategies have been considered at a given site. A combination of strategies will usually be used, and the techniques most suitable for implementation will change over time as a reservoir fills with sediment.

The optimum sediment management strategy may consist of a sequence of different techniques to be applied as the reservoir volume diminishes.

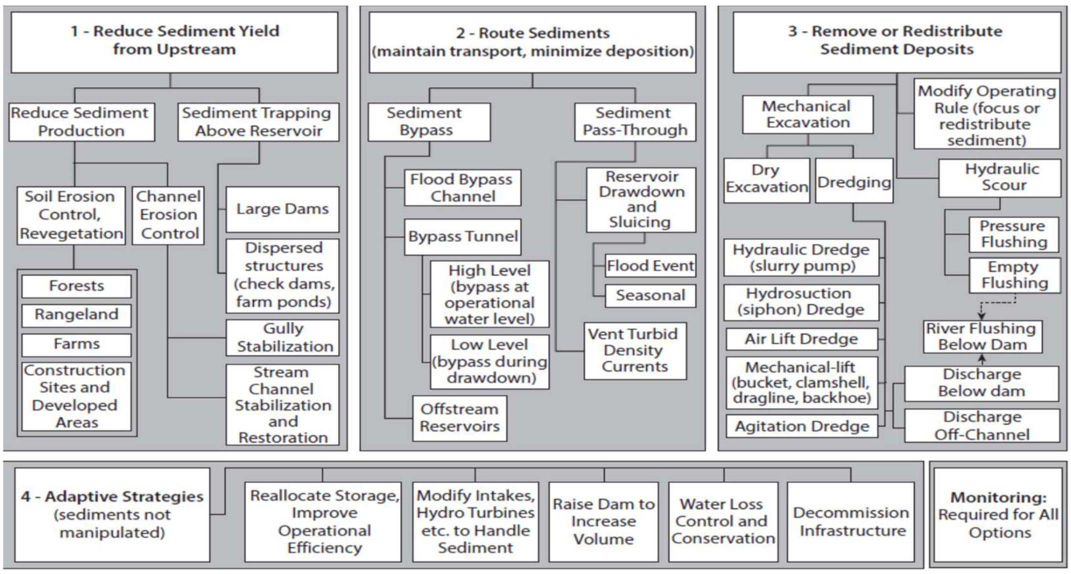


Figure 1 sediment management strategies

The term sediment generally refers to the soil particles that are deposited in a stream channel and then transported by streamflow. Sedimentation, in turn, is the process of deposition and transportation of soil particles in the streamflow.

The amount of sediment deposited in a stream, river, lake, or reservoir is indicative of the amount of soil erosion from the hillslopes and stream channels of the contributing watershed. Excessive sediment can adversely affect water quality characteristics and aquatic habitats. To determine what constitutes excess sediment in a stream it is necessary to recognize that soil erosion and the sedimentation processes occur naturally and, therefore, that the levels of the sediment load in streamflow can vary by region and from one time period to another in a region. The relationships between erosion sources and sedimentation involve the stream channel processes related to sediment supply, transport, and fluvial mechanics.

In the planning and design of new reservoirs, engineers should incorporate the concept of sustainable use and operation (e.g., Palmieri et al., 2003; Reclamation, 2006; Annandale, 2013). For existing reservoirs, engineers should take appropriate remedial measures to prolong their useful functions within economic, social, political, and environmental constraints. Being able to foresee and mitigate sedimentation issues during the design phase, or resolve these issues for existing projects, requires the ability to predict sediment movement.

Note

The abbreviation (masl) means meter above sea level

Chapter 2

Reduce sediment production (watershed management)

2.1 Strategy literature review

Although chapter (2) & (3) discuss the same issue (upstream sediment), it's important to separate the topic in two categories to avoid any confusion. the first chapter titled reducing sediment production which means directly to soil erosion process while the second topic chapter (3) (upstream sediment trapping) which means sediment transportation process.

Watershed is defined as every body of water (e.g., rivers, lakes, ponds, streams, and estuaries) has a watershed. The watershed is the area of land that drains or sheds water into a specific receiving waterbody, such as a lake or a river. As rainwater or melted snow runs downhill in the watershed, it collects and transports sediment and other materials and deposits them into the receiving waterbody.

Watershed management is a term used to describe the process of implementing land use practices and water management practices to protect and improve the quality of the water (in term of sediment concentration) and other natural resources within a watershed by managing the use of those land and water resources in a comprehensive manner.

All activities that occur within a watershed will somehow affect that watershed's natural resources and water quality and sediment production. New land development, runoff from already-developed areas, agricultural activities, all can affect the quality of the resources within a watershed. Watershed management planning comprehensively identifies those activities that affect the health of the watershed and makes recommendations to properly address them so that adverse impacts from sediment production are reduced.

Topography, climate, land use, land cover, edaphic factors, etc. are some of the factors that influence the production and transportation of sediment within a watershed area. Irregular and spatially capricious progressions of erosion will determine the flow of sediment and water. The prime agents of water erosion are the falling raindrops and the running water. When raindrops fall on the soil, it will break up the soil aggregates and splash the finer particles outwards, exposing them to be moved away by the running water very easily. On a steeply land, more than half of the splashed particles and water moves downhill and many of the small particles seal up pores in the soil's B horizon. As the soil becomes progressively shallower, it becomes more easily saturated and both soil detachment and transport are easier and greater runoff. Increased runoff has increased strength to detach and transport soil particles while the cohesion of the soil itself is being reduced by erosion taking away the finer particles. some researches mentioned as the erosion process could include-detachment of the soil particles as a result of the rainfall; sheet erosion and transport of particles; gully erosion; degradation of waterways and bank; soil erosion caused by the slope of the land and wind erosion. Sediment yield is the total volume of sediment that passes through a definite waterway whereby the process of sedimentation is governed by a set of geomorphic processes.

Sediment yield is usually expressed in units of cubic meters/kilometer square/annum or metric tons per annum. In order to know the magnitude of erosion, it is also however imperative to estimate the amount of sediment yield from individual showers of rain. The movement of sediment is impacted by the general situation of the wind and water. Deposition of sediments can occur in different places where the eroding agent energy becomes low.

Watershed management is important because the planning process results in a partnership among all affected parties in the watershed. That partnership is essential to the successful management of the land and water resources in the watershed since all partners have a stake in the health of the watershed. It is also an efficient way to prioritize the implementation of watershed management plans in times when resources may be limited. The serial process can be implemented to reduce the amount of sediment that results from watershed erosion these steps summarized in the following:

A. Erosion control

Many watersheds experience increased erosion rates due to land use and other human practices. Erosion reduction techniques fall into three categories: structural or mechanical, vegetative and operational as shown below:

1. Structural or mechanical measures - such as terraces, conveyance channels, check dams and sediment traps - decrease overland or channelized flow velocity, increasing surface storage and thereby reducing the sediment load in the runoff.
2. Vegetative erosion control takes advantage of plants' natural ability to limit erosion. Agricultural practices that minimize sediment yield are particularly effective.
3. Operational measures minimize erosion through planning, management, and organization. Examples include timing construction work such that erosion is minimized or scheduling timber harvesting to coincide with favorable soil conditions.

Erosion management is perhaps the most widely recommended implemented sediment management technique.

Case study:

Grand Ethiopian Renaissance Dam (GERD) Ethiopia

2.2 Introduction

The Grand Ethiopian Renaissance Dam (GERD) constructed on the Blue Nile river, also known as Millennium dam and locally referred to as 'Hidase Dam', is an under-construction gravity dam, The GERD project is located in a place called Guba approximately 750 km northwest of Addis Ababa and 40 km East of Sudan. The dam is a single purpose hydroelectric facility which controls about 177,700 km2 of the Blue Nile Basin see figure (2). The reservoir at 74 billion m3 storage capacity will be one of the continent's largest man-made reservoirs. The project has envisaged a power plant with an installed capacity of 6,000 MW and 15,692 GWh annual energy.

Figure 2 The Grand Ethiopian Renaissance Dam location (Google earth view)

The major components of the project figure (3) are:

- Main Dam of length 1,780m and 151m height
- Saddle Dam of length 4,800m and height 45m.
- Two powerhouses with 3,750 and 2,250 MW installed capacity containing 10 and 6 generating units respectively each with a capacity of 375MW.

Figure 3 Major components of The Grand Ethiopian Renaissance Dam (GERD)

Both Main Dam and Saddle Dam will create 74 billion m3 impounding capacity reservoirs of which 59 billion m3 is live storage. The dam shall create a surface area of 1,900 km2 at Full Supply Level (FSL). The normal and minimum operating water levels will be 646 and 596 masl respectively. The mean annual runoff volume at GERD is about 50.6 billion m3.

The Blue Nile and its tributaries start from the Ethiopian highlands. It originates from Lake Tana, the largest lake in Ethiopia and joins the White Nile at Khartoum, the capital of Sudan. The Blue Nile is located between longitudes 33°26'55'' and 39°49'12'' E and latitudes 7°39'28'' and 13°50'7''N covering about 210,000 km2 area and is as shown in Figure (4).

Along the way from Lake Tana to Sudan, the Blue Nile River is joined by rivers Beshlo, Derma, Jemma, Muger, Guder, Fincha, Didessa, and Dabus from the left bank and Beles, Birr, and other smaller tributaries from the right bank.

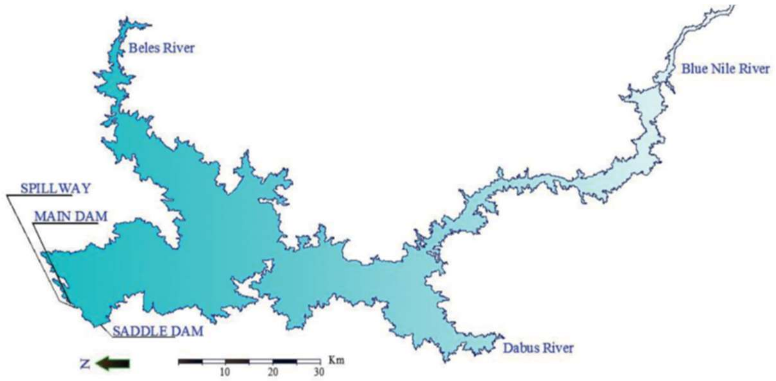


Figure 4 Water spread area of the GERD reservoir at the Full supply level

2.3 The climate and geology of the catchment area

The climate in the Blue Nile is governed by the seasonal migration of the Inter-Tropical Convergence Zone from south to north and back. Mean annual precipitation ranges from about 2000 mm in Ethiopian highlands to less than 200 mm in Sudan. Within the highlands of Ethiopia, the wet season lasts four months from June to September with the maximum rainfall in August. East of Blue Nile, the rainfall pattern is characterized by two wet seasons, the short rainy season and the main rainy season. The short rainy season occurs from mid of February to mid of May and the main rainy season occurs from June to September.

The mean annual temperature in part of the river area located in Sudan is 28.73 °C with a maximum daily temperature of 44 °C in May and minimum daily temperature of 14 °C in January. The spatial distribution of temperature highly depends on altitude. In the Ethiopian highlands, the mean annual temperature ranges from 6 to 9 °C and 23 to 26 °C in the low lands of the area, near the border.

The geology of the basin signifies different formations such as Basalt, Alluvium, Lacustrine deposit, Sandstone, Granite and Marble. The highlands of the basin are composed of basic rocks, mainly basalts and the lowlands composed basement complex rocks as well as metamorphic rocks, such as gneiss and marble. see figure (5).

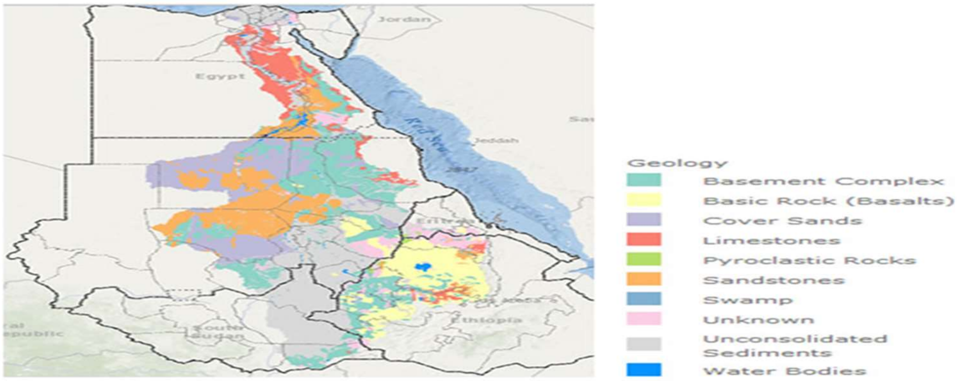


Figure 5 the geological map of the Blue Nile catchment area

2.4 Soil type and land (use &cover) of the catchment area

The predominant soils are generally characterized as vertisols, Luvisols, and lenticels. Soil profiles in the highlands are characterized by permeable soils, underlain by bedrock at depth. Soils are generally deeper at lower reaches of the basin while soil depth is less in the steeper slopes. Based on the food and agricultural organization soil classification, part of the basin in Sudan is dominated by the Eutric Vertisols. The part of the basin in Ethiopia is mainly dominated by Umbric Nitosols in the southeastern part and Lithic Leptosols in the northeastern part (Awulachew and Yilma, 2009).

According to united states geological survey, savannah land occupied 69.8% of the total Blue Nile Basin without Dinder and Rahad river basins, forest covered land about 2.17%, grassland 2.31% of the total area, and cropland, dry land and pasture about one fifth (21.61%) of the area, while built up and artificial areas accounted for 0.03% of the total area see figure (6). The remaining 4.08% being water body, barren and sparsely vegetated land. Though land cover changes from time to time there is no comprehensive data to show a change in land use and land cover of the basin.

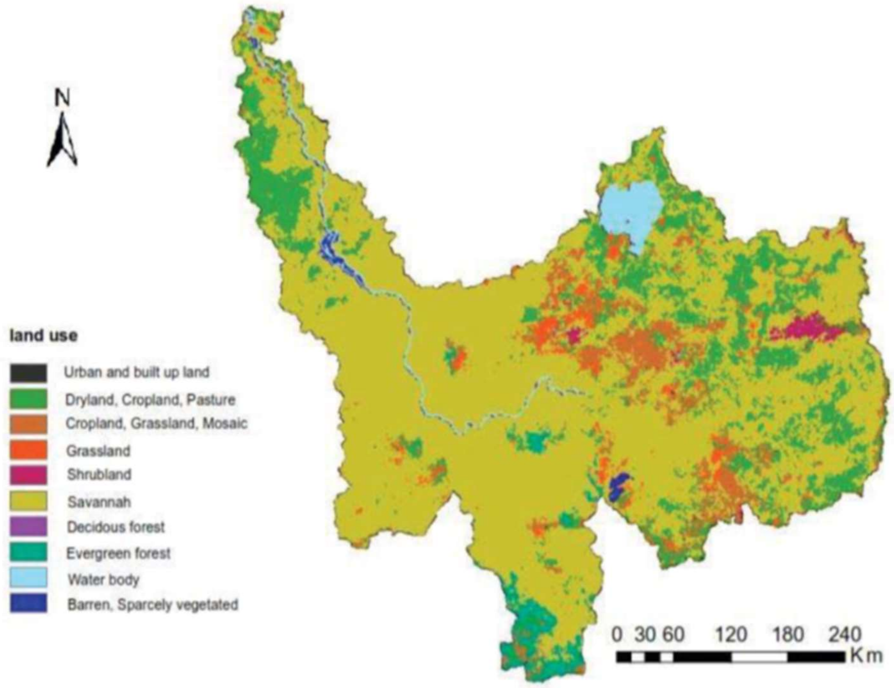


Figure 6 Land use & cover of the Blue Nile river basin

2.5 Hydrological data of the river basin

The average annual runoff volume is about 50.6 billion m3 which equate 241 mm over the catchment area of 209,780 km2. Flow distribution is reflected great extent by the rainfall seasons (Figure 7) but with time-lag and attenuation through which the high-flow season commences first in July and persists until October-November as the high flows gradually recede until low flow condition prevails between December and June. The highest flow months July to October yield about 80% of the annual runoff. Variation in specific runoff of the Blue Nile River at El-deim, Mandaya, Karadobi, Kessie and at the outlet of Lake Tana is given in Figure 7. The basin of the upper Blue Nile tributary to the dam drains the Ethiopian highlands. The Blue Nile has a single wet season and flow is highly seasonal. The Ethiopian highlands range from about 500 to 4,533 m in elevation, with average rainfall varying regionally from 600 to 2,200 mm/year.

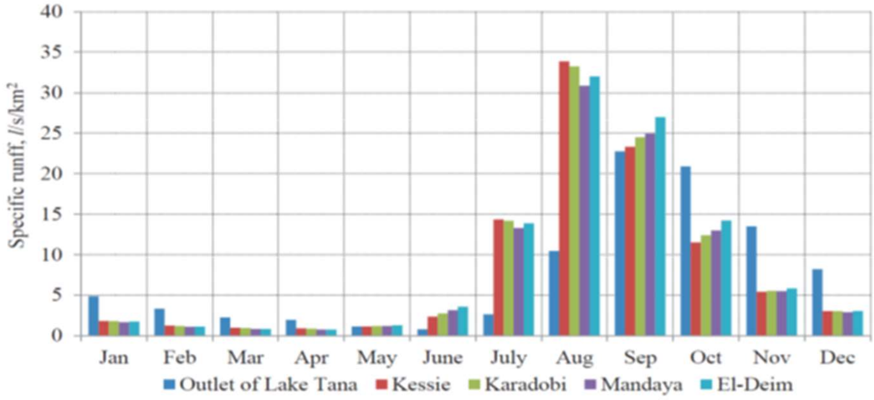


Figure 7 Specific runoff at different locations along the Blue Nile River

2.6 Sediment erosion in the Blue Nile River

Sediment in the Nile is mainly originating from the Ethiopian Highlands. With the fast-growing population and high-density live stocks in the Blue Nile Basin, replacement of forest lands by agricultural lands is a common practice.

The basin is steep, and the vegetation is relatively sparse because of the short rainfall season. The mountainous and steep slopes are cultivated without effective protective measures against soil erosion which with high-intensity rainfall speeds up soil loss in the basin.

Blue Nile Basin is characterized by high runoff when compared to the White Nile through the catchment area of the White Nile Basin is about three times that of the Blue Nile Basin

Blue Nile River which accounts for about 86% of the flood season runoff volume is the main source of flow for the Nile River. The sediment supplied by the river is also of similar proportion. the estimated contribution of the White Nile River to the Nile River sediment load is less than 5%. Runoff from highlands of Ethiopia makes its way to the Blue Nile through dense gullies formed during intense storm season and tributaries. These gullies and tributaries are the main carriers of eroded sediment too.

Sediment concentration peaks one month prior to the discharge peak. Trend analysis at the El Diem gage showed a 61 percent increase in sediment load, from 91 Mt/yr for the 1980-1992 period to 147 Mt/yr for the 1993-2009 period and was associated with a significant increase in suspended sediment concentration, especially during the rising limb of the wet season. The recent sediment yield is 835 t/km^2/yr across the 176,000 km^2 watershed tributary to the El Diem gage see figure (8). A recent study by the Water and Land Resource Centre (WLRC) using a very detailed modeling approach indicates that sediment entering GERD will be in the order of 287 million M3/year (WLRC, 2017 unpublished), much higher than previous predictions.

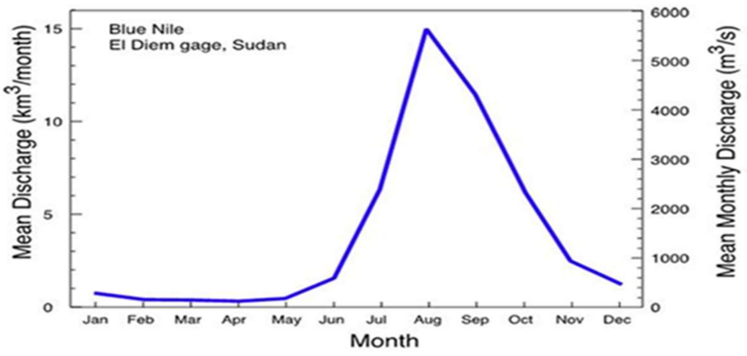


Figure 8 The mean discharge in the Blue Nile at EI Diem gage

Agriculturally based population growth can have a significant contribution to the sediment erosion in the basin. The increasing population expands to forest areas and clear forests in order to prepare more area for farming. The agricultural lands prepared during the first arrival of rainfall can be easily detached by precipitation and then transported by surface runoff into the drainage system.

Construction activities can also supply a significant amount of sediment. Road constructions and site excavations for construction materials loosen the natural and covered soil and remove protective vegetations. The soil when subject to erosive rainfall and runoff on steep slopes can easily be taken to gullies and streams. See figure 9

Figure 9 Soil exposure due to construction activities

Generally, high soil erosion can be expected from the basin as it includes combinations of the following parameters:

- Presence of steep and long slopes is among the major factors for intensive erosion.
- High rainfall intensity: rainfall in the basin is characterized by short and intense storms.
- High soil formation rate can be expected due to the climatic factors of the region.
- Poor vegetation over much of the area of the basin including steeper areas and land management practices which are poorly adapted for soil and water conservation.

2.7 sediment transport

Sediment after joining streams based on its transport mechanism can be classified as bed load or suspended load. Bed load is the transport of sediment that frequently maintains contact with the bed and Suspended load is the transport of finer particles which are held in suspension by eddy currents in the flowing stream. The relative quantities of materials transported in suspension and as a bed load varies greatly. In areas where the sediment is coming from a fine-grained soil such as wind-deposited material, or alluvial clay, the sediment may be transported almost entirely in suspension. On the other hand, a fast-flowing clear mountain stream may have negligible amounts of suspended matter and almost all sediment transports by rolling on the stream bed.

Not all eroded sediment joins the river due to filtration by vegetation and sediment transport capacity loss of the runoff before it joins the river. The part of eroded sediment that joins the river starts making some deposition pattern. Finer particles keep in suspension until the flow velocity falls below the threshold while course sands and boulders start deposition near the river banks.

(a) (b)

Figure 10 Sediment flow pattern in the Blue Nile River near Kessie Bridge (a) September10, 2011(Source: Dr. Kiflom Belete) and (b) June 20, 2009.

The river transporting course sands and boulders from steep areas of the Kessie catchment drops its load as it joins the gentle slope of the river bed. The wide and shallow sand deposits (Figure 10 a,b) that appear on these banks during the falling stage of the flood are the result of the seasonal sedimentation that took place when the progressively decreasing discharge and the consequent drop in flow velocity reduced the river transport capacity. This indicates that a considerable amount of sediment can be transported in the form of bed load.

2.8 sediment problem

About 83 percent of Ethiopia's population lives in rural areas and many derive their livelihoods from agricultural and environmental resources, primarily rain-fed agriculture and cattle grazing. Over 90 percent of the cropland consists of small-scale rain-fed household production systems. Ethiopia’s dramatic population expansion over the last 50 years and future predictions of a growing population has placed extreme pressure on the land, resulting in accelerated erosion, soil degradation, and rural impoverishment. Land degradation occurred because the production system was based on continuously expanding land for cultivation, rather than increasing the production per unit area, as described in the Abbay basin (Zeleke and Hurni 2001):

As cultivated land was expanded at the expense of other land use and land cover units, grassland declined, resulting in less available fodder and a decrease in the number and quality of livestock. This led to a shortage of animals required for plowing and transport, as well as to a reduction of income and food from animals and their products. This series of related impacts indirectly affected the traditional land management system. When livestock and fodder were plentiful (in the 1950s), manuring was an important practice in the area. It increased soil fertility and hence production without extra cost to the farmer except for labor. After fodder availability and livestock had decreased, manuring (traditionally called hura) was gradually reduced. Moreover, manure is now in greater demand than ever not only because of the lower number of livestock but also because of its use as a source of fuel has increased due to the reduction of fuelwood.

Bare lands were used as grazing land. Livestock was forced to stay on these land units, especially during the cropping season, although there was little for them to feed on. This is one of the practices adopted by farmers when the population grows, and land becomes scarce. The farming system remains traditional while most of the grasslands are converted to cultivated lands. In this case, both livestock and cultivation took over marginal lands, eventually leading to even more severe land degradation.

The Ethiopian highlands within the GERD watershed are considered to be one of the severest cases of watershed degradation in the world. Sediment yields in the Lake Tana sub-basin, where the Debre Yakob site is located, average about 2,500 t/km2/yr, and in the areas of highest erosion, hazard sediment yield may be as high as 6,500 t/km2/yr. Areas with the highest erosion potential have been analyzed and identified using the SWAT model, together with climatic time series and GIS spatial databases of soil characteristics (Setegn 2008).

Thus, much more is at stake than the issue of reservoir sedimentation, because the degraded soil conditions result in rural poverty and food insecurity. It is essential to maintain this soil on the farms to support productive and sustainable agriculture, just as it is necessary to keep it out of the reservoir to sustain long-term hydropower production.

2.9 Sediment management strategies

The Debre Yakob watershed encompasses about 325 ha and is located at 11º 16’ 59" N latitude and 37º 13’ 45" E longitude see figure (11). Rainfall averages about 2,300 mm/year. It was selected as a ‘learning watershed’ by WLRC in 2012 to serve as a demonstration site for a variety of interventions aimed at improving land management practices in a way that would substantially improve the economic circumstances for farmers, while simultaneously reducing soil erosion.

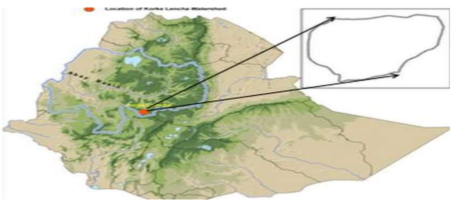


Figure 11 The Debre Yakob watershed

Typical of the region, the Debre Yakob watershed was severely degraded by overgrazing, resulting in soil denudation and gullying. To transform the local watershed, the first order of business, and the greatest challenge was to achieve a shift from free grazing across the entire landscape, to the use of enclosures and cut-and-carry feeding of the livestock (figure 12). Without relieving the continuous grazing pressure, it would not be possible to achieve re-vegetation needed to control erosion.

Figure 12 Watershed was severely degraded by overgrazing, resulting in soil denudation and gullying

There was considerable initial skepticism in the Debre Yakob community, which had no prior experience with a cut-and-carry livestock management system. Many believed it would not work. However, by working closely with cooperating farmers in one area of the watershed, and by providing the initial funds to build check dams and plant vegetation to stabilize gullies, it was possible to demonstrate that the check dams would accumulate eroding soil and grow luxuriant vegetation. By the end of the first wet season, the amount of forage production was exceeding the needs of the livestock that, previously, had barely survived when grazing freely. Feeding in one of the livestock enclosures.

With grazing pressure removed, re-vegetation occurred rapidly in the moist soil held by the check dams see figure (13). Vegetation also began to recover on the upland soils once the livestock was confined and young plants were not immediately consumed by wandering animals. Vegetative growth enhanced soil infiltration capacity and improved soil structure, leading to higher soil moisture levels and, in turn, more vegetation, establishing a positive feedback loop of land restoration.

Figure 13 Vegetation recover on the upland soils

By eliminating free grazing and producing sufficient forage to support the livestock, the community saw the benefits of changing their production systems. Attention then turned to enhance the value of farm production through multiple avenues. The most important management strategies employed at Debre Yakob are:

1. Gulley rehabilitation coupled with community agreements for livestock management incorporating a zero/controlled grazing system linked to cut-and-carry forage production on closed areas, gullies, farm terraces, and around homesteads.
2. Area closures to rehabilitate degraded hills that used to serve as grazing lands even though they were not productive. This requires protecting the land against free grazing (animal exclusion areas as part of the zero-grazing arrangement) but cut-and-carry is allowed through agreements among the communities.

3. Homestead development interventions are designed to enhance household income and empower women as well as households. It incorporates sub-components such as: home garden, an improved fruit tree agroforestry system, forage plantings around the household compound, introduction of new crops (papaya, avocado which has a good export market, hops for beer which has a good local market, etc.), bee-keeping, small-scale poultry, dairy and animal production, compost-making, fuel saving stove and improved water sources (shallow well or pond).
4. Permanently vegetated soil and water conservation terraces were established between fields and planted with fruit trees and forage bushes to make these 'conservation' features economically productive.
5. Techniques to improve soil moisture capacity and fertility through the use of mulches, composting, etc.
6. Small nurseries to produce biological materials such as tree, forage bushes, grass, fruit and other seedlings for transplanting.

While many of these activities do not directly influence soil management, they are all part of a farming technology package that makes responsible land management self-sustaining. The key to long-term success in watershed management lies not in the building of erosion control structures, but in changing the economic activities of the community to embrace sustainable production systems. To be productive and sustainable these systems must retain topsoil on the farm. As a result, erosion control occurs as a natural and self-sustaining product of a successful farming system, as opposed to a top-down programme aimed at benefiting a downstream hydropower reservoir and sustained by costly subsidies. The importance of focusing on the household economic unit is underscored by the differences between unsuccessful and successful long-term interventions in Ethiopia (Zeleke 2015):

In the past focus was given only to the rehabilitation of watersheds and less was done on activities that enhance income at household level. This was proved wrong over time as rehabilitation intervention alone didn't enhance income within a short time and as a result, many watershed development interventions fell back to previous situations. Over the years we have learned that any watershed development intervention should have economic development interventions as a major component of the watershed development plan and this was best organized in the form of homestead development intervention. We have seen that many households graduated from food insecurity through the combination of rehabilitation and economic development interventions.

2.10 Conclusion

Reducing sediment yield by changing land use requires a significant and sustained effort, potentially requiring the intervention with tens of thousands of small farmers. Realistically, an intervention on this scale can only be achieved through the participation of multiple entities including government, NGOs, and the private sector. In some cases, with small watersheds and known erosion hot-spots, there may be the opportunity for effective unilateral action by the dam owner. However, more typically a watershed management project is not a go-it-alone project for the dam owner but may involve many organizations at multiple levels, from the local community up to the national government level. For example, to address land management issues in the North Fork of the Feather River (California, USA), hydropower owner PG&E joined in a formal memorandum of understanding with 17 other organizations (Morris and Fan 1998).

Hydropower producers can play key roles in this process by using their available funds to help develop and demonstrate viable technology packages and to sustain work at demonstration sites which can then be copied and disseminated throughout the watershed by others through both formal workshops and informal means. An economically successful system is likely to be adopted by others, on their own, given access to the information and provided learning opportunities. This is already happening at Debre Yakob Learning Watershed.

In selecting project areas for intervention, it is essential to understand the natural background rates of erosion and sediment yield and to select for intervention those areas where the erosion rate has been greatly accelerated by poor land use practices, and where interventions can be applied successfully and sustainably. Tools such as the SWAT model coupled to GIS databases can be extremely helpful in preparing a sediment budget and identifying areas of greatly accelerated erosion. Equally important is the development of locally-relevant technology packages that are economically self-sustaining.

Watershed management programmes are not always successful. Key factors that point to long-term success at Debre Yakob include the development of technology packages that are economically self-supporting because they increase on-farm income, and a climate with sufficient moisture to achieve rapid re-vegetation. Establishment of such learning watersheds in different parts of hydropower catchments helps to educate and change the attitude of local communities, experts and policy-makers. This facilitates the expansion of successful technology packages into other areas.

The key underlying strategy is to greatly enhance productivity and economic value through optimal management of the best soils while converting the poorer and steeper soils to woodlands (eg firewood, building materials), pasture, or tree crops. Multiple avenues need to be pursued to enable the farmer to enjoy higher income and enhanced economic security, providing self-sustaining economic incentives derived from the land itself which guides farmers to maintain and improve soils and sustain vegetative cover without additional external incentives.

Chapter 3

Upstream sediment trapping

3.1 strategy literature review

To continue what we start in the chapter (2) the following mitigation might be useful to apply: -

A. Check Dams

A check dam is a small barrier concocted of rock, gravel bags, sandbags, fiber rolls, or reusable products, placed across a constructed swale or drainage ditch. Check dams reduce the effective slope of the channel (thereby reducing the velocity of flowing water, allowing sediment to settle and reducing erosion.

Check dams, 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 check dams 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 check dams 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 check dams reduce sediment yield to downstream reservoirs is by trapping sediment before it reaches the downstream reservoir figure (14,15). 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.

Figure 14 check dam

Figure 15 small check dam

B. Sediment Traps

Low dams located just upstream of reservoirs can function as traps for (mostly coarse) sediment. Theses hold 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.

C. 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].

Case study:

Hvammur hydropower project

3.2 introduction

The Hvammur hydropower plant on the Þjórsá river basin in the south of Iceland, located near the north end of Skarðsfjall mountain, on the estate of Hvammur farm in the Landsveit area see figure (16). Landsvirkjun the national power company is developing the project which is still in the preparation phase. The Hvammur dam construction will start at the end of 2018. Figure 16 shows the location of the project as well as other existing and planned projects on the Þjórsá situated above Minnanúpshólmi island, the powerhouse will be mostly underground. The tributary area to the dam comprises 7,300 km^2 of which only 470 km^2 remain unregulated.

Figure 16 location of Hvammur dam and other hydropower plants

The Hvammur dam will create an intake reservoir called Hagalón with a total capacity of 13,2 Mm^3 to serve the 93-MW hydropower plant that would generate 720 GWh annually. The zoned earth-rockfill dam will have a height of 120 m. The operational regime is expected to be normally full, thus, the maximum and minimum operating level will be 116 and 114 masl (meter above sea level) respectively. At full level, the reservoir surface will cover 4 km^2 see figure (17).The spillways at an elevation of 107 masl will have a discharge capacity of 3,800 m^3/s. The power plant will host two Kaplan turbines of 46.5 MW each designed to operate with a gross head of 32 m and a design power discharge of 350 m^3/s.

Figure 17 Hvammur dam aerial view

3.3 The Þjórsá river &basin area

The Þjórsá river is fed by glacial runoff from three glaciers – Vatnajökull (Europe's largest), Hofsjökull and the small Tugnafellsjökull. It is already a strongly regulated river system, with five storage reservoirs with a total storage capacity of approximately 2 billion m3. The largest is Þórisvatn with a volume of 1.33 billion m3. The storage hence represents about 20% of the annual average runoff at the Hvammur project site, where the average discharge is around 317 m3/s. See figure (18)

The Þjórsá is the longest river in Iceland. The river originates in the Hofsjökull glacier at 2,000 masl and runs Southwest through the highlands of Iceland. Due to the ice erosion, the river carries high sediment concentrations and sediment load. The specific sediment yield in the basin is 160 t/km^2 per year.

The river basin is characterized by an average air temperature of 2.2 ^oC and an annual average precipitation of 975 mm. The mean annual inflow is 10,344 Mm^{3}and the coefficient of variation is 0.1 which means that the inflow does not fluctuate far each year. The glaciated area covers 14 percent of the basin and it supports a steady flow during the spring and summer.

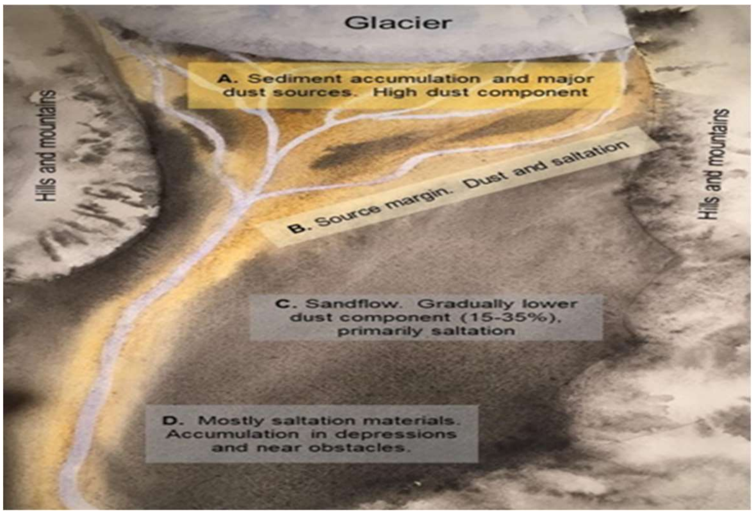


Figure 18 Conceptual drawing of aeolian source components at a glacial margin with rivers depositing high quantities of silty materials on the surface. Area A is the dust-hotspot, but area B is also a very active dust source. Areas C and D are dominated by saltatio

The Þjórsá river is non-regulated state carried high concentrations and loads of fine glacial sediments(dust). The construction of several hydropower plants and associated reservoirs in the upper parts of the Þjórsá catchment has resulted in a considerable deposition in those upstream reservoirs, reducing the number of fine sediments present in the lower reaches of the river.

3.4 The Hagalón reservoir

The Hagalón reservoir will be 4.6 km2 in size, and almost 3 km2 of that was previously river, leaving less than 2 km2 as effective land takes for the reservoir. The water level of the reservoir will be kept at a nearly constant level of 116.00 m.a.s.l. The volume will be only 15.5 million m3, sufficient to run the plant for 14 hours at the long-term average flow of the

river see figure (19).The most important issues concern slope stability in the reservoir banks, birds ‘nests and archaeological remains.
The spillway is designed to pass a flood with a return period of 50 years with a water level that does not exceed the normal water level (NWL). A flood with a 1000-year return period must be discharged while keeping the reservoir level less than or equal to 1.5 m above NWL.

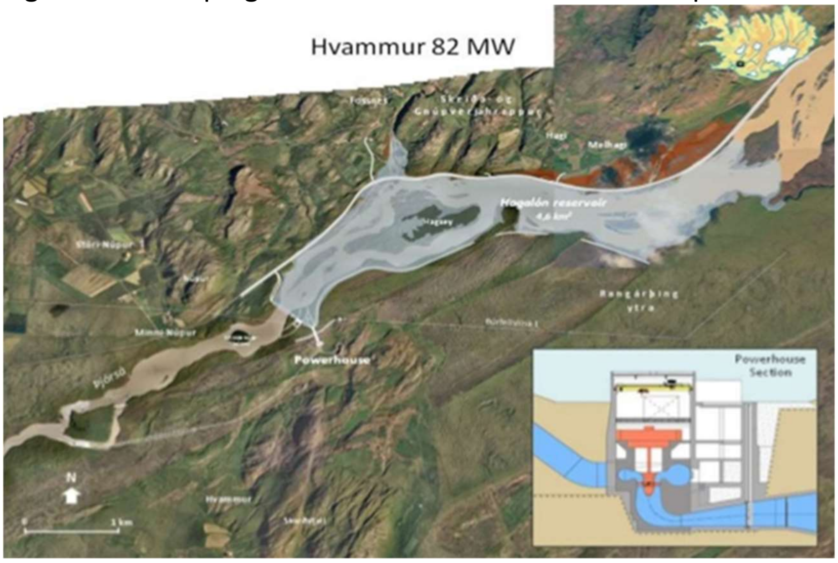


Figure 19 The Hagalón reservoir

The delivery of a downstream flow is determined to be a constant 10 m3/s, believed by experts from the Institute of Freshwater Fisheries to be a satisfactory level for the maintenance of successful salmon migration. The flow will be released as an over-flow over the dam. This design solution means that at the normal operating level of the reservoir, the required flow will automatically be released. As result, the suspended sediment concentration at Hvammur site has been considerably reduced making possible for the salmon to populate the area.

3.5 Erosion in Iceland

Iceland has the largest area of volcaniclastic sandy desert on Earth or 22,000 km2. The sand has been mostly produced by glacial-fluvial processes, leaving behind fine-grained unstable sediments which are later re-distributed by repeated aeolian events. Volcanic eruptions add to this pool of unstable sediments, often from subglacial eruptions. Icelandic desert surfaces are divided into sand fields, sandy lavas and sandy lag gravel, each with separate aeolian surface characteristics such as threshold velocities. Storms are frequent due to Iceland’s location on the North Atlantic Storm track.

Dry winds occur on the leeward sides of mountains and glaciers, in spite of the high moisture content of the Atlantic cyclones. Surface winds often move hundreds to more than 1000 kg m−1 per annum, and more than 10,000 kg m−1 have been measured in a single storm. Desertification occurs when aeolian processes push sand fronts and have thus destroyed many previously fully vegetated ecosystems since the time of the settlement of Iceland in the late ninth century. There are about 135 dust events per annum, ranging from minor storms to >300,000 t of dust emitted in single storms. Dust production is on the order of 30–40 million tons annually, some traveling over 1000 km and deposited on land and sea. Dust deposited on deserts tends to be re-suspended during subsequent storms figure (20).

They are more frequent in the wake of volcanic eruptions, such as after the Eyjafjallajökull 2010 eruption. Airborne dust affects human health, with negative effects enhanced by the tubular morphology of the grains, and the basaltic composition with its high metal content. Dust deposition on snow and glaciers intensifies melting. Moreover, the dust production probably also influences atmospheric conditions and parameters that affect climate change.

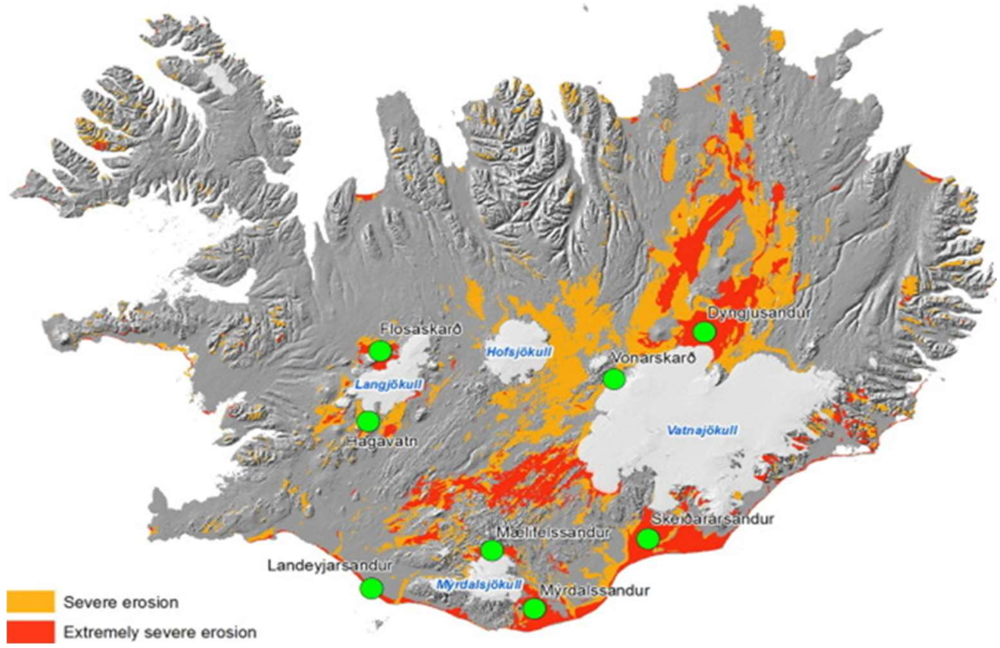


Figure 20 Sandy deserts in Iceland, shown with yellow and red colors, which represent erosion severity (yellow: erosion severity 4, severe erosion; red: erosion severity 5, extremely severe erosion). They cover large proportions of the south-coast and glacial mar

3.6 Sediment problems

Hvammur dam will be located in the lowlands, where the wind erosion dominates. The weathering of the soil pack is severe due to the lack of vegetation. Sand is the main material of the river bed with a D_{50} grain size of 4 mm.

The expected annual suspended sediment load at the dam site is 75,000 tons and it is expected that the Hvammur dam will likely trap 100 percent of sediments above grain size 0.06 mm. The sediment rating curve for the suspended load is defined by the formula Qs=0.000005*Q^2.57 (sediment in kg/s and discharge m3/s). Being the dry bulk density of deposits 1.5 t/m3, the estimated figure is 50,000 m3 annually which the dead storage capacity (6.7 Mm3) of the reservoir will be able to offset in about 134 years. However, sediment eroded from the river banks, the river bed and airborne sediment will also contribute to the sedimentation in the reservoir.

Aggressive-river syndrome has been identified in the Þjórsá river, and detailed calculations regarding how much sediment would be available for entrainment downstream of Búrfell power station have been conducted. Based on a larger river stretch, the figure arrived at was 140000 m3/year, but later studies of sediment availability along that river reach came to the lower figure of 50 000 m3/year. Even with the higher figure, this would yield a half-life of the Hagalón reservoir of approximately 55 years. The lower, more probable figure results in a half-life of around 155 years.

Erosion in the area of the Hvammur project is dominated by wind erosion. Due to the lack of vegetation, the wind has free reign and the soil pack is severely eroded over large areas. Also, Small dikes have been constructed to reduce the bank erosion caused by the higher winter flows resulting from river regulation see figure (21).

The major sustainability aspects to consider for the approximately 3 km stretch of river where the flow of the Þjórsá river will be strongly affected/limited by the Hvammur project are: wind erosion of the river bed when only the downstream flow is being passed through the old river course; aesthetic aspects of having an almost empty river bed, groundwater-table impacts with concomitant impacts on Viðey island with its unique vegetation and protected status and; impact on fish and fish migration.

Figure 21 an example of wind erosion in the area

3.7 Sediment management strategies

The Þjórsá river basin is highly regulated with multiple dams which trap most of the sediments transported through the river flow. In addition, Landsvirkjun has carried out active erosion control throughout several years. These upstream projects and measures will prevent 90 percent of the coarse sediment to reach Hagalón reservoir see figure (22).

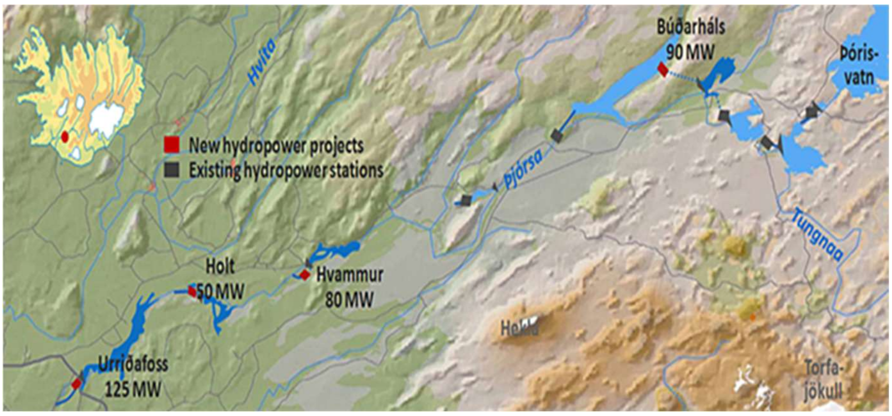


Figure 22 the operating hydropower plants in upstream of Hvammur dam

Erosion and sedimentation issues have been monitored since 1968 in the Þjórsá river basin. This information has been fundamental to assess the potential sedimentation issues at Hagalón reservoir and to decide on the sediment management strategies to implement. Active sediment control has a long history in the catchment, and extensive monitoring has been carried out by Landsvirkjun.

Mechanical excavation will be carried out at the reservoir delta where most sediments carried on the river flow will settle. The plain suction dredge will be used, and the sediments will be deposited on the west bank to enhance the land to farm.

Besides the monitoring, Landsvirkjun also conducted research on ice-related erosion. One of the findings showed that full-level operating regime would reduce the risk of ice-induced erosion of the reservoir banks. A set surface level will allow an ice cover to form easily and the water to flow beneath it. Therefore, the Hvammur dam is planned to operate at the normal full level regime. In addition, small dikes have been constructed to reduce the bank erosion caused by the fluctuation from river regulation.

To address the wind erosion, Landsvirkjun has taken part together with the soil conservation authority in watershed management activities for revegetation.

The 93-M Hvammur hydropower project has integrated into the design measures to avoid, minimize and mitigate sediment-related issues. The operational regime will minimize ice erosion in the river banks, control erosion, and upstream reservoirs will minimize over 90 percent of the sediment load and mechanical dredging will contribute to extend the life of the reservoir and enhance the neighboring farmlands.

3.8 Þjórsá river Monitoring

Extensive hydrological and glacial monitoring is carried out on a continuous basis and the hydrological resource is documented in detail. The Þjórsá river hydropower projects are operated through an integrated control system, which secures an efficient and optimized use of the water resource.

Both regular sediment and water elevations monitoring has been ongoing for years and will continue, both upstream and downstream. After construction of the dam, bathymetry measurements will be made regularly but annual bathymetric surveys are not considered necessary. see figure (23).

The sampling of delta sediment and bottom set bed is already planned. Other measurements include grain size and concentration of released sediment in the downstream area.

Figure 23 upstream of the Þjórsá river hydropower project

Chapter 4

Bypass channel / tunnel

4.1 strategy literature review

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 re-join the river. 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.) see figure (24) below.

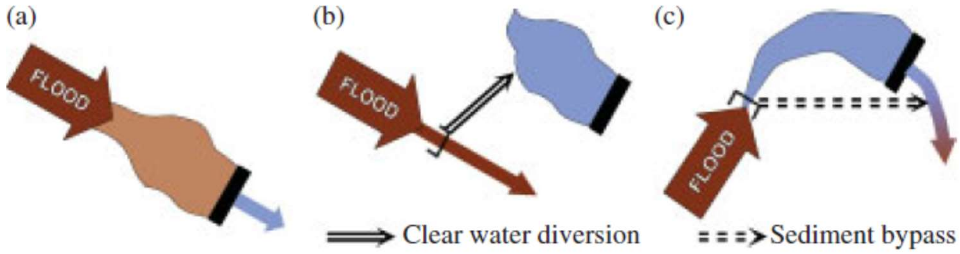


Figure 24. (a) Conventional reservoir, which traps incoming sediment, contrasted to alternative configurations for bypass of sediment-laden flood flows around the storage pool: (b) bypass off-stream storage, wherein a diversion dam in the river diverts water to the off-channel reservoir during times 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 24c). 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

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 on the bend of a river, as this allows for a relatively short diversion between the weir and the downstream side of the dam.

Because of the unique site characteristics required for construction of a bypass channel and the high cost of tunneling, sediment bypass tunnels have been used in only a few hydropower reservoirs in mountainous areas of Japan and Switzerland, but they can be useful for retrofitting dams that were not constructed with outlets for sediment management see figure (25).

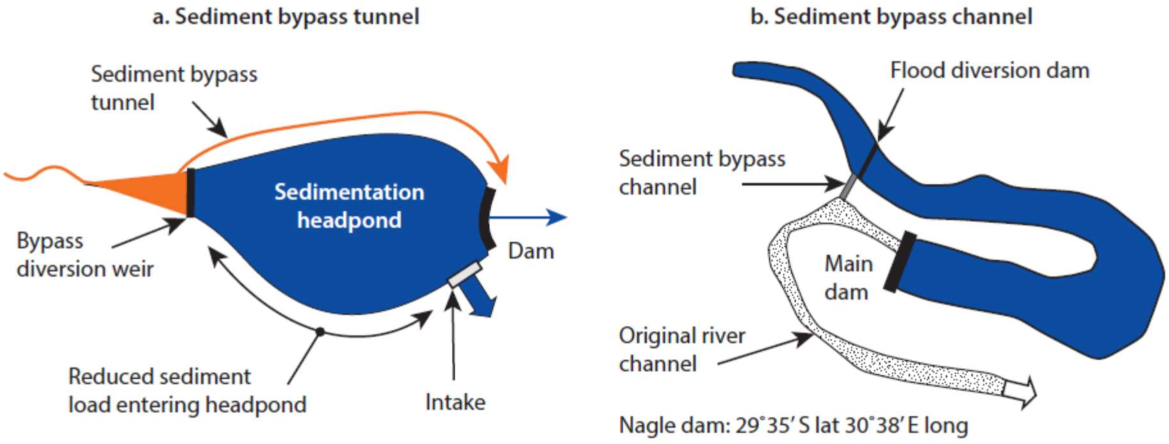


Figure 25 Alternatives for Bypass of Sediment-Laden Floods

Case study:

Japan - Okuyoshino

4.2 Introduction

Okuyoshino hydropower plant is located in the Nara Prefecture, in southeast Japan, as shown in figure (26). The Asahi Dam is situated in the Shingu River System rising from the Omine Mountains in the southern part of Kii Peninsula, is 86.1 m, arch dam created a reservoir with 15.47 Mm^3 of gross storage capacity, of which 12.63 Mm^3 was the original active storage capacity used for pumping water to the upper reservoir. The Asahi reservoir operates at the normal water level of 462 masl and the minimum level of 430 masl. The Seto reservoir, created by a 110.5 m rock-fill dam, offers 16.85 Mm^3 of storage volume for power generation. The Seto reservoir is located in an upper valley with a small catchment area of 2.9 km^2.

Figure 26 Okuyoshino hydropower plant location

The 1,206 MW Okuyoshino hydropower station is a pure pumped storage power plant that shifts water between the Asahi lower reservoir see figure (27) and the Seto upper reservoir. The complex was completed in 1978, but the power station was not commissioned until 1980. Owned and operated by the Kansai Electric Power Company (KEPCO).

The Okuyoshino pumped storage power station benefits from a hydraulic head of 505 m (the difference between two reservoirs). The six Francis turbines of 201 MW each are reversible units that serve to both pump and turbine water with a maximum discharge of 288 m^3/s.

Figure 27) The Asahi dam

4.3 Hydrology and sediment

Japan is located in the Pacific Ring of Fire and experiences many earthquakes and much volcanic activity. There are mountains throughout the country and the geological structures are often fragile. The bedrocks have been fractured and hydrothermally altered due to the intrusion of volcanic rocks and these bedrocks readily collapse as a result of continuous infiltration, freezing, and dissolution of rainwater, as well as bedrock, creep. In addition, severe climatic conditions such as typhoons, rain fronts, and atmospheric depressions cause heavy rains, and thus, a great amount of sediment is produced in the mountains. The average sediment. production is estimated to be about 200 million m3 per year.

Dividing mountain ranges cut through the Japanese archipelago like a backbone, and short steep rivers flow directly into plains and to the sea. The sediment of various particle sizes produced in the mountains is continuously transported downriver and, periodically, in large quantities by floods. In the process, rivers repeatedly overflow, and sediment is deposited in many places and then moves again. The deposit of relatively large gravel and sand has created alluvial fans where rivers flow into the plains from steep mountain regions. Small sand and nutrient salts contained in fine soil particles have been deposited in flatlands to create plains and river mouth deltas. Additionally, the supply of sediment from rivers has formed tidal flats and sandy coasts. Thus, sediment from mountains has played an important role in creating and maintaining Japan's landscape and has nurtured regional climates and ecosystems. At the same time, however, sediment has been a threat to human life.

Okuyoshino hydropower plant is located in one of Japan's rainiest areas, with an annual precipitation rate of over 2,000 mm. there is heavy rain around the month of June, followed by the typhoon season in September see figure (28).In September 1990, a maximum discharge of 662 m^3/s was recorded. rugged mountain land of elevation from 1,000 to 1,800 m is developed in the watershed. River valleys are V-shaped and river gradients are steep, from 1/6 to 1/7.

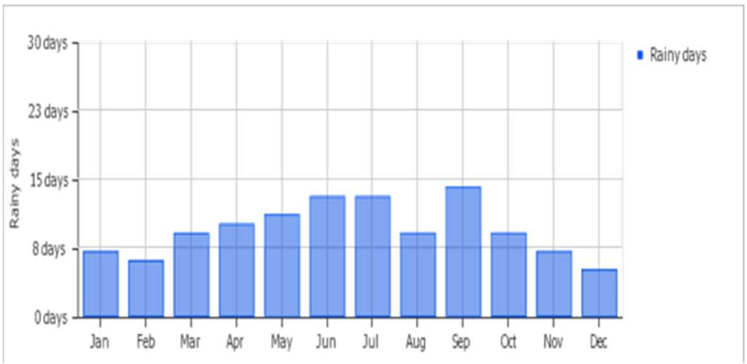


Figure 28 rainy months in Nara Prefecture

The 39.2 km^2 catchment upstream of the Asahi dam produces an average annual flow of 81.3 Mm^3 per year, with an annual coefficient of variation of 0.44. The annual hydrograph does not contain a typical seasonal hydrograph, while the multi-year hydrograph contains some apparent periodicity, as shown in figures 29 and 30.

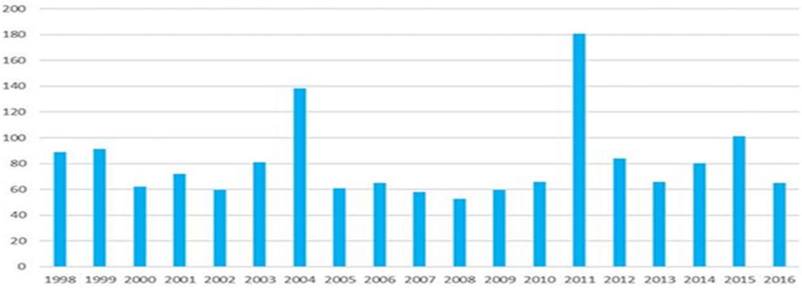


Figure 29 Asahi dam Annual inflow (M m3/year)

The mean total annual sediment load transported by the river at this location is 94,400 m^3/year, consisting of 72,600 m^3/yr of suspended load and 21,800 m^3/yr of bed load. The mean grain size of the bed load is 30 mm, with an estimated maximum size of 100 mm.

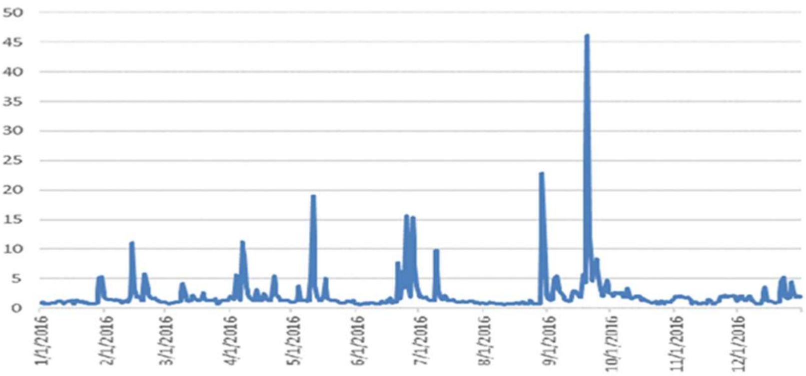


Figure 30 Asahi dam seasonal inflow (m3/s)

4.4 Sediment problems

In the 1989 and 1990 typhoons caused major mountainside collapses, resulting in large-scale flooding with a very high sediment load. In addition, changes in the watershed caused by logging activities increased the erosion rate and therefore the sediment yield. The mean annual accumulated sediment volume exceeded expectations and increased sharply to 85,000 m3/yr. As shown in figure 31, the sediment aggradation between 1989 and 1995 is four times greater than the sediment accumulated between 1980 to 1988. By 1997, the reservoir volume had reduced by about 4 percent.

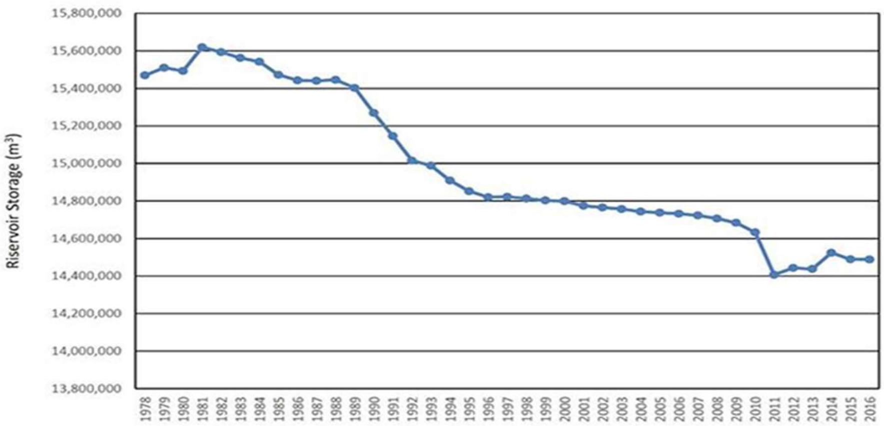


Figure 31 change in reservoir storage since commissioning of the Asahi dam in 1978

When floods occur, the water flowing into the reservoir becomes turbid and remains so for long periods of time. This first became a significant concern in 1990, when high turbidity lasted for more than 200 days because of an increase in collapse areas triggered by the large-scale typhoons of 1989 and 1990. As a result, water releases from the Asahi reservoir remained turbid for extended periods, with a negative impact on the local fishing industry. Figure 32 shows the number of days of turbidity persistence and the ratio of the collapse area. The reservoir sedimentation challenges at the Asahi dam are prolonged turbidity and decreasing reservoir storage capacity. By 2016, the reservoir capacity had reduced by about 6.5 percent. The Seto reservoir, on the other hand, does not experience any sediment-related issues, since the inflow from the catchment is relatively small compared with the water pumped from the Asahi reservoir.

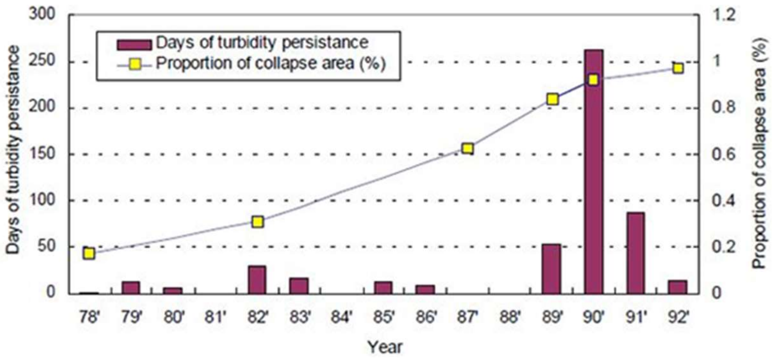


Figure 32 the number of days of turbidity persistence downstream of the Asahi dam and the ratio of upstream collapse areas

Since the problem of turbid water persistence became apparent, daily measurements have been carried out on turbidity and water temperature upstream of the dam, the regulating reservoir of the dam, and downstream of the dam. Also, the water quality of the reservoir has been examined once a month.

Due to turbidity caused by sediment inflow arising from landslides and logging upstream, a bypass tunnel was constructed between 1992 and 1998. The Okuyoshino pumped storage power station layout is shown in figure 33.

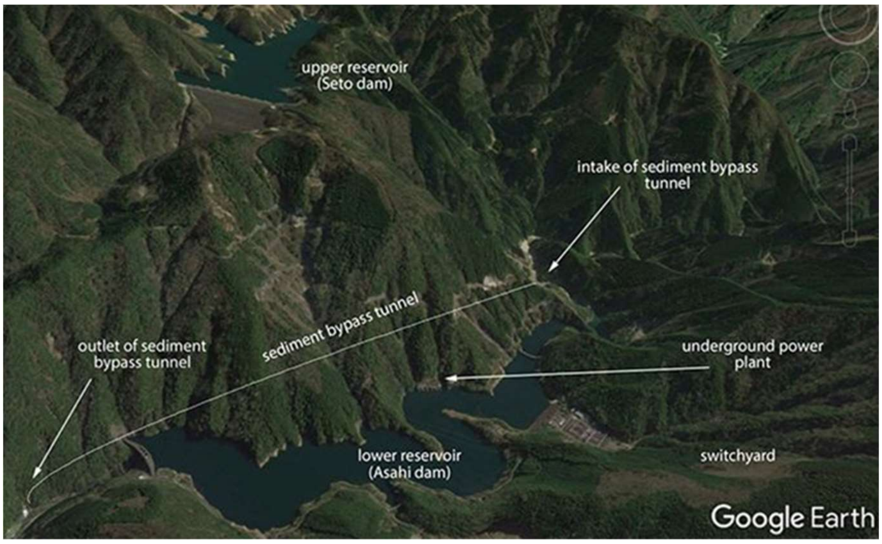


Figure 33 bypass tunnel and other facilities in Okuyoshino hydropower plant

4.5 Turbidity remedies

Various countermeasures to turbid water persistence were carried out since the start of operation of the dam, but satisfactory results were not obtained against lasting turbidity caused by very large floods. With strong requests for improvement from the local community, proposals of mitigation measures were studied from 1991.

Improvements on selective intake operations, protection of collapse areas, gravel filtration in the downstream channel, forcible settling through use of coagulants, filtering with turbidity-preventing membranes, and sediment bypassing were some of the steps contemplated, and installation of a bypass, the first in Japan, which would be a radical measure resolving the problem of sedimentation at the same time, was chosen.

To elaborate, there is no need to store water from the flow of the river since the plant is a stand-alone pumped storage type, while the catchment area is comparatively small. The sediment bypassing facility would consist of a bypass tunnel to route turbid water and sediment load around the reservoir and into the downstream river channel.

In planning and designing facilities, the fundamental layout was first selected based on characteristics of the site such as the river channel configuration, and not only wash load but also suspended and traction loads were considered from the points of view of lessening turbid water persistence and of reducing sedimentation.

This is because the Asahi Dam is for the regulating pond of a pumped storage power station and thus does not require an inflow of water for storage, but inflow would improve circulation of water inside the reservoir and prevent deterioration of water quality.

4.6 bypass channel/tunnel

Worldwide, limited numbers of sediment bypass tunnels have been constructed because of topographical, hydrological or economic conditions. Bypass tunnels, however, have many advantages such as they can be constructed even at existing dams and prevent a loss of stored reservoir water caused by the lowering of the reservoir water level. They are also considered to have a relatively small impact on the environment downstream because inflow discharge can be passed through tunnels very naturally during flood time.

In Japan, sediment bypass tunnels have been studied most exhaustively. Although this technique involves high cost caused by tunnel construction, there are many advantages such that it is applicable to existing dams; it does not involve drawdown of reservoir level and therefore, no storage capacity loss; and it has a relatively small impact on the environment because sediment is discharged not so rapidly as sediment flushing which can be considered as another countermeasure.

The subjects of designing sediment bypass tunnels are to secure the safety of sediment transport flow inside tunnels and to take countermeasures for abrasion damages on the channel bed surface. Among factors that significantly relate to these problems are grain size, tunnel’s cross-sectional area, channel slope, and design velocity. See figure (34)

Technical problems such as determination of the optimum tunnel discharge capacity and avoidance of tunnel blockage by sediment were addressed carrying out model hydraulic tests and numerical simulations. Furthermore, various examinations were made concerning predictions of riverbed changes upstream and downstream of the bypass, hydraulic stability, and problems of maintenance such as abrasion among others. Since the start of operation in 1998, the bypass has basically been used only during floods to detour water and sediment through the tunnel, clear water in normal times being allowed to enter the reservoir.

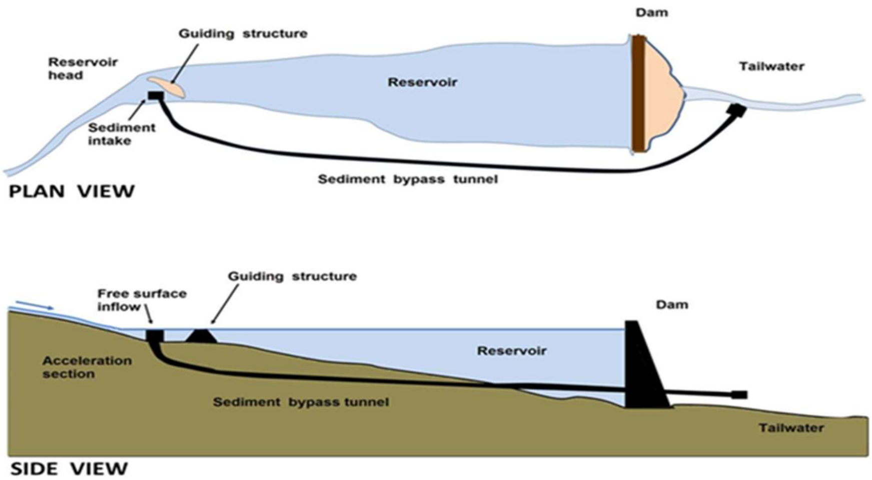


Figure 34 bypass tunnel (plan & side) view

Sediment bypass system in Japan is contributing to sustaining reservoir lives, and completion and realization of other projects are highly desired.

The main problem of sediment bypass tunnels is abrasion along the invert. To counter abrasion, selecting high strength concrete and preparing enough abrasion depth on top of necessary tunnel invert depth is recommended from the viewpoints of initial construction cost and easy maintenance.

In order to operate the sediment bypass system effectively, it is important to predict and to perform real-time monitoring not only the flow discharge but also the concentration of sediment in the inflowing water.

Real-time monitoring is essential for efficient bypassing. Basic monitoring covers flow discharge and sediment concentration. Besides the monitoring of sedimentation, monitoring of turbidity, eutrophication, and aquatic organisms has been also carried out at the reservoir and in the downstream reach.

4.7 Sediment management strategies

To solve the sediment management problems at Okuyoshino, a sediment bypass tunnel was constructed between 1992 and 1998. The sediment bypassing facility comprises a weir, an intake, a bypass tunnel, and an outlet. Figure 35 shows the weir and the tunnel inlet. The steel weir has a height of 13.5 m and a crest length of 45 m. The intake structure of dimensions 14.5 m by 3.8 m is made of steel-lined reinforced concrete and has one gate. The bypass tunnel is 2,350 m long with a 3.8 m by 3.8 m hood cross-section. The outlet structure is also made of reinforced concrete and is 15 m long. The tunnel slope is about 1:35 with a discharge capacity of 140 m3/s and a peak discharge of about 200 m3/s, defined by a one-year return period flood. To bypass sediment, the bypass tunnel is operated on average 40 days each year. The inlet to the tunnel is lined with steel and the tunnel floor consists of high-strength concrete. The sediment bypass tunnel plan, cross-section, and profile are shown in figure 35.

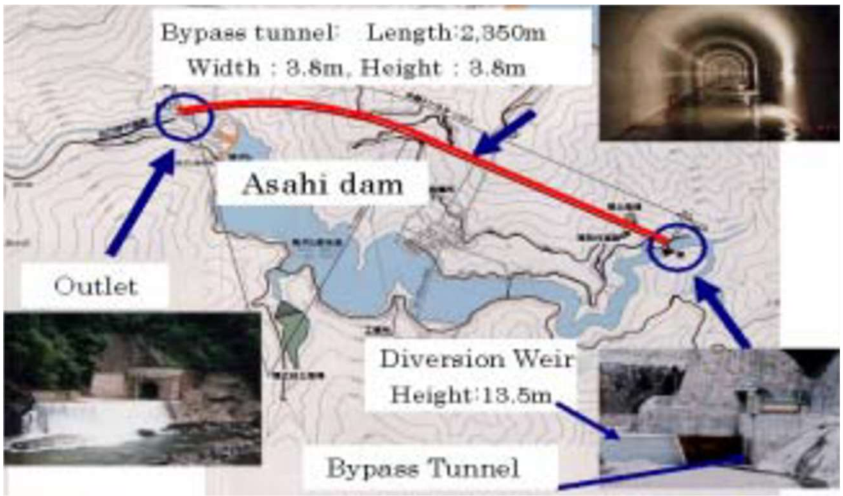


Figure 35 sediment bypass tunnel at Okuyoshino

Over the first four years, the sediment bypass tunnel was used 16 times each year to bypass about 40 percent of the annual run-off. The average operation frequency, however, is 13 times per year.

The advantages of the sediment bypass tunnel over other sediment management techniques are that it can be applied to existing dams and that it does not involve reservoir drawdown, and therefore no storage capacity loss. Another advantage is the benefit to the downstream environment. On the other hand, the main drawbacks are the construction cost and the maintenance cost, due to the abrasion of the tunnel invert.

After significant typhoons, the main problem is abrasion along the invert. The average abrasion depth can be up to 200 mm; hence, the maintenance needs of the tunnel inlet and invert can be significant. The repairs are carried out during the non-flood season and take place approximately every two years.

Real-time monitoring is essential for efficient bypassing. Basic monitoring covers flow discharge and sediment concentration. Besides the monitoring of sedimentation, monitoring of turbidity, eutrophication, and aquatic organisms has been also carried out at the reservoir and in the downstream reach.

The implementation of the bypass tunnel has been deemed successful, with an estimated reduction in annual sediment deposition in the reservoir of about 80 percent. An additional benefit is that the bedload that is passed downstream, enhancing aquatic conditions by replenishing the river bed downstream with coarse sediment. The river profile has recovered, and aquatic species have been conserved. The problem relating to turbidity downstream has also been solved because the highly turbid flow is passed downstream through the bypass tunnel during flood conditions.

As shown in the longitudinal profile (see figure 36) of the Asahi reservoir, storage volume loss has stabilized since the sediment bypass tunnel entered into operation in 1998. However, storage capacity lost prior to the commissioning of the bypass tunnel has not been recovered.

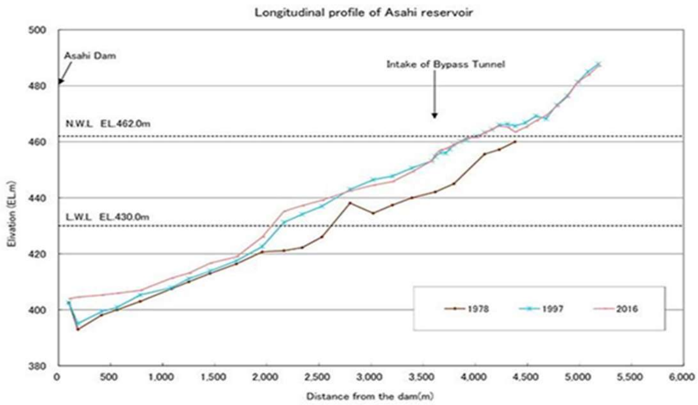


Figure 36 changes in the long section from 1978 (commissioning) and between 1997 (just prior to commissioning of the bypass tunnel) and 2016

Chapter 5

Off-stream reservoir

5.1 strategy literature review

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 [Morris and Fan, 1998] see figure (38).

Similar to sediment bypass, there needs to be a sufficient gradient to drive flow through diversion channels or tunnels to the off-channel storage feature. One advantage of this approach is that all bedload 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 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 that 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 the 125MW capacity with 600m of the gross head, and requires a 0.35Mm3 regulating reservoir to provide 6 h of peak power (Figure 37). Off-channel storage was ideal to provide peaking power at this site because vertical canyon walls made site access difficult for construction of the main stem dam, and the high load of large bed material (up to 1m diameter) presented an unfavourable 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 197MW at five power stations; they are fed by seven intakes, and accumulated fine sediment is removed by dredging.

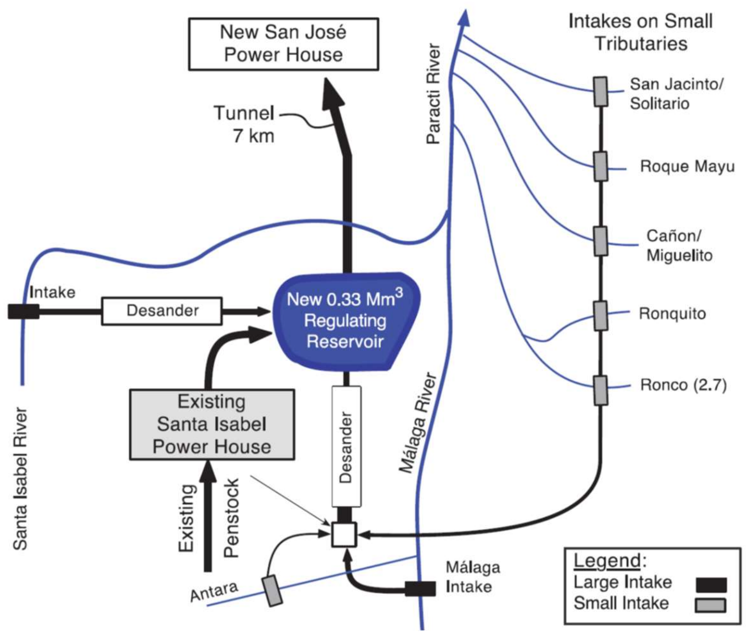


Figure 37 Schematic layout of 125MW San José hydroelectric project, Paractia River, Bolivia, incorporating an off-stream regulating reservoir for poundage and desanders to remove the coarse sediment abundant in the streams.

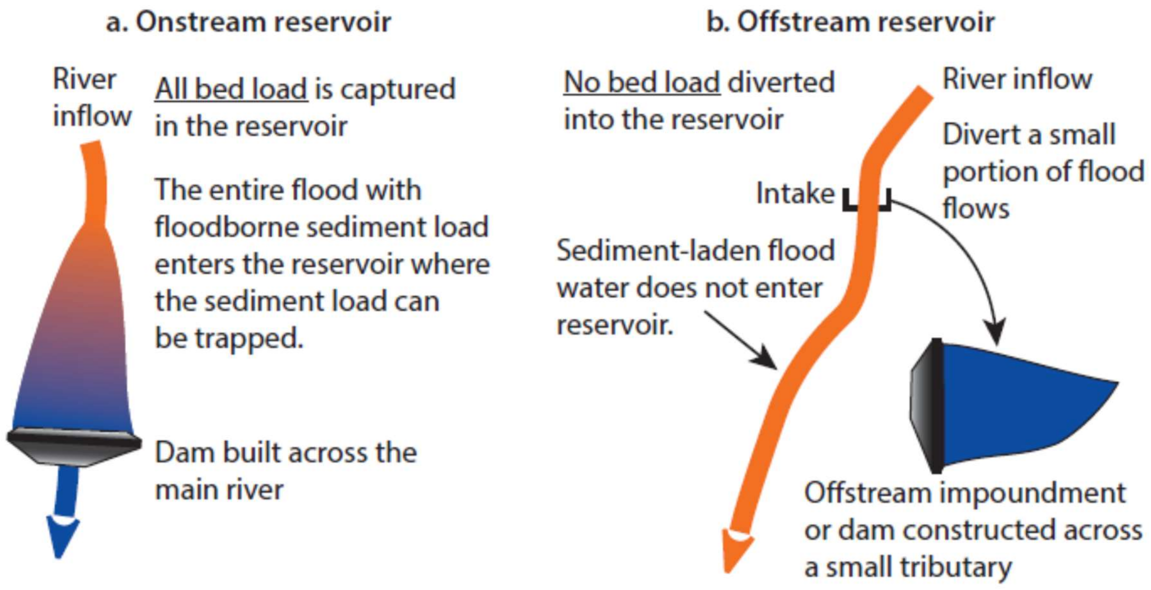


Figure 38 4 Basic Features of Conventional Onstream Reservoir Compared with Offstream

Case Study

Chile - La Confluencia

5.2 Introduction

Chile has a favorable topography for hydropower with the Andes Mountain rising along the eastern border of the country. The Confluencia hydropower project is a run-of-river project located about 160 km southeast of Santiago in the Republic of Chile in the region of (O´Higgins). See figure (39)

Figure 39 location of Chile and its Terrain

The Confluencia project located in the valley of the Tinguiririca, Azufre and Portillo Rivers. These rivers rise in the Andes Mountains and flow generally westwards to the Pacific Ocean. The Azufre and Portillo rivers combine and join the Tinguiririca immediately downstream of the La Confluencia powerhouse. The nearest major town to the project area is San Fernando. The location of the Project activity is shown in Figure (40). The Confluencia project entered into operation in 2010 and has an installed capacity of 163 MW.

Figure 40 location of la Confluencia project

The project uses the water from the Tinguiririca, Portillo and Azufre Rivers, as well as another four small tributaries. The main intakes, Tinguiririca and Portillo, feature weirs and desanders to divert water to the headrace tunnels, of 9.2 km and 12 km, with design discharges of 26.5 m3/s and 25 m3/s respectively. The secondary intakes can divert between 1.5 and 2.3 m3/s. Tinguiririca intake also includes an off-stream regulating reservoir with 1.2 Mm3 of storage to provide peaking services. It can supply water for six hours of generation at full capacity. See figure (41).

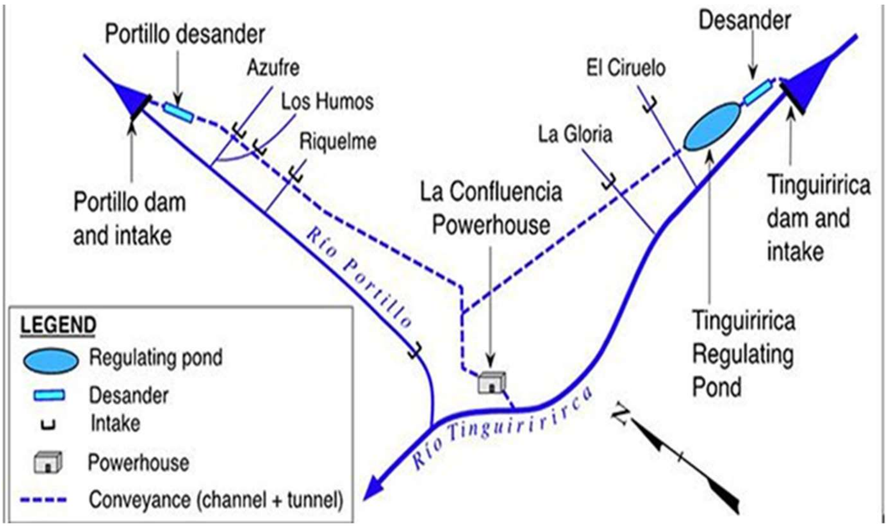


Figure 41 Schematic of intakes and regulating pond for La Confluencia

5.3 Desander system in La Confluencia

The Portillo branch comprises a low weir and spillway on the Portillo River at 1465m asl. Water will pass through a desander and short open channel before entering an 11km low-pressure tunnel that runs to the surge chamber above the powerhouse at the confluence of the Azufre and Tinguiririca rivers see figure (42) below.

Figure 42 aerial photograph of the Tinguirica off-stream storage reservoir fed by a single intake

Desander systems figure (43), are expected to remove the greatest possible amount of sediment from water passing through the plant. Rinsing channels and gravel removal devices often have to deal with very large sediment granule sizes. Furthermore, desander basins also have to remove very fine sedimentation.

Almost all of this work is done in a long and narrow above-ground sand catchment channel that runs along the preflood basin and rinses in the same direction as the main flow; or below-ground in excavated rock caverns with rinsing against the direction of the water catchment. In both cases, a small cross-section desander can raise the shaft in the rinsing channel and lower building costs. The cross-section of sedimentation is determined by the structures of the hydro-plant.

Figure 43 desender structure

An efficient removal system can reduce the cross-section of sediment and the rinsing pipe can be positioned in a fairly high position. In combination with simple basin shapes, it is possible to achieve significant construction cost savings and implementation can be seen to be viable in la Confluencia project.

The removal pipes can be placed in a desander basin with a square cross-section without a drop-in efficiency. This provides a simple, low-cost, high-volume desanding chamber with a minimal excavation section or a higher installation height with less digging required. In the corners above the rinsing pipe and on the opposite side, dependent upon the angle of precipitation, there are persistent sloping sediment deposits.

The rinsing and emptying processes do not remove them completely. However, for the ongoing removal of sediment, this is not an issue. An ideal and clean solution is the setting in the concrete of a 45° slope along the removal pipe.

An extension pipe is required in the removal units for cleaning purposes. The sediment removal pipes can be operated and maintained simply and cheaply. Repairs and replacements can be done easily and without great effort or expense.

The sediment removal elements enable the sediment basin to be designed in such a way as to allow easy access, and maintenance can be conducted in a hazard-free environment. The removal system consists of the following parts:

- Steel pipe (cone) connector integrated during construction and linking up to the rinsing pipe
- Extension pipe for viable servicing opportunities
- Modular rinsing pipe with evenly spaced rinsing chambers
- Adjustable lid to fine-tune the rinsing jet openings

5.4 Sediment problems

The annual observed sediment load through turbines is 71,000 t/yr. The sediment concentration at Confluencia is between 80-1,000 ppm, with about 25 percent hard minerals. The river bedload consists of cobbles and boulders.

The expected generation is 656 GWh, but due to the sediment problems, the production loss is almost half. The current average annual generation is 374 GWh. figure (44)

The rainy season in 2016 was characterized by increasing runoff, which led to higher sediment transportation. The heavy sediment load of the Tinguiririca River caused major damage to the Tinguiririca facilities and access roads. Figure 42 shows an aerial view, where the sediment load has turned the river brown.

The sediment-related costs at the Confluencia project are estimated to be 8 percent of the project's annual revenue. The main sediment-related costs are the maintenance and replacement of components damaged by the extreme sediment concentration, and the sediment mechanical dredging at the intakes.

The civil works to repair the Tinguiririca facilities and access road caused by the high precipitation and heavy sediment load in 2016 include mechanical dredging, the expansion of two gutters to 500 m and 450 m, and other works to improve the access roads.

Figure 44 La Confluencia hydropower plant in Chile

5.5 sediment control strategy

The off-stream reservoir is best suited to providing short-term storage for the Confluencia run-of-river plant, providing daily flow regulation for power peaking.

This off-stream reservoir only uses the Tinguiririca intake and includes a desander prior to the 1.2 Mm3 regulating ponds (see figure 45). The single regulating pond has been sized with respect to the powerhouse discharge rather than the intake capacity, as no regulation volume is provided for the other intakes. Nevertheless, the other intakes discharge directly to the powerhouse following desanding. Desanders are typically provided to reduce sediment load and also to prevent the deposition of coarse sediment in the conveyance facilities. However, the off-stream reservoir for power peaking will be much larger than a desander and will act as a very efficient sedimentation basin for the material not trapped in the desander. This is beneficial from the standpoint of protecting turbines.

The off-stream reservoir entered into service in May 2011 but by 2017 had not yet experienced a sedimentation problem in the reservoir that required dredging. The sediment consists of silt, with negligible amounts of clay, and after an initial period of accumulation the rate of sediment accumulation slowed substantially or halted because the sediment was being carried out of the pond by normal operational drawdowns in the off-stream reservoir.

Figure 45 sediments in Tinguirica intake

Chapter 6

Reservoir drawdown and sluicing

6.1 strategy literature review

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 46). 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 timescale 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 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. Figure (46) present an example of this strategy

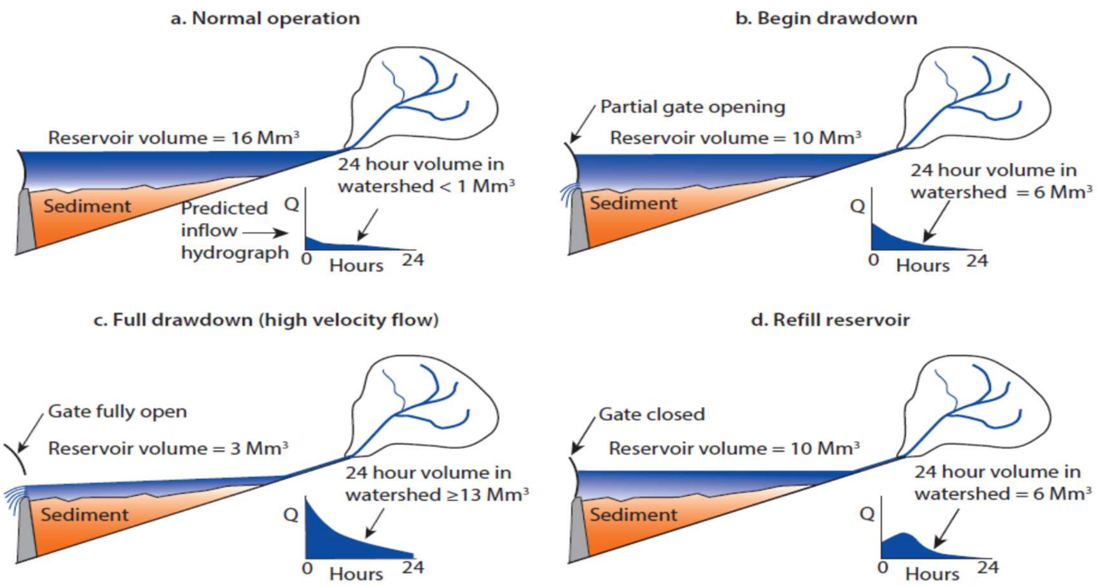


Figure 46 Schematic representation of sluicing operations

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 47). 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, 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.

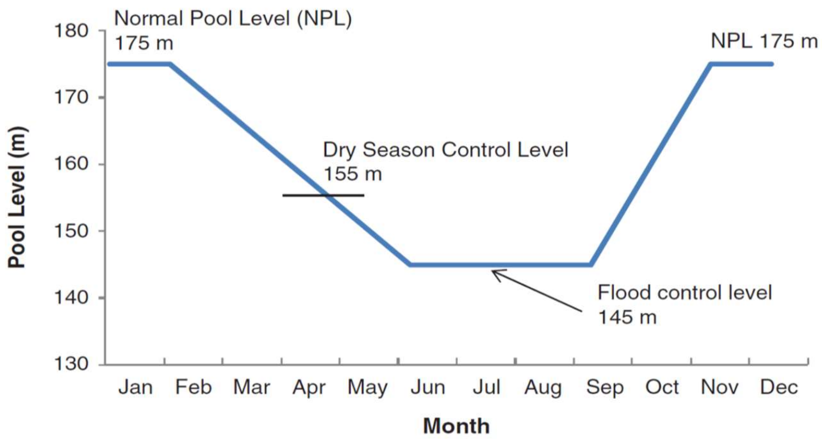


Figure 47 Seasonal pool operation at Three Gorges Reservoir. [Redrawn from Zhou, 2007]

Case Study

Nepal - Kali Gandaki

6.2 introduction

The Kali Gandaki Hydropower Plant (KGAHPP) figure (48), is the largest plant in operation in Nepal. The Plant is located in the Western Development Region of Nepal. Nearly 25% of the grid-connected load of the country depends on this plant. The above facts reflect the importance of the plant in meeting the current electricity demand in the country. The load shedding is projected to be above 14 hours a day in the dry season as most of the power plants are run off the river type and depend on the available flow which is at its lowest during the dry season (November – May).

Figure 48 The Kali Gandaki

Kali Gandaki Hydroelectric Plant is a 144 MW Run-of-River scheme is design to generate about 842 gigawatt-hours (GWh) of electrical energy per annum. The main component of the project comprises of; a concrete gravity diversion dam of about 100 meters in length and 43 meters of height, open surface desander, tunnel of about 6-kilometer length and 7.4-meter diameter and a surface powerhouse figure (49). With the utilization of a net head of 115 meters and the rated discharge of 141 m3/s feeds three Francis type turbines having a capacity of each unit 48 MW is installed in the powerhouse. The power plant has been in commercial operation since August 2002 and the effect of sediment had been appeared in runners, guide vanes, facing plates, labyrinth rings and other underwater components.

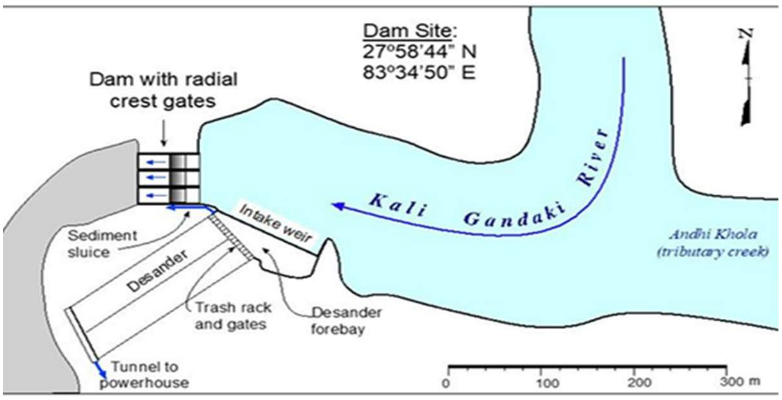


Figure 49 Dam facilities

The project was designed with radial crest gates for operation in a sluicing mode to sustain about 3.5 Mm^3 of storage capacity for power peaking. The general layout of the project's headworks is seen in figure (49). To minimize sediment entrainment during sluicing, the intake was designed as an overspill weir (figure 50). A desanding basin is also operated during the sluicing period.

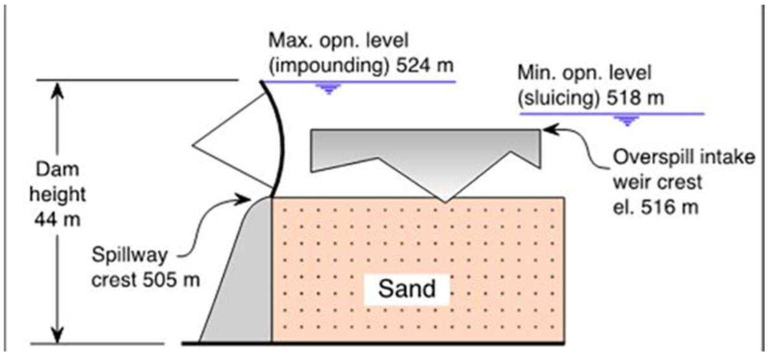


Figure 50 Kali Gandaki dam gate

6.3 Climate and Meteorology

The Kali Gandaki basin covers a wide range of climates, and extreme climatic differences occur over short distances. Altitude and local topography exert strong climatic influences. The climate in the project area is subtropical-to-temperate with hot and wet monsoon summers and cool and comparatively dry winters. Temperatures reach about 40oC (maximum) in early summer, and typically do not drop below 10oC during the winter Figure (51). The monsoon period from June to October contribute 60 to 80 percent of the annual precipitation. Total annual rainfall in the project area is approximately 1500-2000 millimeters (mm). Annual precipitation in the watershed, however, can range up to 4000 mm.

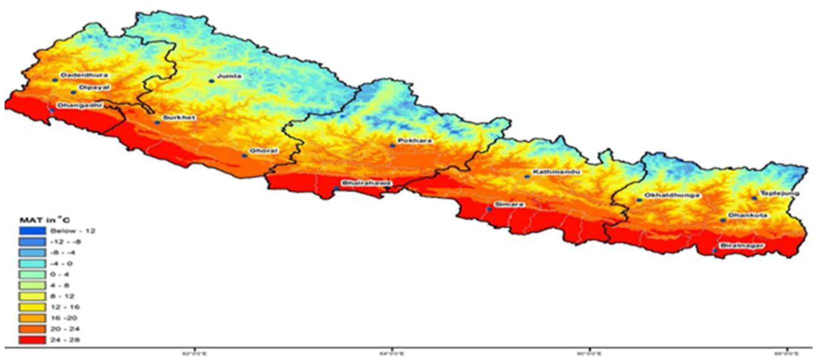


Figure 51 mean annual temperature in Nepal

6.3.1 Seasons in the catchment area

The year is divided into a wet season from June to September—as summer warmth over Inner Asia creates a low-pressure zone that draws in moist air from the Indian Ocean—and a dry season from October to June as cold temperatures in the vast interior creates a high-pressure zone causing dry air to flow outward. April and May are months of intense water stress when cumulative effects of the long dry season are exacerbated by temperatures rising over 40 °C (104 °F) in the tropical climate belt. Seasonal drought further intensifies in the Siwaliks hills consisting of poorly consolidated, coarse, permeable sediments that do not retain water, so hillsides are often covered with drought-tolerant scrub forest. In fact, much of Nepal's native vegetation adapted to withstand drought, but less so at higher elevations where cooler temperatures mean less water stress.

The summer monsoon may be preceded by a build-up of thunderstorm activity that provides water for rice seedbeds. Sustained rain on average arrives in mid-June as rising temperatures over Inner Asia creates a low-pressure zone that draws in moist air from the Indian Ocean, but this can vary up to a month. A significant failure of monsoon rains historically meant drought and famine while above-normal rains still cause flooding and landslides with losses in human lives, farmland, and buildings.

The monsoon also complicates transportation with roads and trails washing out while unpaved roads and airstrips may become unusable and cloud cover reduces safety margins for aviation. Rains diminish in September and generally end by mid-October, ushering in generally cool, clear, and dry weather, as well as the most relaxed and jovial period in Nepal. By this time, the harvest is completed, and people are in a festive mood. The two biggest and most important Hindu festivals—Dashain and Tihar (Dipawali)—arrive during this period, about one month apart. The post-monsoon season lasts until about December.

After the post-monsoon comes the winter monsoon, a strong northeasterly flow marked by occasional, short rainfalls in the lowlands and plains and snowfalls in the high-altitude areas. In this season the Himalayas function as a barrier to cold air masses from Inner Asia, so southern Nepal and northern India have warmer winters than would otherwise be the case. April and May are dry and hot, especially below 1,200 meters (4,000 ft) where afternoon temperatures may exceed 40 °C (104 °F).

6.4 Topography and Land Use

The Kali Gandaki basin cut across the High Mountain and Middle Mountain Physiographic Zones as it emerges to the project site. The watershed contains different natural zones characterized by different landforms, climates, vegetation, and socio-economy. Most of the Kali Gandaki basin is mountainous and the river itself is deeply incised and confined in a V-shaped gorge. Elevation range between 400m and 1600m in the project area. The area is geologically young and tectonically dynamic. Around the project site, the hard rock geology is comprised of deeply weathered black phyllite/slate. The soil cover over the hard rock geology is made up of weathered fragments of phyllite rock held in the silty and clayey matrix. The depths of surface and subsurface soils are shallow and vary from 0-15 cms to 15 -100 cms respectively. see figure (52).

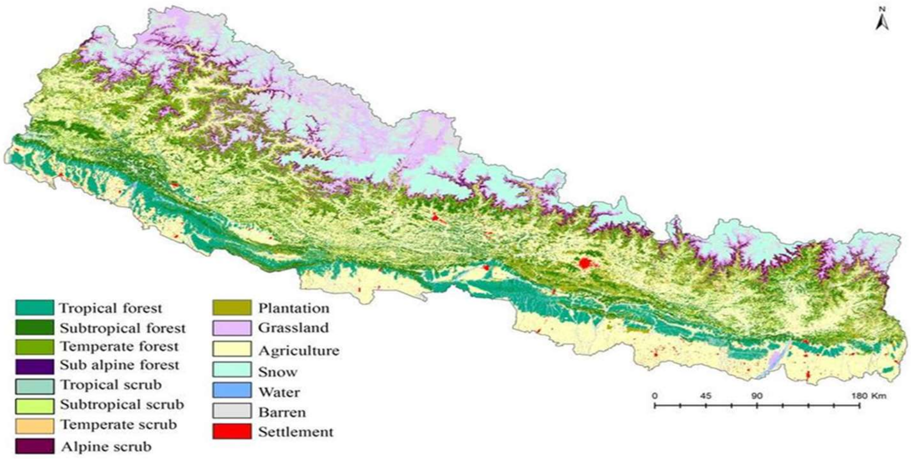


Figure 52 Topography and Land Use

The soils are light in texture, mostly ranging from acidic to slightly alkaline and the organic matter content is high. Various type of erosion: sheet, rill, and gully are conspicuous and are often associated with shallow landslides on the steeply sloping land units around the project area. Topsoil erosion is high in the open less vegetated unmanaged agricultural areas due to steep nature of the terrain and has a risk of runoff wash by heavy rains in the monsoon season see figure (53). The Kali Gandaki River and its tributaries are quite active in cutting through rocks vertically as well as laterally.

Figure 53 catchment area soil type

6.5 Watershed and Geology

The Kali Gandaki watershed is comprised of the rock formations of the Tibetan Tethys Himalaya, Higher Himalayas, and the Lesser Himalayas. The rock formations include sedimentary, meta-sedimentary to high-grade metamorphic rocks. Tectonically, the watershed area is characterized by a number of thrust faults. The most important of the thrust fault is the Main Central Thrusts (MCT) separating the Higher Himalayan high grade metamorphic of the north from the Lesser Himalayan meta-sedimentary rocks of the south. The MCT lies about 75 km to the north of the project site. The rocks of the Tibetan Tethys comprising fossiliferous sedimentary rocks have a tectonic to unconformity contact with the Higher Himalayan high grade metamorphic.

The project area is located in the Lesser Himalayan meta-sedimentary rocks. The rocks exposed at the project site are the black to grey phyllite/ slates with interbeds of silicious dolomites: it is located between the Main Boundary Thrust (MBT) and Main Central Thrust (MCT). The area is geologically young and dynamic. Erosion such as sheet, rill and gully erosion is common and is often associated with landslides on the sloping land around the project area. Erosion rates for the watershed are approximately 4 mm/year, based on sediment discharge for a very wet year with a 1-in-100 year flood event. The total sediment load of the Kali Gandaki River is 45 million ton per year (EIA, 1996).

6.6 Hydrology and Sediments

Kali Gandaki is a major tributary of Sapta Gandaki River located in the Western Region of Nepal. The river originates from the Tibetan Plateau at an elevation above 6,000m and drops to the elevation of about 500m at the project site. The river flows across the Himalayan Range creating a world's deepest gorge between the snow peaks of Mt. Dhaulagiri and Mt. Annapurna. In its southern course in the Lesser Himalaya, it joined by a number of tributaries originating in the southern slopes of the Higher Himalayas such as Myagdi Khola, Modi Khola, Seti Khola, and Andhi Khola as it emerges to the project site. The total length of the river up to the project site is 200 km. The catchment area at the dam site of KGAHPP is around 7,618 km2.see table (1)

Month	River Discharge (m^3/sec)	Tons /Month (10^4)
January	63.56	0.10
February	58.46	0.20
March	55.59	0.26
April	70.88	0.61
May	99.91	1.88
June	308.43	221.76
July	913.82	876.43
August	936.39	569.22
September	733.88	188.88
October	208.17	5.22
November	104.82	0.23
December	74.17	0.16

Table 1 sediment load in Kali Gandaki River in 2012

Sediment transport and the heavy sediment load is a natural phenomenon in the Himalayan rivers, including Kali Gandaki. Given the sediment conditions in the river, regular and periodic repair and maintenance are curing the need for the KGAHPP. The opening of village level motorable roads along either bank of the Kali Gandaki in the reservoir and upstream section in the recent years have added a new dimension in the reservoir sedimentation. The ill-managed earthen roads are the prime site of erosion and increasing reservoir sedimentation during the monsoon season. The emerging towns and villages on the banks of the Kali Gandaki and Andhi Khola rivers also contribute to the floating debris consisting of household garbage such as plastic and paper that clog the trash rack of the Kali Gandaki plant.

The sediment sampling at the dam site of KGAHPP has been carried out regularly by NEA. The typical suspended sediment concentration for different rive discharges for the year 1993 measurement is given in Table 2

Discharge, m^3/s	Sand	Fine	Total
40	5	15	20
75	10	20	30
125	20	220	240
200	160	740	900
300	625	1,675	2,300
500	1,450	2,300	3,750
800	2,250	2,850	5,100
1,200	2,600	3,500	6,100
2,000	33,200	4,500	37,700
5,000	4,500	6,500	11,000

Table 2 suspended sediment concentration at Kali Gandaki site (ppm)

The highest flood in Kali Gandaki River observed in the past 100 years is about 4,500 m3/s at the dam site and the ever-recorded minimum flow is about 40 m3/s in the dry season. The sediment concentration varies from 20 ppm (0.02 kg/ m3) in the dry season to sometimes 50,000 ppm (50 kg/m3) in the wet season from June to September (Mitsui and Co, 2005). The average annual suspended sediment loads (DBM, Morrison Knudsen, 1998) considered during detail design of turbine is as follows:

- Total in the Kali Gandaki River measured at dam site 65 mill. tons/year
- Total entering the sedimentation basins 5.9 mill. tons/year
- Total passing through the turbines 2.8 mill. tons/year

<u>The design of the sedimentation basins is based on the following criteria:</u>

- 100% of sediments with a particle size larger than 0.2 mm are excluded.
- 95% of sediments with a particle size larger than 0.15 mm are excluded.
- Approximately 70% of sediments with a particle size larger than 0.10 mm are excluded.

The river generates a suspended sediment load of 43 Mt/yr, of which around 25 percent consists of sand. This sand has a high concentration of highly abrasive angular quartz. About 95 percent of this suspended sediment load is delivered during the monsoon, between late May and late September and is large enough to completely fill the reservoir in a single monsoon season.

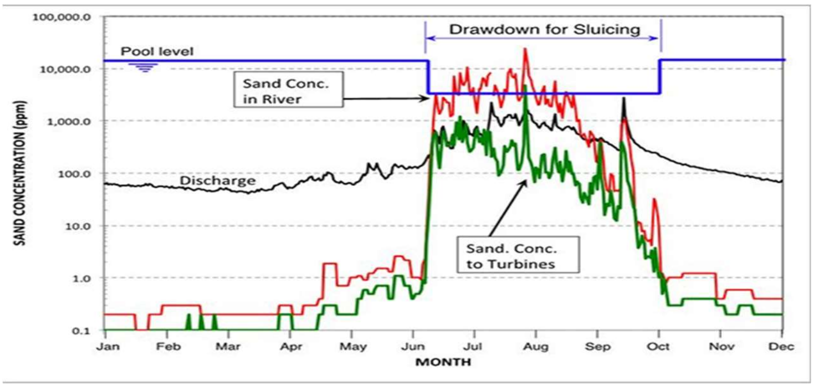


Figure 54 operating rule at Kali Gandaki

Data on discharge suspended sand concentration in the river, and on the flow diverted into the turbines is shown in figure 54. The suspended sand concentration in the river and delivered to the turbines suddenly spikes in early June. This corresponds to the date that the reservoir level is lowered, thereby mobilizing sand. The sand concentration drops again when the reservoir level is brought back up to its impounding level, reducing both the flow velocity through the reservoir and the rate of sand transport. This sluicing procedure has nearly stabilized reservoir capacity, producing a sediment balance across the reservoir (see figure 55).

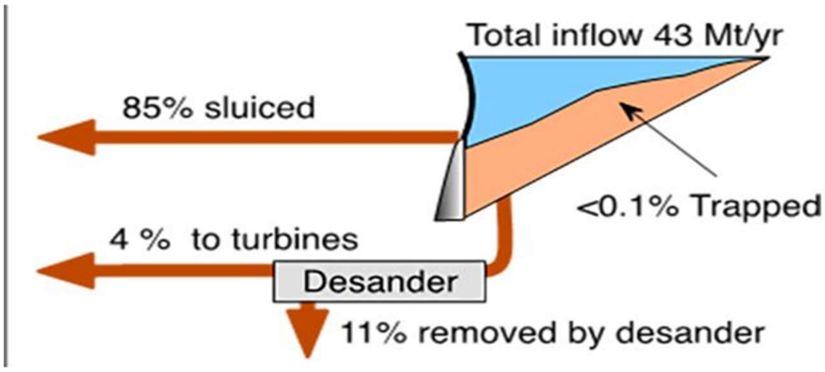


Figure 55 sediment balance across the reservoir

Sedimentation measurements in the reservoir section of the Kali Gandaki show that the reservoir has lost about 4 million m_3 in 10 years of operation which is about 51% of the original capacity of the reservoir and 7 % of the total live storage capacity. Thus, sedimentation in the reservoir has depleted the reservoir volume, and in turn, reduced the peaking capacity causing a build-up of sediments along the river channel. This phenomenon can adversely affect the intake weir that controls the sediment entry with the power flow and access to the Holy Stone in Setibeni. Such sediment builds up in the reservoir is related to the non-compliance with the draft operational manual which mandates flushing of the reservoir to lower the river bed. Such flushing operation for three days has been envisaged to lower the river bed level up to the religious site.

6.7 River Water Quality

The diversion of the river has created reduced flow stretch of 13-km between the dam and the confluence with the major tributary, the Badigad River. To maintain the water quality as well as the other ecological functions of the river in the dewatered zone, the EIA (environmental assessment) of original KGAHEP recommended a continuous flow of 4 m3/s, particularly during dry months, for the operation period.

Due to water regulation for power generation, there are no noticeable changes in the water quality in the downstream region as well as in the upstream reservoir areas. As the project operates in daily peaking mode with low retention time the changes in the water quality is low. The in-situ measurements of parameters like pH and DO revealed that the operation of the project has not degraded the river water quality.

6.8 sediments problems

The sediments in the reservoir are transported from the catchment area. The problem in the reservoir sedimentation seems not to be the finer sediments but the coarser sediments of a size larger than sand. As the coarser bed load of the river is dumped at the anterior end of the reservoir when the river velocity is checked by the stagnant water conditions of the reservoir, the sediment building is high in these areas. The flooding risk to the Setibeni might be related to this change in the river bed level. Besides, within the reservoir limit, the new opening of earthen motorable access roads through haphazard construction and operation (through the use of bulldozers and excavator) have also added coarser sediment to the reservoir during road opening and subsequent monsoons runoff in the form of small slumps, slides and debris flow. The sediments into the river are the result of a number of anthropogenic activities (agriculture, deforestation, cattle grazing, and infrastructure development such as roads) and the naturally occurring or human-influenced mass wasting in the river catchment. The extent of such activities in the catchment greatly increases the sediment load into the river. The original KGAHEP's EIA study (1996) has a limited focus on the watershed management to minimize the sediment load into the Kali Gandaki River and then into the KGAHPP reservoir. As a result, there is little effort from the original KGAHEP in the watershed management. Further, it is also not known which part of the Kali Gandaki catchment is contributing higher sediment load into the river.

6.8.1 Effect of Sand Erosion on Turbine Components

The inspection and measurement data of the turbine components during the annual maintenance of machines were collected for the year of 2003 to 2013. Till the year 2014 from commissioning of the total five major turbine maintenance of the Units has been carried figure (56&57) shows the photos of damages due to the sand erosion of non-coated and coated turbine components. Since then the practice of applying HVOF coating on under components of all machines has been implemented to resist the sand erosion during maintenance of turbine.

The Damage to turbine runners was attributed to a combination of sand abrasion plus cavitation. This is being dealt with through a reconfiguration of the intake weir to provide a uniform crest elevation of 516 m and improved geometry at the intake and desander inlet, based on physical model testing.

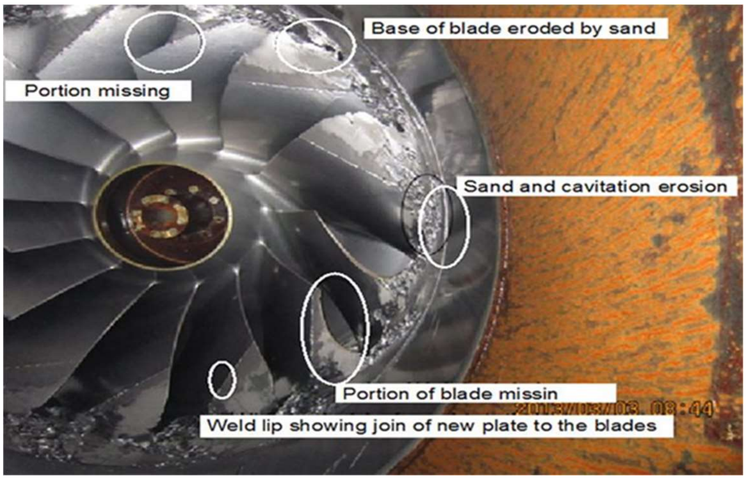


Figure 56 damage to Francis turbine runner

Figure 57 Photos of damaged turbine parts due to sand erosion and placing of cloth pieces

6.9 Reservoir drawdown & Sluicing

Sediment pass-through, also known as sluicing, is another way of abating sediment deposition in reservoirs. For this method, the reservoir level is drawn down during the flood season and allowed to flow through the sluice gates to maintain the incoming sediment in suspension (Tigrek and Aras, 2011). When particles enter the low-velocity area of a reservoir, they settle and form a delta consisting first of the heavier coarse sediments, then further on a shallower layer of fine sediment. This phenomenon can be seen in the illustration in Figure 58. the depiction of the sluicing technique to reduce the development of this delta is shown in Figure 59, the study of the Kali Gandaki hydropower plant determined that using sluicing as a sediment-management technique viably maintained the equilibrium of sediment between the reservoir and downstream environment over an extended operating period. The study also showed that sluicing would not result in adverse impacts on the fish habitat downstream as long as it followed the suggested operating rules.

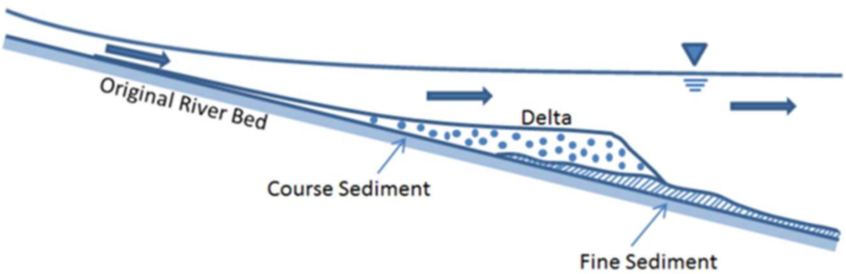


Figure 58 longitudinal reservoir profile with delta formation

One restriction of sluicing is its dependence upon the existing structure of the dam, as sluice gates must be positioned appropriately along the bottom for the sediment to flow through efficiently. A 1988 assessment of several countries' sluicing techniques recommended that the sluice gates be at a height of 1.5 to 2.5 meters with an area determined from design curves presented in their paper (Paul and Dhillon, 1988). They also advised that only the width of the gate should be changed to increase effectiveness. In addition, Bogardi (1974) suggested that the sluicing technique is most effective when: 1) water depths are low and discharge is high; 2) sluice gates are wide and located near the bottom of the dam; 3) the original stream bed is steep and the reservoir has a short, straight bottom; 4) and the reservoir is in an advanced stage of siltation and the deposits consist of fine-grained, recently settled material. With these specifications met, sluicing has been found effective in many instances, especially in Nepal, where it is practiced routinely due to high sediment loads (Hotchkiss, 1990).

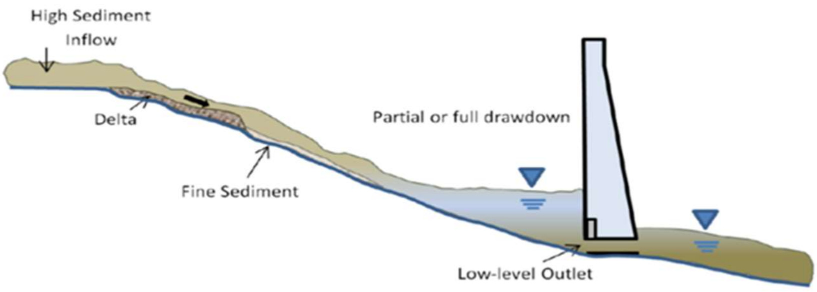


Figure 59 longitudinal reservoir profile with sediments sluicing

6.10 Sediment management strategies

Change in the river morphology downstream the dam due to sediment flushing operation is unavoidable. The water quality change particularly turbidity related to increases in suspended sediment is also not avoidable and will remain as the short term residual impact of the project. To address sand abrasion, field tests and physical modeling were undertaken (figure 60) to determine how the efficiency of the intake and desander could be improved. It was also envisaged to improve the debris-shedding characteristics of the intake since the trash rack was becoming overloaded by debris.

The as-built intake structure geometry contained a dog-leg section, which differed significantly from the straight intake wall originally specified. Model testing focused on identifying modifications which would optimize intake operation while constructing on top of the existing dog-leg foundation. A modification to the inlet configuration of the desander basins was also identified, which would reduce the effect of hydraulic short-circuiting due to plunging of sediment-laden flow at the entrance to the basins.

An analysis of operational data was also undertaken, and it was found that water levels were not always being held at prescribed levels. Better operational control and operator training and monitoring were identified as essential factors for achieving the most efficient operation from the installed sediment management infrastructure

Figure 60 physical model of Kali Gandaki intake and desander

Chapter 7

Turbid density Current Venting strategy

7.1 strategy lecture review

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 61). 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 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 certain (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.

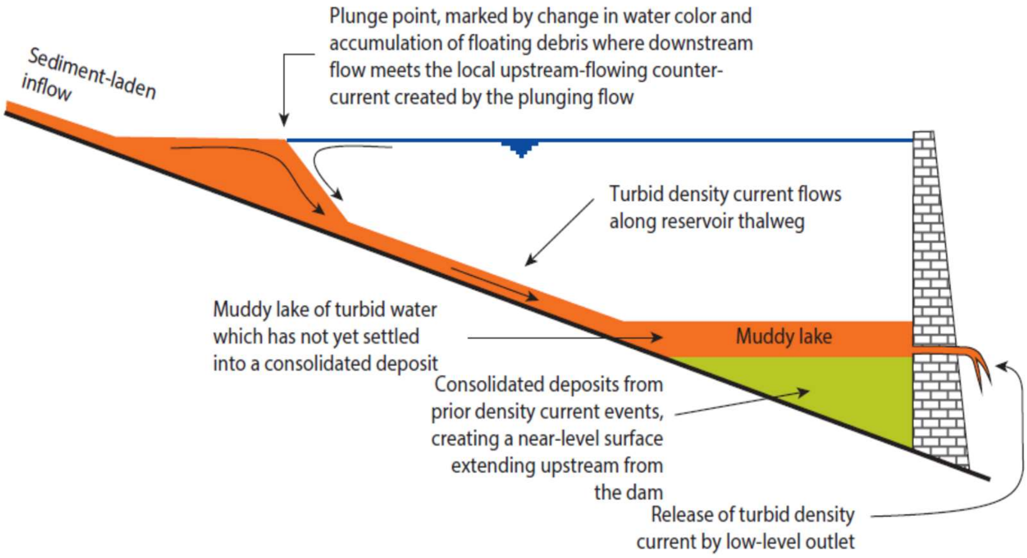


Figure 61 Schematic representation of density current venting

Case study

Shihmen hydro-power plant Chinese Taipei

7.2 introduction

Shihmen dam is a rockfill embankment across the Dahan River, near Taoyuan City in northern Chinese Taipei see figure (62). Construction began in 1955 and the dam was completed in 1964.Owned by the Taiwan Water Resources Agency, it provides irrigation services in Taoyuan, flood control for the Taipei basin, hydropower (90 MW), and domestic water supply for more than three million inhabitants in northern Chinese Taipei. The annual water use is in the range of 800 to 1,000 Mm^3. It is also a popular tourist spot in the region.

Figure 62 View of the Shihmen dam& reservoir

The project was designed by a US company, Tippetts-Abbett-MaCarthy-Stratton (TAMS). As shown in table 3, the original design consisted of a surface spillway, two 4.5 m diameter penstocks, a low-level permanent river outlet (PRO), an irrigation canal outlet, and a 2 Mm^3 after bay. About 10 years after the initial construction, two tunnel spillways were added to increase discharge capacity. Figure 63 depicts a plan view of the dam and outlet structures.

Figure 63 plan view of Shihmen reservoir outlet structures prior to modification for sediment release

Structure	Invert or Intake & Elevation (m)	Design capacity (m^3/s)
Surface Spillway	EL.235.0	11,400
Tunnel Spillway	EL.220.0	2@1,200=2,400
Power Penstock	EL.173.3	2@68.6=137.2
Permanent River Outlet (PRO)	EL.169.5	34.0
Shihmen Irrigation Canal Outlet	EL.193.5	18.4

Table 3 Shihmen reservoir outlet structures

The Shihmen reservoir is located in Taoyuan County, northern Taiwan. It is adjacent to four counties and close to two townships, namely, Fuxin and Jianshi downstream and upstream, respectively (Fig. 64). This reservoir is 16.5 km long in a basin area of 763 km2. Thirteen main tributaries flow into the truck Dahan stream. The Shihmen Reservoir watershed comprises seven sub-watersheds: Shihmen, Hsiayun, Kaoyi, Lengchiad, Shankuang, Yunfeng, and Hsiuluan. The elevation of the Shihmen reservoir basin is from the southeast for over 3,500 m to the northwest 135 m in the basin. Over 56% of the basin has a gradient of over 30%. The effective storage capacity of the reservoir is currently 2.33 * 10^8 m3. The average rainfall in the basin area is 2,476 mm/year, and the average water runoff from the reservoir is 1.4 * 10^9 m3.

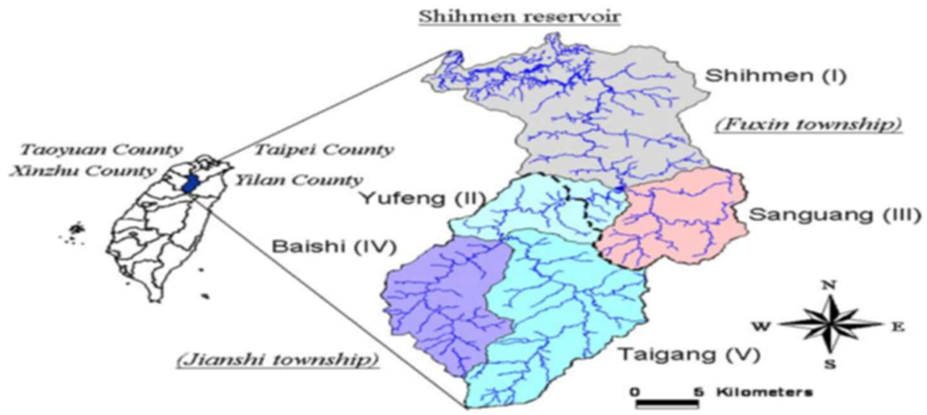


Figure 64 Site location of the Shihmen reservoir basin and the drainage network

7.3 Hydrology and sediment

The 763.4 km2 watershed above the Shihmen reservoir has steep slopes, high-intensity rainfall during typhoons, and a weak geology, resulting in high sediment load. The slate and sandstone, all heavily weathered and very erodible. Average annual precipitation is about 2,300 mm and peak discharge per unit area for different recurrence periods are shown in table 4. The peak 100-year inflow would be 763.4 km2 by 11.4 cm/km2, or about 8,700 m3/s.

Return Period	2 yr.	5 yr.	10 yr.	25 yr.	50 yr.	100 yr.	200 yr.
Peak Surface runoff cm/km^2	2.62	4.91	5.24	5.98	7.61	11.4	11.8

Table 4 - estimated peak runoff from Dahan watershed above Shihmen dam for various return periods

The two typhoons that strongly influenced the basin, Aere(23–26 August 2004) and Matsa (3–6 August 2005) brought more than 1,600 and 1,200 mm of rain, respectively. The two typhoons passed through northern Taiwan, and the rainfall distribution extended from the north to the mountainous regions of middle Taiwan. Figure 65 displays the distribution of accumulative and maximum rainfall intensity in the basin during Aere (2004) and Matsa (2005). During Aere and Matsa, the maximum accumulative rainfall was 1,607 and 1,274 mm, respectively; the maximum rainfall intensity was 88 and 95 mm/h, respectively. The rains from both these events were concentrated in the Yufeng and Baishi catchments because of the topography and similar paths of the two typhoons. Such a rainfall event historically occurs every 100 years in Baishi and every 200 years in Yufeng.

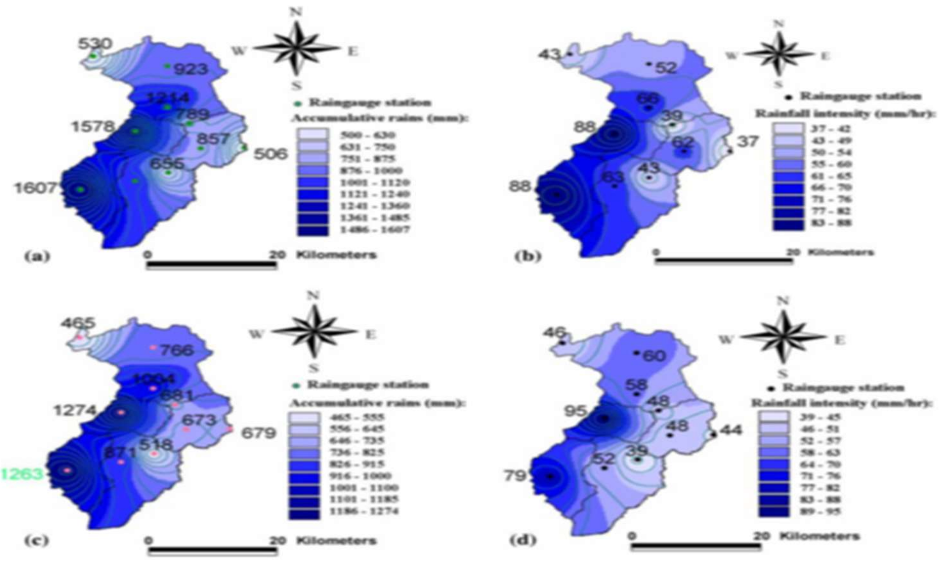


Figure 65 Distributed rainfall in the watershed(a) accumulative rainfall and (b) maximum rainfall intensity during Typhoon Aere (from 23 to 26 August 2004) (c) accumulative rainfall and (d) maximum rainfall intensity during Typhoon Matsa (from 3 to 6 August 2005)

The reservoir operations were shut down during Typhoon Gloria (1963) induced torrential floods, leading to

1.947 * 10^7 m3 of suspended sediment accumulated in the reservoir. Two tunnel spillways were constructed in 1979 to drain the suspended sediment at the lower dam of the reservoir. Figure(66) shows the annual silt accumulation in the reservoir. The annual average suspended sediment yield in (2000) was 7.6 * 10^5 m3. The sediment production after Typhoon Herb (1996) was 8.67 * 10^6 m3. The total suspended sediment yield before Typhoon Aere (2004) was 5.615 * 10^7 m3. The increased suspended sediment was about 2.79 * 10^7 m3 following Aere. The suspended sediment transport to the reservoir caused by Typhoon Matsa (2005) was about 1 * 10^7 m3 and left 69% storage capacity of the reservoir.

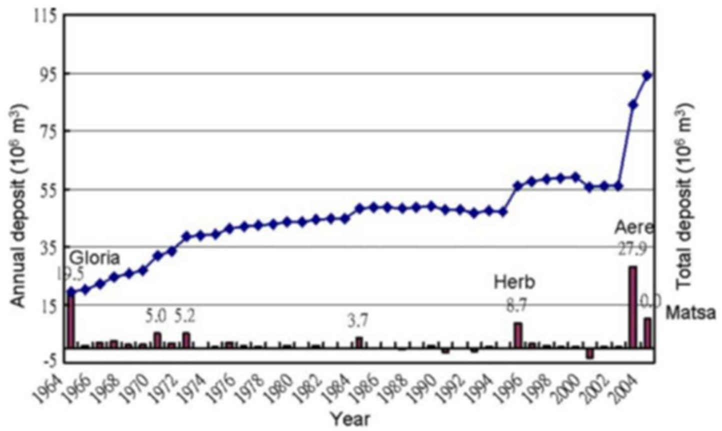


Figure 66 Annual suspended sediment yield in the reservoir

7.4 Soil and geological conditions

The soil surrounding the reservoir comprises clay, with sandstone/shale stone weathering into yellow to brown and loose red-soil downstream. The middle stream comprises red soil covered by dark brown or yellow soil, while upstream soils also contain blue lithosols. Table

3 summarizes the sediment contents (classified as CL) in the reservoir, which were 37.6% silt and 60.3% high clay. The gravity was 2.73; the liquid limit was 46.6%, and the plastic index was 22.9% see Table (5).The clay content of the suspended sediment in the reservoir is the highest among the 17 reservoirs in Taiwan.

AASHTO	Content (%)				Gravity	LL (%)	PI (%)
	Gravel	Sand	Silt	Clay			
CL	0	2.1	37.6	60.3	2.73	46.6	22.9

Table 5 Sediment content in the reservoir

The geological structures in the basin are dominated by two faults, four anticlines and two synclines (Fig. 67). The upstream contains argillite, slate, quartzite and coaly shale. Argillite, sandy shale-sandstone, and slate are located in the middle stream, while sandstone and shale dominate the downstream. In general, the unconfined compressive strength of the rock was 50–100 MPa in the basin, but only 25–50 MPa in the coaly shale layer. The gouge in the interbeds is easily washed out by a flash flood. The geologic structures and environment form fragile but complex geologic conditions.

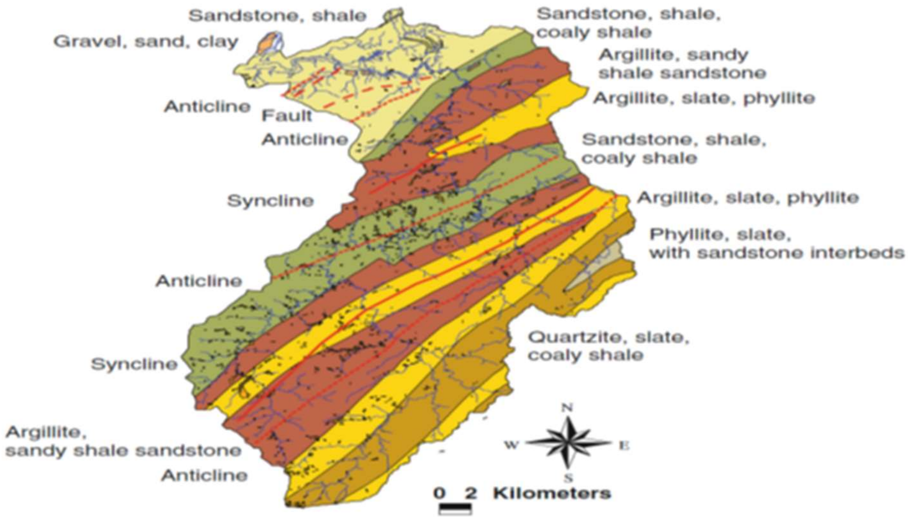


Figure 67 Landslides after Typhoon Matsa (2005) and their corresponding geologic conditions in the basin

7.5 landslide problem

Landslides cause considerable loss of human life and damage to property and sedimentation from landslides impacts watersheds for years. Sediment from landslides is frequently deposited in channels. In watersheds with reservoirs, the downstream transport of landslide sediment reduces reservoir storage capacity and hence diminishes reservoir function and lifespan. Landslide sediment can also degrade water quality, aquatic habitat, and municipal water supply systems. However, a comprehensive understanding of the effects of landslide sediment requires quantification of landslide sediment yields and sediment routing.

After a landslide occurs, the debris moves downslope but only a fraction of the sediment is delivered to the stream channel networks. According to field studies, the delivery of landslide sediment to channels ranges from 20% to 70% and depends primarily on the volume of the landslide, the mobility of the material on the hillslope, the type of mass wasting process, the behaviour of sediment at hillslope–channel junctions, and the characteristics of the terrain. Landslide sediment delivery ratios vary considerably and determining the delivery ratio is a site-specific task that depends on the site characteristics of each landslide. However, simple, empirical relationships can be used to estimate sediment delivery. For example, landslide volume, distance from landslide to stream, hillslope gradient, and tributary junction angles have been identified as important controls on landslide sediment delivery. Although more field measurements and studies on the process of landslide sediment delivery are required the delivery of sediment to streams can be approximated according to dominant geographical parameters.

Catchment	Landslide area (km^2)	Landslide ratio[a] (%)	Landslide related to		
			River Within 40 m (%)	Road	Human activity (%)[b]
Shihmen (I)	1.20	0.46	54.1	25.8	56.6
Yufeng (II)	1.47	1.84	39.6	41.6	62.1
Sanguang (III)	0.51	0.48	41.2	16.0	26.6
Baishi (IV)	2.08	1.73	63.6	5.8	7.1
Taigang (V)	1.77	0.89	33.5	3.7	14.9
Total	7.03	0.92	47.7	16.9	30.4

[a] The landslide ratio = the landslide areas in the catchment/the catchment area

[b] Including human development, road related and plant land for bamboo

Table 6 Typhoon Aere (2004) induced landslide characteristics analysis

The year 2004 deserves more attention due to the occurrence of Typhoon Aere, which played a significant role in the landslide sediment production of Shihmen Reservoir watershed. Typhoon Aere crossed specifically over northern Taiwan, bringing extremely heavy rainfall. The typhoon runoff to the reservoir carried extremely high concentrations of sediment, considerably increasing the turbidity of the Shihmen Reservoir see Table (6) above. Because the 1986–1997 period exhibited the largest increase in the landslide area, most of the studies focus on landslide sediment issues from this time period, as well as the 1998–2003 and 2004 periods, and model sediment routing from the landslide initiation sites to the reservoir.

Landslide erosion and sediment delivery to the Shihmen Reservoir watershed in Taiwanwas estimated using empirical landslide frequency–area and volume–area relationships, empirical landslide runout models, and the Hydrological Simulation Program- FORTRAN (HSPF). Landslide erosion rates ranged from 0.4mm/yr to 2.2mm/yr during the period 1986–2003 but increased to 7.9mm/yr following Typhoon Aere in 2004. The percentage of landslide sediment delivered to streams decreased from 78% during the period 1986–1997 to 55% in 2004. Estimates of the mean volume of landslide sediment delivered to streams ranged from $3.62*10^4$ to $8.09*10^6$ m3 for individual sub-watersheds, which was 40% to 89% of the total landslide volume. The proportion of sediment delivered to channels from individual landslides varied over time, with a high proportion of landslides delivering >75% for the period 1986–1997, relative to later periods (Figure 68)

Figure 68 Slope land hazards at the upland of the watershed for (a) road related landslide (plant bamboo) (b) water incision-induced riverside land sliding after Typhoon Matsa (2005) (c) isolated village d big land sliding at Baishi catchment for 0.64 km2 after Typhoon

7.6 Sediment problems

Typhoon Gloria (1963) deposited 19.5 Mm3 of sediment when the dam was newly constructed, and to control sedimentation, 121 check dams with a total storage volume of 35.8 Mm3 were constructed by different agencies on the Dahan River and its tributaries. These dams trapped mainly coarse materials, but as they filled, the sediment load entering the reservoir increased.

Reservoir bathymetry is normally mapped each year at the end of the wet season, and 34 permanent cross-sections are prepared from this mapping to track sedimentation conditions. Longitudinal bed profiles for selected years are plotted in figure 69. Above section 24, the reservoir is constricted to a relatively narrow gorge. From section 24 to 29, the bed level has risen 15~20 m since 2003, and the delta has migrated downstream. Figure 8 also shows the grain size from sampling the deposited sediments. With the exception of the inlet area, most deposits are fine sand, silt, and clay. The average (D50) diameter near the dam is 0.008 mm.

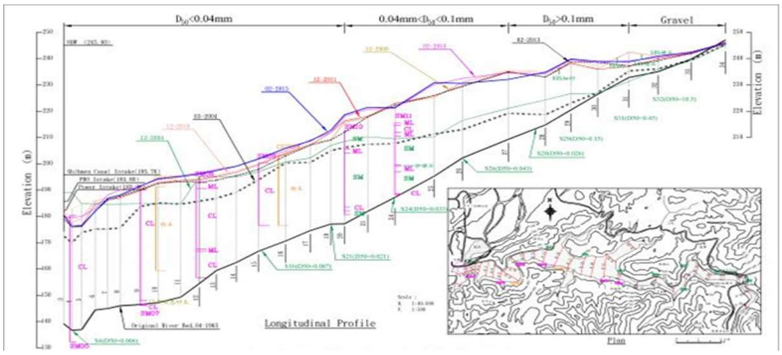


Figure 69 variation in longitudinal profiles for Shihmen reservoir over time due to sedimentation

The 2015 reservoir volume of 204.7 Mm3 represents about a third of the reduction in the original volume. Figure 70 shows the loss in reservoir volume over time, showing the loss of 19.5 Mm3 of storage due to typhoon Gloria when the reservoir was newly constructed, plus the effect of Typhoon Aere. Together, these two typhoons accounted for about 45 percent of total sedimentation over 52 years of operation.

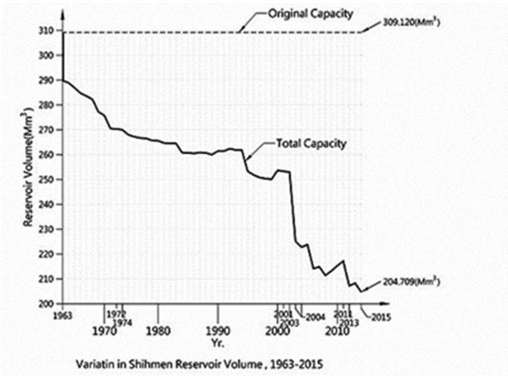


Figure 70 Shihmen reservoir volume loss from 1963 to 2015

The resulting landslides and runoff deposited 27.88 Mm3 of sediment into the reservoir, reducing its volume by 11 percent. In addition to the loss of reservoir volume, the submerged lake of muddy water that formed in the deeper part of the reservoir in front of the intakes was too turbid to be purified, leading to a suspension of potable water supply for 18 days during a hot and humid summer. Figure 71 shows that on or before 1 September, the reservoir had formed a submerged muddy lake below El. 207 m; turbidity was less than 100 NTU above the interface versus 100,000 NTU below.

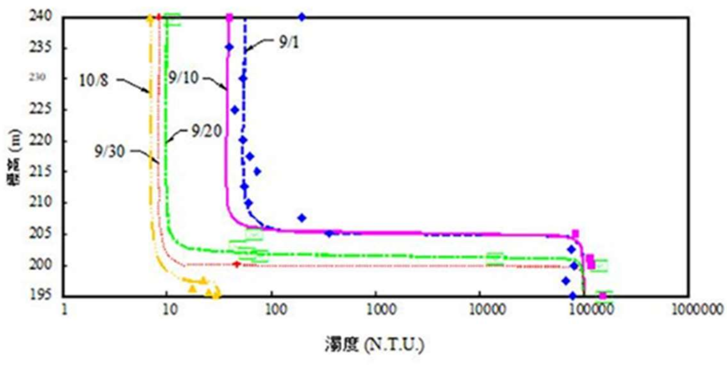


Figure 71 turbidity in front of intake following Typhoon Aere, 2004

From 1 September to 30 September, this interface lowered by only 7 m, at an average rate of about 1 cm/hr. This is about 1/180 of the fall velocity of a discrete 0.008 mm diameter particle, the average grain size of deposits near the dam, reflecting the hindered settling in the non-Newtonia mud-flow. Figure 72 shows the consistency of the mud that was in the penstock, as seen via an access hatch.

Public pressure from the interruption of potable water supply caused the government to pass legislation for the renovation of Shihmen reservoir. The scope of the renovation included construction of a new surface intake for potable water release during turbidity events and development of the schemes necessary sustain long-term reservoir capacity.

Figure 72 consistency of residual mud that collected in the penstock during Typhoon Aere, as seen in an access hatch

7.7 Estimate of average annual sediment inflow

To develop a sustainable sediment management strategy, an estimate of the average annual sediment inflow is essential. Two methods were used. First, sampling data were used to develop a sediment rating curve suspended load Qs (kg/sec) versus inflow Q (m3/s). This was applied to the historical inflow time series to estimate the average suspended load entering the reservoir from 1964 to 2010 as 3.392 Mt/yr. Assuming a 15 percent bed load contribution the total sediment is thus about 4 Mt/yr. Taking an average unit weight of 1.13 t/m3, the equivalent volume in the reservoir would be about 3.53 Mm3/yr.

Sediment inflow can also be estimated from the following:

- Average annual volume loss: 2.16 Mm3/yr
- Average sediment discharge from PRO, turbine, and spillway: 0.47 Mm3/yr
- Average annual dredging and excavation: 0.32 Mm3/yr (since 1985)
- Estimated additional annual sediment inflow could be expected due to loss of check dam trapping capacity: 0.21 Mm3

The summation of the above is 3.16 Mm3. An average annual sediment inflow of 3.53 Mm3 has been adopted for planning sediment management works.

Most sediment inflow is associated with typhoon rainfalls. As seen in figure (73), 89 percent of total sediment inflow from 1963 to 2005 was produced by typhoon rains occurring in nine typhoon years. Given these data, a sedimentation management strategy was selected based on developing outlets capable of releasing inflowing sediment during and immediately following typhoon floods.

Yr.	Amount of Deposition (10^3m^3)	Typhoon (Date of occurrence)	Total Inflow (10^3m^3)	Peak Inflow (m^3/s)
1963	19,470	GLORIA (9.8~9.12)	893,040.000	10,200
1966	2,190	CORA (9.3~9.7)	182,912.256	2,200
1969	5,030	ELSIE (9.25~9.27)	316,082.304	5,400
1971	5,230	BESS (9.20~9.23)	431,753.760	5,270
1976	2,028	BILLIE (8.8~8.10)	246,952.800	5,490
1985	3,695	NELSON (8.20~8.24)	355,072.032	4,906
1996	8,670	HERB (7.29~8.1)	448,561.152	6,363
2004	27,884	AERE (8.23~8.26)	774,747.072	8,594
2005	2,332	HAITANG (7.16~7.20)	272,032.992	3,198
		MATSA (8.3~8.6)	546,437.664	5,323
		TALIM (8.30~9.1)	222,345.216	3,689
Sum	76,529 (88.6%)	-	-	-
Other years	9,831 (11.4%)	-	-	-
Total	86,360 (100%)	-	-	-

Figure 73 major sedimentation events in Shihmen reservoir and associated typhoons through 2005

7.8 Sediment transport investigation

7.8.1 Hydraulic model study

To help understand sediment transport behaviour in the reservoir and evaluate alternative outlet structures for releasing sediment, a 1/100 scale undistorted hydraulic model was constructed at the Water Resources Planning Institute of Water Resources Agency, Ministry of Economic Affairs. Typhoon Aere was used as the input condition in all tests. The model clearly demonstrated sediment transport by turbid density currents and the formation of a submerged muddy lake in front of the dam. Though the model cannot completely simulate the prototype phenomena due to scaling effects, it did provide a good qualitative physical comprehension of the transport phenomena within the reservoir and expected function of proposed outlet schemes.

7.8.2 Field sediment transport monitoring

To document in-situ turbidity current behaviour a TDR (Time Domain Reflectometry) technique was developed and applied in Shihmen Reservoir to track density current movement and sediment concentration profiles. This method is based on suspending an array of sensors in the water column, and by measuring the round-trip travel time of a pulsed electromagnetic wave the sediment concentration at each sensor location can be determined in real time. The measured result requires compensation for water temperature but is independent of particle size. Several monitoring stations were installed along the reservoir. One of these stations is shown in figure 74

Figure 74 platform for TDR monitoring array at Shihmen reservoir illustrating method of sensor deployment

Monitoring data from typhoon Fungwong (figure 75) shows the time variation of suspended sediment concentration at the reservoir inlet, Section 24, and the irrigation canal intake. Reduction in peak concentration as the current flows along the length of the reservoir is clearly evident. In this typhoon, it took about nine hours for the turbidity current to flow from the reservoir inlet to the dam, and the peak concentration decayed from about 28,000 ppm at the inlet, to 18,000 ppm at section 24, and then to 8,000 ppm at irrigation intake due to sediment deposition. The longitudinal deposit profiles previously shown in figure 8 reflect this deposition pattern. Figure 76 shows the vertical variations in sediment concentration at section 24 over time.

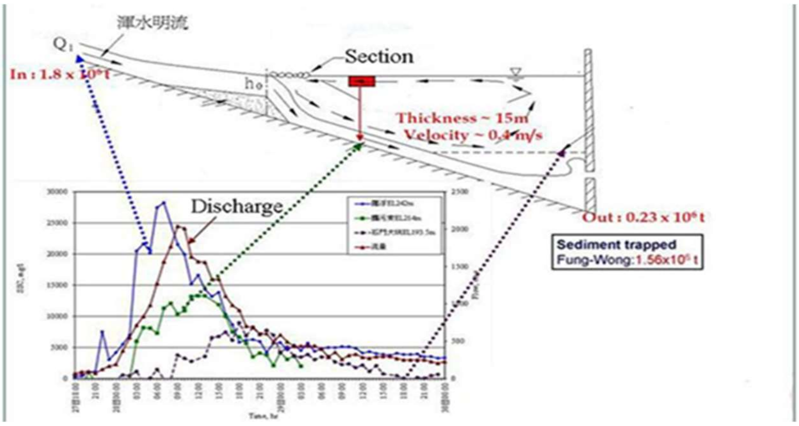


Figure 75 turbidity current characteristics in Shihmen reservoir during Typhoon Fungwong, 2014

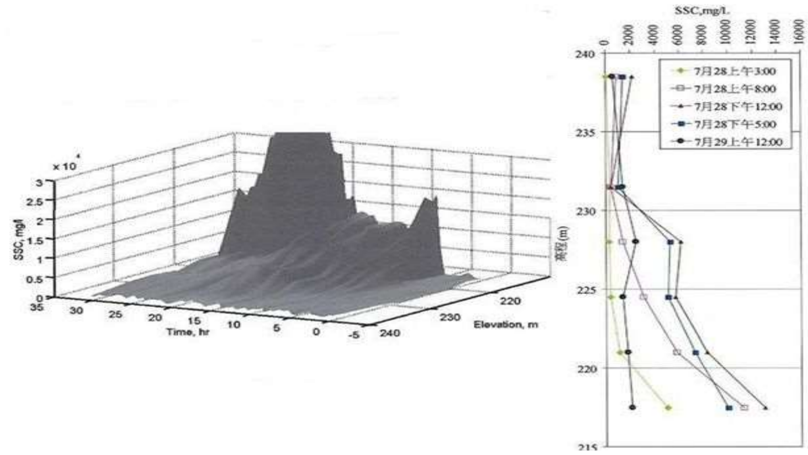


Figure 76 vertical variation of sediment concentration at section 24 during Typhoon Fungwong, 2014

7.9 Sediment management strategies

There is no suitable alternative dam site to replace the function of the Shihmen reservoir. Therefore, the only viable strategy is to sustain storage capacity in the existing reservoir. Based on sediment inflow and other characteristics of this reservoir, the following management strategies were selected to balance the long-term sediment inflow and outflow while preserving reservoir storage.

7.9.1 Watershed soil conservation

Typhoon-induced landslides are an important source of sediment, but studies showed these to mostly be due to a natural process in non-accessible mountain regions. Therefore, soil conservation work to reduce sediment production from this source will be very limited. A reduction of sediment load by only 0.1 Mm3/yr has been allocated to watershed management.

7.9.2 Venting of turbid density currents and submerged muddy lake

The dam was designed 'to store turbid water and to release overflow clear water', a strategy which has maximized sediment trapping in the reservoir. Since this water supply reservoir cannot be lowered for flushing or drawdown sluicing, the adapted strategy has been to create new outlets for releasing turbid density currents as they flow along the reservoir bottom and also after they pond to create a submerged muddy lake at the dam.

7.9.3 Convert Existing Penstock to Vent Turbid Density Current

The reservoir was built with two 4.5 m diameter steel-lined penstocks feeding two Francis turbines. Sediment has now risen to a level slightly higher than the penstock intakes (see figure 77), meaning these intakes will be submerged by the muddy lake formed by typhoon-generated turbidity currents.

Figure 78 depicts the different sections of the penstocks. To convert to sediment sluicing, penstock #1 was modified to power both turbines, while penstock #2 was converted to a 300 m3/s sediment sluice by removing a section and diverting into to a new 3.6 of steel pipe, as shown in Figure 16. Within the new gatehouse, the 3.6m diameter steel pipe was bifurcated into two flow passages, each equipped with an upstream vertical gate, a downstream jet-flow gate and a flip-bucket terminal structure. Flow is discharged into the after bay. Figure 79 shows a 3D view of this sediment release structure.

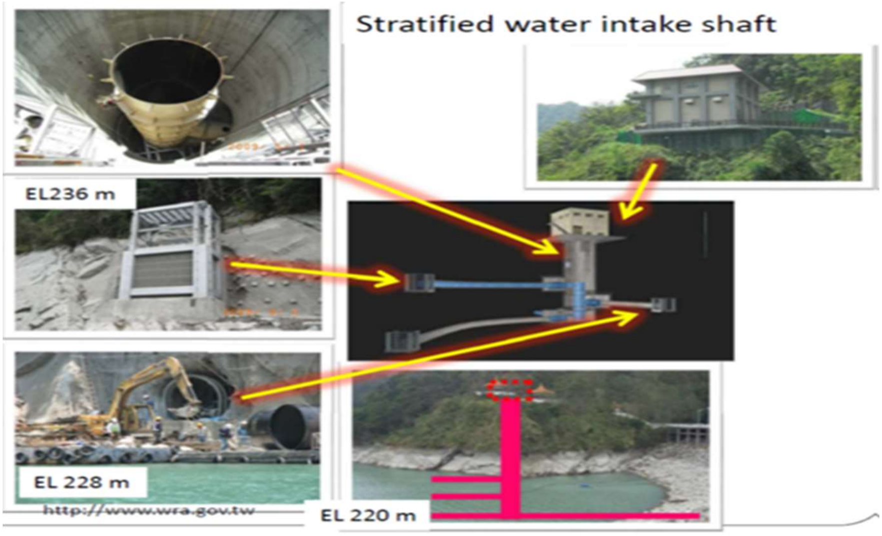


Figure 77 general features of penstocks

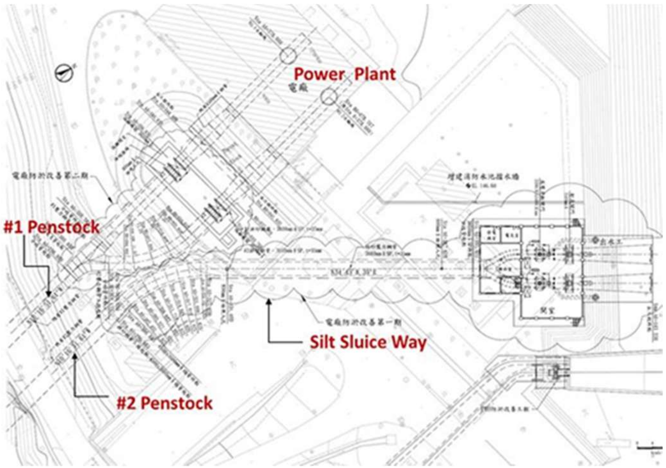


Figure 78 penstock modifications for sluicing of turbid density currents

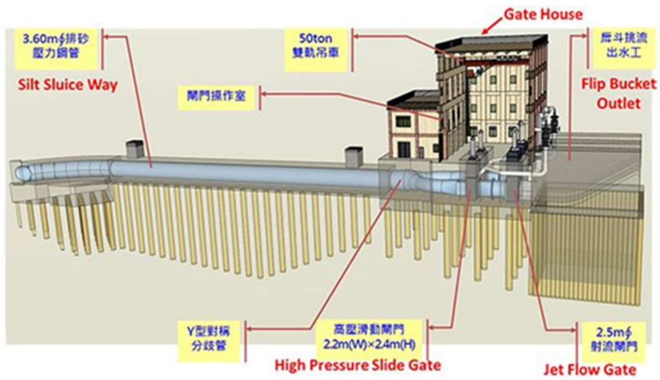


Figure 79 3D view of penstock converted for silt sluicing

Construction was completed in 2012, and figure 80 shows the initial sediment sluicing operation in 2013 during Typhoon Soule. The contrast in discharge between the surface spillway and the silt sluiceway is obvious. Since 2013, turbid density currents have been vented through the sediment sluice during five mediums to small-scale typhoons, discharging about 1.575 Mt. As compared to the cost of dredging this same volume of sediment, the project benefit has already exceeded its construction cost.

Figure 80 simultaneous operation of spillway and penstock sluice venting turbid density current during Typhoon Soule

7.9.4 Dawanping Silt Sluice Tunnel

To further enhance silt sluicing capability during typhoons, Dawanping was selected as the intake location for an additional sediment venting tunnel based on both numerical simulation and physical model testing. Figure 81 shows the overall layout of this project, which is not yet constructed.

The reservoir bed elevation at this intake site is about El. 195 m, which is 50 m below the normal water level of El. 245 m. To avoid constructing an intake cofferdam to this depth, two 10 m diameter 'elephant-trunk' steel pipes are planned to extend from the tunnel invert at El. 220 m down to the reservoir bottom, thereby withdrawing from the level of the turbidity current (see figure 82). A similar 'elephant-trunk' system has been successfully constructed and installed at another silt sluice tunnel project in southern Taiwan. This system is designed to discharge 1,600 m3/s by two parallel intakes and tunnels, regulating flow from each passage by a radial gate.

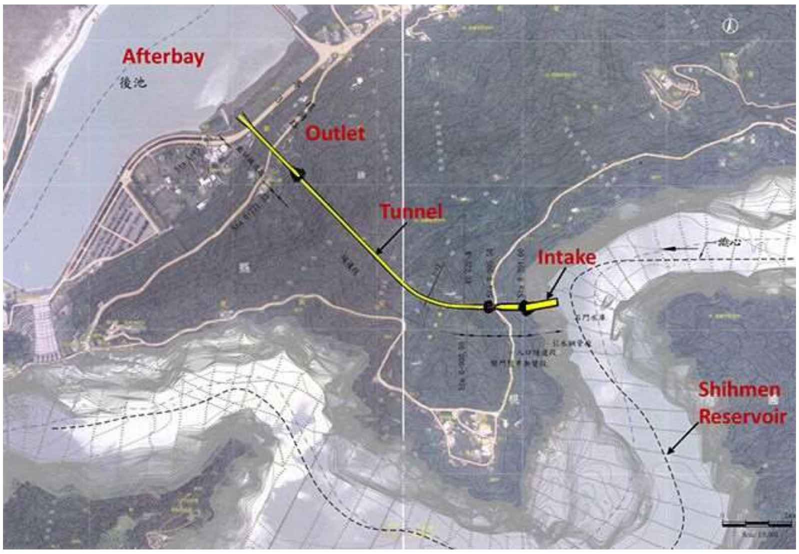


Figure 81 plan view of Dawanping tunnel for venting turbid density currents

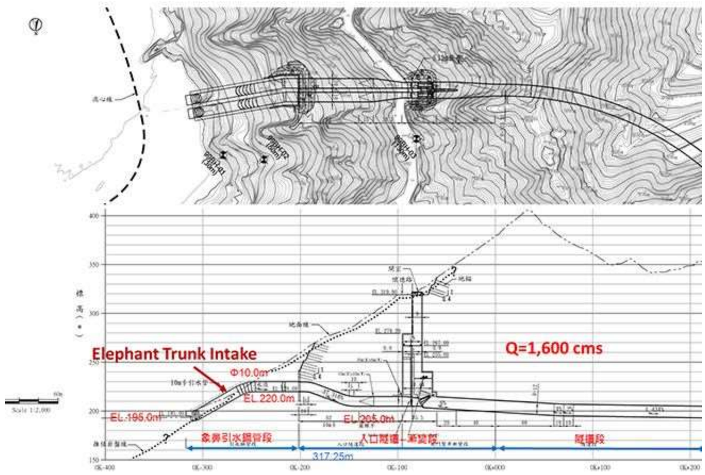


Figure 82 Dawanping tunnel showing 'elephant trunk' type intake

7.9.5 Excavation and dredging

As turbid flow entering into a reservoir, coarser materials deposit near the reservoir inlet while finer sediments are deposited between the delta and the dam. Since flushing is not an option, dredging is the only means to remove these deposits. Dry excavation has been ongoing at the upstream end of the reservoir since 1977 and dredging near the power intakes since 1985. However, the current dredging rate does not keep pace with sedimentation and additional dredging capacity must be added.

7.9.5.1 Dry excavation at reservoir inlet

Coarse sediment deposits at the reservoir inlet have been excavated over eight months of each year since 1977 using conventional earth moving equipment. Limited by road conditions, the plan is to remove at a rate of 400,000 m3/yr.

7.9.5.2 Amuping material handling facility

Core sampling of deposited material revealed that a change in grain size occurs in the vicinity of section 20 (figure 83). Upstream of this station the material is significantly coarser than downstream. About 40 Mm3 of sediment is deposited between section 20 and the area of dry excavation. About half of this is sand which may be used in concrete aggregates. These materials can only be removed by dredging. Due to lack of storage space adjacent to the reservoir, the facilities shown in figures (84 to 86) were designed to transport the dredged slurry, to sort out useable sand, and dispose of silt onto the Dahan River below the dam. This project has the following main components:

- A 4 km long dual-purpose horseshoe tunnel (8 m wide x 7 m high) will convey dredged material to the sorting facility near the tunnel outlet via four 30 cm diameter slurry pipes installed near the crown of the tunnel. The lower half of the tunnel can discharge up to 600 m3/s during typhoon events.
- A silt sorting facility is designed to segregate silt and sand. Sand will be used as aggregate while silt will be temporarily stored in a silt detention basin 600 m long and 62 m wide with storage capacity up to 200,000 m3.

- The tunnel outlet discharges into the detention basin to flush accumulated sediment into the Dahan River downstream of the afterbay. Flushing water will come from pre-typhoon reservoir drawdown to empty a flood control pool, plus typhoon flood water.

Construction of this project began in June 2017 and is expected to be completed by 2021.

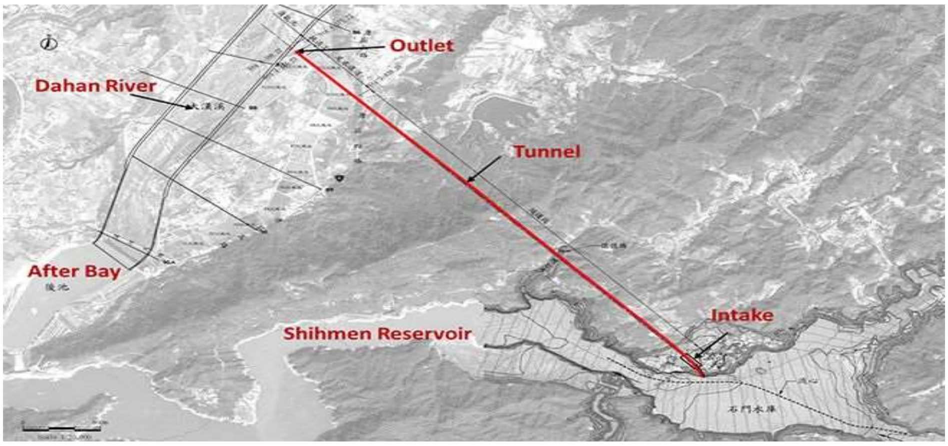


Figure 83 - plan view of Amuping tunnel

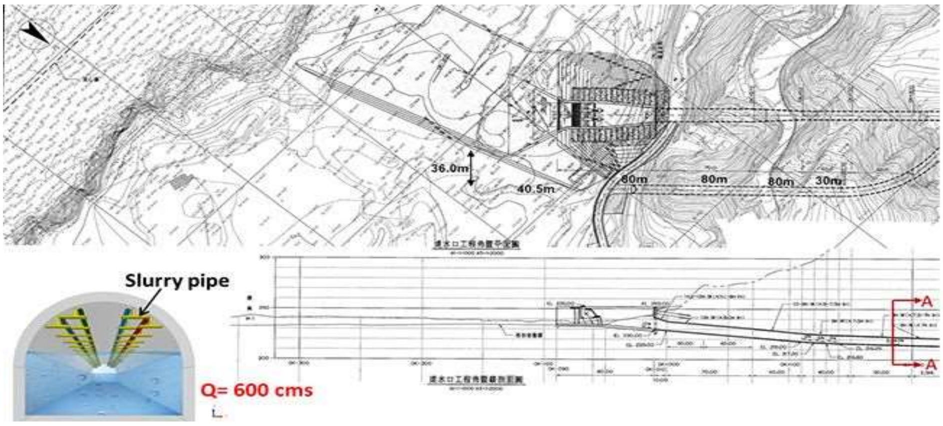


Figure 84 - intake and cross-section of Amuping tunnel

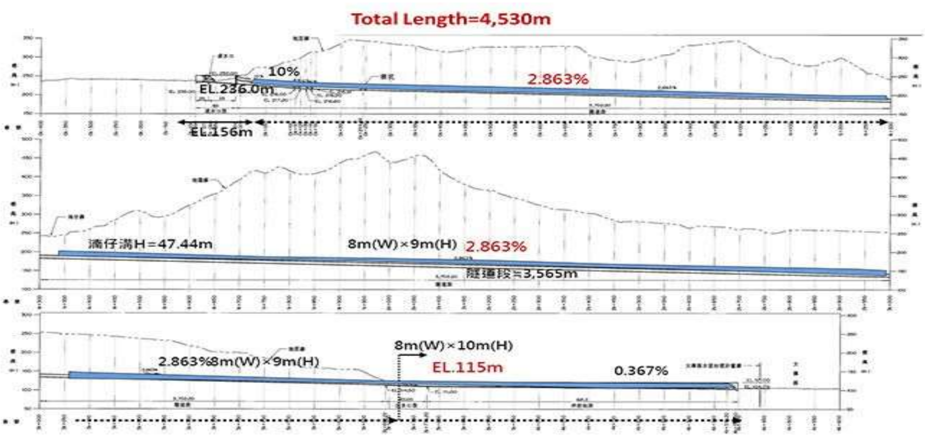


Figure 85 Amuping tunnel profile

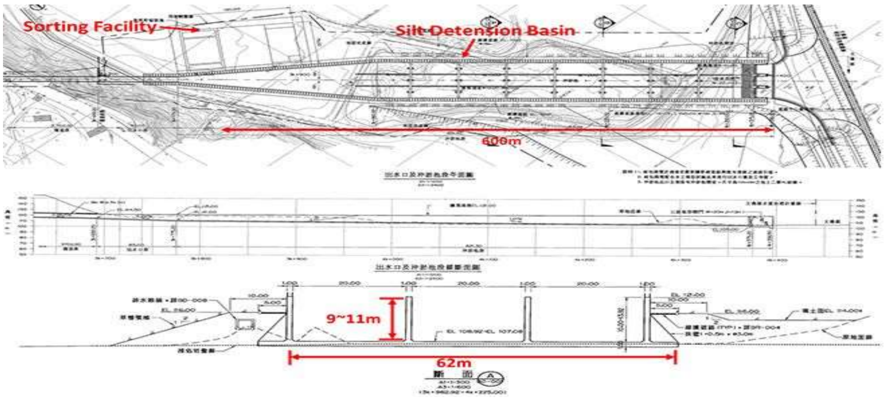


Figure 86 Amuping tunnel outlet and temporary storage basin

7.9.5.3 Dredging Near Power Intake

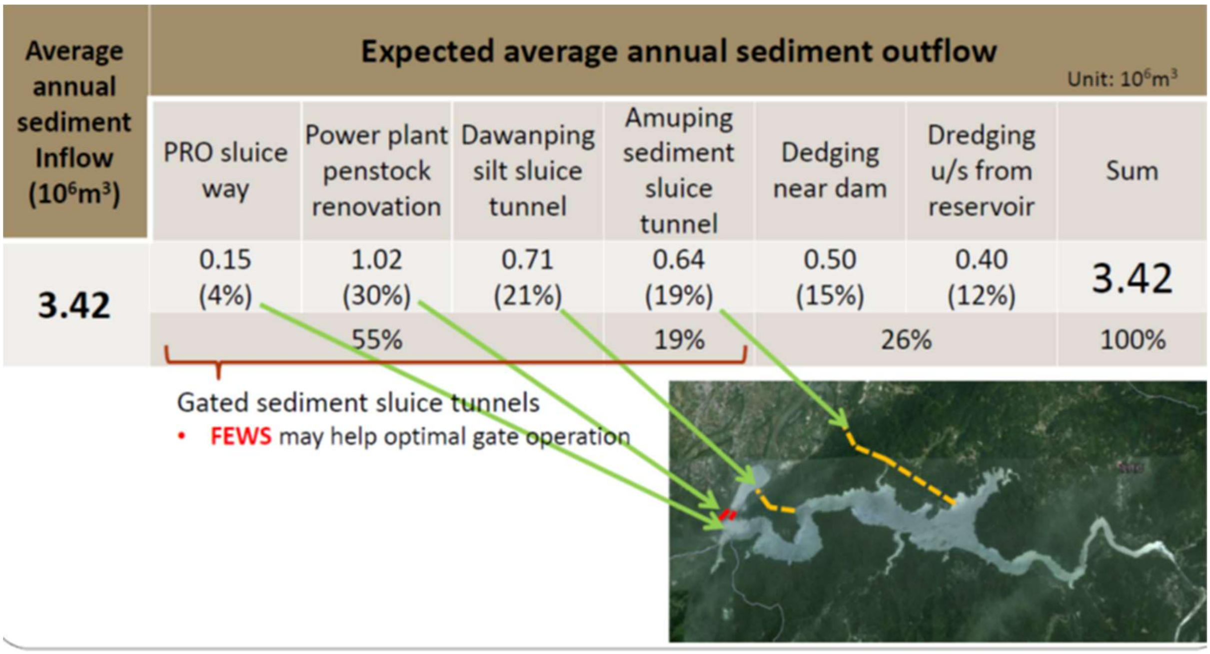
Sediment removal near the dam and power intake has been performed by a hydraulic dredge operating in water about 70 m deep with a planned removal rate of 500,000 m3/yr. The dredged fine silt (D50 0.008 mm) is transported by pipe to ponds located downstream of the afterbay for dewatering and subsequent trucking to disposal sites.

7.10 Sediment management strategies summary

Table 7 shows the planned long-term sediment discharge from the reservoir by each method needed to stabilize the volume of Shihmen reservoir. On average, about 55 percent of the sediment inflow will be discharged through the PRO, turbidity current penstock sluiceway, Dawanping tunnel, and other outlets. The remaining 45 percent will be trapped and subsequently removed by excavation of the delta, dredging in the upstream reach via the Amuping tunnel, and deep dredging near the dam. Figure (87) shows the expected average annual sediment outflow.

Average Annual Sediment Inflow	Average annual sediment outflow (thousand m^3)							
	Sluiced Sediment				Dredging Sediment			Sum
-	PRO Sluice way	Power Plant Sluice way after Power Plant modification	Dawanping Sluice Tunnel	Other Discharge Facilities	Dredging at Reservoir Inlet	Dredged Through Amuping Tunnel	Dredging at Dam	-
3,430	50 (1.4%)	410 (12%)	1,370 (40%)	60 (1.6%)	400 (12%)	640 (19%)	500 (14%)	3,430
	55%				45%			100%

Table 7 planned sediment discharge methods for Shihmen reservoir



Average annual sediment Inflow ($10^6 m^3$)	Expected average annual sediment outflow (Unit: $10^6 m^3$)						
	PRO sluice way	Power plant penstock renovation	Dawanping silt sluice tunnel	Amuping sediment sluice tunnel	Dedging near dam	Dredging u/s from reservoir	Sum
3.42	0.15 (4%)	1.02 (30%)	0.71 (21%)	0.64 (19%)	0.50 (15%)	0.40 (12%)	3.42
	55%			19%	26%		100%

Figure 87 Sediment sluicing and dredging for Shihmen Reservoir

Chapter 8

Dredging and Mechanical Removal of Accumulated Sediments strategy

8.1 strategy literature review

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 hydro suction 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 2.4Mm3, removed and taken to a nearby upland disposal site, at a cost of $5.60/m3 (or $6.47/m3 if planning and permitting are included) [Morris and Fan, 1998]. Another 2.55Mm3 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].

Case study:

Jirau hydropower plant Brazil

8.2 Introduction

The Jirau hydropower plant is located on the Madeira River, in the state of Rondônia in northern Brazil see figure (88). The power plant´s first electrical unit was commissioned in 2013, with inauguration taking place in 2016 when the final unit entered into operation. Jirau is a run-of-river project, owned and operated by the Energia Sustentável do Brasil (ESBR), of which 40 percent belongs to Engie, and the remaining 60 percent is divided equally between Electrobras Electrosul, Electrobras Companhia Hidroelétrica do São Francisco, and Mitsui.

Figure 88 aerial view of Jirau hydropower plant (Google Earth)

The 7 billion USD hydroelectric project includes a 62 m-high asphalt core dam with a 1,150 m-long crest at an elevation of 94 masl. The eighteen 30.1 m-high sluice gates have an invert elevation of 69 masl and a total discharge capacity of 82,587 m3/s. See the Jirau hydropower plant aerial view in figure 89 and, in more detail, the powerhouse on the left bank, the sluice gates, and the spillway in figures 89,90,91 and 92 respectively.

Figure 89 Upstream view of the Jirau hydropower project

Jirau features two powerhouses, one on the left bank with 22 units and one on the right bank with 28 units. In total, the project has 50 bulb turbines designed to operate under a low head, which is among the most powerful ever manufactured at 75 MW each. The power plants benefit of 15.4 m gross head with a design discharge of 27,500 m3/s. Jirau's total installed capacity of 3,750 MW at Jirau contributes 19,136 GWh annually to the National Interconnected System (SIN).

At the dam site, the river bed elevation is just 47.4 m, and the river slope is 0.03 mm/m. Due to the plain topography, the dam creates a large reservoir that is 141.8 km long with a total storage capacity of 2,746.73 Mm3 and a live capacity of 1,496.07 Mm3. The reservoir operates between the levels of 82.5 masl and 90 masl, with a significant annual drawdown, resulting in the reservoir area varying between 21 and 207.7 km2. The maximum reservoir surface area, including the river area, can reach up to 361.6 km2 during the wet season.

Figure 90 downstream view of the Jirau powerhouse on the left bank

Figure 91 Jirau sluice gates on the right side

Figure 92 Jirau spillway on left side

8.3 Hydrology and sediments

The Madeira River is the main southern tributary to the Amazon River, which drains part of the Peruvian and Bolivian Andes. The catchment tributary to the Jirau hydropower plant comprises 972,710 km2, characterized by an annual average temperature of 25.1 ºC, an annual average precipitation rate of 2,174 mm and a mean annual inflow of 589,000 Mm3. The coefficient of variation of annual inflows is 0.167.

The monitoring programme measures the river aggradation in the delta of the reservoir at Mutum station. The particle size distribution analysis shows that the sediment deposits in the delta contain 98 percent sand. On the other hand, the analysis of the sediment deposits in the bottom set shows that the percentage of sand decreases to 29 percent while the silt percentage increases to 54 percent. Clay represents the lowest proportion, with 17 percent. Sand is the main material of the river bed with a D50 grain size of 0.225 mm.

The mean annual bed load is 44.9 Mt which represents less than 10 percent of the total load; therefore, the mean annual suspended sediment load is significantly greater with 582 Mt.

The Madeira River contributes approximately half of the sediment load of the entire Amazon River basin. The daily sediment load varies in the range of 2-4 Mt per day during the peak flow period. The design sedimentation rate is 20 Mm3 per year and the sediment rating curve for the suspended load is defined by the formula Qss = 0,0017 * Q2.0654.

Figure 93 shows the relation between the operating levels, the storage volume and the area covered by the plant operation.

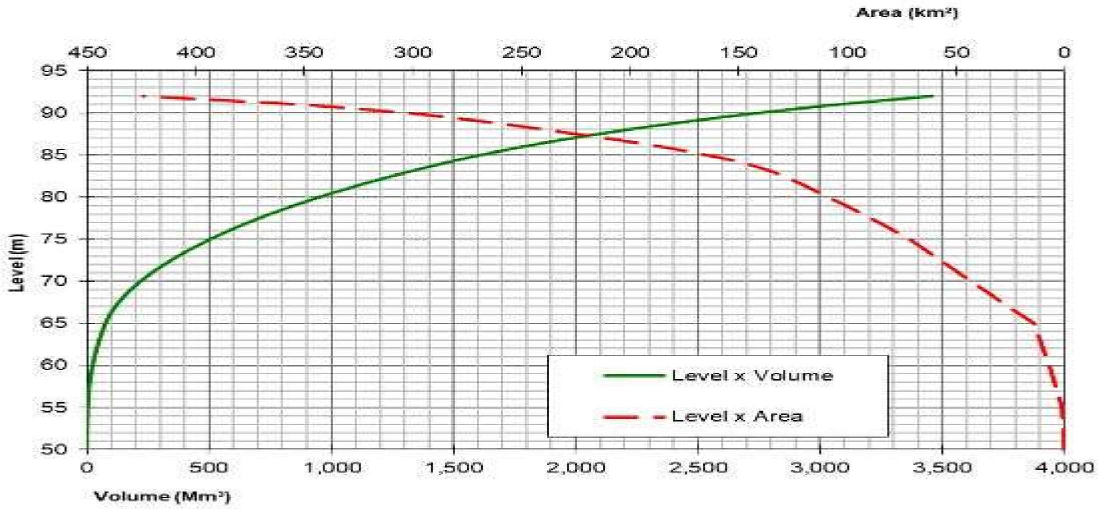


Figure 93 Jirau reservoir level-storage curve

8.3 Sediment problems

The first sedimentation problem occurred one year after commissioning. A historic flood in 2014 mobilized a large amount of sediment, changing the river's topographic profile, causing aggradation near the water intake structures and wear to the hydromechanical equipment.

The aggradation created water damming effects along the river. Sedimentation near the concrete structures and the water intakes resulted in difficulty moving the stop log gates of the power plants. Pump pipes, drainage, and sewage wells suffered from sediment accumulation and the filters of the refrigeration systems experienced blockage. The suspended sediment eroded the pumps, the concrete on the spillway intake and the hydromechanical equipment. Other minor issues included damage to the water level sensors.

Future sediment problems identified include the loss of reservoir capacity, decrease in the load for power generation and increase in the frequency repair needed to the turbines and their components, meaning increased operations and maintenance costs for the power plant.

8.4 Sediment management strategies

The Madeira River carries very high sediment loads which originate primarily in the Beni sub-catchment in Bolivia. Approximately 70 percent of the tributary basin to the Jirau dam is located outside Brazilian territory, making sediment data monitoring difficult and the application of watershed management strategies beyond the control of the project. However, tree planting has been implemented in the vicinity of the reservoir to minimize the erosion and avoid washout during flooding.

It is of fundamental importance that the natural sediment transport is maintained in the Madeira River without causing negative impacts on the socioeconomic and biophysical environment, or the project infrastructure and its generation potential. The safe transport of sediments, logs, debris, larvae, eggs and juvenile fish through the dam is necessary to secure the maintenance of biophysical environments and therefore comply with environmental regulations. The proper functioning of the fish ladder at Jirau, shown in figure 94, is crucial for the conservation of the multiple fish species in the Madeira river.

Figure 94 fish ladder at Jirau

During the planning and design phase of Jirau, four programmes relating to sediment management were considered: the sediment monitoring programme; the programme for recovery of degraded areas; the Environmental Plan of Conservation and Use of the Influence Area of Reservoirs (PACUERA); and the monitoring programme of marginal and unstable slopes.

During the construction phase, following the programme of recovery of degraded areas, the topsoil of excavated areas was stored for reuse in the enhancement and recovery of affected areas following construction. The PACUERA programme is a regulatory requirement that addresses the conservation, recovery and land use of the reservoir's influence area. ESBR shares satellite imagery with the Brazilian authority responsible for socio-environmental monitoring of the Amazon region to identify any marginal or unstable slopes and maintain a comprehensive database of the area.

Mathematical and physical models contribute to identifying and minimizing sedimentation issues. Prior to construction, the models helped with the design of large dikes on the river banks to minimize the lateral sedimentation and channel the flow to the powerhouses and spillways.

Operating with variable reservoir water levels, as shown in figure 95, prevents the creation of a delta at the end of the reservoir, with sediment deposition being spread more gradually throughout the reservoir. Modification of the operating rule when needed also avoids any sediment damming effect across the Bolivian border.

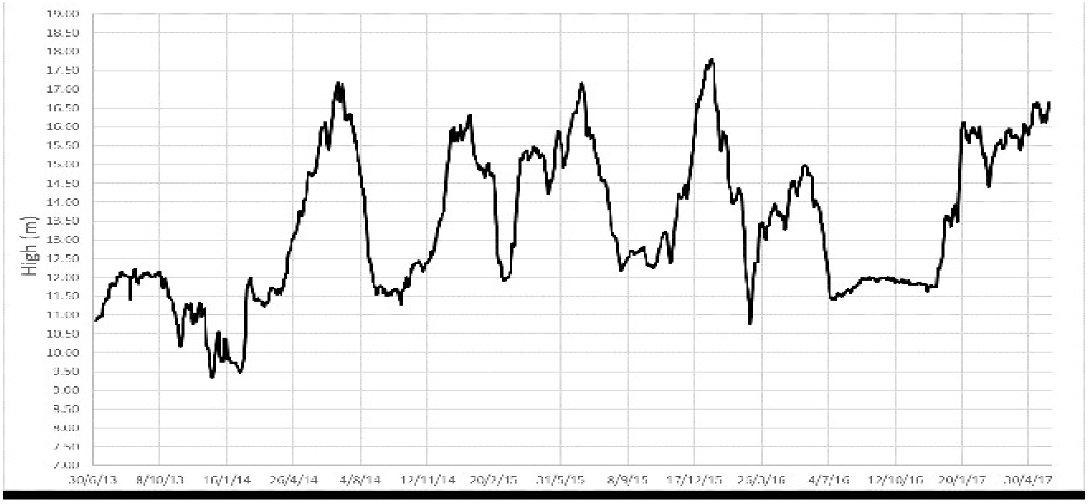


Figure 95 Jirau operation gross head 2013-2017

The abrasion-resistant coating has been applied to the 50 turbine units in order to minimize the loss of efficiency and maintenance requirements due to the effects of sediment erosion. The operations and strict regulations against sediment flushing effectively avoid the potential of turbid water with an extremely high sediment concentration passing through the turbines.

Hydro suction dredging is occasionally carried out to remove sediment deposits along the reservoir to avoid sediment damming effects.

8.5 Monitoring

The monitoring programme was in place three years prior to impoundment. It consists of six stations, five upstream and one downstream of the Jirau dam, where the suspended and bedload sediment concentration is measured twice a week upstream and once a week downstream. Over the first five years, bathymetric surveys including 23 control sections measured the changes to the riverbed area annually. The field campaigns also included samplings of delta and bottom set sediment.

To identify potential areas of erosion and evaluate the erosion rate, the monitoring programme uses a digital terrain model and high-resolution satellite imagery. A precipitation-runoff model calculates the runoff using data from six telemetric stations in the upper catchment and 13 gauges along the river.

Water quality measurements include the monitoring of abiotic and bacteriological variables, limnologic parameters and aquatic communities (phytoplankton, zooplankton, zoobenthos), water quality index, and groundwater quality at the Velha Mutum station upstream.

The Hydro-biogeochemical monitoring programme consists of mercury and methylmercury measurements in the environment and the calculation of the trophic state index.

Chapter 9

Pressure flushing strategy

9.1 strategy literature review

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 scouring just upstream of the outlet, see figure (96). 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 the 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.

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.

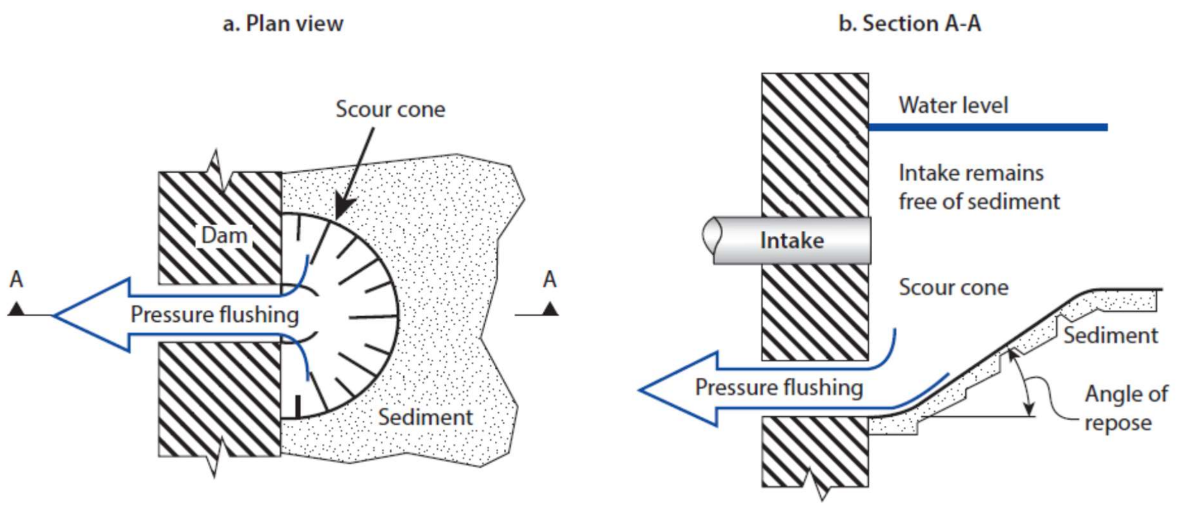


Figure 96 Localized Scour Cone Created by Pressure Flushing

Case study:

Bakura in Indonesia

9.2 introduction

The Bakaru hydropower plant represents the major power supply source in the South Sulawesi region in Indonesia, where the total installed capacity was about 400 MW in 2008. The Bakaru dam, completed in 1991, is located on the Mamasa River, as shown in figure 97. The Bakaru plant's current installed capacity is 126 MW (comprising two 63 MW Francis turbines), operating under a maximum head of 322.2 m, with a design discharge of 45 m3/s.

Figure 97 location of the Bakaru hydropower project

The project consists of a 16.5 m high concrete gravity dam with a crest length of 122.5 m, fitted with two steel roller flushing gates, two steel roller regulating gates and four radial spillway gates. The maximum operating elevation is 615 masl and the minimum operating elevation 612 masl. The original reservoir volume was 8.28 Mm3 with a live storage capacity of 2 Mm3. The flood discharge capacity of the spillway is 2,500 m3/s. The dam is located at the upper edge of a significant drop in the river, where the original river bed slope (prior to sedimentation) was 1/570 immediately upstream of the dam, increasing to 1/5.8, with large amounts of rock immediately downstream of the dam, as illustrated in figure 98.

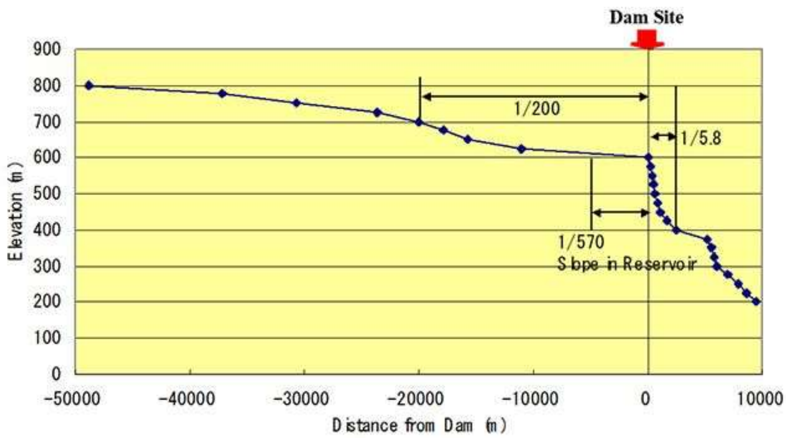


Figure 98 longitudinal river bed profile

9.3 Hydrology and sediment

The catchment area of 1,080 km2 upstream of Bakaru hydropower plant produces an annual average mean flow of 1,794 Mm3, with an annual coefficient of variation of 0.22. The small variability in annual flows, as well as the mean distribution of monthly flows, are shown in the hydrographs in figure 99.

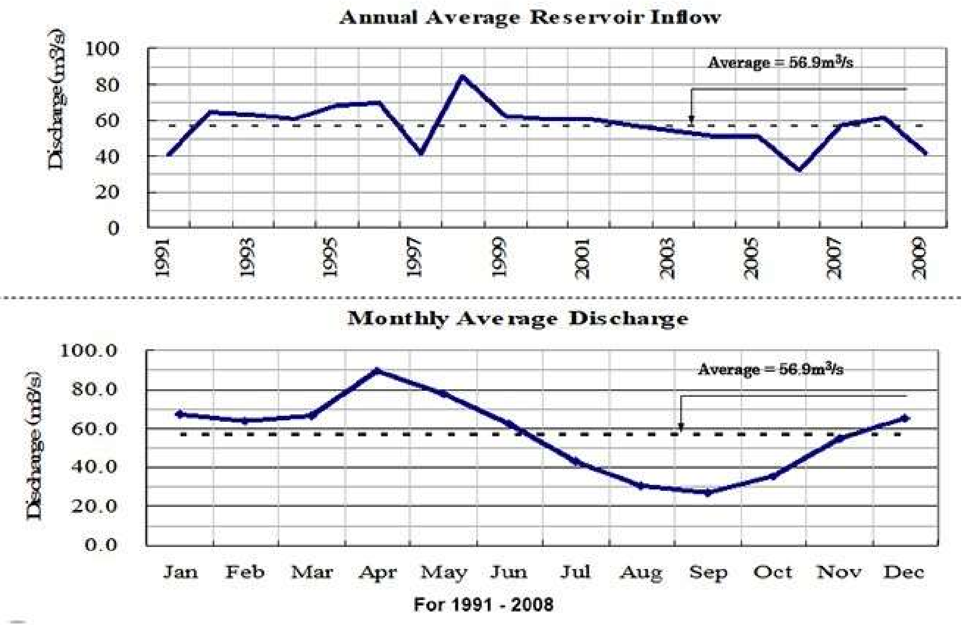


Figure 99 annual average reservoir inflow and monthly average discharge at Bakaru dam

The sediment load in the Mamasa River at Bakaru is currently estimated as 988,000 t/yr (760,000m3/yr), which is equivalent to a specific sediment yield of 915 t/km2/yr. The bed load largely consists of sand, and the suspended load contains silt and clay. The catchment conditions are poor and erodibility high. The hydrographs for water and sediment discharge for three monitoring events, cumulative sediment inflow, and a sediment rating curve are shown in figures 100, 101 and 102.

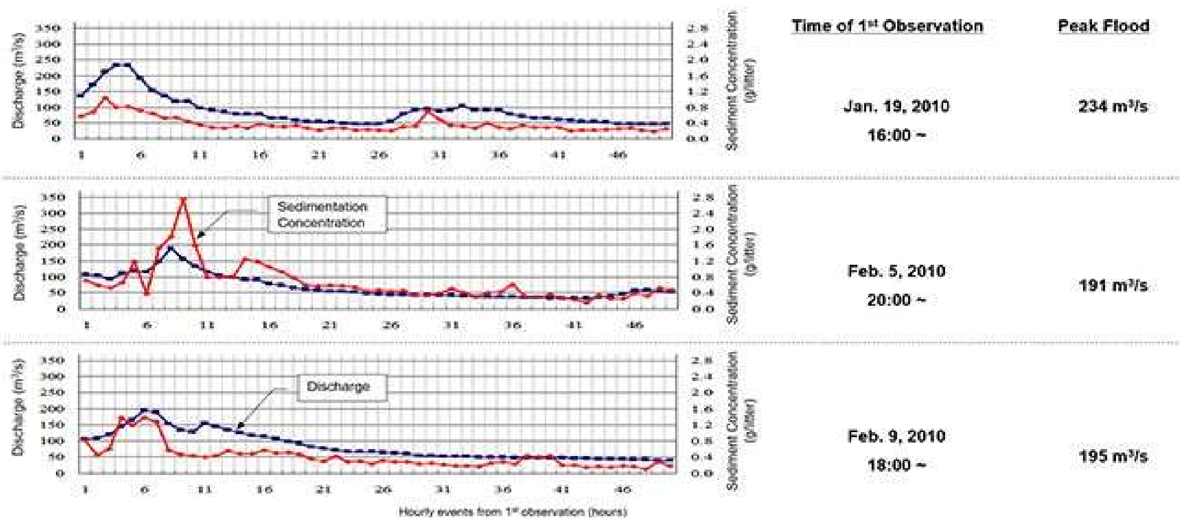


Figure 100 hydrographs of three precipitation events in 2010

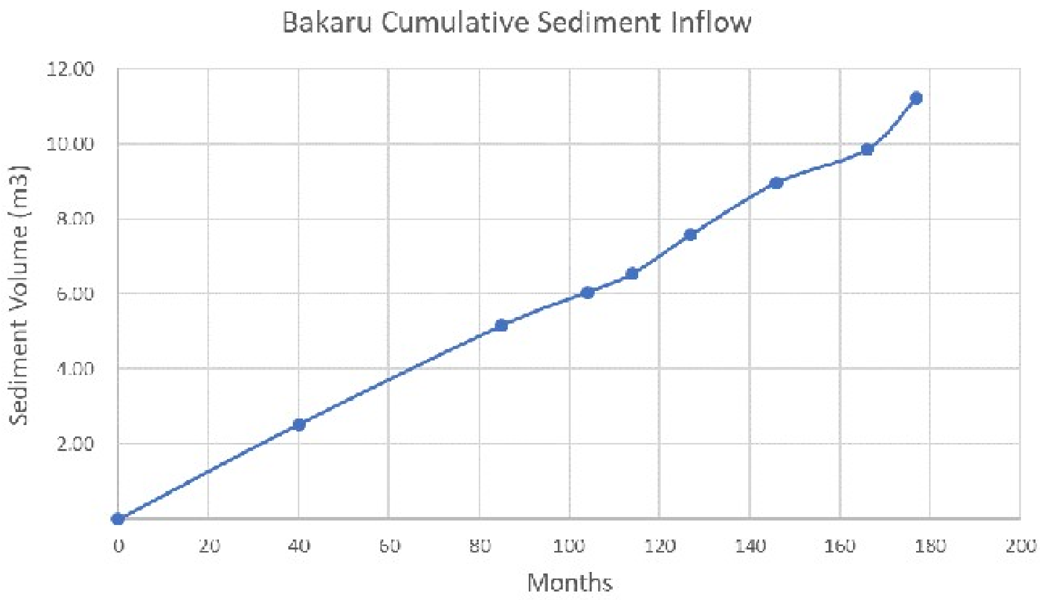


Figure 101 cumulative sediment inflow at Bakaru reservoir

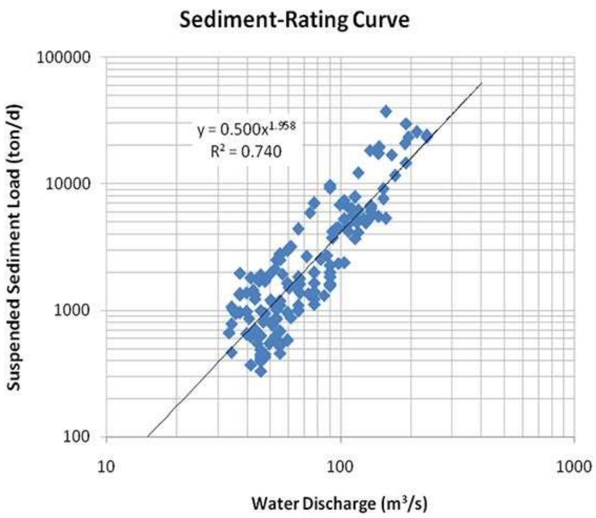


Figure 102 sediment rating curve at Bakaru dam

9.4 Sediment problems

The main sediment challenges experienced at the project are storage loss and abrasion of turbines. By 2000, storage loss amounted to about 70 percent of the total original storage and then stabilized, as shown in figure 103, at about 73 percent. The live storage was affected but to an unknown degree. Sediment management efforts were intended to keep the reservoir volume stable at about 27 percent of the original total storage volume. Damage to the turbines, as shown in figure 104, was significant due to abrasion by sediment flowing through the system.

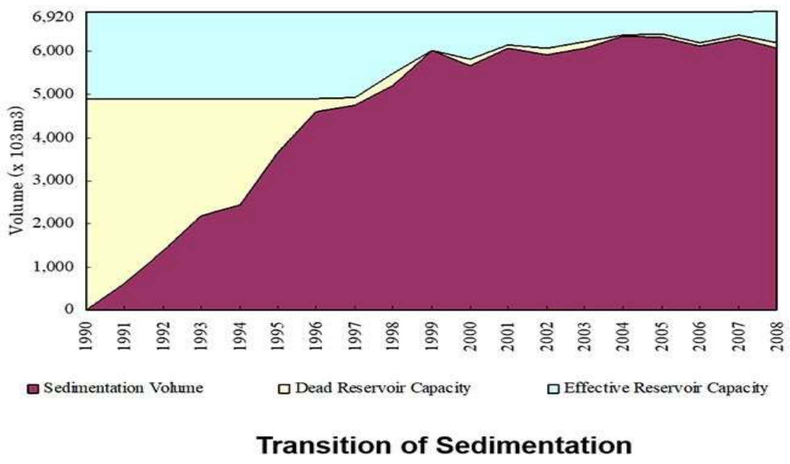


Figure 103 sedimentation from 1990 to 2008 in Bakaru reservoir

Figure 104 damage to the turbines

The principal reasons for the high rate of sedimentation at Bakaru are that the actual sediment yield is much greater than that estimated during the design phase. The sediment yield used in the design was 133,000 m3/yr (about 172,900 t/yr), which amounts to a specific sediment yield of 160 t/km2/yr. The actual sediment load was later estimated at 760,000 m3/yr (about 988,000 t/yr), amounting to a specific sediment yield of 915 t/km2/yr. The sediment yield was therefore underestimated by a factor of five to six.

The project was originally designed to manage sediment through drawdown sluicing. The standard operating procedure as regards drawdown sluicing has not been implemented consistently, due to the fact that Bakaru supplies a significant amount of power to South Sulawesi. Dispatching needs overruled the implementation of sediment management procedures, as indicated further on in this case study.

9.5 Sediment management strategies

The project was originally designed to execute sluicing of sediment whenever the discharge in the river exceeded 400 m3/s. However, the low frequency of these flood magnitudes resulted in the frequency of sluicing not being sufficient. The standard operating rule (SOP) was changed in 2002 to sluice the reservoir whenever discharges in the Mamasa River exceeded 200 m3/s. Figure 105 illustrates the operating rule for a precipitation event in November 2008.

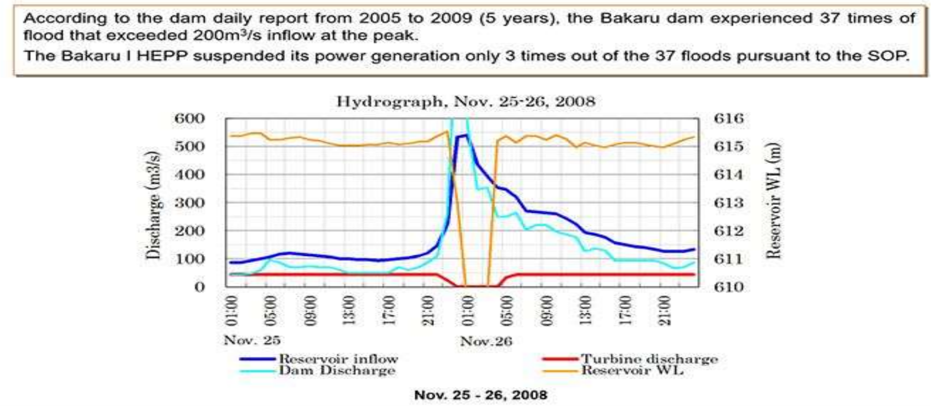


Figure 105 standard operating rule operation

The SOP decision process is shown schematically in the figure(106) below.

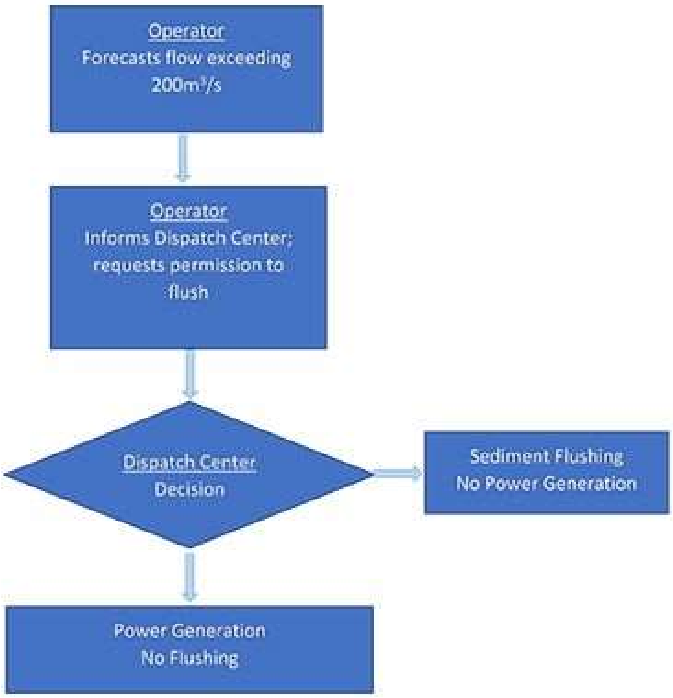


Figure 106 standard operating rule decision scheme

In many cases when the reservoir could have been sluiced, the dispatch center chose not to, giving priority to power generation. Figure 107 illustrates that during the period 2000 to 2009, there were 24 events when discharge exceeded 200 m3/s, but sluicing was only implemented nine times, and the duration of the sluicing events was limited to about four hours, which is not sufficient. When sluicing, the flushing gates were sometimes only partially opened to maintain the water level for concurrent power generation. In such cases, pressure flushing rather than drawdown sluicing was implemented.

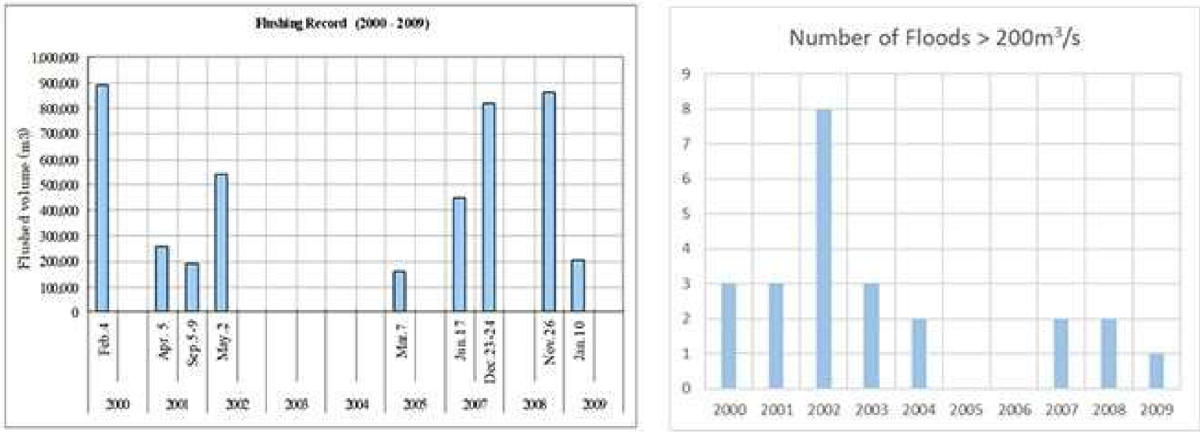


Figure 107 drawdown and sluicing records

The difference in the amount of sediment that can be removed when the gates are fully opened and when they are not fully opened is illustrated by the following example. On 4 February 2000, sediment was sluiced, and power plant operation was completely suspended. This amounted to 863,000 m3 of sediment being sluiced while the daily inflow of water was 584.7 m3/s. Conversely, on 5 April 2001, a pressure flushing operation was carried out while simultaneously generating power; i.e. the water surface elevation was kept high while the gates were only partially opened. This resulted in removing about 256,840 m3 of sediment, while the average water inflow to the reservoir was 100 m3/s. Sluicing was not performed when the flows exceeded 200 m3/s, but pressure flushing was executed at a lower flow. The events in 2001, 2005, and 2009 were likely to have been pressure flushing events that did not follow the standard operating procedure to sluice. The relationship between the number of events when the discharge exceeded 200 m3/s and the number of sluicing events performed can be observed in the graphs.

After sedimentation problems became significant, the sluicing of sediment was complemented by dredging. Comparison of achieved and contracted mechanical excavation amounts of sediment are shown in table 108, and figure 109 illustrates the activity.

No.	Duration	Contract amount	Achievement
1	15-Nov-05 - 2006/4/22	820,000	80,000
2	2006/12/29 - 2007/9/5	994,600	696,220
3	2007/12/28 - 2008/11/22	700,000	700,000
4	2008/12/31 - 2009/4/24	1,400,000	1,346,000

Figure 108 contracted and achieved the amount of mechanical excavation of sediments

Figure 109 dredging activity at Bakaru reservoir

9.6 conclusion

The sedimentation problems at Bakaru are partially due to the sediment yield being underestimated by about a factor of 5.7 during design. This is a common problem in many projects, due to a lack of concurrent historic sediment concentration and water discharge data. This emphasizes the importance of collecting sediment concentration and water discharge data on a regular basis, and over the long term.

Another challenge is that Bakaru contributes a significant portion of the energy demands of the South Sulawesi region, making it difficult to implement the SOP for sediment management when the opportunity occurs. The difficulty that arises if drawdown sluicing is not regularly carried out during high flow events is that the sediment that discharges into the reservoir deposits and is not conveyed through the reservoir.

Experience also shows that pressure flushing only clears sediment immediately upstream of the gates, as shown in figures 110 and 111. To remove deposited sediment further upstream it is necessary to implement drawdown flushing (instead of drawdown sluicing), which will likely be unsuccessful in the case of Bakaru because its reservoir is relatively wide compared to achievable flushing flows of 200 m3/s. To successfully implement drawdown flushing, it will be necessary to open more gates and use higher flushing flows, which is not likely to be possible given the important role that Bakaru plays in supplying power to the South Sulawesi region.

Figure 110 sluicing event in 2013

Figure 111 sluicing event in 2013

Chapter 10

Empty flushing

10.1 strategy literature review

Empty flushing, or simply flushing, entails opening a low-level outlet to completely empty the reservoir, thereby scouring sediment deposits.

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 112). 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.

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].

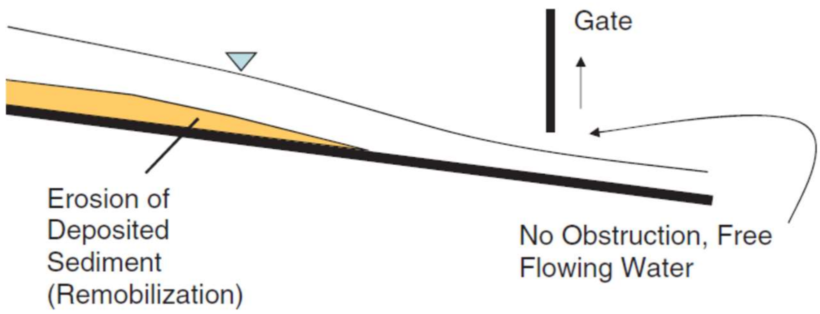


Figure 112 Schematic representation of drawdown flushing.

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].

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]. 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 the 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, 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.

As a general rule, flushing sediment-laden water through the powerhouse is not recommended because it can cause abrasion of the turbines. Sand, in particular, will quickly destroy turbines.

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.

Case Study

South Africa – Welbedacht

10.2 introduction

Welbedacht Dam, a 32 m high gravity dam located in the Caledon River, South Africa, which is part of the Orange-Senqu River system, was completed in 1973 with an original storage capacity of 114 Mm3. The reservoir is 43 km long, with a slope of 0.00048. The dam was built to supply water to Bloemfontein City, supplying 35.98 Mm3/yr on average. Since sedimentation has severely reduced its reservoir storage capacity an off-stream storage reservoir, Knellpoort Dam, was constructed to supplement storage. See figure (113)

The dam houses six radial gates serving as a spillway with an invert of approximately 1395 masl, which is 15 m above the original river bed. The maximum (Full Supply Level (FSL)) and minimum operating levels are 1402.9 masl and 1385.22 masl respectively. The original riverbed elevation at the dam was 1380 masl, which has increased to 1394 masl due to sedimentation.

Figure 113 The Welbedacht Dam

Bloemfontein is the sixth-largest city in South Africa, with a population around 300 000. It is situated in the Modder River catchment, which has insufficient water resources to meet the growing water requirements. The water supply to Bloemfontein is, therefore, augmented from the adjacent Caledon River by means of the Caledon - Modder River Government Water Scheme (CMRGWS).

Bloemfontein was originally envisaged to receive Orange River water from Vanderkloof Dam and the outlet works for the transfer scheme still exist at the dam wall. For various reasons, however, constructing a smaller scheme on the Caledon River was implemented before completion of the Vanderkloof Dam. The Welbedacht Dam on the Caledon River was constructed as the main storage element of the CMRGWS and water is abstracted from this dam for transfer to Bloemfontein and various smaller users along the way.

The Welbedacht Dam is constructed by the Department of Water Affairs. Its purpose was to supply water to the city of Bloemfontein via the 115-km-long Caledon-Bloemfontein pipeline, which has a capacity of around 1.157 m^3/s. Due to the high sediment concentration in the water, the transfer from Welbedacht Dam is first purified at the

Welbedacht Purification Plant which is located just downstream of the dam. The purification plant has a capacity of 1.68 m^3/s. The hazard potential of the dam has been ranked high.

Due to siltation, the storage capacity of the Welbedacht Dam reduced rapidly from the original 114 million m^3 to roughly 16 million m^3 during the 20 years since completion. This reduction in storage created problems in meeting the Bloemfontein demand at an acceptable level of reliability and as a result, the 50-m-high Knellpoort Dam was completed in 1988.

Although the dam was designed to facilitate empty flushing it is not effective because the invert level of the gates is too high above the river bed and the flushing duration is limited by the downtime allowed at the water treatment plant, which is very short.

10.3 Hydrology and Sediment

The catchment area upstream of Welbedacht Dam is 15,285 km2, with mean annual precipitation equalling 700 mm/yr. The Caledon River at Welbedacht Dam produces mean annual flow equalling 1,241 Mm3/yr with an annual coefficient of variation of 0.589. As shown in figure 114, most of the inflow is received from April to June.

The average total sediment load is 15 Mt/yr, consisting of estimated bedload of 1.5 Mt/yr and suspended sediment load equalling 13.5 Mt/yr; equating to a specific sediment yield of 838 t/km2/yr. The sediment is composed of a fine material mainly silt and clay. The particle size distribution of the sediment is 5 percent gravel, 15 percent sand, 50 percent silt, and 30 percent clay. The rating curve used to calculate the suspended sediment load is C = 793.32* Q0.664 (where C = sediment concentration in (g/m3) and Q = water discharge (m3/s)).

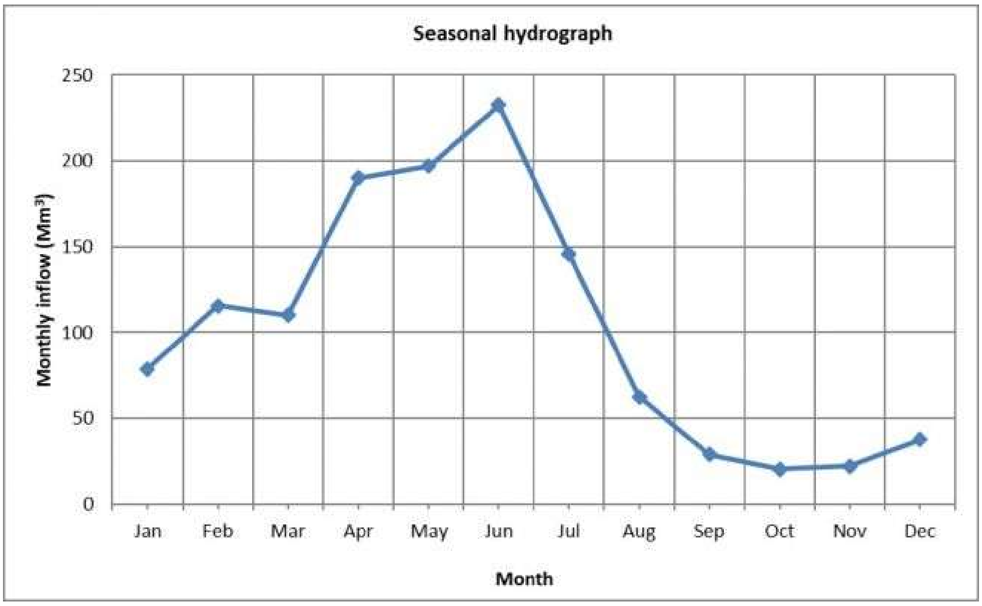


Figure 114 Seasonal hydrograph (catchment area upstream of Welbedacht Dam) Monthly inflow average (Mm3) from 1995 to 2017

10.4 Sediment problems

The original reservoir volume of 114 Mm3 reduced by 50 percent within the first five years of operation. Sedimentation continued, and the current reservoir volume is 5.4 Mm3. The original relationship between the reservoir volume and average annual flow was 0.092, which, based on the Brune curve, originally trapped 85 percent of the incoming sediment. The current reservoir volume – average annual flow ratio is only 0.004, which means that the sediment trap efficiency is very low (almost zero). The maximum storage loss that occurred in a single year was 12 Mm3, while the average annual storage loss is 2.48 Mm3/yr. This is equivalent to 2.2 percent storage loss on average per year.

By 1978, only five years after completion of the dam, it was clear that there are problems because nearly 50 percent of the original Full Supply Capacity (FSC) was lost due to sedimentation. Plans were put in place to deal with the reduced storage capacity by designing the off-stream Knellpoort Dam and Tienfontein pump station to deal with the loss in storage capacity of Welbedacht Reservoir. Based on the bathymetric surveys, by 1978 it was clear that the sluicing/flushing of sediment through the Welbedacht Dam is not as effective as the designers and operators hoped it would be. In figure 115, the longitudinal profiles show the increase in sedimentation. The first five years was a relatively wet period and further downstream on the Orange River one of the large dams was under construction. To protect the construction site against flooding, Welbedacht Dam was operated to store flood water and empty flushing was not implemented. This increased the rate of sedimentation, especially during the first 3 years.

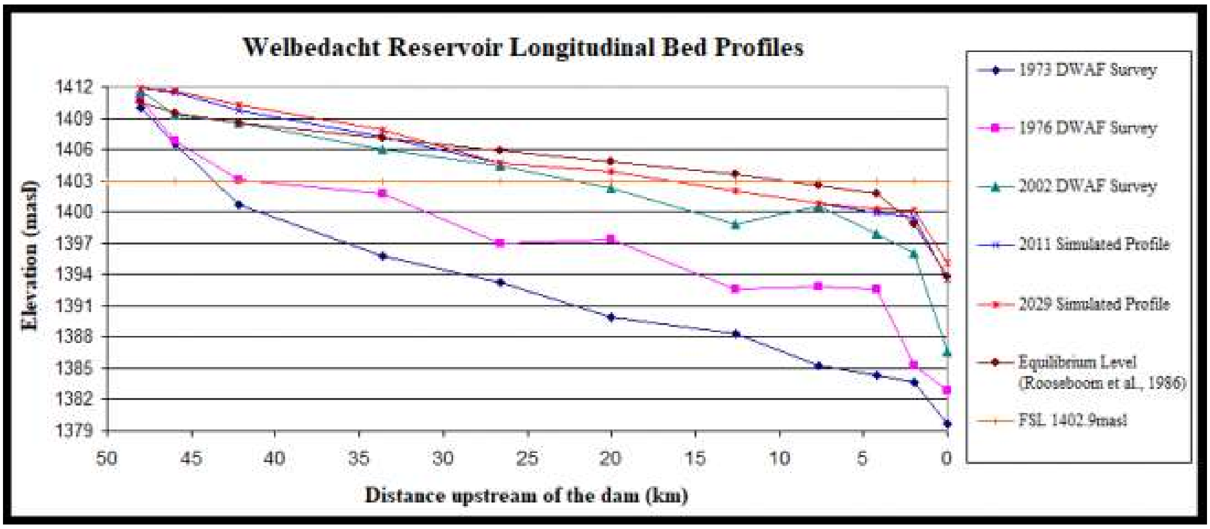


Figure 115 Welbedacht longitudinal bed profiles calculated by bathymetric surveys

The high inflowing sediment load has decreased the reservoir storage capacity to currently only 5 percent of the original full supply volume as seen in the graph in figure 116. The small storage capacity now makes it difficult to deal with droughts that normally last 3 to 5 years. Near the dam, the intake to the potable water treatment plant is affected by the reservoir sedimentation, which due to high suspended sediment concentrations results in higher chemical treatment costs. Further upstream in the reservoir the Tienfontein pump station was constructed during the 1980s to pump to an off-stream storage called the Knellpoort

Dam. The pump station is now due to the rise in the reservoir bed level, which is much higher than the full supply level of the reservoir.

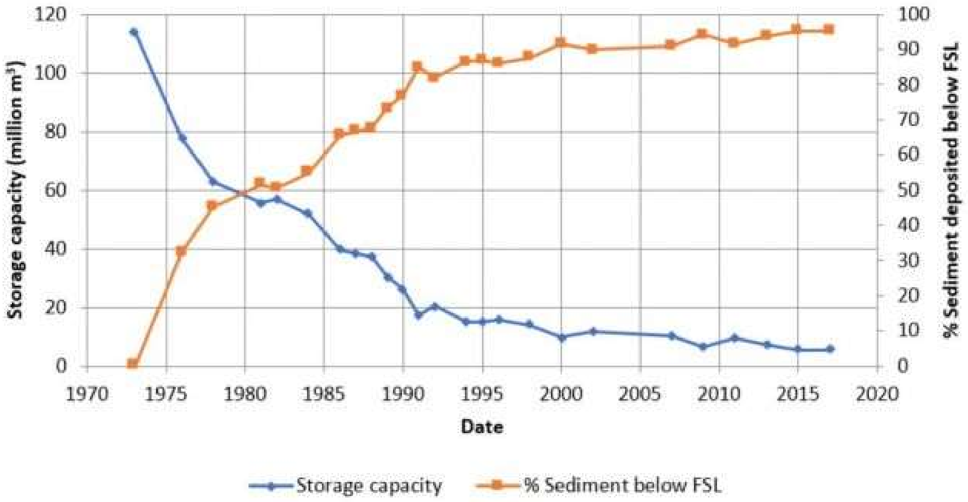


Figure 116 Evolution of Welbedacht storage capacity (%) and sediment below the full storage level (%) from 1973 to the present

The experiencing severe problems Bloemfontein to Wepener road bridge which crosses the river about 50 km upstream of the dam, had to be raised by more than 10 m during the past decade due to the reservoir sedimentation causing significantly higher flood levels; even during annual floods, the bridge deck was submerged before the raising. Figure 117 and 118 are two images taken during the 2000s of the rivers at the Dewetsdorp-Wepener bridge. This was before the raising of the bridge. The first photo shows the sediment near the deck and the second photo the regular flooding of the road due to the high silt levels.

The sedimentation problems cannot really get worse than what they are at present, with the reservoir silted up 95 percent, the water treatment plant at the dam operating as run-of-river abstraction and with the upstream abstraction at Tienfontein pump station having difficulties to deal with the high reservoir bed and silt loads.

Figure 117 De Wetsdorp-Wepener bridge during a flood event

Figure 118 The Bloemfontein-Wepener road flooded

10.5 Sediment management strategies

The sediment management methods used include watershed management, empty flushing, and off-stream reservoir.

Watershed management entailed constructing weirs in the upstream river during the 1950's. These weirs rapidly filled with sediment, causing downstream erosion. Gullies are natural features of the catchment and are not considered the main source of sediment. It is estimated that catchment management activities have been about roughly 10 percent effective.

Empty flushing was implemented for the first time in 1992, which is about 19 years after project commissioning. Efforts to remove sediment from the reservoir through flushing has not been very effective, partly since the invert elevation of the radial gates used for flushing is about 15 m higher than the original river bed. The drawdown of the water surface elevation occurs at a rate of 8 m/day, and flushing may occur twice a year for a period of one day. The water treatment plant prefers to limit downtime to about 12 hours, which further reduces the effectiveness of drawdown flushing.

The amount of sediment flushed during a single flushing event in 1992 was about 3 Mm3. The upstream view of the flushing operation in 1992 and the downstream discharge can be seen in figure 119 and 120. The sediment concentration during flushing events ranges from an average of 73,128 mg/l to a maximum of 134,400 mg/l. Empty flushing is deemed to be about 10 percent effective.

Off-stream reservoir through the construction of Knellpoort Dam, which was constructed in 1988 is deemed 70 percent successful. Its rate of sedimentation is very low and its storage capacity has not reduced significantly since commissioning. However, the problems experienced at the pump station due to high sediment levels in Welbedacht Reservoir presents difficulties.

Recently, without flushing, the reservoir volume is approaching equilibrium at about 95 percent storage loss. Routing, empty flushing, and off-stream storage will be further sediment management strategies to be considered in the future.

The effectiveness of flushing may be improved in the future by reconstructing the dam outlets through lowering them. Furthermore, to improve the efficacy of flushing longer downtime periods at the water treatment plant are required. This may be accomplished by providing additional raw water storage for a minimum of three days at the water treatment plant. Other alternatives include constructing a pipeline from Gariep Dam to Bloemfontein for more water supply and a pipeline from Knellpoort Dam to the Welbedacht Dam water treatment plant.

Figure 119 Flushing operation 1992, viewed looking upstream from the right bank at the dam

Figure 120 Flushing discharge with high sediment concentrations looking downstream from the dam

10.6 conclusion

Although Welbedacht Dam was originally designed to facilitate flushing the invert of the radial gates was too high and the acceptable downtime at the water treatment plant too short to ensure removal of enough sediment through flushing. It may also have been possible to maintain more favorable storage conditions if flushing commenced soon after commissioning of the reservoir, instead of waiting almost 20 years to implement it for the first time.

Chapter 11

Modify operation rule strategy

11.1 strategy literature review

The principal technique used to modify the sedimentation pattern, or to redistribute deposited sediment is to manipulate water levels in the reservoir.

Reservoir deltas are normally composed of coarse sediment that cannot be passed through turbines without causing severe damage. Every time the reservoir is drawn down the river flows across the top of the delta and scours sediment, moving it downstream and closer to the power intake. This downstream progression of a delta. To slow the advance of the delta, the reservoir's minimum operating level may be gradually raised, focusing delta deposition into the upper portion of the reservoir. Figure 121 compares delta advancement for a constant minimum operational level against an increasing minimum operational level, showing that by gradually increasing the minimum operating level the downstream advance of the delta is retarded. As a trade-off, raising the minimum operating level accelerates the decline of operational storage volume.

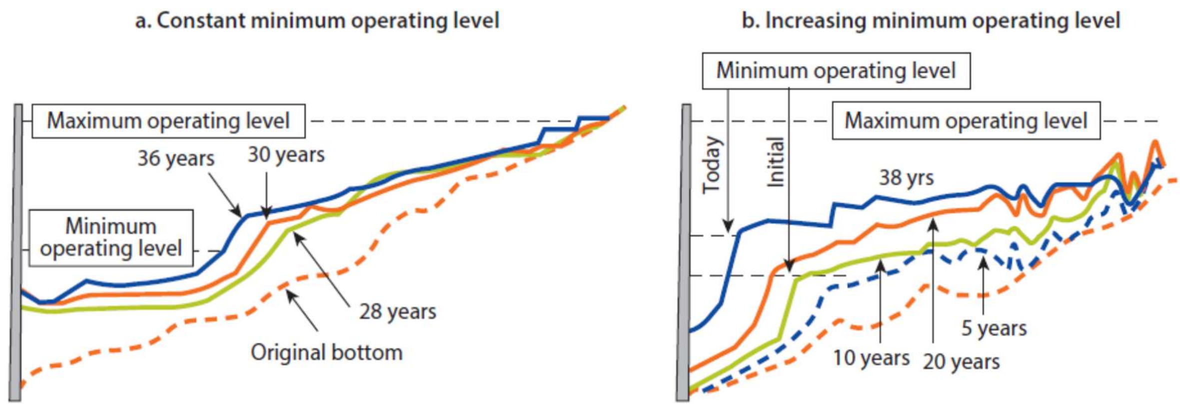


Figure 121 Delta Advance Depending on Reservoir Operational Levels

Case study:

Chivor hydropower plant Colombia

11.2 introduction

The Esmeralda reservoir supplies the 1,000 MW AES Chivor hydropower project, located in the Boyacá province of Colombia, about 90 km north-east of Bogotá. The project is owned by AES Chivor & Cia., a subsidiary of AES Corp. see figure (122).

The earth fill dam is 237 m tall and impounds a narrow 18 km reservoir which receives inflow from the Garagoa and Somondoco rivers, with added contributions by diversions via tunnels from the Tunjita, Negro and Rucio rivers. A schematic of the reservoir layout is shown in figure 123. Water is diverted via a 7 km tunnel to the Chivor powerhouse, which discharges to an adjacent tributary, Río Langupá. Power is generated by eight vertical-axis Pelton units operating under 800 m of the head and a total design flow of 160 m3/s.

Figure 122 chivor dam

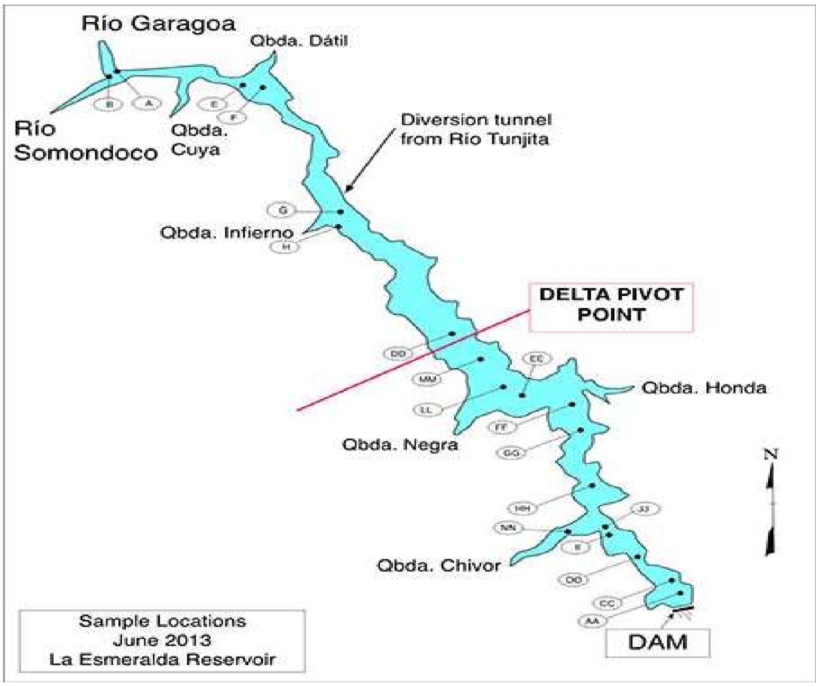


Figure 123 reservoir schematic

11.3 Hydrology and sediment

The mountainous 2,420 km2 catchment produces a mean annual inflow of 2,471 Mm3. The seasonality of inflow as compared to turbine capacity is shown in figure 124.

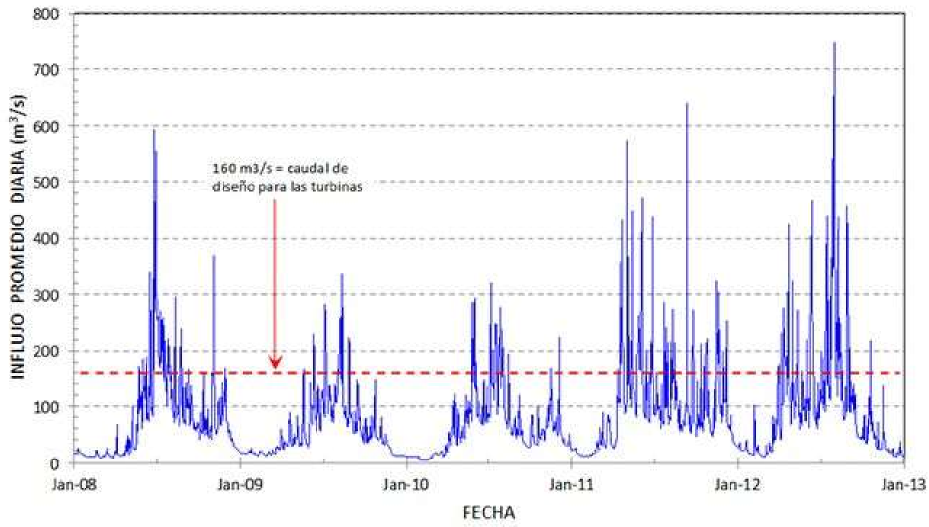


Figure 124 inflow hydrograph for La Esmeralda reservoir and turbine capacity

When filling began in 1975, the 758 Mm3 reservoirs had a capacity: inflow ratio (ratio of gross storage capacity to mean annual inflow) of 0.31. Of this total, 90 Mm3 consisted of dead storage. The rate of storage loss has averaged about 3.4 Mm3/yr (about a 0.4 percent annual loss), which is not unusually high, but after 41 years of operation the reservoir had lost 18 percent of its total volume and sediment beds were approaching the intake.

The delta deposits are comprised primarily of sand (d50 ~0.2 mm) which is deposited underwater during the wet season, but during drawdown is remobilized and transported deeper into the reservoir. The photograph in figure 125, taken in the upstream portion of the reservoir in Garagoa and Somondoco confluence, shows sand deposits that have been scoured and moved further downstream, exposing the gravel riverbed created by bedload transport.

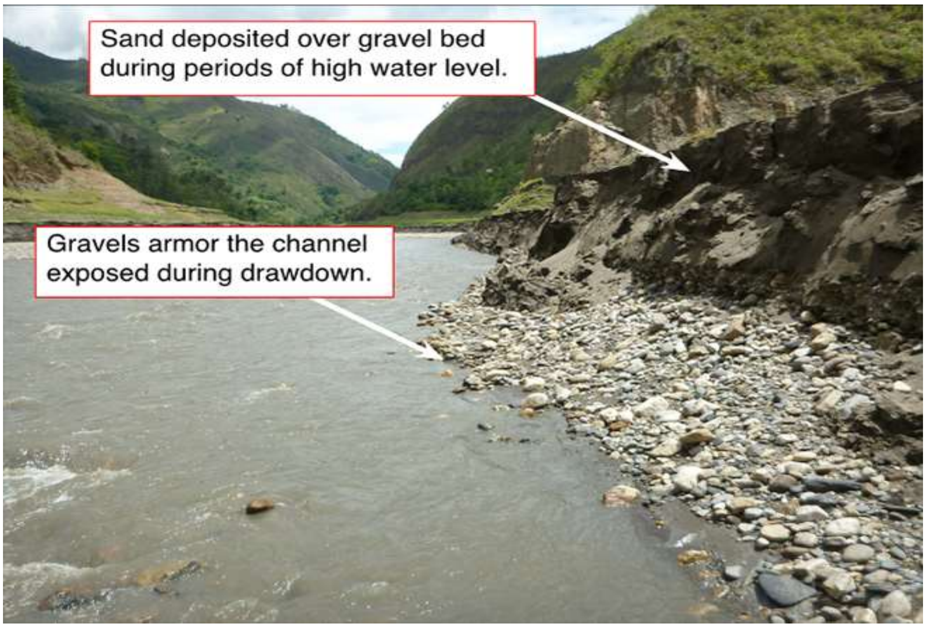


Figure 125 sand deposits eroded and transported further downstream during the annual drawdown, uncovering the river's gravel bed

Because the reservoir is drawn down to similar levels each year, the delta exhibits little vertical growth; most sediment is deposited on the face of the delta, maximizing its rate of advance toward the power intakes, as shown in figure 126.

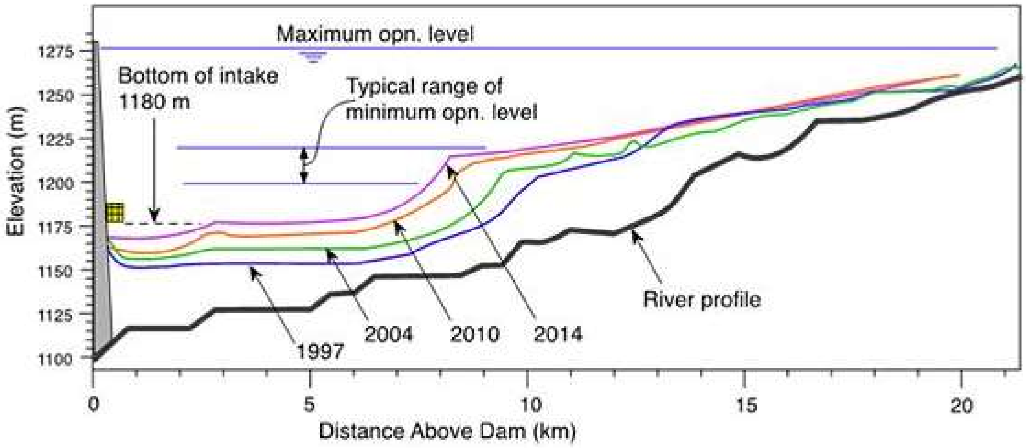


Figure 126 longitudinal profiles along La Esmeralda reservoir showing the pattern of delta growth

11.4 Sediment problems

The project experienced a severe sediment-related incident in 2004 when an out-of-season flood occurred with the reservoir drawn down to a low level. This inflow transported a high concentration of sediment along the length of the nearly-empty reservoir and into the intake and may have also included sand scoured from the delta.

The power station continued operating throughout this event, as mandated by the grid power dispatcher and was not taken offline until it became apparent that severe damage was occurring. The turbines, as well as the spherical and needle valves, were severely eroded.

Figure 127 gives an example of the damage that occurred over less than 24 hours of operation to the Pelton needle valve, compared with normal damage after approximately 10,000 hours of operation.

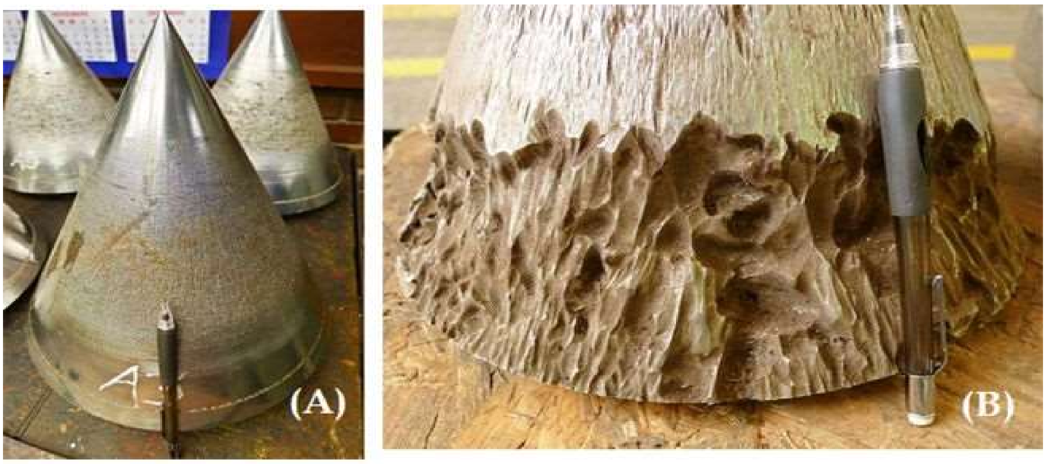


Figure 127 damage to the Pelton needle valve. (A) normal damage after ~10,000 hours of operation and (B) catastrophic erosion in 2004 which occurred in less than 24 hours of operation under high sediment concentration

11.5 Monitoring

Responding to the damage in 2004, a submersible pumping system was installed to sample water at the intake, and a basic sediment laboratory was installed at the dam for real-time sample analysis. Samples are pumped whenever significant inflow events occur while the reservoir is at a low level. The minimum operational level was raised from the 1,190 m design level to 1,205 m. In addition, dispatch arrangements were made to enable the plant to be taken offline to avoid future sediment damage.

Reservoir bathymetry was originally performed at intervals of three to four years using cross-section surveys. However, with increasing sedimentation concerns, the interval between surveys was shortened to annual measurements, and the methodology was changed to contour survey instead of cross-sections.

In two particular years, 2014 and 2016, both contour and range-line surveys were performed, with a survey difference between them of < 1 percent in both cases. However, because the annual rate of storage loss averages 0.4 percent, which is smaller than the margin of error of bathymetric survey measurements, these close-interval surveys showed the reservoir to be losing capacity in some years and increasing capacity in others.

It was decided that a better monitoring strategy would need to be implemented to perform a bathymetric survey at two-year intervals, and to use the remaining monitoring budget to perform vibracore sampling, also at two-year intervals. This way, it would be possible to track not only the configuration of the deposits but also to detect any change in their composition which could make them more abrasive to the turbines.

With sediment beds advancing to the area of the intake, it was desired to document the composition of the sediment in the vicinity of the intake, to determine if sands were being transported beyond the delta and into the area of the power intake. It was also desired to determine the extent of sands delivery by lateral tributaries near the dam. The first sediment sampling was performed by vibracore over a two-day period. Figure (128 a,b) shows the sediment sampling in La Esmeralda reservoir using the battery-powered portable vibracore equipment.

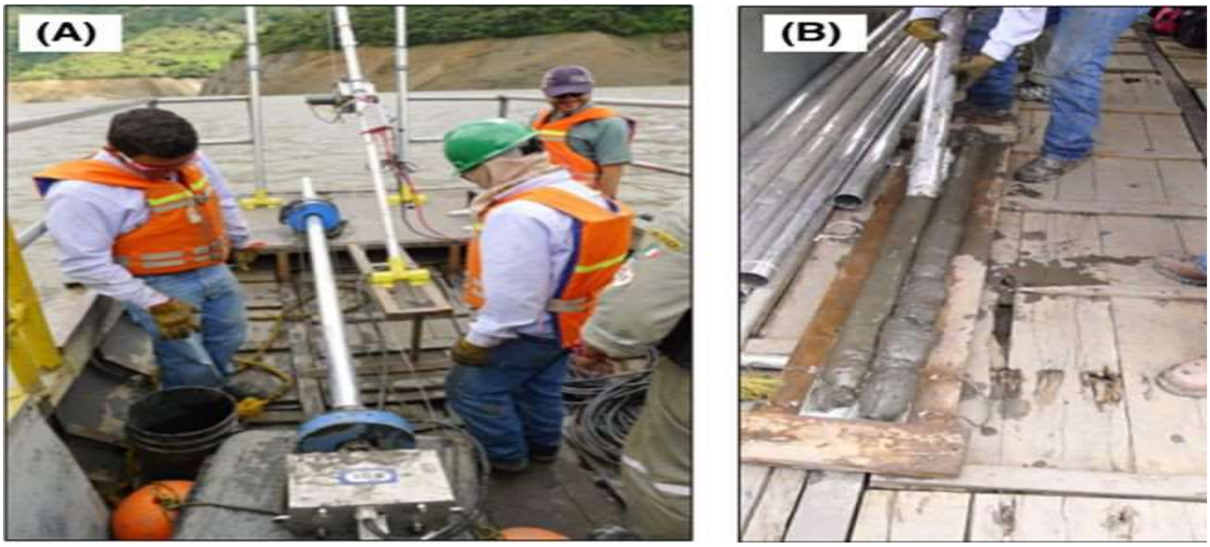


Figure 128 sediment sampling in La Esmeralda reservoir using the battery-powered portable vibracore equipment. (A) shows the electrical-powered vibrating head with the 76 mm coring tube attached, and (B) shows the extrusion of 3 m cores near the dam

Vibracore was selected as the sampling method because multiple locations could be sampled over a short period of time (about 10 sample locations per day). Furthermore, by examining the samples as they arrived on deck, it was possible to adjust the sampling locations depending on the type of material encountered in each core. Sub-samples were collected from different depths in each core for laboratory analysis. The upstream portion of the reservoir, consisting of delta deposits exposed and scoured during the seasonal drawdown, were observed and sampled by hand (see figure 129).

Figure 129 sampling by hand of delta sediment in the reservoir exposed and scoured during the seasonal drawdown

In 2015, at LISST real-time laser diffraction system was installed at the powerhouse, sampling water at the draft tube. The objective of this monitoring is to better document the changing grain size and concentration of sediment passing through the turbines as sedimentation progressed and to provide better data for correlation to turbine abrasion rates.

11.6 Sediment management strategies

Sustainable Sediment Management Plan

A Sustainable Sediment Management Plan was developed in order to define a set of actions leading to a viable long-term strategy.

Regulatory agencies in Colombia, accustomed to clear-water releases below dams, have not yet embraced the need to begin releasing sediments.

As a result, regulations currently impede some management options, but these may become more viable in future.

It was also recognized that long-term sediment management measures could be expected to become better refined over time as a result of both regulatory changes and technical considerations, as more complete monitoring data come available and the success of initial management measures are evaluated.

As such, the Sediment Management Plan was developed with three objectives:

- Define actions that could resolve the immediate sediment challenges.
- Identify the long-term strategies to achieve sustainable utilization.
- Refine the monitoring data and studies needed to finalize and implement sustainable long-term project re-design and operation.

The first version of the Sustainable Sediment Management Plan was developed based on the available design and hydrologic data, the sediment sampling data described above, 1-D sediment transport modeling, and preliminary energy modeling to evaluate the sensitivity of power production to diminishing live pool volume.

Sediment transport modeling: The long-term evolution of reservoir sedimentation was simulated for different operational scenarios using the SRH-1D sediment transport software from the U.S. Bureau of Reclamation. Simulations up to 100 years were performed using a one-day time step. Modeling showed that under the current operational regime, the toe of the delta with coarse sand could reach the intake in as little as 20 years. However, by increasing the minimum operating level by 0.5 m/year, coarse sediments would be focused on the top of the delta instead of at the downstream delta face, thereby delaying the arrival of sand at the intakes by 40+ years.

Energy simulations: Energy modeling simulated the effect of reduced reservoir volume on annual energy production. Because inflow is relatively well-distributed throughout the year, the reduction in live storage from 500 Mm3 to 100 Mm3 would represent only a 5 percent reduction in an annual generation, if following an operating rule that maximizes energy production when the reservoir is at a high level to maintain a reserve capacity to capture small flood events. However, it would have a greater impact on income because it would shift more power production away from drier months, when energy prices are higher, and into the wetter months when prices are lower. It would also complicate the planning and contracting of power dispatch since the firm power capacity would also be diminished.

<u>The following options were analyzed:</u>

- Immediately begin raising the intake level to avoid the entrance of sediment and continue raising the intake until it converts to run-of-river operation.
- Delay raising the intake level, passing as much fine sediment as possible through the turbines and thereby delaying the arrival of the coarse delta sediment to the intake.
- Rehabilitate the river diversion on the right side of the dam and use this to flush or sluice sediment.

The Sediment Management Plan was developed and then reviewed by a panel of four experts (two international and two local), including both sedimentation and civil design expertise. This panel was convened at the dam site to review the data and sediment management options and finalize recommendations for sustainable management.

<u>The alternatives examined at this site are briefly outlined below:</u>

1. Immediately increase the level of the intake to prevent the entry of fine sediment, and progressively raise the intake as required to stay above the sediment bed.

This has the disadvantage of trapping almost all the fine sediment in the reservoir, which would accelerate the arrival of coarse sediment to the dam as the delta progresses over the previously deposited fine sediment.

2. Allow for the ability to increase the intake level in the future, but do not raise the level until the abrasion rate on the turbines requires it.

This alternative would pass as much fine sediment as possible through the turbines, minimizing the trapping of fine sediment and thereby preserving reservoir volume for storage of the coarse sediment, which cannot be passed through the turbines.

3. Progressively raise the reservoir level to retard arrival of the delta at the intake.

This alternative may be implemented independently of the other alternatives and will focus coarse sediment deposition further upstream in the reservoir and further away from the intake, but it will require the progressive raising of the minimum operating level. The benefit of this operation was already demonstrated by the 1D model simulations, plus prior experience at another reservoir.

4. Perform reservoir flushing to achieve a sediment balance and sustain long-term storage capacity. Flushing could be accomplished by rehabilitating the abandoned river diversion on the right abutment.

This alternative has the disadvantage of construction difficulties (since the bypass tunnel entrance is deep underwater and buried in sediment), and there are also regulatory restrictions on flushing that would impede the rapid implementation of this measure. This measure may be considered as a future long-term alternative.

5. Continuous dredging to stabilize reservoir capacity and preserve long-term storage capacity.

Dredging would be potentially feasible if it were possible to discharge sediment below the dam. However, under the current regulatory environment, this was not considered to have an assured positive outcome in the regulatory process. It might be considered as a complementary measure in the future for the control of coarse sediments as they approach the intake.

These measures are in addition to the real-time monitoring and sediment-guided operation that was already being performed.

11.7 Actions taken

Given the need for immediate action to be taken to protect the power plant and based on sediment sampling which revealed an absence of sand in the fine sediment being deposited near the intake, a combination of alternatives #2 and #3 described above were selected for immediate implementation. The minimum operating level was increased to 1,210 m and programmed to increase thereafter by 0.5 m/yr until modified by new recommendations from a Sediment Management Plan update.

A design was prepared for the modification of the intake to include three new intakes at progressively higher levels (see figure 130). Only the lowest of the new intakes would be constructed at this time so that it could be placed into operation immediately as dictated by the rate of sediment advance and turbine abrasion. However, the tunneling work for all intake levels would be completed, except that the final 12 m of rock excavation would be completed when it became necessary to construct the successive intake level.

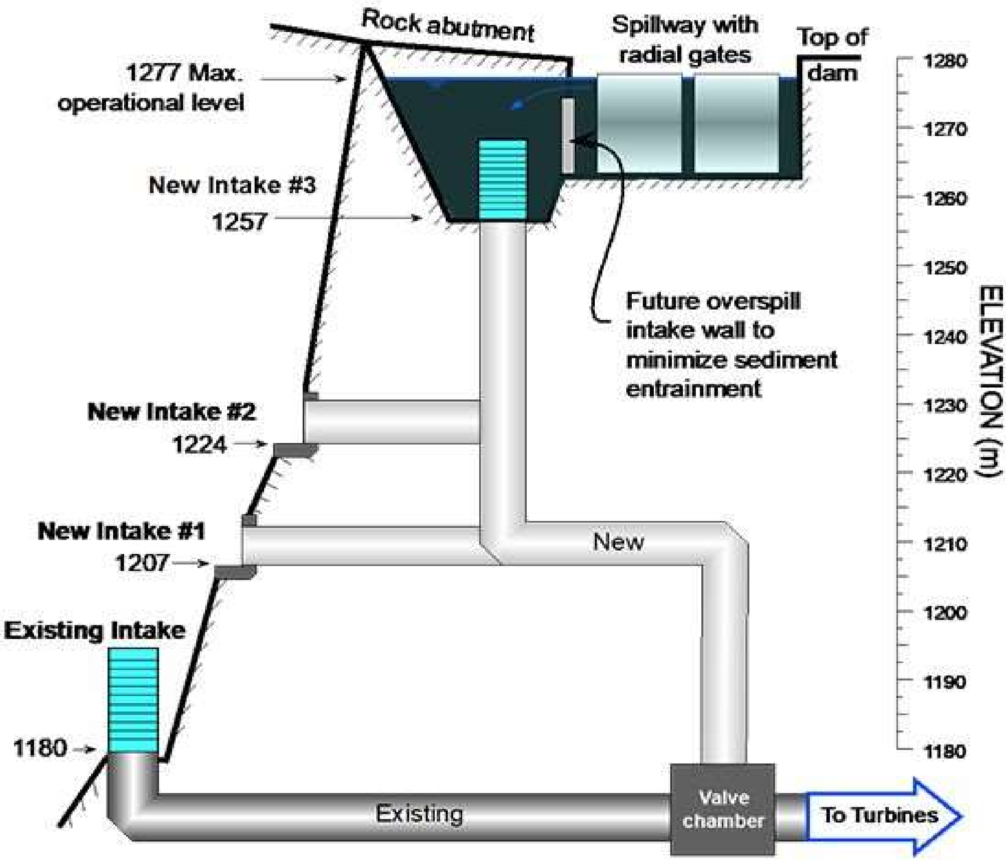


Figure 130 conceptual schematic showing the relationship between existing and new intakes

Additional sediment management activities are also being implemented to help define the elements which will support the transition to long-term sustainable operation:

- Preparing sediment balances and the initial Sediment Management Plan for immediate action, which will be updated over time.
- Monitoring sediment inflow from the Somondoco and Garagoa rivers.
- Completing a study of turbine abrasion and potential remedial actions, being undertaken through the University of the Andes.
- Performing bathymetric studies and vibracore sampling of sediment deposits for granulometric analysis, every second year.
- Performing feasibility studies for: sediment contribution from each watershed and methods to reduce sediment yield; sediment release alternatives (flushing, sluicing, dredging) to achieve a sediment balance; analyse alternative operating rules and the value of storage volume, to better define the target long-term storage to be sustained; environmental evaluation of different sediment management alternatives.

Given the growing severity of the sedimentation problem, and with 70 percent of all electric energy in Colombia being generated by hydropower, AES Chivor has also begun working with other energy producers, universities, engineering associations, and environmental organizations to promote legislation that focuses on achieving a long-term balance between sediment input and discharge in the interest of sustaining the existing renewable hydropower generation infrastructure.

11.8 Conclusion

The studies performed at AES Chivor showed that sustainable operation is feasible at a large 1,000 MW storage hydropower facility, which did not incorporate any consideration of long-term sediment management into its original design. The studies also point to the increasing complexity associated with the need to incorporate sediment management into project design and operation. Finally, experience at this site highlights the value of making an early start on the transition to sustainable use and the importance of developing adequate monitoring data as the basis for identifying and implementing both short and long-term strategies.

Chapter 12

Adaptive strategies

12.1 strategy literature review

Adaptive strategies are actions to mitigate the impacts of sedimentation but that do not involve handling the sediment. They may be used along with or instead of active sediment management. Several types of adaptive strategies are outlined below.

• **Reallocate storage and improve operational efficiency**. Multipurpose reservoirs may be divided into two or more beneficial pools defined based on water level.

For example, a reservoir may have a high-level normally empty pool reserved for capturing flood flows, and a lower-level normally full water conservation pool used for water supply storage (figure 131). The lowest pool, dead storage, may be allocated to “sediment storage,” although sedimentation will normally affect all pools. However, sedimentation does not affect all pools equally, and in many reservoirs, the flood control storage pools have experienced much less sedimentation than the lower pool(s) used for water supply, especially in areas where sediment inputs are primarily composed of fines. As a result, sedimentation will affect water supply much more quickly than it will affect flood control.

Pool limits may be modified to reallocate the storage loss in a more equitable manner among users so that sedimentation affects both pools to the same degree. This pool reallocation can be accomplished by adjusting the boundary limit between the two pools, thereby raising the elevation of the top of the conservation pool at the expense of the flood control pool.

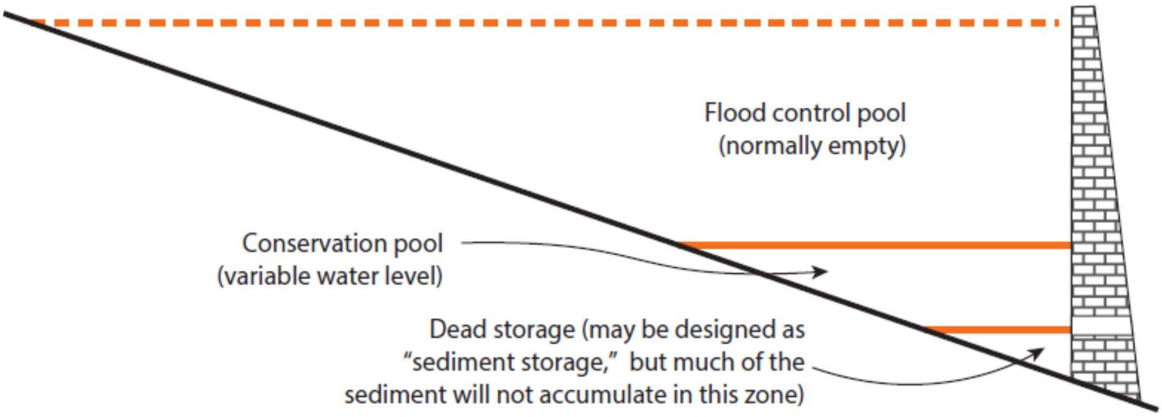


Figure 131 Allocation of Flood Control and Conservation Pools in a Multipurpose Reservoir

- **improve flood control efficiency**, for example, by refining the reservoir operating rules to optimize utilization of the available storage, replacing a decades-old operating rule with a modern operating rule based on real-time hydrologic data. In some regions, the conjunctive use of surface and groundwater may be an effective strategy for reducing the impact of storage loss by sedimentation. In hydropower reservoirs, as storage is lost the operating rule can be modified to maximize energy production, progressively raising the minimum operating level and moving the power operation closer to run-of-river operation. Improvements in operational efficiency are typical, very economical compared with many types of active sediment management, or the construction of new dams.

- **Modify structures to avoid sediment**. Sediment accumulation will eventually reach critical structures and equipment including spillways, intakes, and hydromechanical equipment. These components may be modified to handle the sediment, for example, by raising or otherwise modifying intakes, by providing protective coatings to hydromechanical equipment, or other measures.
- **Raise the dam to increase volume**. Storage may be increased by raising the dam or constructing new storage, thereby temporarily offsetting the storage loss. A new replacement reservoir may be constructed that incorporates a sustainable design.
- **Water loss control and conservation**. Water supply systems frequently contain multiple opportunities to increase water use efficiency, sustaining productivity while using less water. This may include water use conservation, water reuse, and similar techniques. Water-intensive low-value activities may be eliminated.
  This strategy provides considerable opportunities for addressing water shortages from drought, climate change, and reservoir sedimentation.
- **Decommission infrastructure**. The long-term sustainable use of all reservoirs is not justified, and a dam may be decommissioned when sedimentation renders its continued operation no longer economic or otherwise of sufficient benefit.
  However, this decommissioning must plan for the long-term management of sediment. For example, will sediment flowing over the dam eventually endanger the structure? Will the Delta continues to grow upstream and threaten upstream communities or land uses? Should the dam be modified or removed to restore environmental conditions along the river? What is the fate of the sediment released by dam removal?

Case study:

Binga hydropower plant Philippines

12.2 introduction

Binga hydropower plant, owned and operated by SN Aboitiz (SNAP) since 2008, is located in the upper reaches of the Agno River, on the island of Luzon in the northern Philippines. see figure (132&133). The plant was commissioned in 1960 with the purpose of generating electricity and providing flood control services.

Figure 132 Aerial view of the Binga hydropower project

Three dams in a cascade complex on the Agno river supply water to the 105 MW Ambuklao, the 140 MW Binga and the 345 MW San Roque hydropower plants. Binga dam, located 19 km downstream from Ambuklao, is a rock-fill dam with an inclined clay core. At a height of 107.4 m, the dam crest elevation is 586 masl, and the dam originally impounded a volume of 95 Mm3. The maximum and minimum operating levels of the reservoir are 575 and 566 masl respectively.

Figure 133 Aerial view of the Binga dam

The spillway is located at the left abutment, while the intake is on the right side leading to the underground powerhouse through an 800 m headrace tunnel. The design spillway discharge for a return period of 10,000 years is 10,521 m3/s. A location map is shown in figure 134.

Figure 134 Binga hydropower plant location downstream of Ambuklao dam (Google Earth)

Following its refurbishment in 2013, the 140 MW Binga plant now hosts four Francis vertical shaft turbines of 35 MW each. The net head is 156 m and the design discharge is 25 m3/s. The average annual generation is 238.43 GWh.

12.3 Hydrology and sediment

The catchment tributary of the Binga dam comprises 936 km2, of which 72 percent is regulated by the Ambuklao dam upstream. Although the Ambuklao reservoir traps most of the sediment, the Binga tributaries, the Leboy, Adonot, and Bisal Rivers, carry very high sediment loads. This is deposited in the upper section of the Binga delta, as shown by the white sediment deposits in figure 134.

The Philippines is one of the countries most exposed to tropical storms. Approximately 20 cyclones and typhoons hit the country each year. They are concentrated in the months of June to September but can occur throughout the year.

Due to its geographical location, the Philippines also suffers from high magnitude earthquakes. Since the middle of the 20th century, there have been eight earthquakes above 7 points in magnitude. In 1990, the island of Luzon experienced a 7.8 magnitude earthquake.

As shown in figure 135, the water inflow to the Binga reservoir has increased over the years, with the peak flow reaching up to 2,000 m3/s in 2017.

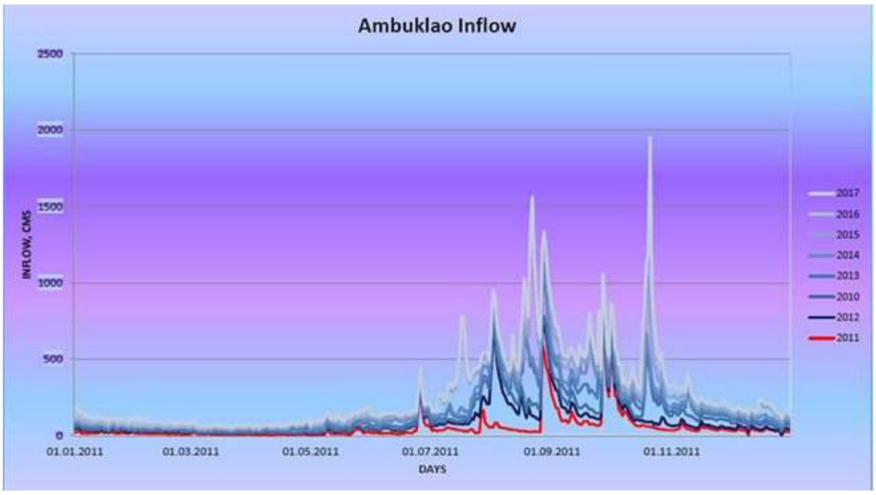


Figure 135 annual water inflow to Binga reservoir

12.4 Sediment problem

Cyclones and typhoons cause major floods and landslides that increase water inflow and sediment load in the rivers. In combination with earthquakes, the sediment load in the rivers can be very high and can contain heavy boulders that have the potential to seriously damage a power plant's units.

The annual observed sediment load through the turbines at Binga is 2.2 million tons, while at Ambuklao it is 4.5 million tons. Hard mineral concentration is not an issue because this represents just 10 percent of the sediment load.

Based on a traditional approach, the Binga reservoir was designed without any sediment management strategy. In addition, the sedimentation rate was underestimated due to the limited sediment data available at the time. After commissioning in 1960, the Binga reservoir rapidly filled up with sediment as shown in the storage capacity-elevation curve displayed in figure 136. By 1986, the reservoir had lost 35 percent of its original capacity. In 2015, the storage volume was just 21 Mm3, equivalent to 22 percent of the original storage capacity.

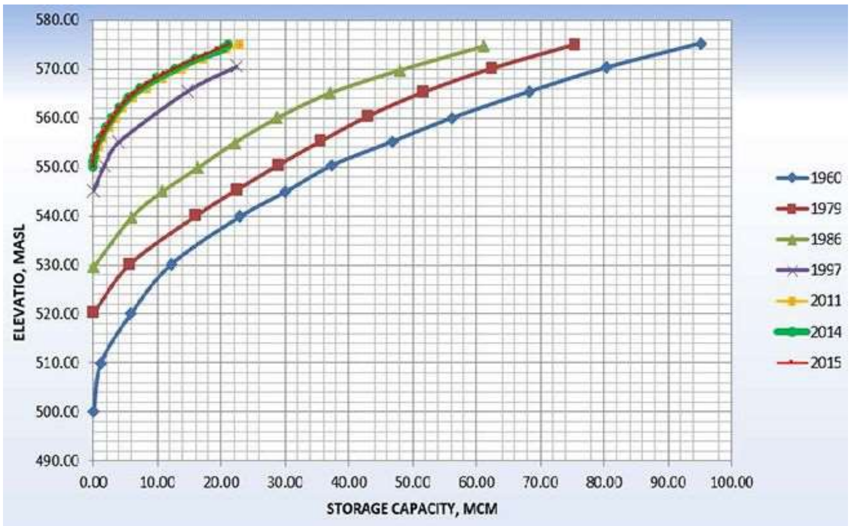


Figure 136 storage capacity (Mm3) and elevation (masl) curve of Binga reservoir from 1960 to 2015

In 2008, SNAP acquired both the Ambuklao and Binga power plants for USD 325 million. Both plants required major refurbishment due to the damaged hydro-mechanical equipment. The Binga power plant was not operational and the sediment deposits almost reached the intake level.

Due to the bathymetry of the Binga reservoir, the sediment has filled the dam and developed into a delta with a growing backwater effect, which could affect and bury the Ambuklao outlet. Figure 137 shows boulders and gravel in the backwater of the Binga reservoir.

Figure 137 sediment deposits in the backwater of Binga reservoir

An extreme precipitation event occurred in October 2009, following SNAP's acquisition of the Ambuklao and Binga power plants. The peak inflow to the Binga reservoir reached 4,000 m3/s. Figure 138 shows the water inflow to the Ambuklao and Binga reservoirs due to the extreme flood.

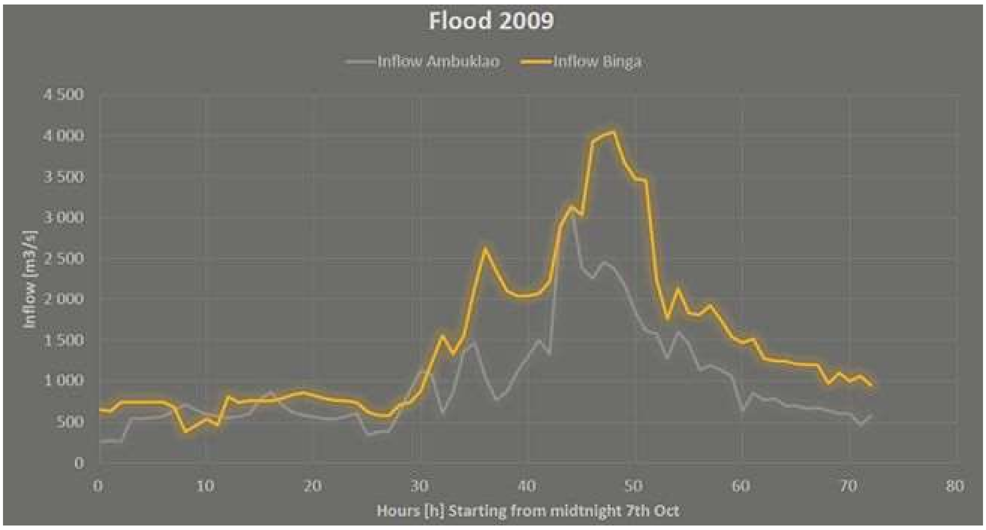


Figure 138 water inflow to Ambuklao and Binga reservoirs during the extreme flood in 2009

This extreme flooding clogged up the waterways, and sediment deposits trapped in the Binga dam increased. The loss of storage limited Binga's operational flexibility and therefore reduced the plant's revenue. In the case of Ambuklao, the power plant had to shut down. A total of USD 280 million was required to rehabilitate both the Ambuklao and Binga plants, between 2010 and 2013.

12.5 Sediment management strategies

Since the acquisition and refurbishment of Binga, the implementation of sediment management strategies is key to keeping the plant operational in the long term. Due to the high rate of storage loss, the stabilization of sediment inflow and outflow is crucial for operating Binga as a run-of-river project.

Any alternative approach to managing sediment requires changes in the operating rule of the floodgates. The operating rule, shown in figure 139, is based on the water level and does not include sediment routing during flood events greater than 500 m3/s.

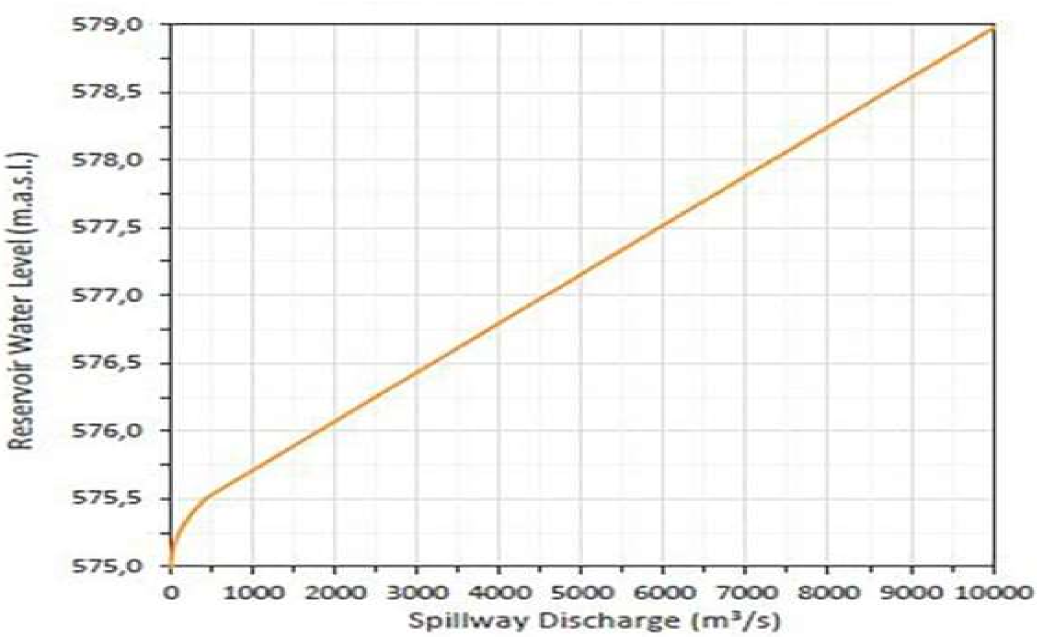


Figure 139 flood rule curve at Binga dam - reservoir water level-based operation

Ongoing studies are looking at technically-feasible solutions to convert Binga into a run-of-river power plant. The proposed sediment management strategies will have to meet the following objectives:

- Protect the intake from deposition and slide;
- trap the suspended load during normal flood season operation;
- flush deposited suspended load during floods;
- provide passage of incoming bedload during floods;
- maintain the small reservoir for peaking/ancillary services;
- maintainability to delay and dampen flood peak; and
- maintain dam safety and the integrity of the spillway.

A significant sediment management challenge is the high risk of clogging the current Binga intake, with an invert elevation of 555 masl. The longitudinal profile in figure 140 shows that sediment deposits are reaching that level.

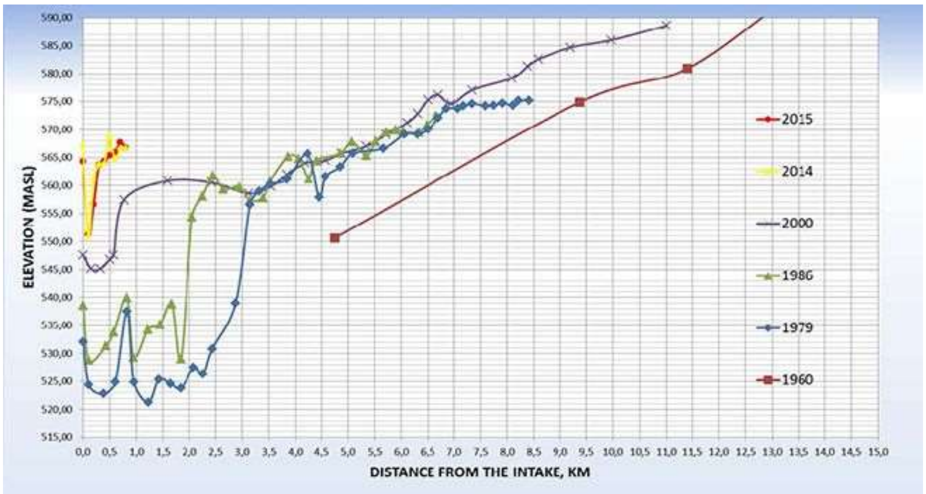


Figure 140 longitudinal profile of Binga reservoir. The intake invert elevation is 555

Other challenges include maintaining the existing storage volume, avoiding backwater effect, the burying of the Ambuklao outlet, and maintaining dam safety when the bed load passes over the spillway to the downstream river reach.

Physical model studies include several sediment routing options and intake-level modifications to find a technically feasible solution and acceptable and implementable operational regime, which would provide for a reliable run-of-river operation in the long term.

12.6 Conclusions

Sediment management considerations are fundamental during the initial concept/design phase when building dams and hydropower plants. Without them, sediment is deposited in reservoirs, minimizing a plant's benefits, shortening its operational life, damaging the hydro-mechanical equipment and eventually losing sites for power generation and other benefits.

Monitoring and gathering sediment data taking account of the impact of natural disasters such as earthquakes and typhoons into the design is key to planning adequate sediment management strategies.

The annual cost of the research on sediment and sediment management at Binga is estimated to be around 2.5 percent of the annual operation and maintenance costs, which are estimated at USD 2 million. Raising awareness of the benefits of regular monitoring and sediment management strategies in the operation and maintenance of a power plant could lead to an increase in the resources dedicated to sediment management.

Chapter 13

Conclusion & Recommendations

13.1 Conclusion

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.

Large numbers of research works have been done on soil erosion, sediment yield and sedimentation in various reservoirs and all research works to guide us to understand the practical importance of the sedimentation problem. However, it remains unexplored in different aspects. Research on erosion process, sedimentation as well as their modeling approaches is still ongoing. Models that are capable to correlate both erosion and sedimentation at the basin scale have not been explored for the reservoir. Different approaches may be developed to predict the effect of future climate change on sedimentation of the reservoir. Relationships between upstream and downstream of a reservoir can be established by studying the complex phenomena of soil erosion, sediment yield, and sedimentation of a reservoir. Research on water quality impact of sediments on water availability is also expected.

Water resources are currently under increasing stress in many regions of the world. However, issues concerning sediment management and control often receive less attention in water management policies and programmes.

The case studies referred to in this master thesis represent a useful contribution towards the global sharing of knowledge and experience essential for developing a set of best practices in sediment control and management. The hope is that these case studies will encourage further information exchange and sharing of data and promote international dialogue on sediment control and management issues.

13.2 Recommendations

Reservoir sediment management, around the world, is becoming more and more a major problem for the hydro projects. It is therefore important that aspects related to improved reservoir sedimentation management is better understood and practiced. We would strongly recommend that:

- Concern about reservoir sedimentation becomes an integral part of design standards, so that hydro and storage dams in sediment-rich areas become as sustainable as possible.

- Project operators and designers should try to use known technologies and also when possible advance the state of the art in sediment management by using innovative ideas and new technology.
- Due attention must be given to all the parameters related to sediment source, its transportation and deposition patterns in the reservoir.
- Try to develop reservoir storage volume maintenance methods adapted to local conditions
- We must say that the above recommendations summarize very well the challenge that all engineers involved in storage reservoir sedimentation management should keep in mind and work towards finding reasonable solutions.

<u>For new projects this would mean:</u>

- Having a good knowledge of the watershed sediment yield and if necessary and/or possible propose long term solutions which would either maintain the present sediment yield if considered satisfactory, if not, take actions which will gradually reduce the sediment yield from the watershed area.
- Confirm predicted sediment yield by actual field measurement of the total sediment load (sand, silt and clay) that is being transported by the river.
- Amongst other criteria used for determining the proposed dam and reservoir characteristics also include the impact of the expected sediment load on short and long-term evolutions of the project and possible remedial measures.
- Analyse reservoir sedimentation management strategies by using numerical model like RESCON proposed by the World Bank
- Incorporate in the dam design possibilities of future structural modifications or retrofitting of structural arrangements to alleviate the problems that might be created by a reservoir full of sediment.

<u>For existing projects with severe reservoir sedimentation, it will be necessary:</u>

- Sediment management actions must be reasonable and justified.
- Understand the sediment related problem and identify its cause.
- Identify and prioritize the functions of the watercourse.
- Identify and appraise management options based on risk analysis Balance multiple goals of sediment management.
- Appraise maintenance outcomes by inspecting reservoir conditions with respect to targets set for all relevant functions.
- Develop a small-scale physical model for studying sediment issues and make benefit from (GIS) technology.
- Set a regular monitoring plan in the reservoir and implement bathymetry survey including laboratory tests for sediment sample.

As a believer that such design procedures have great potential for reducing the initial construction cost increase the project life and defer costs for structures not necessary at the project inception and eventually completely eliminate structures like the de-sanding structures for projects with a large reservoir. Where it is not required when the reservoir is free of sedimentation and with the reservoir full of sediment the concentrations during the flood flows are so high, that the de-sander is no longer capable of trapping sand particles adequately to prevent turbine abrasion, and plant shutdown becomes often necessary.

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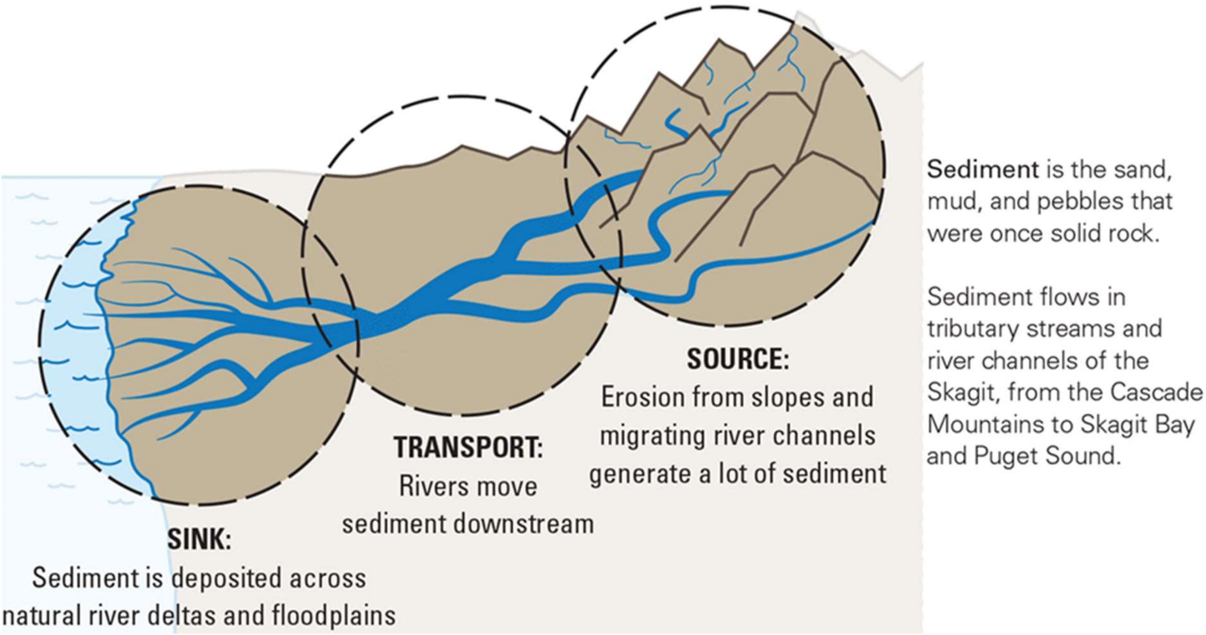
Appendix

Appendix A chapter (1)

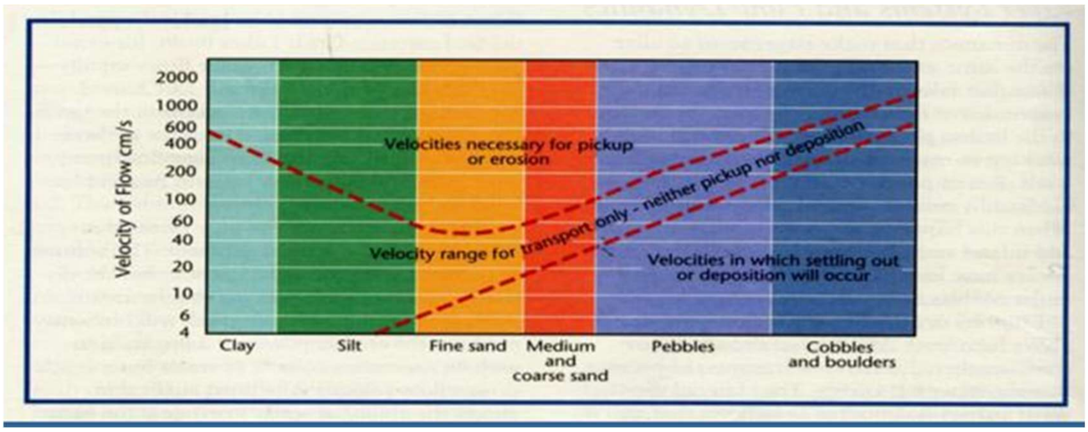
The fundamental principles of erosion, transport, and deposition of sediments



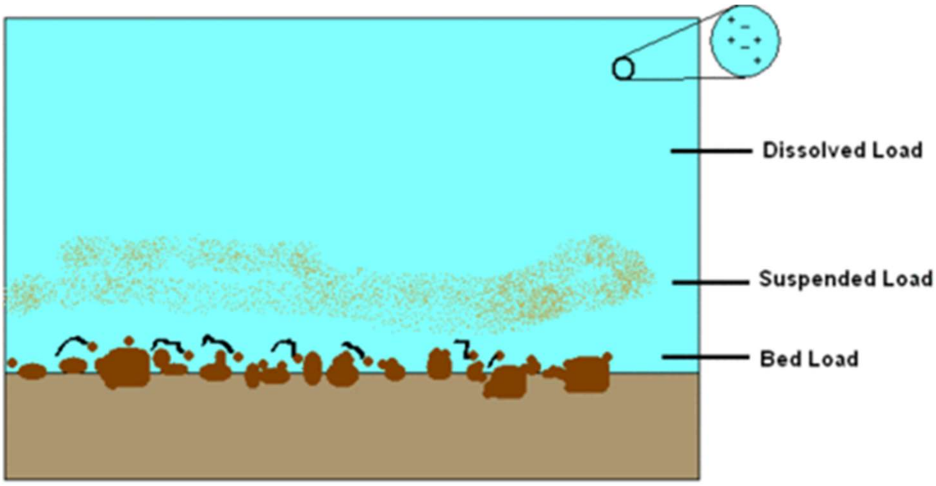
A 1 definition of sediment and its process

	size (millimeters)
Clay	< 0.0040
Silt	0.0040 - < 0.065
Gravel	0.065 - < 2.0
Cobble	2.0 - < 256.0
Boulder	256.0 - 5000

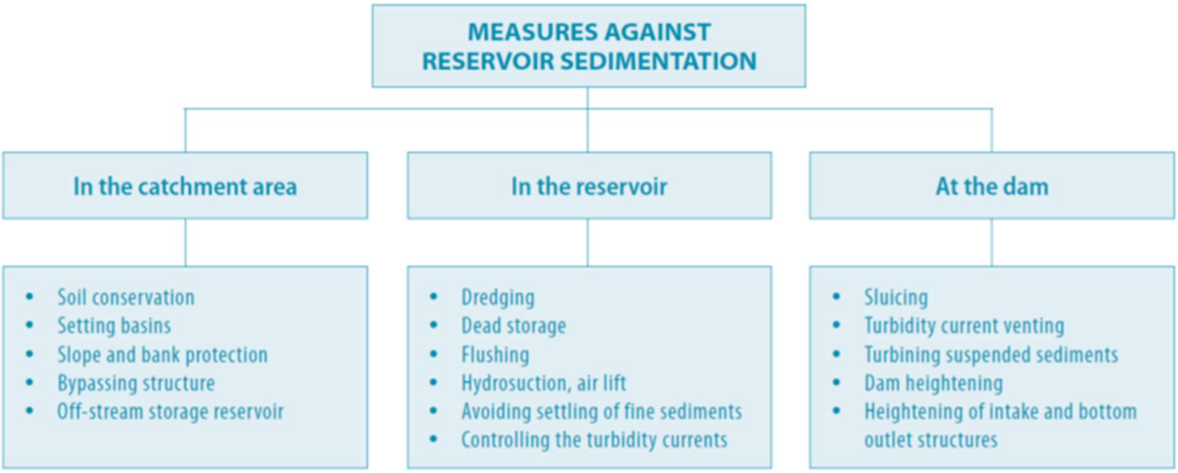
A 2 classification of sediment by size of the soil particles



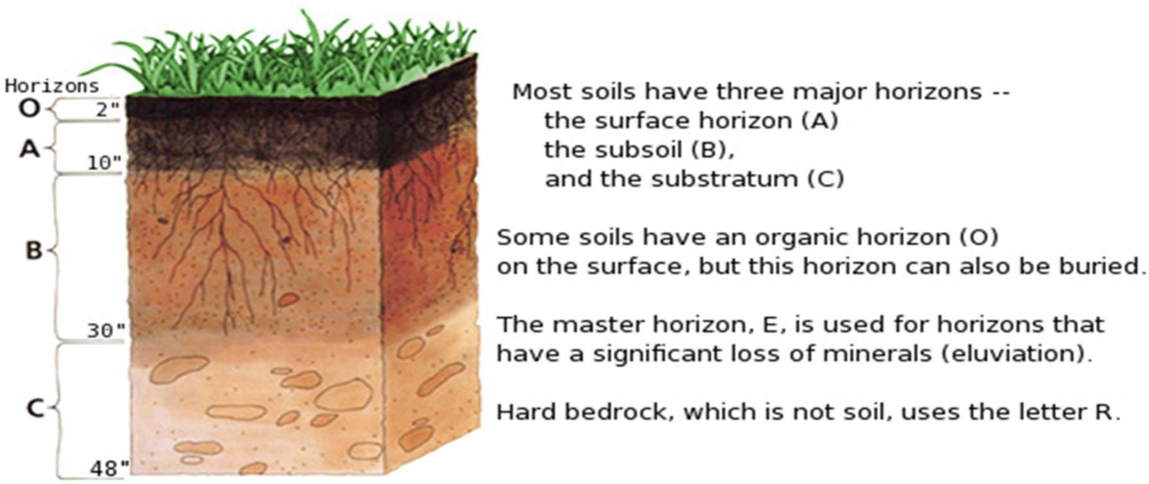
A 3 the relation between sediment type and the velocity



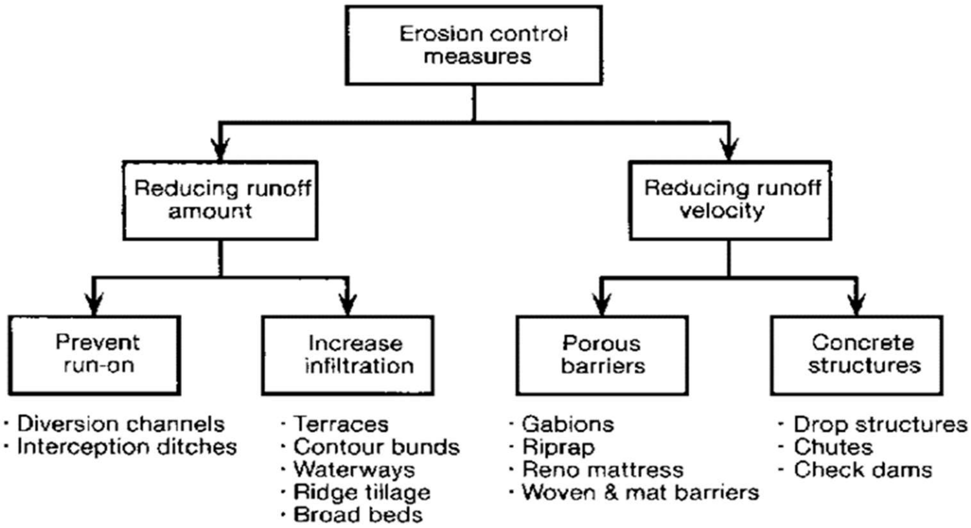
A 4 types of sediment load



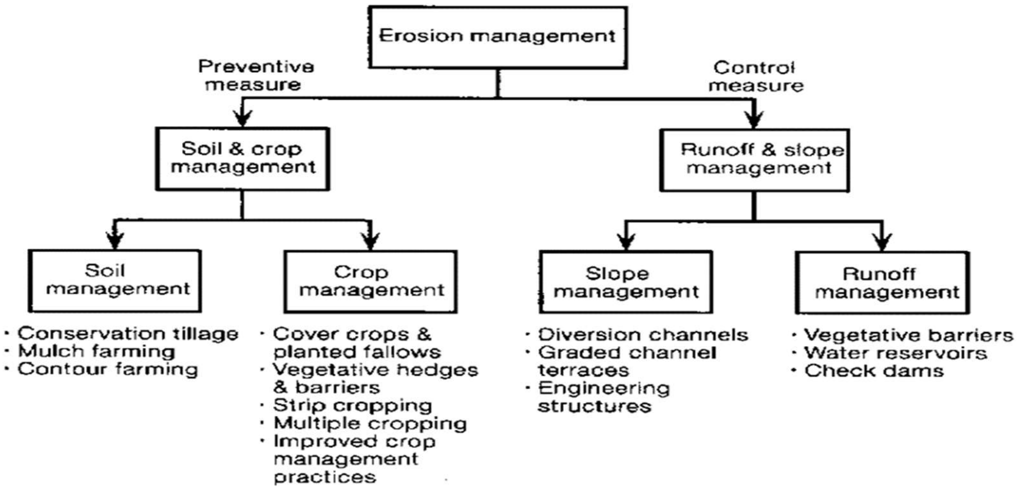
A 5 measures against reservoir sedimentation



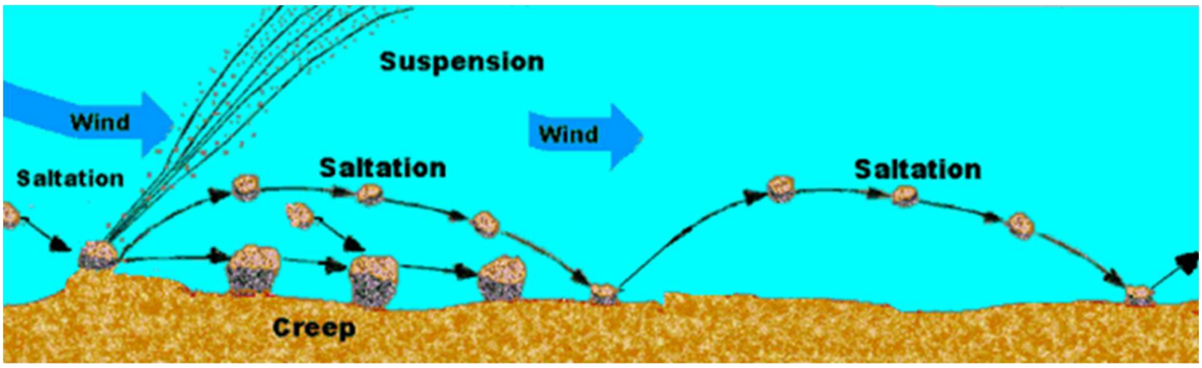
A 6 typical soil profile layers



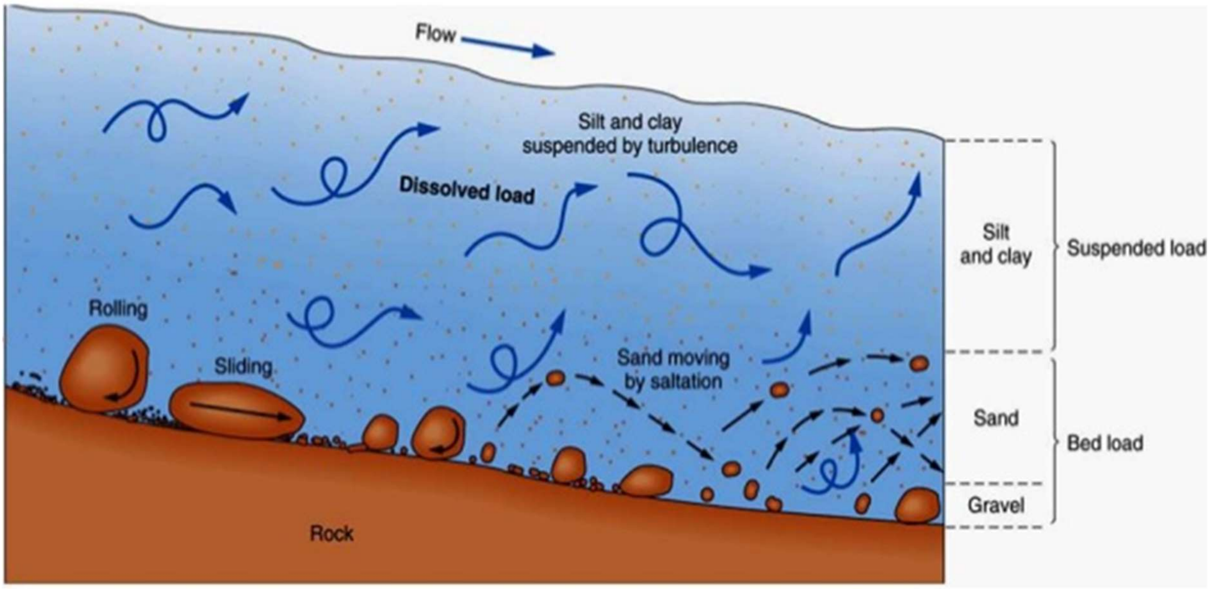
A 7 erosion control measures chart



A 8 Erosion management chart

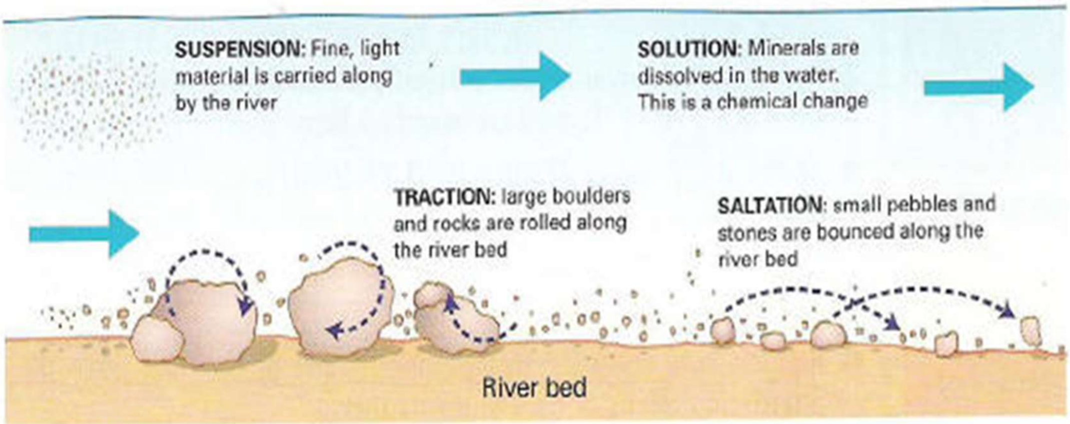


A 9 sediment transport by wind

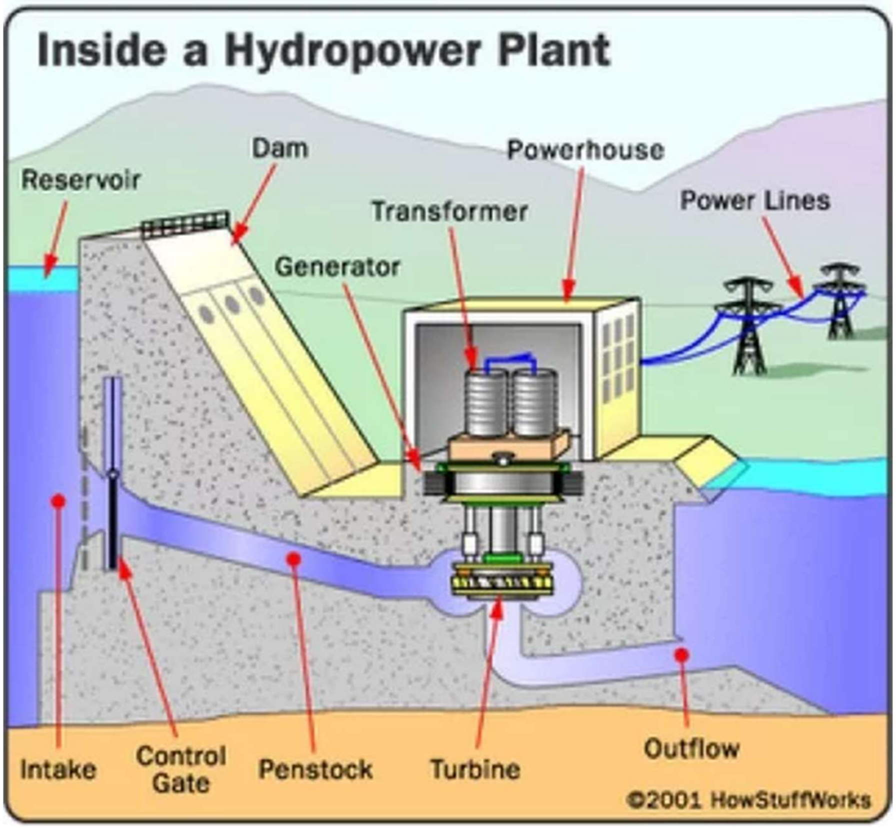


There are three ways in which sediment is transported by rivers, bedload (rolling, sliding, saltation), suspended load (floating), and dissolved load (individual ions).

A 10 Modes of sediment transport



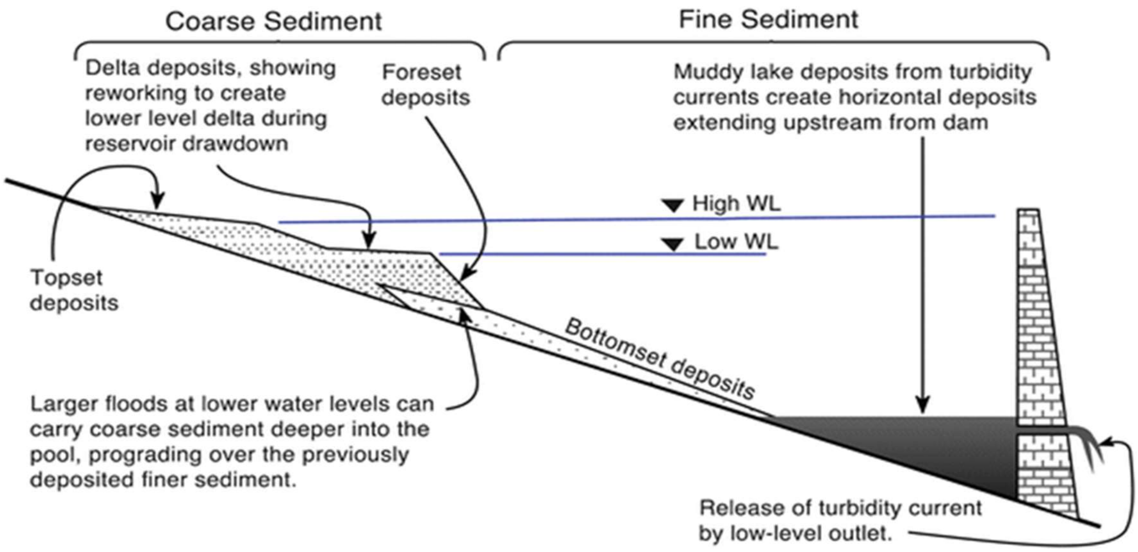
A 11 transportation of sediment process



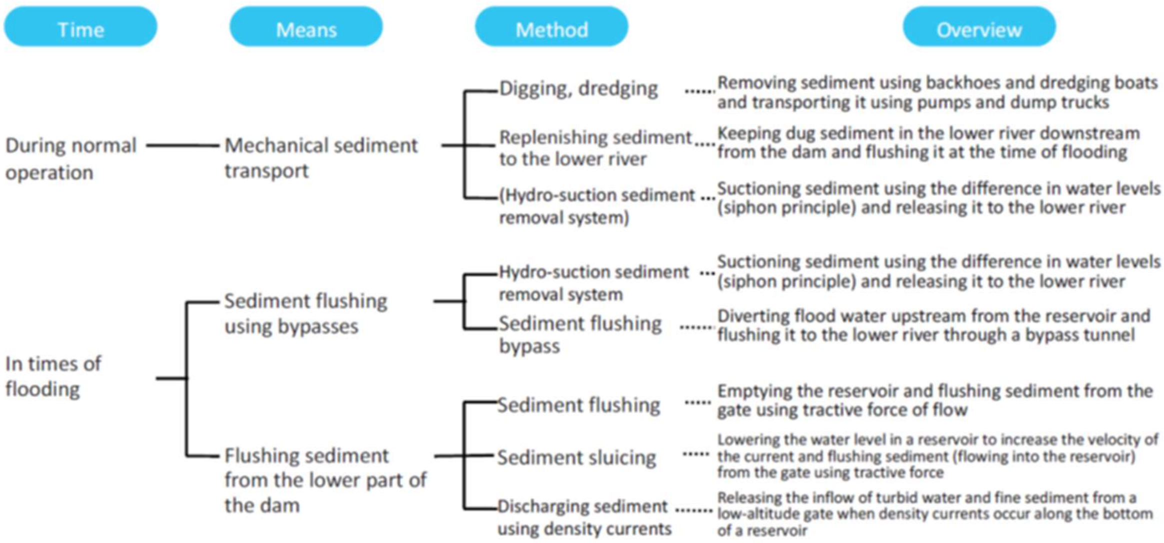
A 12 main components of hydropower plant

Criteria for selection of dam type		
Factor	**Condition**	**Dam type**
Topography	Narrow U-shaped valley	Concrete overflow dams
	Narror V-shaped valley	Arch dams
	Low plain country	Earthfill dams
Geology	Solid rock	Almost every kind of dams
	Gravel foundation	Earthen and rockfill dams
	Silt and fine sand	Earth dams
	Clay foundation	Earthfill dams
Availability of Materials	The materials required for the construction of a specific dam type must be available locally or at short distances from the construction site.	
Seismicity	Earthquake zone	Preferably earthen and concrete gravity dams

A 13 criteria for selection of dam type



A 14 Sediment distribution in the dam reservoir



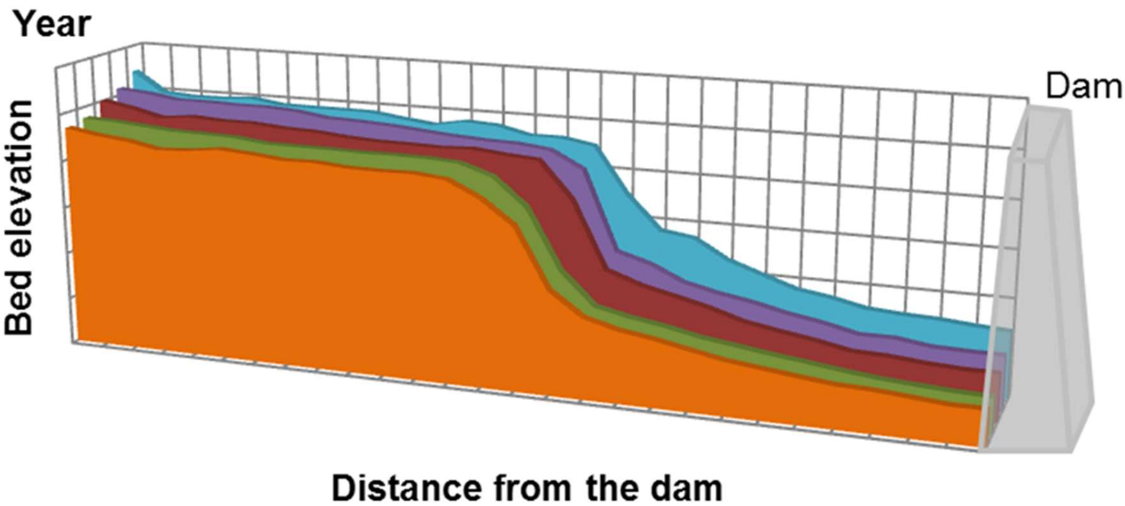
A 15 Technologies to Flush Sediment from Dams

A 16 Aerial view of sediment flow through the stream

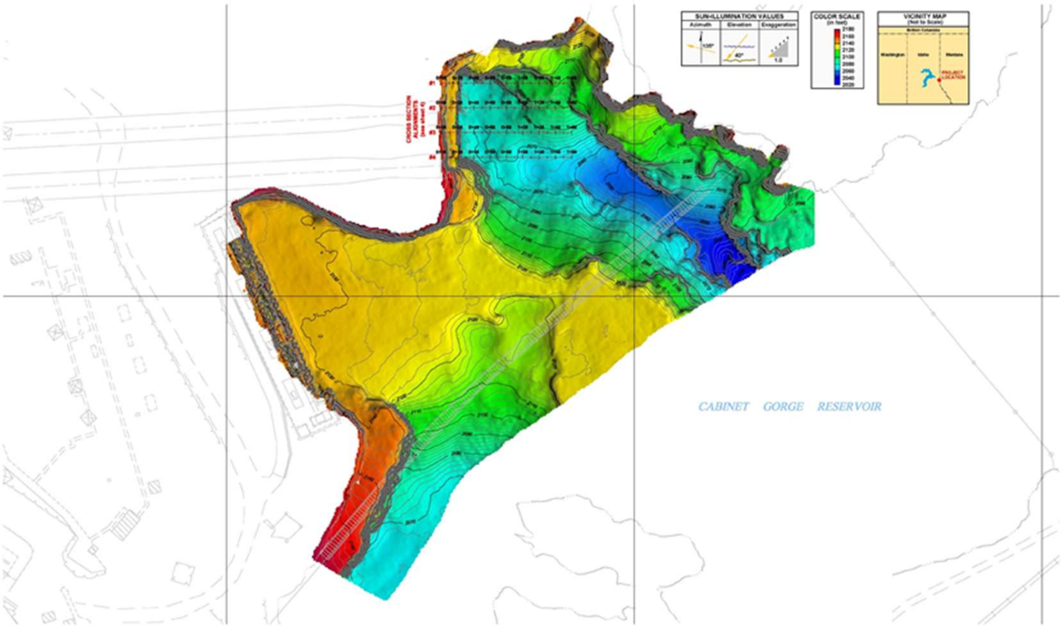
A 17 sediment discharge in the ocean

A 18 sediment sampling

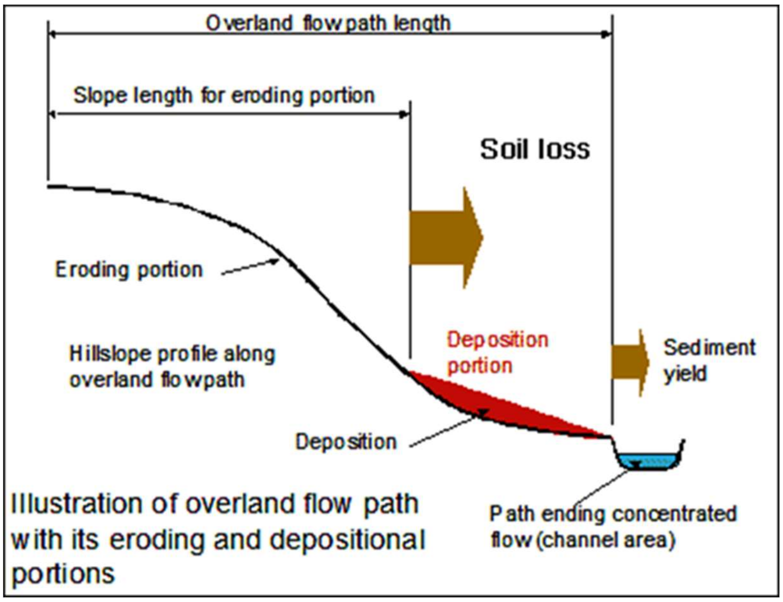
A 19 sediment sampling



A 20 Modelling reservoir sedimentation

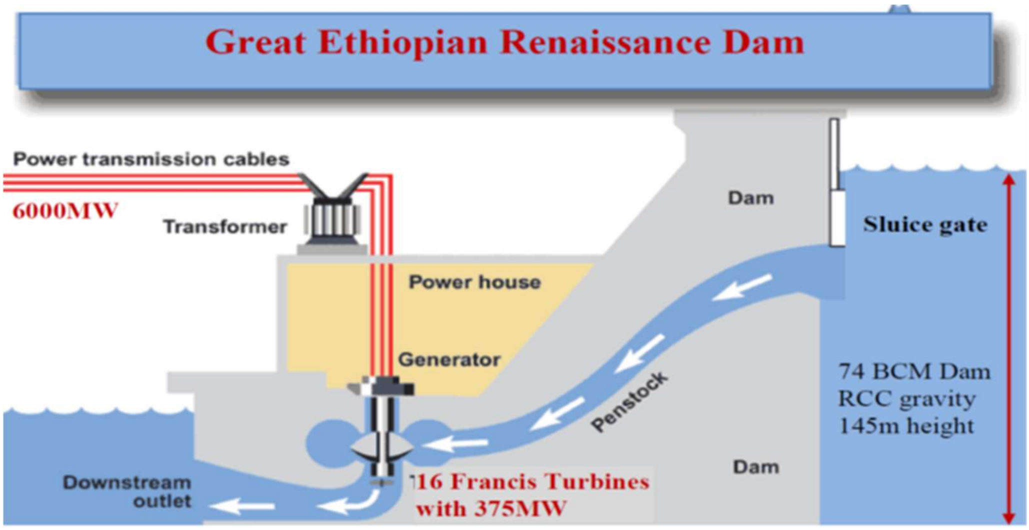


A 21 digitalize Bathymetric Survey model of Cabinet Gorge Reservoir

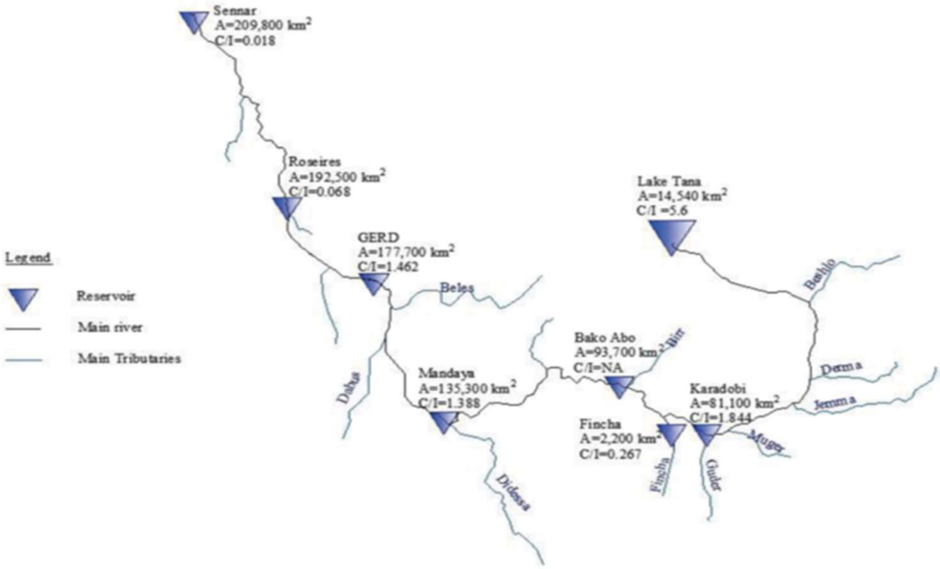


A 22 scheme shows sediment yield in rivers

Appendix B chapter (2)

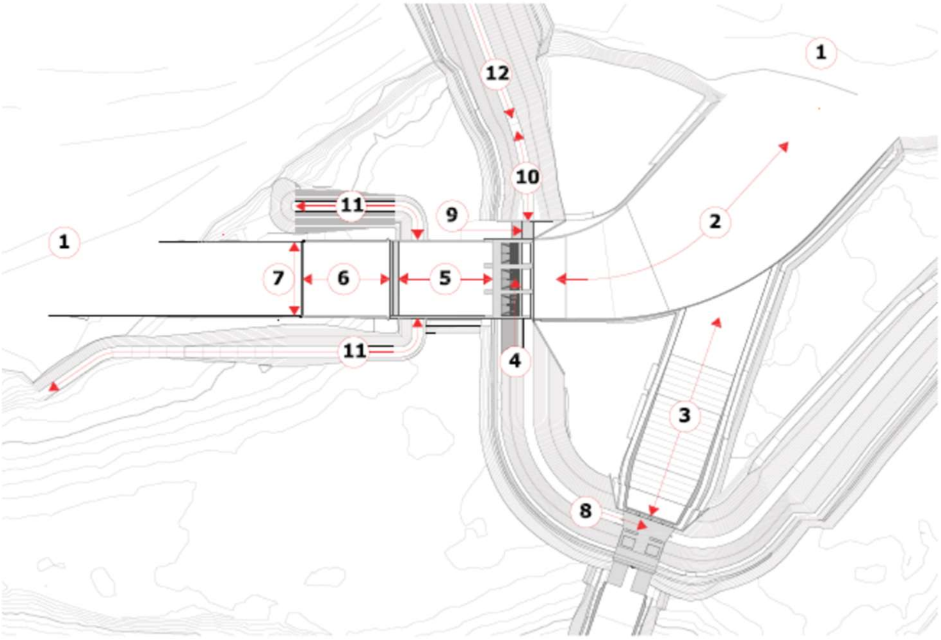


B 1 The Schematic representation of GERD lay out



B 2 Reservoirs in the Blue Nile Basin, their catchment area and main tributaries of the Blue Nile River

Appendix c chapter (3)



C 1 Overview of the Hvammur HEP project final design for Design Layout

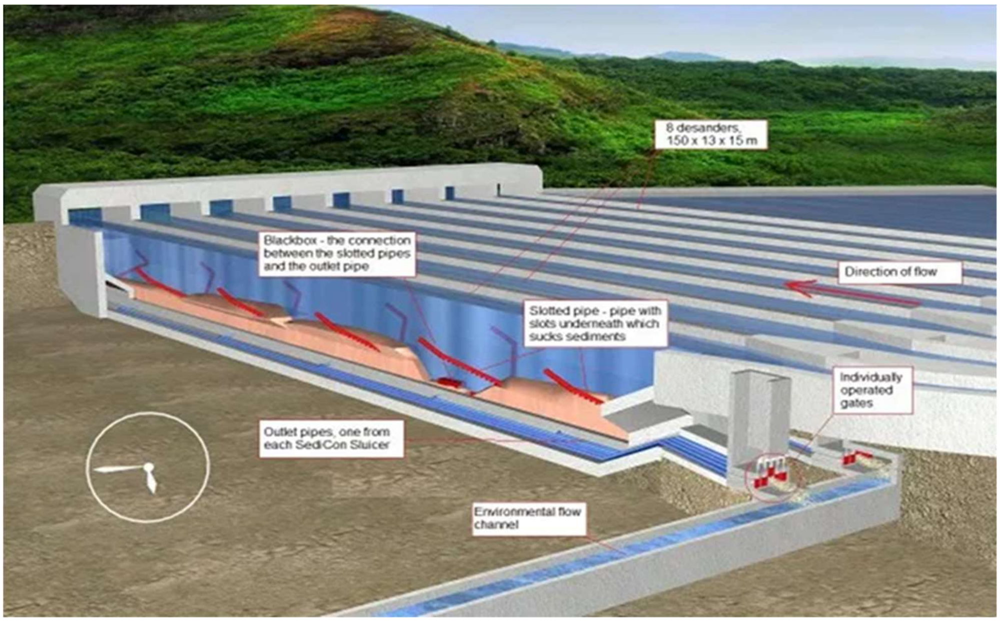
(1) the original riverbed, (2) spillway approach _ow channel, (3) intake approach _ow channel, (4) the spillway structure, (5) stilling basin, (6) downstream discharge channel, (7) control section in the downstream discharge channel, (8) intake to the power house, (9) the mandatory release spillway, (10) the fuse plug, (11) supporting levees for the downstream channel, (12) Hvammur dam (Landsvirkjun 2010).

Appendix D chapter (4)

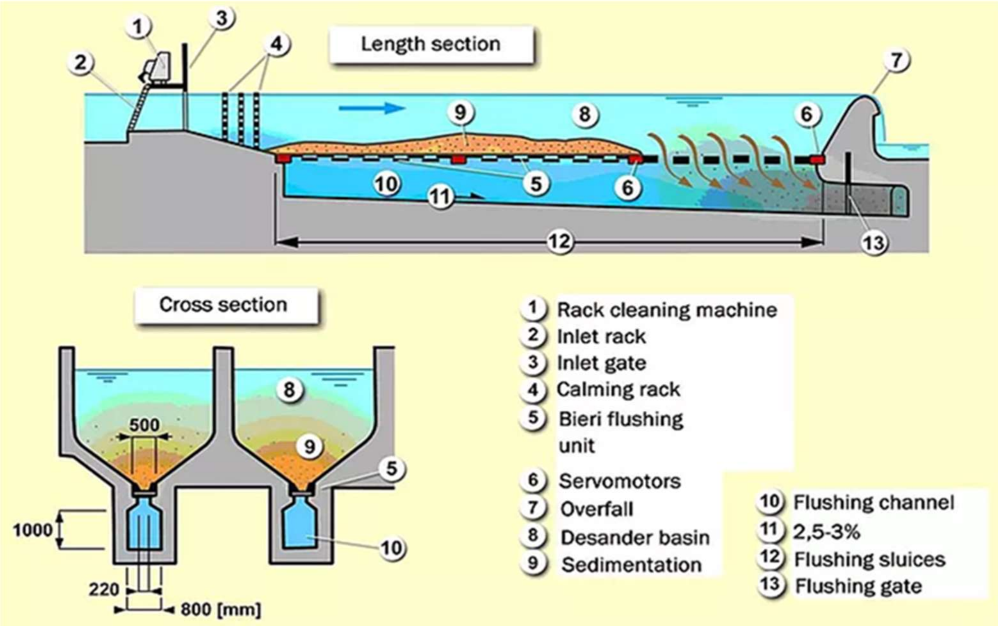
D 1 Sediment Discharge Operation of Asahi Dam Reservoir at the Outlet of Bypass Tunnel

D 2 ahAsi Dam Reservoir

Appendix E chapter (5)



E 1 general desender profile in hydropower plant



E 2 different sections of desender

Appendix F chapter (6)

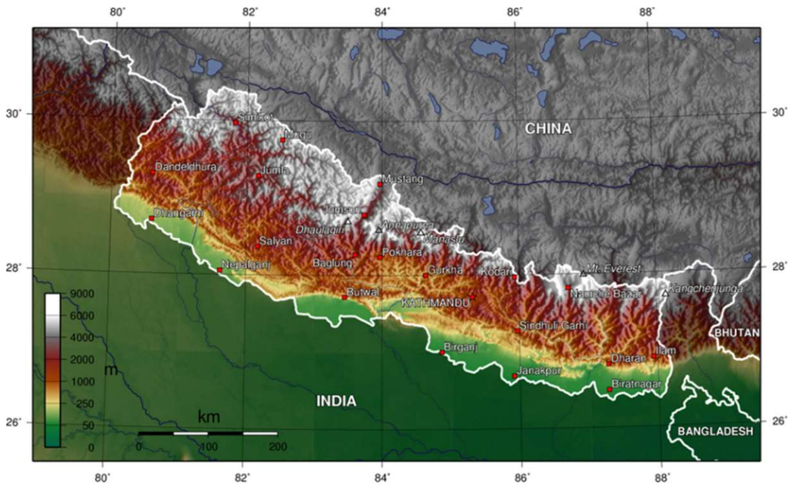
F 1 rivers in Nepal

F 2 river basin in Nepal

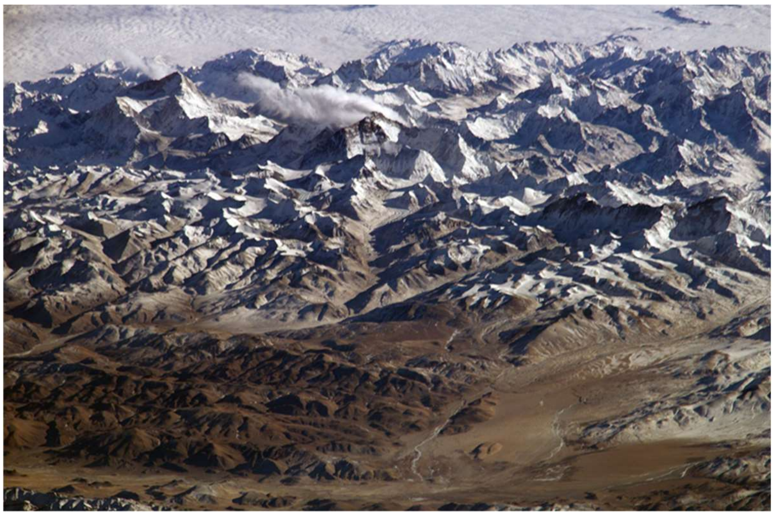
F 3 hydropower plants in Nepal

F 4 aerial view of Kali Gandaki Hydroelectric Plant

F 5 Kali Gandaki radial crest gates



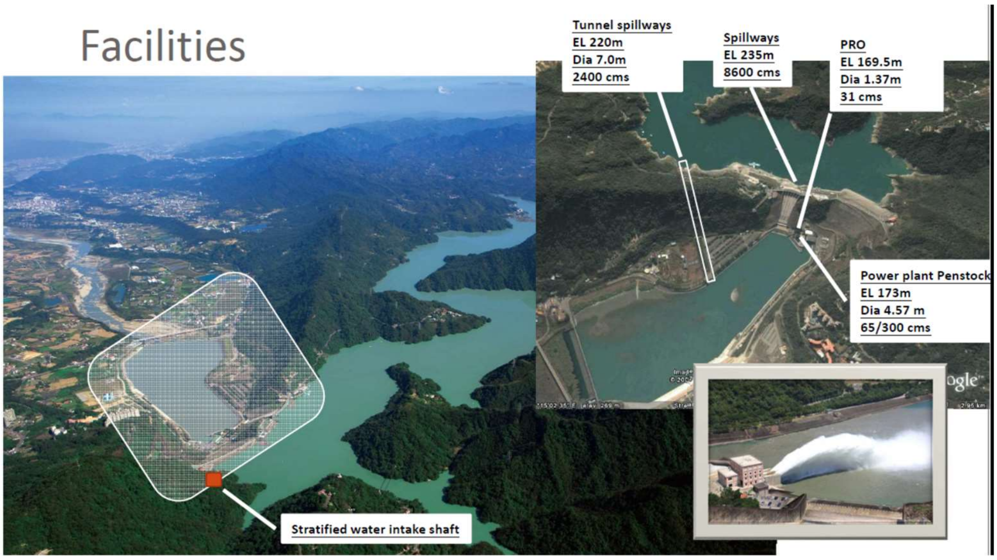
F 6 land elevation in Nepal



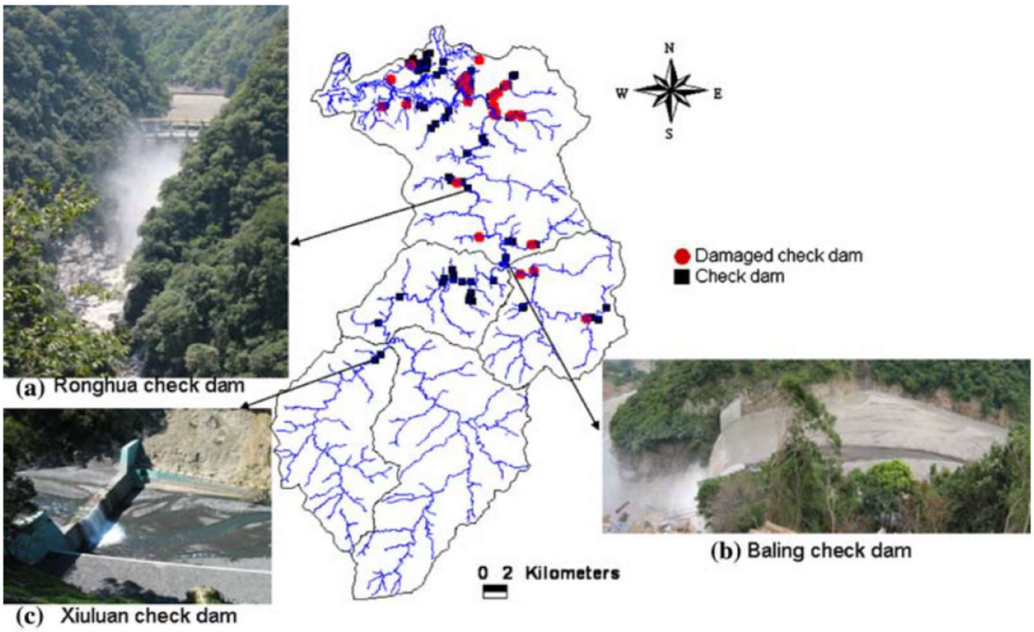
F 7 catchment area of the dam

F 8 excessive turbine abr

Appendix G chapter (7)

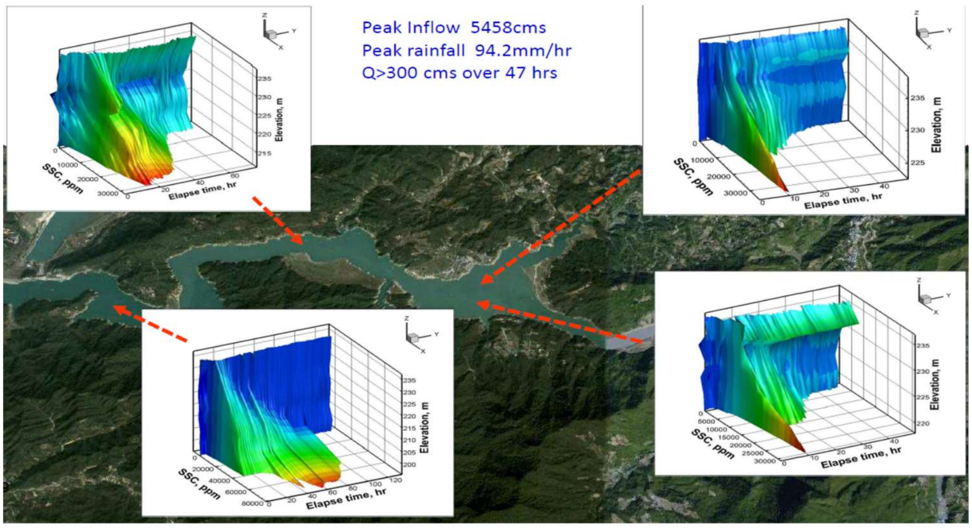


G 1 Shihmen dam facilities

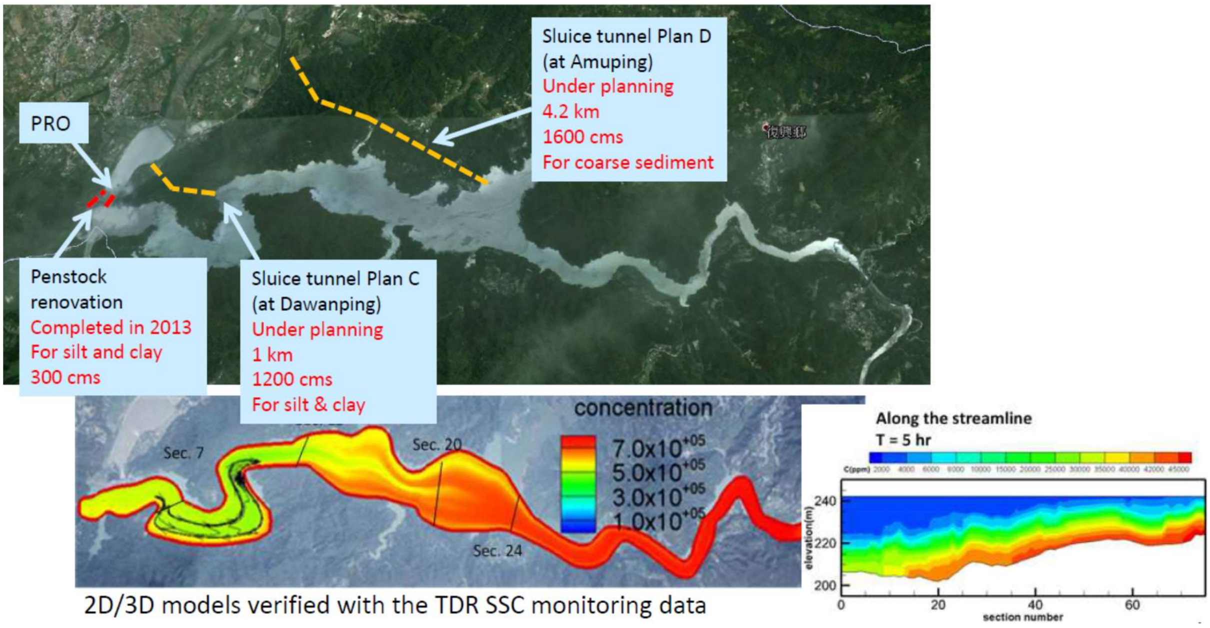


G 2 different Sites location of the check dams in the watershed

G 3 Damages by 2004 Typhoon Aere



G 4 SSC monitoring during 2013 Typhoon Soulik in

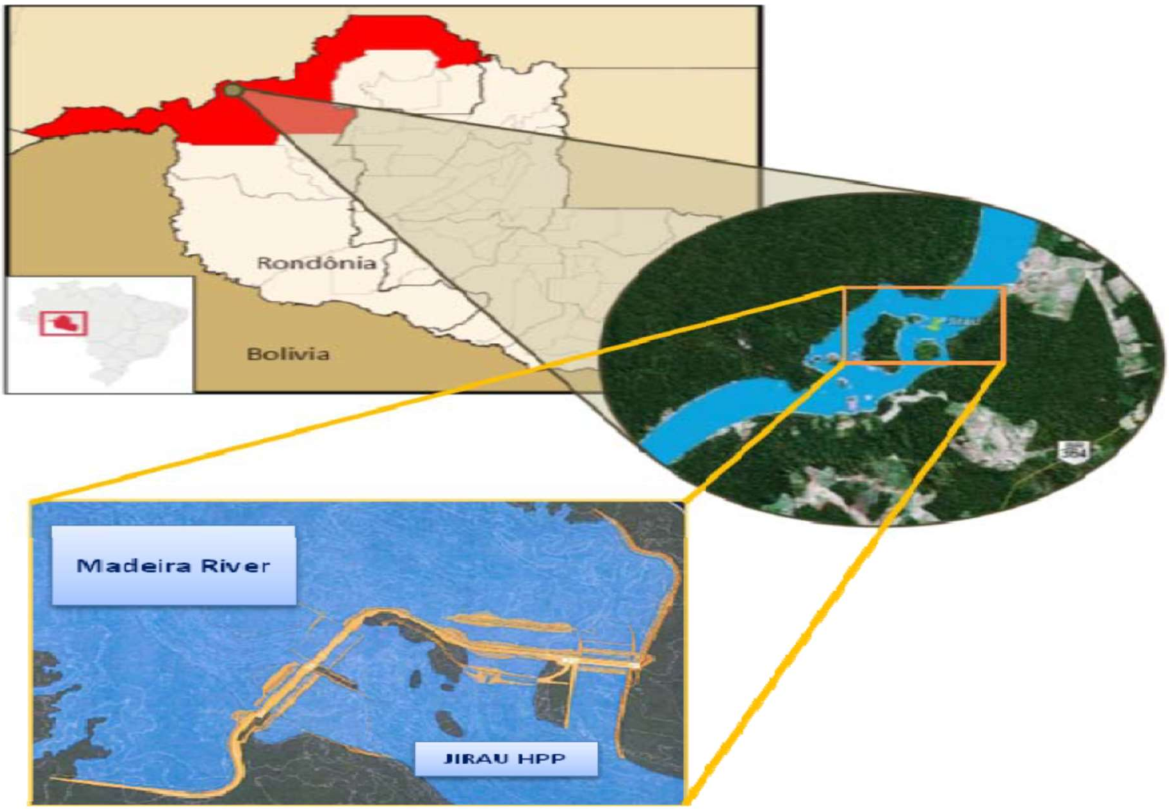


G 5 Sediment transport modelling sediment sluice tunnel planning

G 6 Sediment discharge through penstock 2013 Typhoon Soulik

Appendix H chapter (8)

H 1 The Madeira River is one of the Amazon's most important tributaries.



H 2 Jirau location

H 3 The left-bank dyke for sediment channelling to power houses and spillway.

H 4 Vegetation-cleared area in the future reservoir.

H 5 Stored topsoil for later recovery of spoil and borrow areas.

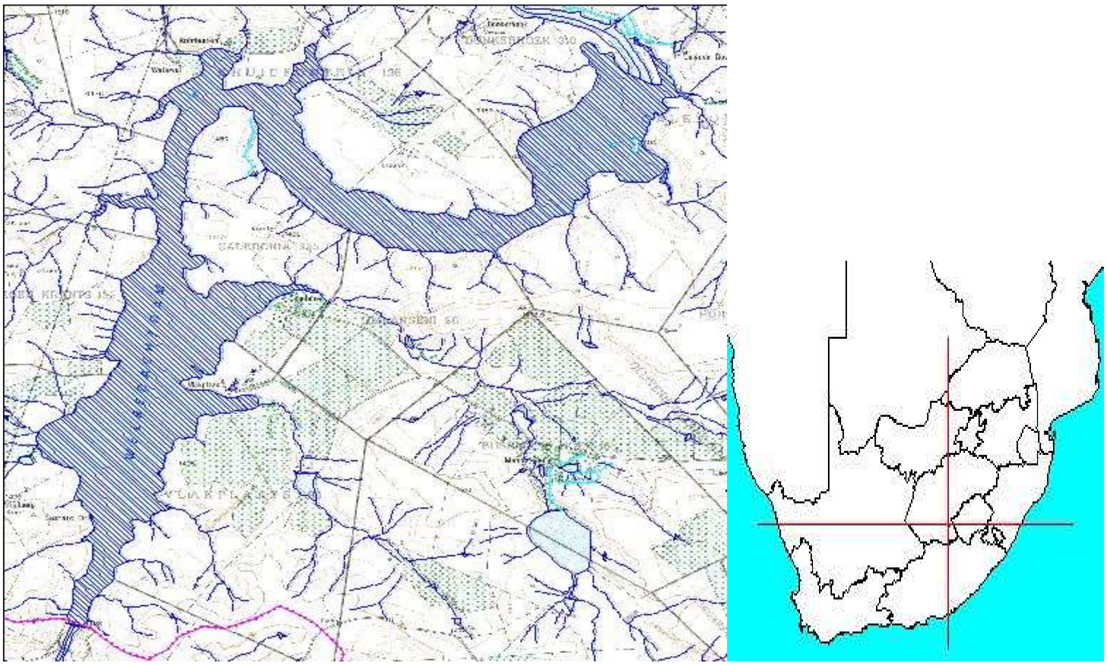
H 6 Testing of re-vegetation species.

Appendix I Chapter (9)

L 1 Bakaru hydropower project

L 2 Bakaru project gates

Appendix J chapter (10)



J 1 Welbedacht (reservoir) location (29o52'05"S 26o53'53.2"E

J 2 auf-laden stream in Welbedacht Dam site (When designing a dam, the quantity of sediment that will flow into the reservoir has to be considered. The reservoir is designed to reduce the amount of sediment deposited, and to maximise the sediment flow downs

J 3 Aerial view of the Caledon river with large open sandbanks during the dry season

J 4 High load of sediment downstream Welbedacht Dam (wet session).

J 5 Bloemfontein City, The dam was built to supply water. Supplying 35.98 Mm3/yr on average

Appendix K chapter (11)

K 1 La Esmeralda Dam (Chivor hydro-power plant)

K 2 The Esmeralda reservoir downstream

K 3 Garagoa river one of the rivers that feed the La Esmeralda reservoir

K 4 View of the Esmeralda reservoir

K 5 La Esmeralda dam (Chivor hydro-power plant) location

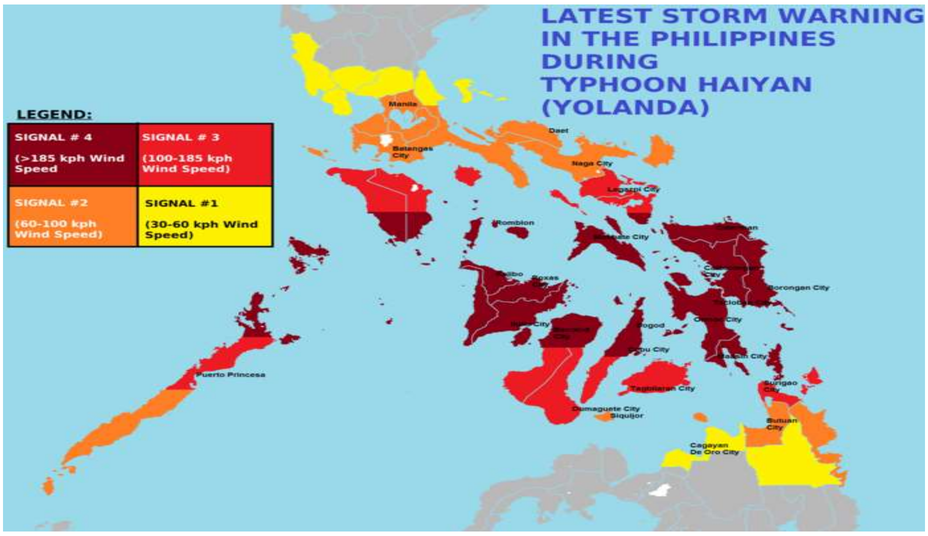
Appendix L chapter (12)

L 3 Agno river basin

L 4 Ambuklao dam which Binga dam located (19 km) downstream

L 5 Binga dam spillway and dam body

L 6 Binga dam downstream



L 7 Typhoons in Philippines Approximately 20 cyclones and typhoons hit the country each year

L 8 Island of Luzon in the northern Philippines experienced a 7.8 magnitude earthquake