SEDIMENT MANAGEMENT IN RESERVOIRS: National Regulations and Case Studies

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SYNOPSIS

This bulletin provides a concise summary of environmental regulations associated with sediment management activities in reservoirs (as of 2017) followed by a series of case studies which compare sediment management techniques from various projects around the world.

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1. INTRODUCTION

Sediment management in reservoirs is of great and growing importance in the water storage field. The construction of a dam across a river inevitably triggers a change in the flow regime and a modification of the sediment transport balance. The sediments accumulated upstream of the dam reduce the reservoir capacity, can damage hydropower turbines and can impact proper functioning of the outlets. Downstream, lack of sediment in flow releases, especially coarser sizes, can result in lowering of the stream bed, erosion of structure foundations and instability of streambanks and tributary channels. Sediment also provides important substrate to interstitial habitats and plays an important role for estuaries and coastal waters.

Management of this volume of solid material is thus very important to maintain the benefits provided by an impoundment and also to ensure a long lifetime for the reservoir. Many sediment management techniques are in practice around the world - some solutions are well developed while others are still considered experimental. Regardless, the scarcity of good information on predicting effective management methods and results of methods currently employed prompted the interest in preparing this report. Professionals all over the world are dealing with similar issues related to sedimentation of reservoirs and associated impacts. The aim of this bulletin is to share experiences in management of sediment in and around reservoirs to help engineers and scientists expand their knowledge about both well-known and novel solutions. The analysis of various case studies should help engineers and other professionals in the water management sector to strengthen their knowledge on this topic.

The first part of this bulletin sets the stage with a summary of regulations related to sediment management in different parts of the world, as this is often a controlling factor as to what management activities may be considered. Regulations and permitting requirements can range from the very specific (e.g., a certain concentration that cannot be exceeded) to the very general (e.g., “continuity of sediment shall be maintained”). Thus, the regulatory environment can impact both project requirements and project constraints.

The second part of the bulletin contains case studies of sediment management activities and uses a common framework to compare the various projects. Case studies were provided by committee members and other interested volunteers that provide some insight as to current management practices around the world. The particular case studies included in this bulletin are just a sampling of activities world-wide, but shed some light for those dealing with sedimentation issues as to what has been done elsewhere, whether successful or not.

2. NATIONAL REGULATIONS ON SEDIMENTS IN RESERVOIRS

Many countries specify regulations concerning the sedimentation of reservoirs and the quality of the river environment. Regulations related to sustainability of reservoirs and limitations placed on the movement of sediments can define which management measures may or may not be acceptable within a given country. A brief overview of regulations in a small sample of countries is provided to set the stage for the following case studies. It is also hoped that professionals looking to establish or update regulations in their home countries might take some useful lessons from the material contained in this section.

2.1. REGULATIONS

2.1.1. European Union Regulations

The European Union Water Framework Directive[1] (EU-WFD) established a framework for community action in the field of water policy as a binding act for all EU member countries. The WFD recognizes the important role of rivers, lakes and groundwater for the ecosystem, aiming to safeguard and improve the aquatic environment as a primary resource for life. Actually, all EU river sections need to achieve good ecological status - or good ecological potential, if being a heavily modified water body such as a reservoir.

The EU-WFD defines general minimum standards for water. Despite being a binding document, for applicable legislation each of the 28 member countries has had to transfer the EU-WFD into national law. Though the general standards remain the same, the special focus on details such as riparian obligations vary. Administrative and technical issues are detailed in Annexes of the EU-WFD which are also legally binding for all member countries. Annex V gives information about the status of rivers and applicable standards. The core assessment criteria are biological quality, physical-chemical quality and hydromorphologic quality. This last factor includes continuity concepts which are applied to water, species and sediment. The first improvement round for river status focused on fish migration. Later, hydrology, sediment transfer and other hydromorphological issues gained importance so that now within the WFD-criteria downstream sediment transfer is considered essential to achieve good and very good ecological status (see EU-WFD Annex V, 1.2.1). This also affects reservoirs which in most cases hold back sediment and other solids.

Although operating within the WFD framework, the different EU countries have a variety of legal requirements on how to deal with sediment transfer, dredging and overall sediment management. In general, it is widely desired to keep the sediment within the river to lower the erosion ratio of river stretches downstream of reservoirs. Sediment also provides important substrate to interstitial habitats and plays an important role for estuaries and coastal waters. As long as the sediment quality is not causing chemical harm and the quantity is transferred in a near-nature-scope, sediment transfer is desirable to maintaining the reservoir and the river. A question often discussed is how to transfer sediment downstream. For most river sections within the EU, flushing and sluicing campaigns were performed in past decades that in some cases caused significant ecological and fish damage and led to massive public protests. A consequence was a widespread ban on flushing for most reservoirs with only few exemptions in Austria, France, Italy, and Germany. However, due to a lack of other alternatives reservoir sedimentation is continuing.

[1] Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000

2.1.1.1. Germany

Continuous sediment transfer through, over, or around dams in Germany[2] usually is permission-free and can be applied by any reservoir operator as long as it fulfills the usual standards and appropriate authorities are informed in advance. In addition, several legal acts explicitly ask for a sound sediment transfer in case of maintenance dredging of reservoirs. The only major exclusion is heavily polluted sediment which is applicable for only a few projects. Flushing or sluicing, if done infrequently, is only rarely permitted by the authorities in Germany.

If sediment is dredged and removed from a reservoir or dammed river, an extensive licensing process considering all possible alternatives has to be fulfilled. A different licensing process is required to landfill sediment. This option has become costly within most parts of the EU, as land is not available in abundant quantity anymore. In downstream river stretches suffering from a lack of sediment (due to sediment trapping in upstream reservoirs), significant amounts of solid material have been dumped to reduce the erosion rate (e.g. River Rhine, River Elbe). For quarrying solid material in areas next to downstream river stretches as well as material placement within these river stretches, additional licenses are required.

2.1.1.2. Austria

The general situation in Austria is similar to the German one. However, one difference is that a license is required for sustainable sediment management. The licensing process involves a study report and an official license for sediment management, involving relevant stakeholders.

Another difference is that in recent years flushing or sluicing in specific reservoirs was still allowed, although the number of permits has been reduced drastically. The major reason for the permissions was safety, such as foreseeable bottom outlet sediment blockage or the threat of additional sediment load on the dam. Flushing nevertheless has led to massive protests from environmental agencies.

2.1.1.3. Italy

National Regulations

The evolution of Italian laws referring to the management of sediment accumulated in reservoirs has been quite complex; the following is a list in chronological order of the main national laws that have gradually been issued and subsequently amended or repealed:

1. Law n.319/1976 (Merli Law) on the prevention of water pollution
2. Decree n.130/1992 on water quality, in order to support fish life
3. Law n.584/1994 competences of National Service for the Large Dams
4. Decree n.152/1999 Environmental Code
5. Decree June 30th 2004 of the Ministry of the Environment concerning the criteria for preparation of the project management of the reservoirs
6. Plans for protection of the regional water
7. Decree n.152/2006 New Environmental Code

The main laws are the "Environmental Code" (law n.152/2006) and the Decree n.30 /2004 of the Ministry of the Environment for preparation of a project management plan for reservoirs.

[2] see German WHG, § 9, 39

The project management plan contains investigations carried out on the river basin, including the chemical characteristics and water quality of the reservoir and sediments. Based on this information, the plan defines outlet operation for evacuating sediment to maintain the functional efficiency of the project and to maintain or recover reservoir capacity lost through siltation.

The project management plan also contains specific preventive measures that must be implemented during operations to protect the receiving stream, the aquatic ecosystem, fisheries, etc.

The Institute for Environmental Protection and Research (ISPRA) prepared guidelines regarding the investigations and studies that should be carried out for the preparation of the project management plan for reservoirs. This document is a reference but not law; some of the directions therein are particularly onerous, and could require extensive investigation.

Regional Regulations

The June 30th 2004 Decree of the Ministry of the Environment requires that regions enact regulations for reservoir management for small dams subject to regional supervision. Currently, only some Italian regions have enacted the regulations. These regional regulations are important as for some specific issues they are the only source of technical information.

The regions that have approved the regional regulations are:

- Autonomous Province of Trento (December 30, 2004)
- Autonomous Province of Bolzano (January 21, 2008)
- Veneto (January 31, 2006)
- Valle d'Aosta (February 8, 2006)
- Piemonte (January 29, 2008)
- Sardegna (April 4, 2008)
- Toscana (2009)
- Abruzzo (June 27, 2013)
- Sicilia (May 7, 2012)

In Lombardia, Lazio and Friuli-Venezia Giulia guidelines are being drafted but have not yet been published.

In Umbria there is a regional law dated October 12, 2009 which excludes small reservoirs from the obligation to present a project management plan.

These documents describe how water and sediment must be characterized, and provide regulations for the disposal of removed sediment; in case of flushing or sluicing they establish the suspended solids limits that should not be exceeded in the water body. They also establish the mitigation and prevention interventions and the monitoring plan, and distinguish between specific and ordinary operations. In addition, they provide guidance for reservoir project management for different types of basins and explain the authorization process for sediment removal activities.

2.1.1.4. France

The French Ministry of Ecology, Sustainable Development, and Transportation implemented in September 2013 a law defining the new classification of rivers according to their ecological state. The difficulties of migration for many fish species and the modification of the flow regime caused by the construction of any hydraulic scheme across a river justify the measures imposed by the law. In the same manner, the law requires sediment continuity in order to avoid the loss of substrates necessary for aquatic species.

Two classes of rivers are defined according to their state and management objectives:

Class 1: Rivers to be preserved (waterways in very good ecological state, biological reserve, high stakes rivers for migratory species)

- Any new obstacle to ecological continuity, whatever its goal, cannot be authorized on such rivers.
- For existing projects, the renewal of authorization to operate will be subject to the preservation of the very good ecological state of the river, the good ecological state of the catchment area and the guarantee of migratory species protection.

Class 2: Rivers to be restored (which require a sufficient transport of sediments and the circulation of migratory species)

- Schemes have to be brought into conformity (sediment management or fish passage) within five years of the list publication.
- Rivers must be managed in order to ensure optimal sediment transport. This phenomenon depends on many factors such as the size and volume of sediments carried by the river, average flow rate, and age and characteristics of the hydraulic structures.

The hydraulic structures interrupting flow continuity can be identified in three categories:

1. <u>Weir or small dams with small reservoir volume</u>. For these small structures, if they have gates, the normal management process should ensure a good sediment transit thanks to regular opening operations. It is still necessary to pay attention to potential polluted sediments and to the vulnerability of species downstream. For weirs without gates, the operations have to be adapted for each case, depending on individual impacts to sediment accumulation.
2. <u>Large capacity dams blocking most of the coarse sediments</u>. The impact of the structure on the sediment transit is generally very high. Restoration measures override simple regular gate opening rules. This can imply modification of the dam structure, mechanical sediment transfer, excavation, etc.
3. <u>Hydraulic structures designed for sediment retention</u>. The obligation to ensure sediment continuity in this case is not applicable in the same way. The goal of sediment retention has to be taken into account as long as there is no structural deterioration or major catchment area changes. Feasible measures can include:

    - Removing the structure if its role is not justified anymore
    - Partially transferring the sediments if the goal of the structure is to protect downstream areas from massive debris flow and not to reload a river reach
    - Doing nothing concerning sediment transport

2.1.1.5. Other EU Countries

Outside of the general European context, sediment management is included within national laws for protection of water bodies and the environment. Examples include:

<u>Holland</u>

There is a specific law that covers all aspects of water management.

<u>Spain</u>

Laws relating to water quality determine the quality requirements for the river.

Slovakia

There is a general law setting out the criteria for water and water body management, and the relative responsibilities and competencies regarding sediment management. It should be noted that most dams are managed directly by the State.

Czech Republic

Similar to Slovakia, there is a general law setting out the criteria for water and water body management.

2.1.2. Swiss Regulations

Switzerland is a confederation of Cantons, so there are federal laws (valid for all Cantons) and cantonal regulations that can vary from one Canton to another. The owners of reservoirs are obliged to maintain the plants in a suitable state and are responsible for damages caused during the concession period, except for extraordinary natural events. With regards to necessary flushing of impoundments for hydroelectric plants, the owner must avoid or minimize damages to the environment. Extracts from federal law on water protection are listed below:

- Art. 40 Flushing and drawdown of reservoirs
  - The owner must avoid any negative effects on fauna and flora in the downstream river.
  - For flushing or emptying a reservoir a cantonal authorization is requested. If the flushings or drawdowns are necessary for security reasons, only the cantonal authority may fix the period and modality of the operation.
- Art 41 Floating debris
  - The owner is not allowed to release withdrawn floating debris downstream.
- Art 43a Solid transport balance
  - The balance of the solid transport in a river cannot be modified by hydroelectric plants if this would significantly damage the local fauna and flora, their biotopes, groundwater or flood protection.

The federal water protection decree includes the following provisions:

- Art 42 Flushing and drawdown of reservoirs
  - Before the release of a flushing or drawdown authorization, the authority must verify that the sediments cannot be extracted by other means that are respectful of the environment and economically supportable.
  - In case of washout, the authority must make sure that the damage downstream is limited and must specify in particular: the moment and modality of flushing or drawdown; the maximum concentration of solid suspended material that has to be maintained during the operation; and the procedure, after operation, to rinse fine sediments from the downstream bed.
- Art 42b Restoration of the solid transport
  - The cantons and the owners must plan the restoration of the solid transport.

2.1.3. United States Regulations

The regulatory environment within the United States is ever changing and continues to grow in complexity. The environmental review process is increasingly driven by a comprehensive stakeholder engagement process involving many meetings and discussions with resource agencies and special interest groups. Engineers must have a working knowledge of federal, state, and local laws and regulations that address waterways and sediment.

2.1.3.1. Federal Laws

Whenever any federal agency proposes to undertake an action, including granting a permit, the National Environmental Policy Act (NEPA) requires the agency to assess the effects of its action on the quality of the human environment. The process typically entails the preparation of an environmental assessment (EA) to examine the potential environmental consequences of the proposed federal permit decision. Based on the EA, the agency either issues a “finding of no significant impact” (FONSI) or determines that a full environmental impact statement (EIS) must be prepared. Most sediment management plans will require an EIS.

Because most reservoir sediment management projects are within jurisdictional waters of the United States, the lead federal permitting agency is most often the U.S. Army Corps of Engineers (Corps), although other federal agencies are often involved in some capacity. Table 2.1 contains a partial agency list. Because reservoirs are normally part of waters of the United States, and if release of sediment to waterways below a dam is part of the sediment management plan, Section 404 of the Clean Water Act and Section 10 of the Rivers and Harbors Act of 1899 must be addressed. Section 404 requires that private, state and federal entities obtain a permit from the Corps before discharging dredged or fill materials into waters of the United States. Section 10 governs activities that could obstruct or alter navigable waters of the United States. The Section 404 guidelines and following memoranda of understanding require that projects should avoid or minimize adverse effects on jurisdictional waters of the United States. The Corps issued a Regulatory Guidance Letter in August 2005 to provide permitting guidance to regulators on the discharge of sediments from or through a dam. This letter’s main conclusion is that a permit will almost always be required for discharge of sediments from reservoirs to satisfy the Section 404 and Section 10 regulations.

2.1.3.2. State Laws

In addition to federal laws, sediment management activities need to satisfy state review. Most states have their own laws, regulations (including permitting requirements) and agencies that deal with water quality and fish and wildlife issues. At the state level, an Environmental Impact Report (EIR) can address both federal and state requirements in a single document. Section 401 of the federal Clean Water Act requires a state to issue certification for any activity which requires a federal permit and may result in a discharge to state waters. The state must certify that the discharge will comply with the state’s water quality plan (where the plan has been approved by the EPA). No license or permit may be issued until the certification has been obtained.

2.1.3.3. Local Laws

Depending on the location and size of the project and the anticipated management activities, counties and cities may also have regulations or other interests that need to be satisfied, or at the very least will provide input to the permitting process at either the state and/or federal level.

2.1.3.4. Regulatory Environment

The complex regulatory environment and stakeholder engagement process means that permitting a sediment management activity can take years to complete. There are multiple and sometimes conflicting laws and regulations to navigate as well as the need to assemble input from multiple and diverse stakeholder groups. In addition to the government agencies mentioned above it is not uncommon for special interest groups and non-governmental organizations (NGOs) to participate in the review process. Some of these groups are interested in providing input to promote a better project while others are focused solely on either changing or preventing change from current practices.

Table 2.1
United States Regulations

Agency	Regulation	Authority
U.S. Army Corps of Engineers	Clean Water Act – Section 404	Regulate the placement of dredged or fill material into waters of the United States
	Rivers and Harbors Act of 1899, Section 10	Regulate work in navigable waters of the United States
U.S. Environmental Protection Agency (EPA)	Clean Water Act – Sections 401 & 404	Enforcement of regulations. Section 401 usually delegated to states. May veto Section 404 permit
	NEPA	Commenting authority
U.S. Fish and Wildlife Service (USFWS)	Fish and Wildlife Coordination Act	Reviews/comments on federal actions that affect surface waters; includes section 404 permit applications
	Endangered Species Act	The Corps must consult with USFWS if listed species may be affected
	NEPA	Commenting authority
National Marine Fisheries Service (NMFS)	Fish and Wildlife Coordination Act	Reviews/comments on federal actions that affect coastal waters, including section 404 permit applications
	Endangered Species Act	The Corps must consult with NMFS if listed anadromous fish or marine species may be affected
	NEPA	Commenting authority

2.1.4. Japanese Regulations

The Japanese regulations can be divided into three periods: before 1958, 1958-1997 and after 1997.

Before 1958, the *Dam Design Guideline* by the Ministry of Interior (1936) did not describe any information on reservoir sedimentation. The *Design Standard of Agricultural Land Improvement Project* in 1954 indicated a design value for sedimentation depth based on the location in the river basin, reservoir water depth and storage volume.

In 1958, *Technical Criteria for River Works* by the Ministry of Construction indicated that the necessary design time to accommodate reservoir sedimentation is 100 years and showed some examples of recorded specific sediment yield rate ranging from 25 to 600 $m^3/km^2/yr$. In 1976, *Technical Criteria for River Works: Practical Guide for Planning* by the Ministry of Construction showed updated examples of recorded specific sediment yield rate ranging from 49 to 5,257 $m^3/km^2/yr$. The revision to *Technical Criteria for River Works: Practical Guide for Planning* by the Japanese Ministry of Land, Infrastructure, Transport and Tourism (MLIT) in 2005 describes necessary storage capacity for sedimentation as follows.

Normally the sediment deposition estimated for the next 100 years is used as the storage capacity for sedimentation. However, the design sediment storage can be reduced in the case of a facility that releases sediment from a flood spillway, one that removes inflow sediment in the reservoir or other facilities for which special measures have been implemented.

Regarding the reservoir sedimentation database, the first guideline was released in 1966 and 1967 to collect necessary information on riverbed aggradation in order to prevent flooding risks upstream of reservoirs caused by sedimentation. In 1982, a more detailed guideline was released which required owners of all dams having a storage capacity over 1 million m^3 to report sediment conditions to the Ministry of Construction every year. Required data includes measured sedimentation volume both in dead storage (B), lower than low water level (L.W.L.), and active storage (A), between the normal water level (N.W.L.) and L.W.L., as shown in Figure 2.1.

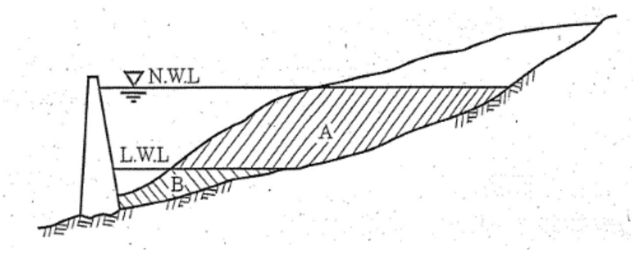


Fig. 2.1
Definition of sedimentation in (B) dead and (A) active storage volumes

Based on this guideline, as of 2013, 971 dams reported annual changes in sedimentation volume and the shape of accumulated sediment (Sumi 2013). These dams account for approximately 1/3 of 2800 Japanese dams over 15 m in height. We are not aware of any countries outside of Japan that have established such a nationwide survey system; this accumulated data has considerable value on a global basis. Figure 2.2 shows how reservoir sedimentation storage losses depend on regions and dam purposes. The three columns show Multipurpose, Hydropower and other dams, respectively. Here, an average annual capacity loss rate for all dams is 0.24%/year and it is very high, up to 0.42%/year, in the Chubu region along the Tectonic Lines where a large amount of sediment is produced in the catchment. Figure 2.2 also shows the “Sediment yield potential map of Japan” that is made by GIS using reservoir sedimentation records, existing geographical features and geological data (Okano et al., 2004). This map is currently used to check sedimentation in planning for new dams and to estimate future sedimentation for existing dams.

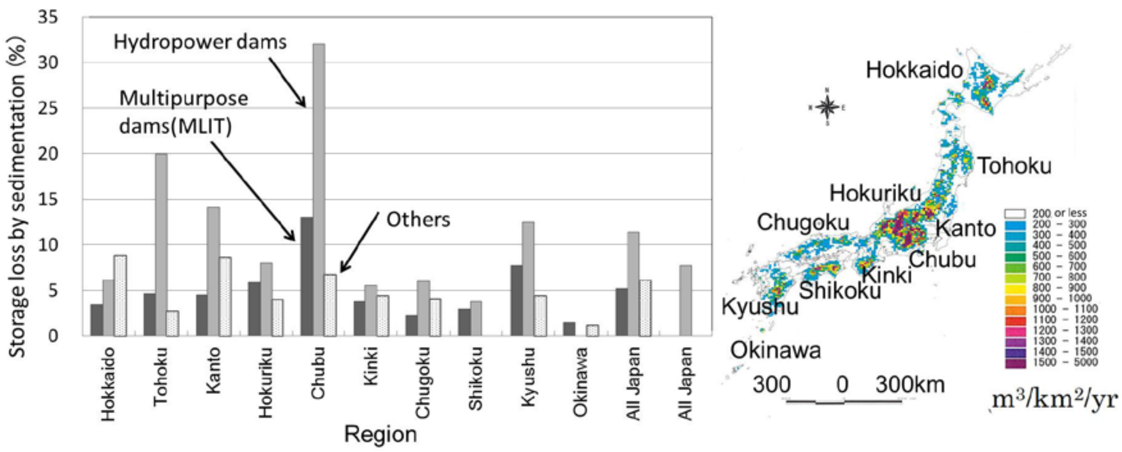


Fig. 2.2

Reservoir storage loss by sedimentation and sediment yield potential map in Japan (After Sumi (2013) and Okano et al. (2004))

The amount of sediment supplied from rivers to seacoasts (hereafter sediment routing system) was radically reduced after World War II (1950-80) with construction of many check dams and storage reservoirs in mountain areas, and acceleration of gravel mining from riverbeds. As a result, various problems arose including riverbed degradation in downstream channels, increased river channel maintenance, and beach erosion as well as severe environmental changes in river and coastal areas. These environmental changes included vegetation growth in river channels and loss of suitable habitats for native aquatic species that largely depend on armoring of the river bed and reduced sediment transport.

Based on these circumstances, and following a recommendation by the River Council of Japan, the comprehensive sediment management concept as shown in Figure 2.3 was proposed in 1997 in order to recover sound sediment transport in the sediment routing system. The new concept required that for sediment routing systems where problems related to sediment movement are apparent, efforts shall be made to understand the characteristics of sediment movement. This includes determining the characteristics of the river or seacoast and performing monitoring surveys of sediment movement. Comprehensive sediment management needs to take into consideration spatial continuity, such as longitudinal continuity from upstream to downstream in the river or continuity in the longshore direction along the seacoast. Since riverbed configurations are changed by sediment movement not only caused by flooding but also occurring in normal times, sediment movement at normal times should be included in considerations of temporal continuity. In addition, since a mixture of diverse grain sizes exists in areas from mountain lands and hillside lands to estuaries, and since ecosystems and natural environments that are suitable for grain size distribution and river flow as well as different patterns of utilization of river spaces exist, not just the sediment quantity but the river channel morphology and the quality of sediment (grain size, etc.) need to be considered. Although sediment travels in a river discontinuously, its primary moving force is flowing water. For this reason, it is important to examine the quantitative characteristics of the river flow regime in the sediment transport system for adequate implementation of sediment management.

In order to support this new concept, erosion control dams in upstream regions are planned to be converted to slit dams with notches, which are designed to pass, not to trap, as much fine sediment as possible, diminishing sediment issues. For storage dams, sediment supply to the downstream river is strongly desired in order to reduce storage loss for reservoir sustainability and mitigate adverse environmental impacts as much as possible. Recovering sediment transport continuity can be accomplished by sediment bypass or sediment flushing outlets as well as sediment replenishment in an attempt to return the excavated and dredged sediment to the downstream river.

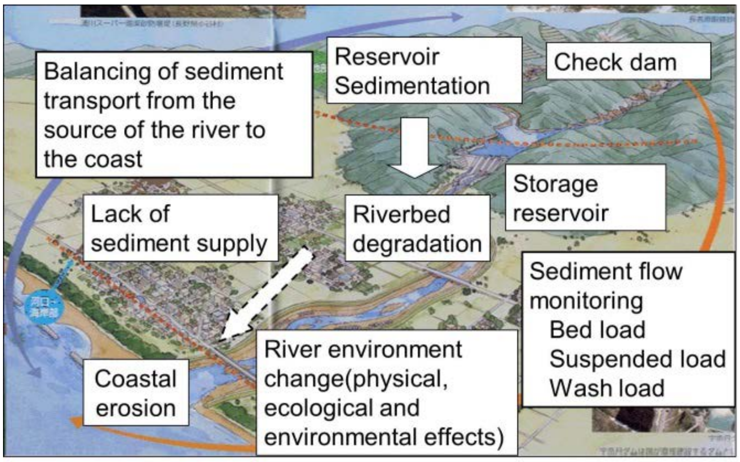


Fig. 2.3
Comprehensive sediment management in the sediment routing system

2.1.5. Korean Regulations

Regulations exist in Korea to encourage sediment continuity and prevent ecologic damage. However, specifics such as studies that must be conducted prior to sediment releases or as part of a management plan are dealt with differently depending on the role of international, national, and local systems of laws and regulations for each project. General guidelines are given in the following paragraphs.

2.1.5.1. Investigation of Sedimentation

General details

1. The amount of sedimentation is estimated by investigating the watershed area, topography, geological state, etc. within the vicinity of sediment prone areas.
2. The sedimentation in each area is estimated by considering the derived empirical formula through the correlation between the sediment factor and observed data based on the topography, geological state, watershed area, stream slope, etc. of the area.

Method for estimating specific sediment load

1. The method for estimating unit sediment yield can be used to estimate reservoir sedimentation volume for designing dams.
2. There are several estimation methods for determining the specific sediment load and the most appropriate method can be selected based on the local conditions and characteristics of the watershed:

   - Sediment rating curve or Q – Q_s curve
   - Reservoir sedimentation data in a watershed
   - Empirical formulae
   - Specific sediment load of other watersheds

2.1.5.2. Sediment Flushing Equipment

<u>General details</u>

1. The basic methods for reservoir sedimentation control include both dredging and the use of sediment flushing equipment. Additionally, the emergency spillway can be utilized as a sediment flushing tool.
2. A sediment flushing plan can be established through the investigation of the formation of a delta caused by backwater effects from the stream.

<u>Methods for recovering reservoir storage capacity</u>

1. Establish a reservoir flushing plan by considering the reservoir's sediment density currents and the reduction of conservation storage.
2. Since there is a correlation between the sediment flushing technique in reservoirs and the function of the sediment flushing gate, the effects of the chosen sediment flushing method(s) (such as use of a sedimentation basin or grit chamber, upstream check dam, sediment bypassing, reservoir dredging, or other sediment flushing equipment) on the flushing gate should be considered.

<u>Sedimentation basin or grit chambers</u>

1. The sedimentation basin or grit chamber is installed upstream of the reservoir and is dredged annually before the start of the rainy season and after the occurrence of large floods.
2. The sedimentation basin or grit chamber is designed considering the magnitude of the stream network, inflow, sediment inflow, concentration, etc.
3. The optimal frequency of the removal and dredging of sediment in the sedimentation basin or grit chamber is determined according to the amount of accumulated sediment.

<u>Check dam and sediment bypassing</u>

1. In order to reduce the sediment load into the check dam of the reservoir, a subsidiary dam should be installed at the entrance of the reservoir.
2. The downstream water level of the check dam and the upstream water level of the main dam play an important role in preventing sedimentation at the main dam reservoir.
3. Since the sediment bypass channel is only operational during the time of flooding, it is necessary to maintain sufficient tractive force to prevent blockage caused by sediment deposition.

<u>Sediment flushing equipment</u>

1. For the efficient operation of sediment flushing equipment in dams, reservoir silting equipment is installed at the front of the sedimentation area.
2. Since deposits can cause blockage of sediment flushing equipment, which may lead to flushing malfunctions, flow injection or jet equipment should be installed for maintenance purposes.

2.1.6. Regulation summary

The overarching goals of the majority of the regulations examined are twofold:

1. To maintain sediment continuity which will prevent excessive deposition upstream of the barrier and excessive degradation on the downstream side

2. To prevent ecological damage by limiting sediment concentrations in releases (this could vary by magnitude of discharge) and/or release of contaminated sediments

Specifics such as studies that must be conducted prior to sediment releases or as part of a management plan, operation plans, lines of authority and permissions are dealt with differently depending on the role of international, national, and local systems of laws and regulations for each country and/or region.

2.2. CONCLUSIONS

In countries with established laws regarding sediment management activities such as those described in the preceding sections, actions by dam owners must comply with national and local regulations. In countries with few regulations for protection of the environment, conscientious owners should still look to the two goals of maintaining sediment continuity and limiting concentrations to acceptable limits. Advancing towards these goals will promote ecologic, social and economic benefits. For projects in the planning stage, sediment balance should be considered from the beginning to ensure a sustainable project and to minimize future sediment management costs. For existing projects prone to sedimentation, the challenge is complex and a change in operation, retrofitting, or retirement of the project will be necessary to recover lost storage and promote ecological river connectivity.

The case studies presented in the following section illustrate some of the ways reservoir sedimentation is managed around the world.

3. CASE STUDIES

The case studies gathered hereafter cover a very large range of reservoir types, operations, objectives and methods of management. They are the result of design studies, construction projects or experience gained from long-term project operation. Hence, they deal with causes of siltation, measurement techniques, sediment management methods, process sustainability, and beneficial and debilatory factors and consequences involved with sediment management.

In addition to a description of the project and sediment management measures each case study is characterized by three important parameters:

- CAP: The reservoir capacity
- MAF: The mean annual runoff (sometimes abbreviated MAR)
- MAS: The mean annual sediment inflow

The ratio CAP/MAS defines the reservoir life, while the water turnover rate is defined as ratio of CAP/MAF. Following the work of previous ICOLD bulletins (1999 and 2009), Sumi (2005), and Annandale (2013), each project is displayed in a figure which suggests which type of sediment management actions may result in sustainable or non-sustainable futures.

3.1. CLASSIFICATION OF MANAGEMENT METHODS

Sedimentation management encompasses a large variety of strategies including flushing, sluicing and bypassing (e.g., Morris and Fan 1998, Kondolf et al. 2014). Fig. 3.1 shows an overview of these techniques and their corresponding strategies: (1) sediment yield reduction, (2) routing sediments around or through the reservoir, and (3) recover volume by sediment removal or dam heightening. Furthermore, two more strategies may be added: (4) dam removal and (5) no action.

As these strategies are dealt with extensively in the literature (e.g., Morris and Fan 1998, ICOLD 1999, ICOLD 2009, Annandale 2013, Kondolf et al. 2014) they will not be discussed in this bulletin.

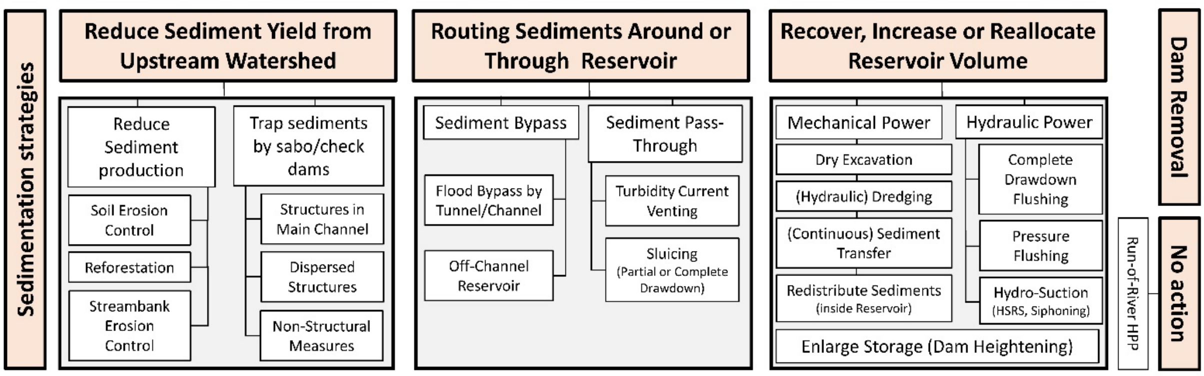


Fig. 3.1
Classification of strategies against reservoir sedimentation (Auel et al. 2016a)

A classification of these management methods based on the CAP, MAF, and MAS parameters was developed by Sumi (Sumi, 2005). Note that while the catchment area is also an important parameter to estimate sediment yield, it is directly correlated with the MAF and the MAS.

Each case study contains a classification graph which plots the theoretical reservoir life (CAP/MAS ratio) versus the retention time (CAP/MAF ratio). Figure 3.2 below reveals the typical zones of parameters which are well suited for various management methods:

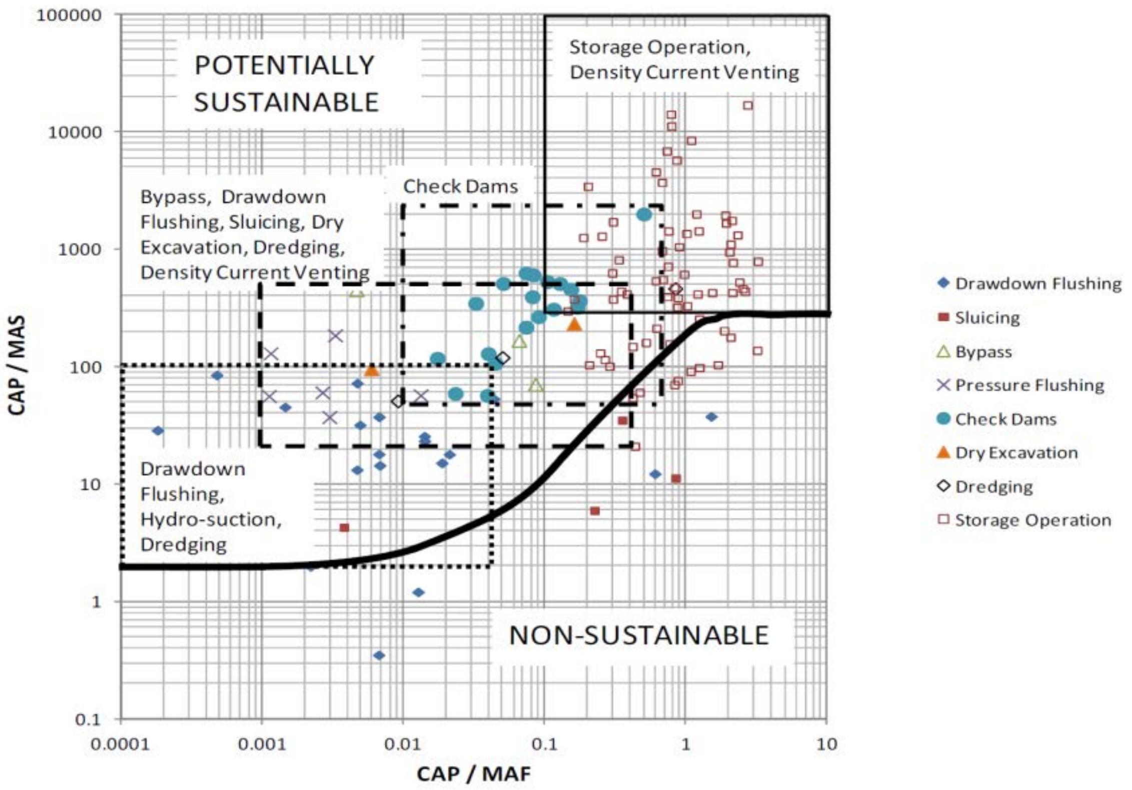


Fig. 3.2
Sediment Management Activities (Annandale, 2013)

3.2. SYNTHESIS OF CASE STUDIES

Each case study was voluntarily submitted. In order to provide some uniformity and a common frame of reference for the disparate cases, the following items were requested from each preparer (in some cases items could not be addressed due to lack of data):

1. Regulatory constraints (including environmental, sediment or fish continuity)
2. Special items, such as
    - Density currents
    - Sediment bypasses
    - Reservoirs filled with sediment (management methods and success of methods)
3. Hydrology
4. Basic dam/reservoir data
5. Sediment data (if available)
    - Transport, grain sizes, etc.
    - Annual inflow versus capacity of sediment and water
6. Economics/sustainability

- Rehabilitation
- Cost comparisons

7. New dam versus retrofit of existing dam
8. Owners
9. Political issues, if any
10. Classification of sediment management, perhaps using Dr. Sumi's chart
11. Plot of capacity versus mean annual flow

Addressing these key items was also requested in order that the case studies could prove more useful to readers who are researching alternatives for their particular project. In order to be included in this bulletin, submitted case studies were required to include as much of this data as possible. A list of the projects chosen for inclusion is shown in Table 3.1 below.

Table 3.1
Sediment Management Case Studies

Case Study	Location	Key Words	Submitting Country
Heisonglin	China	Lateral Erosion	China
Xiaolangdi	China	Density Current Venting	China
Flumet	France	Dredging & Downstream Release	France
St. Egreve	France	Modeling, Flushing	France
Upper Rhone River	France & Switzerland	Monitoring-informed Releases	France
Karnali	Nepal	Physical model	France
Bunji	Pakistan	Large hydropower, flushing	France
Khashm El Girba	Sudan	Irrigation, annual flushing operations	France
Bakaru	Indonesia	Dredging, Bypassing	Indonesia
Simbrivio	Italy	Sediment excavation, quarry restoration	Italy
Asahi	Japan	Bypass Tunnel	Japan
Unazuki and Dashidaira	Japan	Flushing	Japan
Mimikawa	Japan	Sluicing	Japan
Miwa	Japan	Check Dams, Bypass Tunnel	Japan
Shimokubo	Japan	Sediment Trapping, Downstream Placement	Japan
Spencer	USA	Sluicing	USA
Kali Gandaki	Nepal	Seasonal Sluicing	USA

3.3. SCHEMES AT STUDY STAGE OR UNDER CONSTRUCTION

3.3.1. Nepal – Karnali: Management of Sediments in the Karnali Reservoir

3.3.1.1. Introduction

The Upper Karnali Hydro Electric Project is under design in Nepal. The reservoir will collect water from the Karnali River and the associated hydropower plant will have about 900 MW capacity. This project will need to consider both bedload and suspended load sediment transport. A physical model built at Artelia Laboratory helped to characterize the behavior of the reservoir and to define a sediment management scheme.

3.3.1.2. Owners

The project is being developed by the GMR Upper Karnali Hydropower LTD which contracted Artelia Eau & Environnement for the construction of a scale model of the scheme and the associated studies in 2010 (hydraulic tests, suspended load tests and bedload tests).

3.3.1.3. Hydrology

The dam is located on the upper Karnali River and the catchment area is about 20120 km². The mean annual estimated flow at the headworks is 500 m^3/s. High water and floods occur mainly during the summer period and last for about three months. Three types of floods have been tested on the model:

- Low flood Q_{max}=1 420 m^3/s (range 800 m^3/s-1 420 m^3/s, duration 8 days)
- Mean flood Q_{max}=1 600 m^3/s (range 800 m^3/s-1 600 m^3/s, duration 9 days)
- High flood Q_{max}=2 600 m^3/s (range 1 280 m^3/s-2 600 m^3/s, duration 8 days)

Moreover, the scheme has been designed for the following discharge values:

- Design discharge: 6 750 m^3/s
- Maximum discharge: 8 000 m^3/s

Figure 3.2 below shows the river rating curve close to the future dam location.

3.3.1.4. Basic dam and reservoir data

The scheme will be built on the Upper Karnali River in the western part of Nepal. It consists of:

- A gate-structure dam (about 200 m wide and 64 m high) of five bays equipped with five radial gates (each gate 11 m wide, opening 14 m) and a sixth bay for an auxiliary gated spillway (width 3 m, opening 6 m).
- A dissipation basin for each bay.
- A lateral power intake immediately upstream from the dam on the right bank (length 146 m) supplying four turbines in a powerhouse located on the other side of the mountain, the maximum turbine discharge is 675 m^3/s at the normal reservoir level (633 m asl).
- A diversion tunnel (horseshoe cross-section 9 m, length 1 034 m) whose outlet is located on the right bank just downstream from the dam. The tunnel is closed at the downstream end by a radial gate and upstream by a vertical lift gate. The maximal discharge diverted through the tunnel can reach about 750 m^3/s.

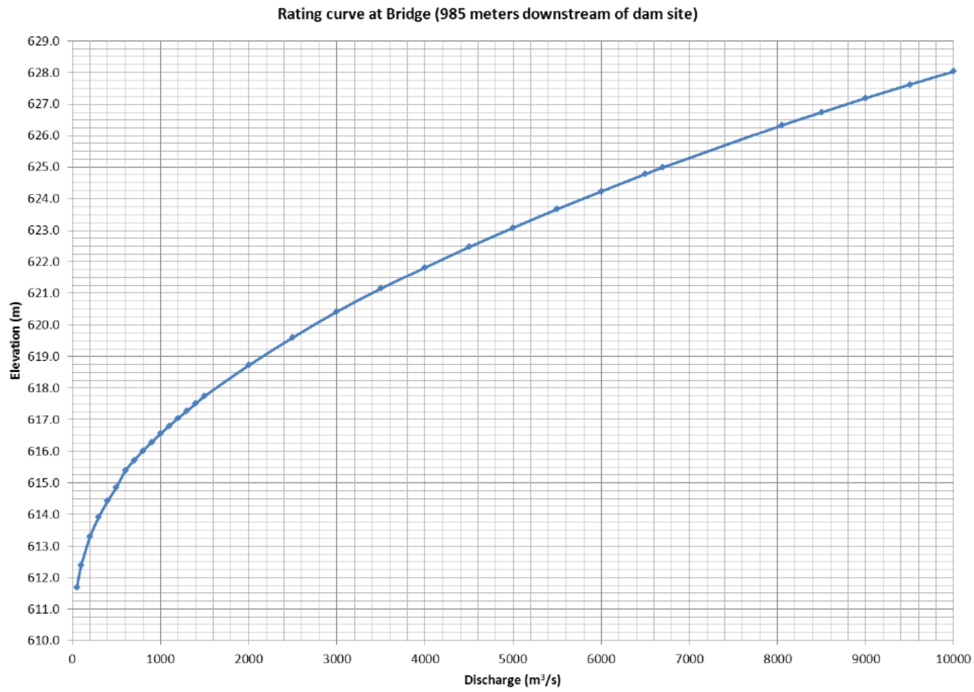


Fig. 3.3
River rating curve (985 m downstream of the dam site)

The maximum water level is fixed at 637 m asl. Figures 3.4 and 3.5 show the cross section and plan view of the site, respectively.

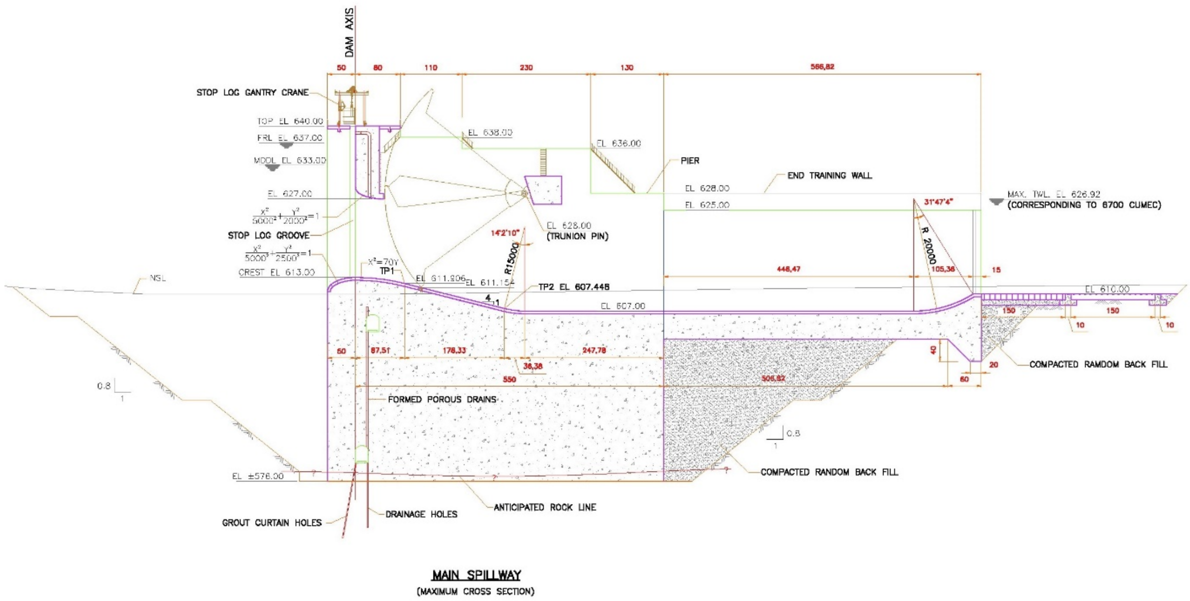


Fig. 3.4
Typical cross section of the dam and the spillway

The model represents all the hydraulic works as well as the reservoir over a length of 3 km and the river downstream of the dam over a length of 1 km. It has been built at a scale of 1/100 to have a large area represented and a correct scale of the sediments. The geometric scaling is done according to Froude similitude and there is no distortion between the vertical and horizontal scales. The sediments are scaled according to the conservation of Shields parameter so that the sediment in the model initiates its motion for the same hydraulic conditions as in the prototype. Figure 3.6 shows a view of the laboratory model.

The same model is used to study the bedload and the suspended load. But they have not been tested simultaneously since the time scales are different and the areas of concern from the bedload and the suspended load are not exactly the same.

3.3.1.5. Political issues

The development of the Upper Karnali project faces some local opponents and requires a national debate on the benefits of such a scheme.

3.3.1.6. Regulatory constraints

Limitations to the flushing operations could apply due to environmental reasons (maximum concentration allowed for aquatic life or downstream water intakes) or security reasons (maximum discharge step increase to prevent human injury).

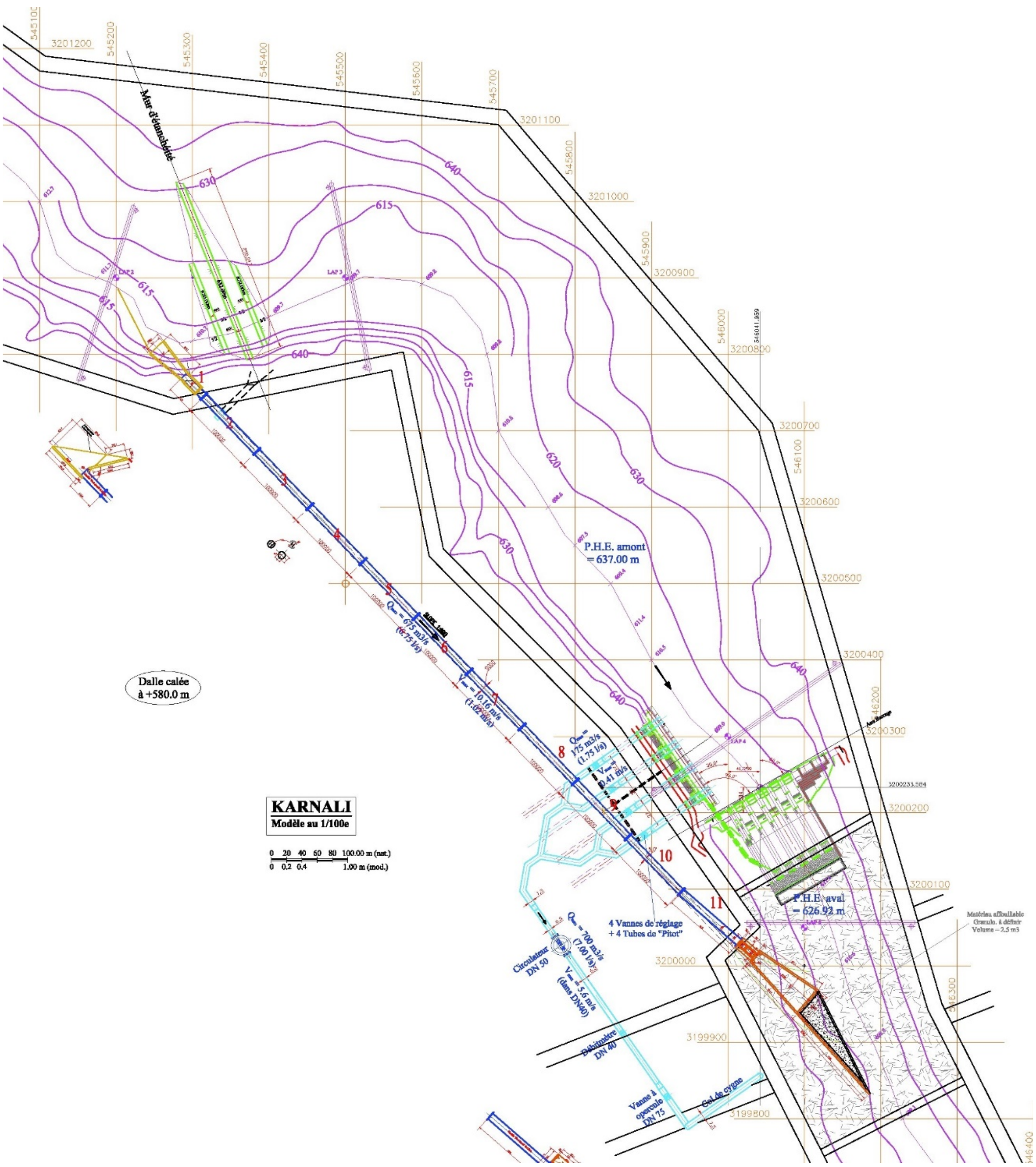


Fig. 3.5
Plan view of the Karnali hydroelectric scheme

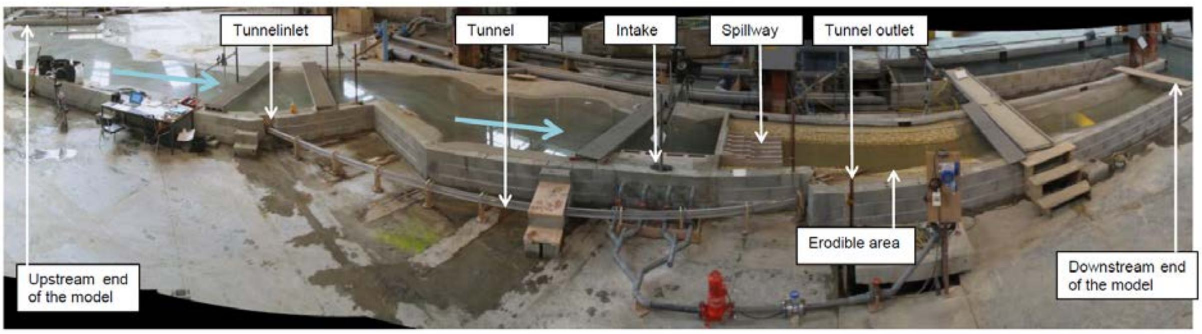


Fig. 3.6
Panoramic view of the physical model

3.3.1.7. Sediment data of the site

For the year 2009, the measurements indicate about 13 M tons of suspended sediment passing at the dam site. Much more was recorded in 2010 (57 M tons) but civil works upstream partially explain this difference.

The following curves present the discharge and the simultaneous suspended sediment concentration for the available observations supplied to Artelia by GMR (for the period: 26 May 2009 – 31 January 2011).

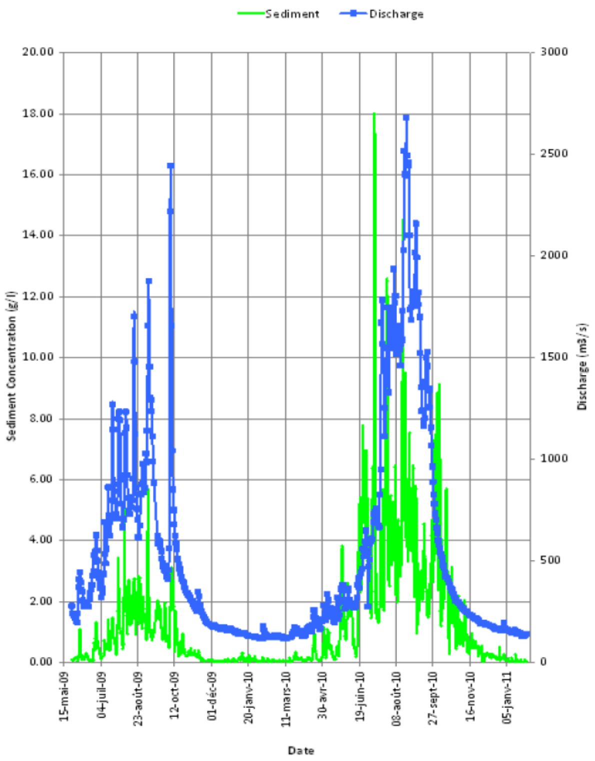


Fig. 3.7

Discharge and sediment hydrographs for 2009 and 2010

The size of the suspended sediment is not well known. Observations made on pits sampled by Aadhar Engineering & Consultancy Services show that all the sediments are finer than 0.4 mm and that possibly at least 50% are smaller than 0.15 mm (indeed the samples contain sediment that probably belongs to the coarser part of the suspended load as particles could settle).

For this study, the prototype sediment is characterized on the basis of suspended sediment and riverbed or bank sediment grain size analyses:

- Prototype bedload sediment: d_{10}=2 cm, d_{50}=5 cm, d_{90}=8 cm
- Prototype suspended load sediment: d_{10}=0.1 mm, d_{50}=0.15 mm, d_{90}=0.3 mm

The flood period extends approximately from the 1st of May to the 10th of November. For the study, two typical flood events have been chosen to characterize the flood and the linked sediment transport:

- A mean flood: Peak discharge 1 740 m^3/s, duration 8 days (July 2010)
- A high flood: Peak discharge 2 700 m^3/s, duration 11 days (August 2010)

These events are not exceptional. They are commonly observed many times each year for the mean flood and probably every year or two for the high flood.

Two different grain size distributions have been used in the model to represent the real materials. At the model scale (1/100), the prototype suspended load has to be distorted in order to not be too fine or cohesive and to respect the Shields criterion. Preliminary tests in flumes helped to choose the adequate sediment density and size. Artificial sediment was consequently chosen (density 1.04/1.05, d_{50}=0.3 mm) to represent the grain size curve. The graphs below show their distribution curves.

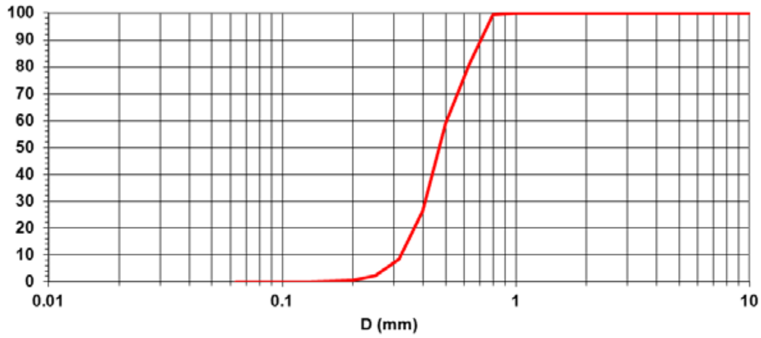


Fig. 3.8
Model bedload grain size curve

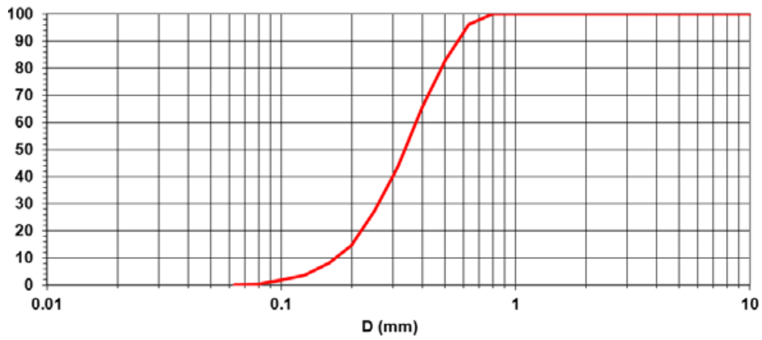


Fig. 3.9
Model suspended load grain size curve

3.3.1.8. Management of suspended sediments

When the discharge increases such that the spillway is opened to maintain the reservoir water level at elevation 637, it is preferred to systematically close the power intake to avoid a significant increase in suspended sediment concentration therein.

Depending on the discharge value of the flow entering the reservoir, different operations are proposed to handle the sediments. It is recommended:

- To open the tunnel before opening the spillway to pass discharges between 675 m^3/s (discharge for the power intake) and the maximum tunnel capacity able to maintain the normal water level at elevation 637 in the reservoir (variable discharge according to the quantity of bedload sediment passing simultaneously in the tunnel, but possibly around 750 m^3/s if the state of the tunnel revetment is not very good after some years of bedload transport). This operation aims at diverting the excess discharge before it reaches the lower part of the reservoir so as to optimize the settling effect of the reservoir upstream from the water intake.
- To avoid opening the power intake as soon as the spillway is open as this operation strongly increases the suspended sediment concentration.

- To clean the reservoir by flushing the deposited sediment when the discharge reaches about 1 800 to 2 000 m³/s with the water level lowered to elevation 633 in the reservoir during a few days. The duration depends on the state of sedimentation in the reservoir. After 2.5 months with five mean floods of nine days and four low floods of eight days, a maximum of five days of flushing are sufficient.

The flushing operations are necessary to remove fine sediments deposited during the period when the discharge is less than about 1 420 m³/s and the spillway remains closed. There are two options to clean the fine sand deposits from the reservoir:

- Using a high flood (Q>1 600 m³/s) at elevation 633, spillway open (tunnel and power intake closed).
- Using a lower discharge (around 675 m³/s), spillway open (tunnel and power intake closed).

3.3.1.9. Management of bedload sediments

A bedload bypass tunnel, hydrosuction dredging and flushing operations were considered to handle the bedload sediments.

Tests were carried out to estimate the capacity of the bypass tunnel to divert the incoming delta bedload from the reservoir to the downstream reach of the river. Several configurations were tested with different cofferdams upstream of the tunnel intake. Results revealed that it is not advisable to keep a cofferdam in the river bed. The risks are larger than the advantages.

Based on observations, it was proposed to test an innovative hydrosuction dredging system, aiming at removing the bedload in a larger area around the bypass tunnel intake. This system consists of:

- A vertical lift gate at the bypass tunnel entrance, which is partially closed during hydro suction operation.
- An underwater pipe, with upstream boundary to be moved within the reservoir, and downstream boundary to be fixed on the bypass tunnel invert, with its end located immediately upstream of the upstream vertical lift gate.

This system, which is displayed in Figure 3.10 below, allows for dredging bedload from the incoming delta through the bypass tunnel without using external power.

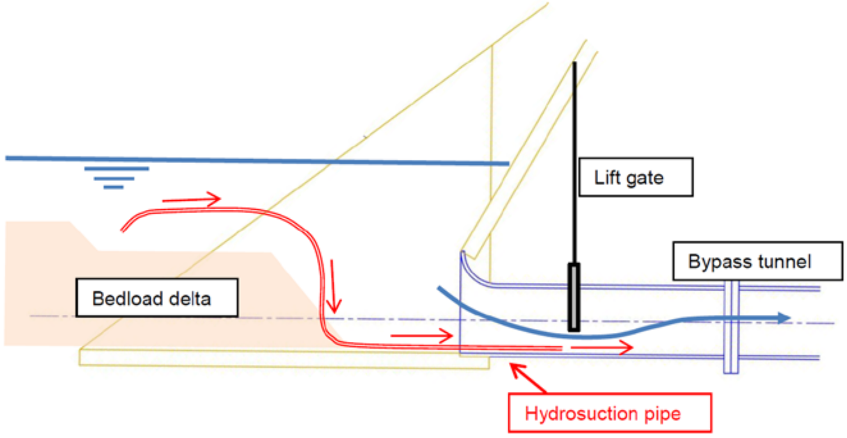


Fig. 3.10
Hydrosuction dredging system

The third and final hydraulic method of removing the bedload delta from the reservoir is to proceed with a flushing operation, in order to generate high flow velocities, greater than the threshold velocity of the bedload material. The delta bedload is then transported through the spillway with completely open gates.

During such operations, the power intake is shut down and the bypass tunnel is closed in order to maximize the main discharge through the spillway gates.

Tests have been carried out on the model to define if such an operation is efficient. Results show that it is possible to quickly move a large amount of bedload sediment. Therefore, operation of the reservoir by regularly flushing the incoming bedload appears possible. On the other hand, this flushing effect used to remove the fine sediment deposited near the power intake, will simultaneously draw the bedload sediment downstream into the pool of the reservoir.

3.3.2. Pakistan – Bunji: Management of Sediments in the Bunji Reservoir

3.3.2.1. Introduction

The Bunji Hydropower Project, one of the largest in the world, is currently under construction in Pakistan. It includes dam construction, underground powerhouse digging, headrace and tailrace tunnels drilling, bridge building, mechanical equipment design, etc. The dam, located on the Indus River, approximately 45 km south-east from Gilgit, will supply a power house with an installed capacity of 7100 MW. The water in the Indus River shows very high concentrations of suspended sediment which is a serious problem for turbine erosion and siltation of the reservoir. Solutions to handle the sediments have to be carefully considered.

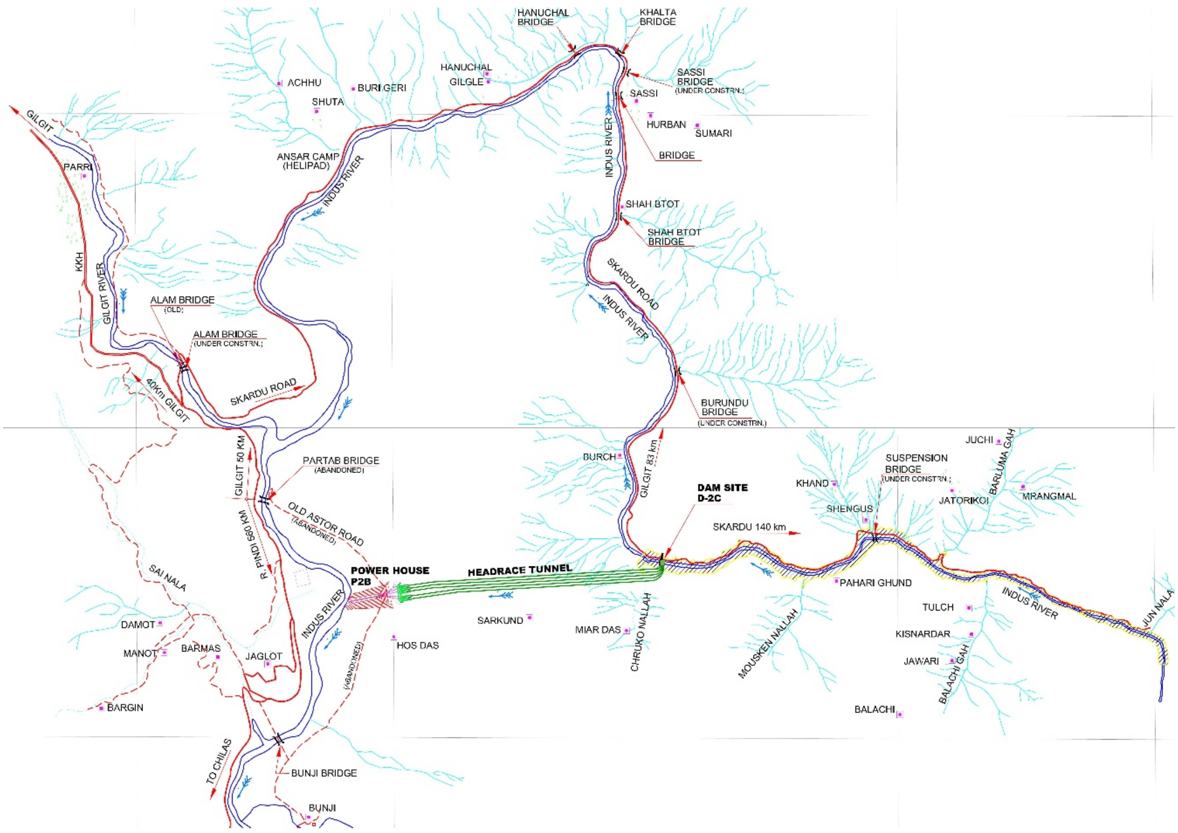


Fig. 3.11
Location of the Bunji Dam

3.3.2.2. Owners

The Bunji Hydropower Project is owned by the Pakistan Water and Power Development Authority. The overall estimated cost after the detailed design stage is about $8 billion USD. The main objective of the scheme is the production of electricity using a configuration that provides high potential head over a short direct distance. During the past few years, Sogreah has contributed to the design of this project as a member of Bunji Consultant JV, a joint venture of international companies.

3.3.2.3. Hydrology

The mean annual flow of the Indus River, estimated using long-term records (last 35 years) from weather stations at Skardu and Bunji, is 1 137 m^3/s. The catchment area of the Indus River at the dam site is 114 890 km^2 and the average annual run-off in the reservoir is about 36 billion m^3.

There are three distinct events which could cause exceptional floods at the Bunji dam site: Meteorological flood events (snowmelt and rainfall-runoff processes), glacial lake outburst floods, and landslide events along the Indus River. The maximum discharges associated with each of these types of events are quite different, from 10 000 m^3/s for the meteorological flood (1 000-year return period) up to 36 000 m^3/s for a major landslide.

The 1929 flood, which is the largest historical event for which data is available, was caused by an outburst of the Chong Khumdan glacier lake. The peak flow of this flood has been estimated to have been 16 000 m^3/s at the dam site. The estimated hydrograph at the dam site for this event is shown in Figure 3.12. The return period of this event is estimated to be 150 years.

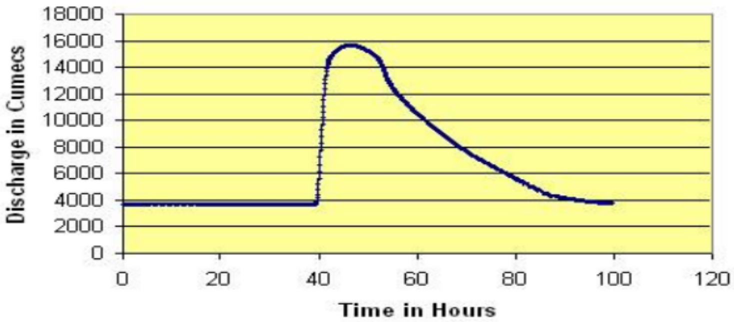


Fig. 3.12
Estimated hydrograph for the 1929 GLOF

A GLOF (Glacial Lake Outburst Flood) event of 22 400 m^3/s, corresponding to a return period of 1 000 years, is adopted as the design flood. It is considered to safely exceed the greatest flood on record and it has been used for all hydraulic structure design. Table 3.2 below presents the frequency distribution of glacial lake outburst floods at the proposed dam site.

Table 3.2
Frequency distribution of GLOF at proposed dam site

Return period (years)	**Estimated peak flow (m^3/s)**
10	4 310
25	9 552
100	14 673
1000	22 419
5000	27 750
10000	30 042

The safety check flood is 36 000 m^3/s which corresponds to a major landslide into the reservoir. For this flow, damages to the dam and spillways are acceptable but there shall be no catastrophic release of water from the reservoir.

3.3.2.4. Basic dam and reservoir data

A 200 m high roller compacted concrete gravity dam is adopted as the least expensive solution that will meet the required technical criteria. This dam blocking the Indus River will create a 22 km long reservoir retaining about 250 Mm^3 of water at an elevation of 1 685 m asl.

The designed spillway contains six large gates (18 m wide x 16 m high) able to pass the design flood of 22 400 m^3/s which corresponds to a 1 000-year GLOF. The dam is designed to be overtopped in the event of higher flood flows (safety check flood about 36 000 m^3/s), with a tailwater dam creating an effective plunge pool. Mid- and low-level openings allow reservoir drawdown and sediment flushing.

The underground power plant is equipped with twenty Francis turbine units of 368 MW each under a hydraulic head of 420 m. The design flow of the power intake structure is 1 900 m^3/s for a global installed power of about 7 100 MW considering the generators' efficiency. The turbine-generator units will be installed in the powerhouse in five groups of four units, each being connected to a 5.8 m diameter steel lined penstock.

An auxiliary powerhouse in the right abutment will, during the periods when the reservoir is not spilling, use the minimum environmental release of 20 m^3/s to generate around 30 MW with the available head of about 160 m. Additional facilities have been provided to allow extra generation up to a maximum of 90 MW during the high flow season.

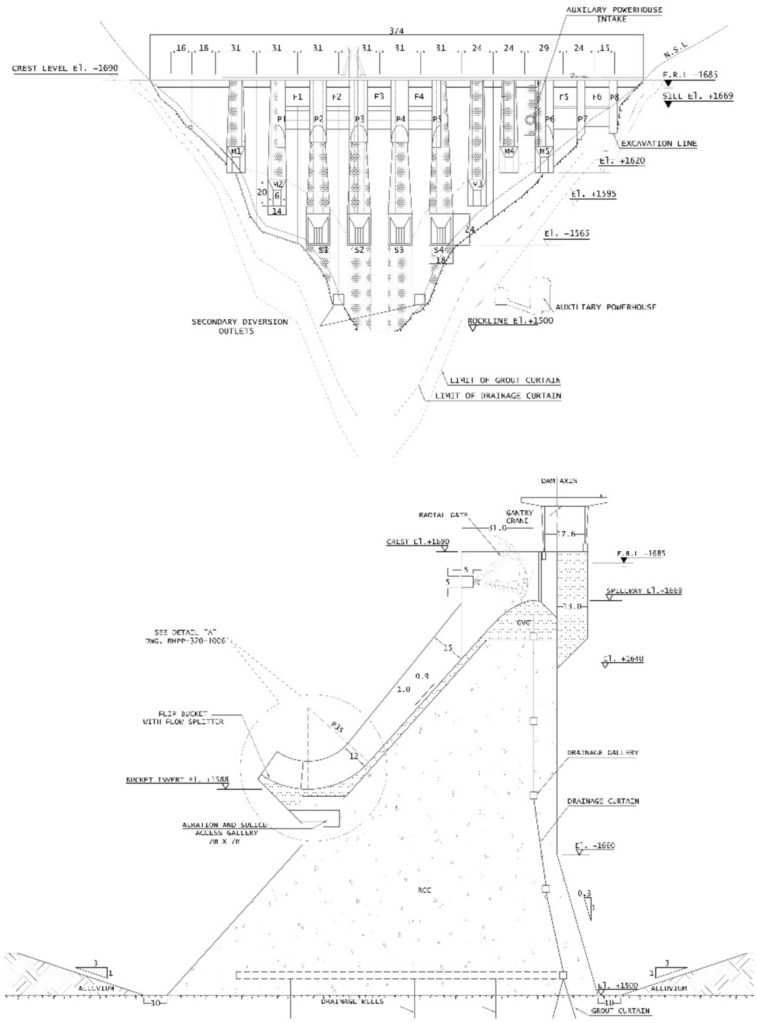


Fig. 3.13

Developed upstream view and nominal section of the dam

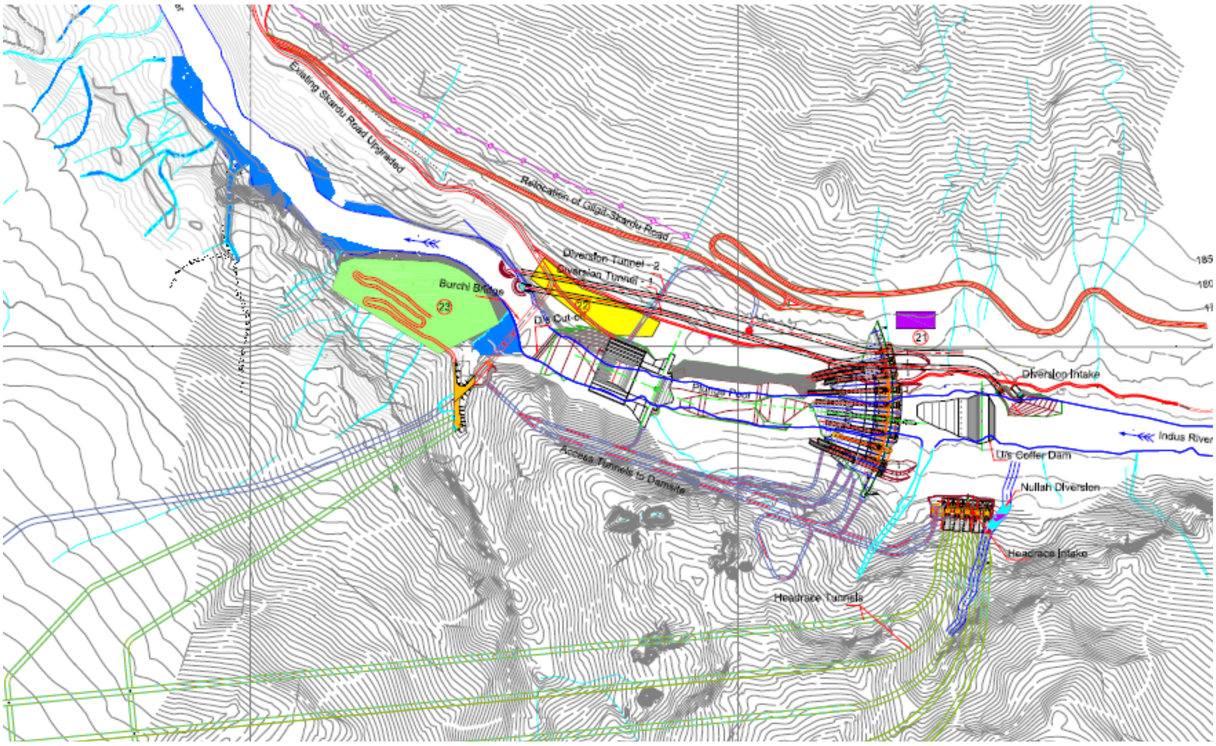


Fig. 3.14
Plan view of the dam site

Table 3.3
Key project features

Design flood, dam site	22 400 m^3/s (1000-year GLOF)
Safety check flood, dam site	36 000 m^3/s (landslide)
Dam height	200 m (incl. 5 m freeboard)
Dam type	RCC gravity
Gross head	approx. 440 m
Design flow (Power Intake Structure)	1 900 m^3/s
Reservoir length when full	22km
Reservoir surface area	4.18 km^2
Reservoir volume when full	252 Mm^3
Reservoir top water level (full)	1 685 m
Reservoir minimum operating elevation	1 675 m
Spillway crest elevation	1 669
Spillway gates size	18 m wide x 16 m high
Upper mid-level gate invert elevation	1 620 m
Lower mid-level gate invert elevation	1 595 m
Total diversion capacity	7 000 m^3/s (10-year flood)

3.3.2.5. Plot of capacity versus mean annual flow

Stage storage and stage surface area characteristics for the reservoir are given in Figure 3.15 below.

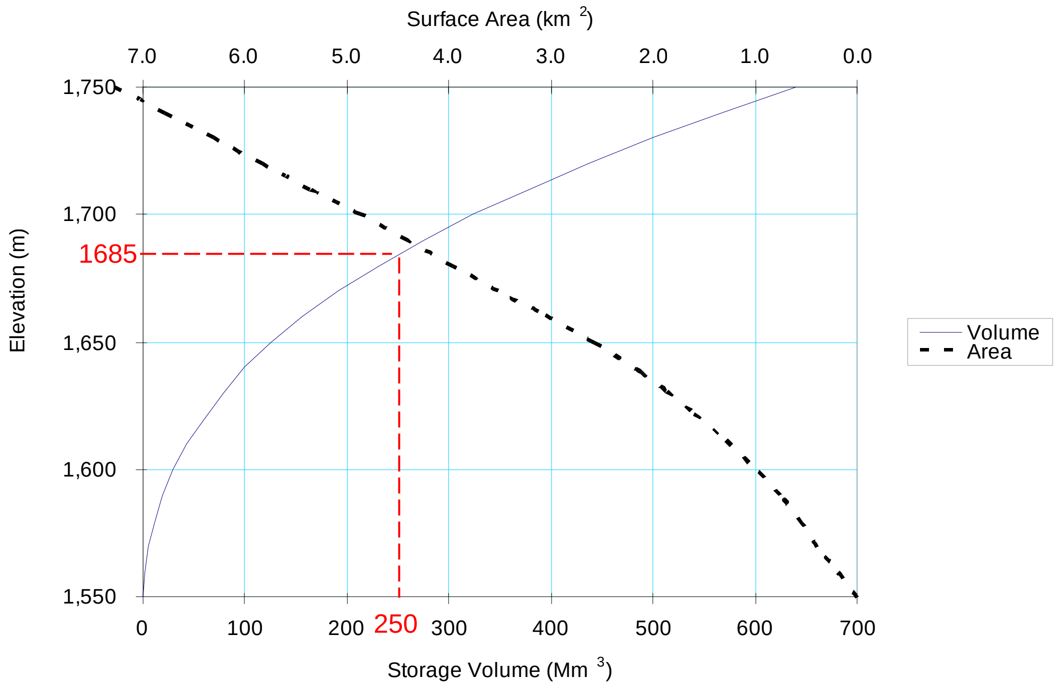


Fig. 3.15
Bunji reservoir characteristics

3.3.2.6. Political issues

The project development necessitates a very large investment, which will probably be hard to recoup. Despite the exclusive energetic goal of the scheme, Bunji is part of the Long Term Projects of the Water Resource and Hydropower Development Vision 2025 Program to be developed within ten years.

Other projects may take priority in Pakistan. For example, construction began on the Diamer-Basha Dam in 2011. It has a larger reservoir and will contribute to the Indus River regulation as well as offer irrigation and drinking water storage.

3.3.2.7. Regulatory constraints

An environmental flow discharge of 21 m^3/s is required.

3.3.2.8. Sediment data of the site

Various measurement campaigns have been carried out during the design studies. The last one from 2009 allowed for the analysis of sediment samples taken from the river at the dam site.

The 10-day averaged gradations and a weighted gradation (based on the total weight of material at each gradation) for all samples are shown in Figure 3.16 below. The weighted gradation reveals that the proportion of clay and silt is around 28%. The suspended sediments are graded as follows: d_{10}=0.010 mm, d_{50}=0.100 mm and d_{90}=0.450 mm.

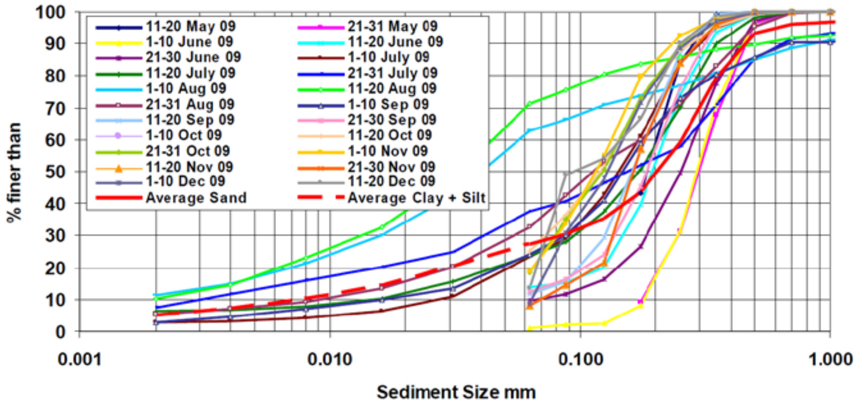


Fig. 3.16
Sediment grading in the Indus River at the dam site

The relationship between flow and concentration is shown in Figure 3.17. The high sediment concentrations around flows of 1 000 m³/s occur during the start of the high flow period. The plot of the concentrations of particle sizes shows a more consistent relationship with flow, although the relationship differs below about 2 000 m³/s to that above 3 000 m³/s.

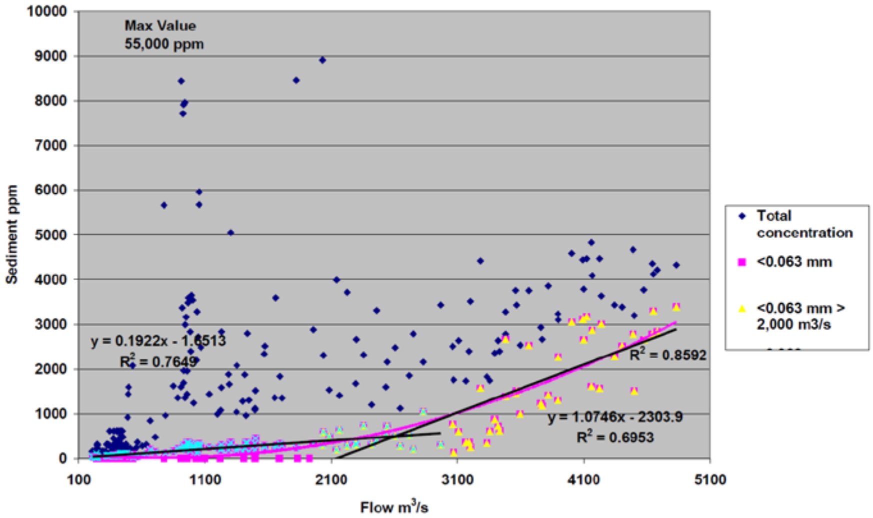


Fig. 3.17
2009 pumped sampling – Flow concentration

The estimated average annual quantity of sediment is about 110 M tons, predominantly entering the reservoir in the high flow season of summer. The dam site has a catchment area of 115 000 km² and an average yield of 950 tons per km².

A numerical model of the reservoir sedimentation process has been established using the program HEC-6KC. This software, developed by the U.S. Army Corps of Engineers, can be used to evaluate deposition in reservoirs (both the volume and location of deposits), estimate possible maximum scour during large flood events, and evaluate sedimentation in fixed channels.

Three sets of analysis were carried out covering normal operation, floods, and landslide in the reservoir. For each set, sediment deposition was modeled for different typical flows: low (1972), average (1983) and high (1994) as well as for the year for which pumped sediment data was available (2009). The efficiency of the flushing was also examined in the model for each case.

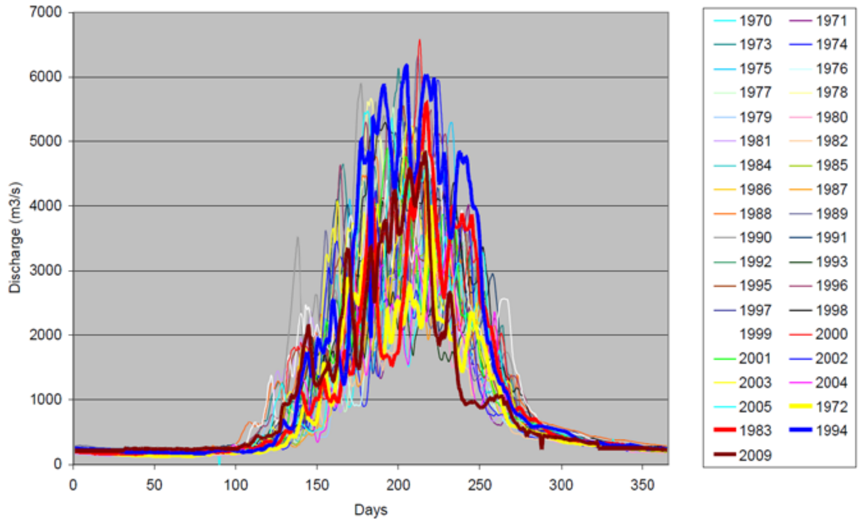


Fig. 3.18
Annual flow series of average daily flows

Results show that the average quantity of sediment passing through the turbines each year is on the order of 11 M tons of which just over half is silt and just under half is clay. The longitudinal bed profile shows the formation of a sizeable delta in the reservoir depending on the flow pattern of each year.

3.3.2.9. Modeled flushing scenarios

The removal of sediment from the reservoir in a particular year depends on the flow pattern, flushing discharge, and flushing period. In this exercise, the maximum flushing discharge is kept at 3000 m^3/s and the flushing period starts on the 21^{st} of August. The results in terms of bed levels after 5, 10, 15 and 20 days of flushing are presented in Figure 3.19 below jointly with the situation prior to flushing operations for 1983 (average flow conditions). As a general conclusion, we can observe that the higher the annual flow is, the larger the delta will be and the longer the flushing period will need to be to evacuate the sediments.

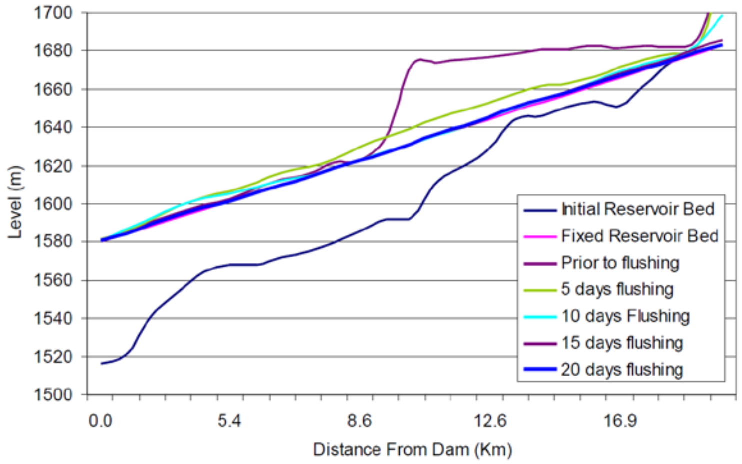


Fig. 3.19
1983 sedimentation and bed profiles – normal operation

The reservoir model was executed with two different floods: the 1 in 100 year meteorological flood (three months long with a peak discharge about 8 500 m^3/s) and a landslide breach flood, which is considered to be the extreme flood (96 hours long with a peak discharge of 36 000 m^3/s). Results reveal that substantially more sediment will pass through the turbines during these events (30 M tons), as would be expected, since the flow velocities in the reservoir are greater and the retention time shorter. Also, as expected, the proportion of silt is higher, approximately twice that of the clay (20 M tons and 10 M tons respectively).

The flushing events modeled show that the longer duration 1 in 100 year snow melt flood will require over 20 days of flushing, whereas the shorter duration extreme flood may be flushed within a few days (Figure 3.20).

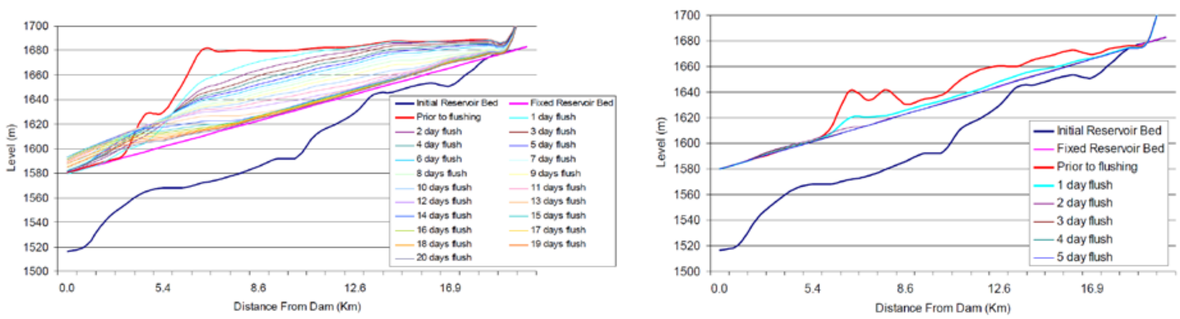


Fig. 3.20
Sedimentation and flushing bed profiles for 100-year return period flood (left) and extreme flood (right)

Finally, regarding the reservoir landslide event, the results show that whilst the landslide changes the sedimentation profile in the reservoir, it does not alter the quantities of sediment passing through the turbines. The study has considered possible sudden movement of material graded up to 2 m in size into the reservoir creating a 50 m high blockage. The longitudinal bed profile at the end of the 1983 sedimentation modeling year is shown in Figure 3.21 below. Compared to the results of the normal operation model, the landslide has only a minor effect on the flushing levels and this is reduced when a channel is formed through the blockage.

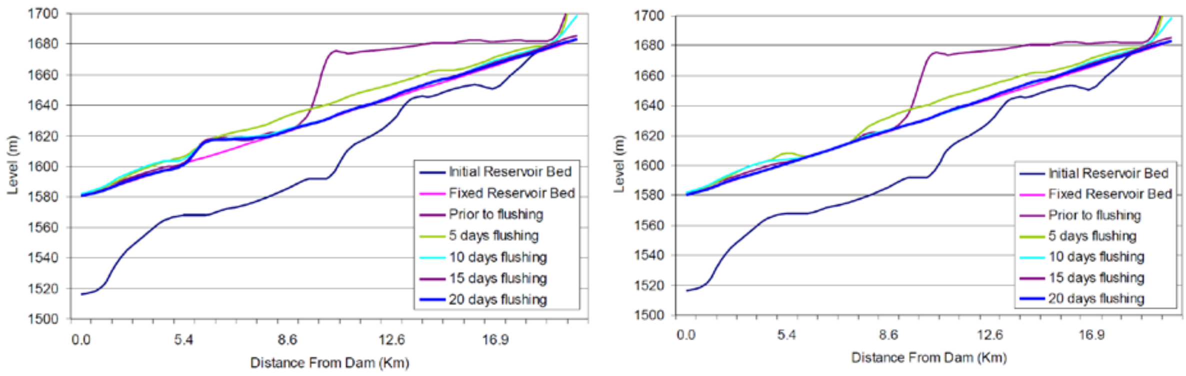


Fig. 3.21
1983 sedimentation and flushing bed profiles – landslide without channel (left) and with channel (right)

3.3.2.10. Classification of sediment management

The classification of the sediment management techniques is done considering the mean annual inflows of water and sediments in the reservoir. The graph below shows the situation of Bunji reservoir in comparison with many other cases. It is located close to the limit of non-sustainable solutions but the flushing operations seem to be a coherent choice with respect to the other sediment management approaches.

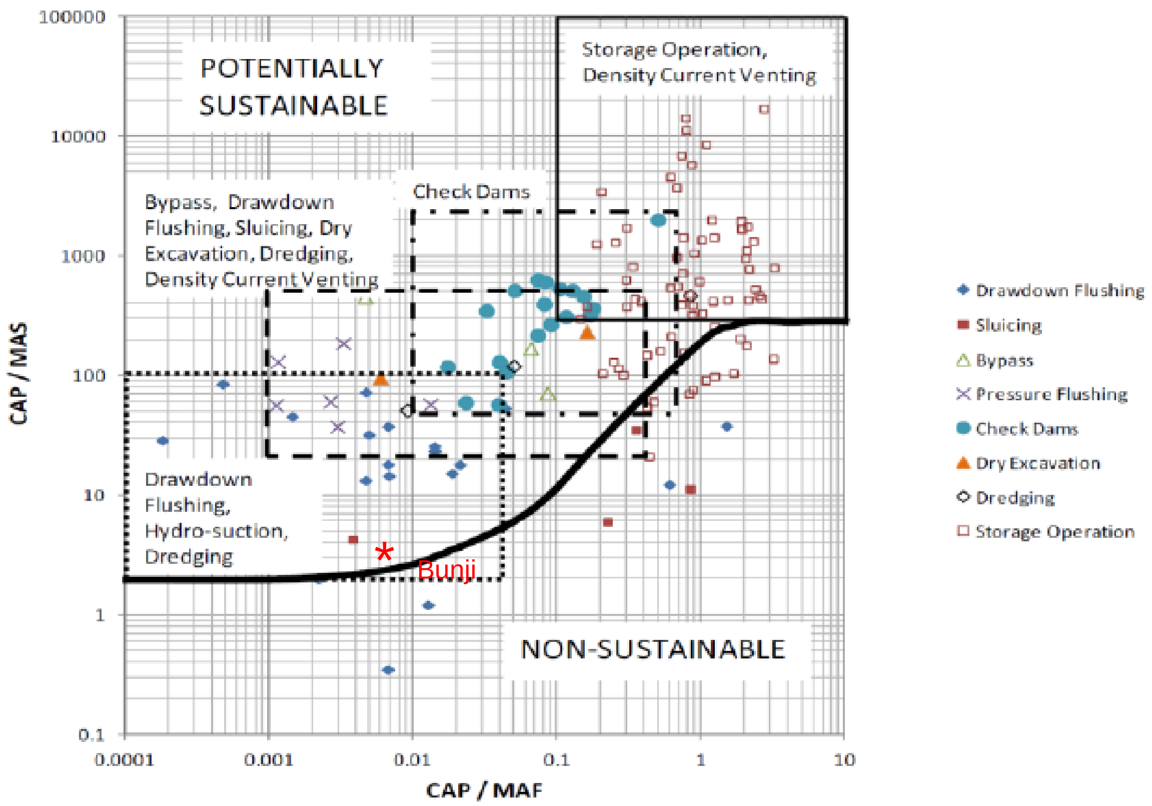


Fig. 3.22
Classification of sediment management approaches and the situation of Bunji Reservoir

3.3.2.11. Planned sediment flushing operations

Annual flushing is planned during the exploitation period to ensure a low siltation rate of the reservoir.

The sedimentation studies have shown that the reservoir needs to be drawn down rapidly to avoid excessive loss of energy production. Flushing has to be undertaken when there is sufficient inflow to mobilize the sediments and move them though the dam. Detailed analysis shows that four openings are required, each 6 x 12 m (width x height) located all at the same elevation as low as possible in the dam. The space between the openings has to be such that there will be sufficient concrete present to ensure the structural integrity of the dam. The elevation of the sluices is thus affected by the required thickness of the pillars between them and the valley shape.

The sluice gates will be subject to an average head of 114 m and, given their large size, they cannot be operated at this pressure head. To allow operation, the reservoir has to be first drawn down as far as possible using the flood spillways and then by using mid-level outlets. The mid-level outlets have the same intake size as the sediment sluices (6 x 12 m).

3.4. RESERVOIRS IN OPERATION

3.4.1. China – Heisonglin: Heisonglin Reservoir

3.4.1.1. Foreword

Heisonglin Reservoir is one of 21 key sediment observation reservoirs. Heisonglin Reservoir is located at LIushudian in Chunhua County and is 10 km upstream from Kou town. Heisonglin Reservoir is a medium sized reservoir and its purpose is irrigation combined with flood control. The controlled basin area of Heisonglin Reservoir is 334 km^2. The average runoff is 17.05 million m^3, the initial storage capacity is 14.3 million m^3, the utilizable storage capacity is 7.9 million m^3, and the dead storage capacity is 0.7 million m^3.

3.4.1.2. Treatment approach of sediment

Clear water impounding and muddy flow releasing

During the period of clear water impounding and muddy flow releasing, the treatment approaches for sediment and muddy flow are storing flood waters and releasing muddy water, density current flow, empty reservoir scour, base flow scour and artificial scour and so on. By the operation of clear water impounding and muddy flow releasing, from 1962 to 1978 the amount of sediment was 1.76 million m^3, and the deposition rate decreased from 0.54 million m^3 to 0.104 million m^3 a year.

High channel scour

Through extensive testing, the dredging technology of high channel scour (also known as "lateral erosion") was developed in Heisonglin Reservoir. The approach of high channel scour is as follows: a low dam or sluice is built in the upstream part of the reservoir, and the water intercepted by the low dam flows into a high channel built around the reservoir. Making use of water head, beach sediment can be scoured, and the balance of erosion and deposition can be attained, as illustrated in Figures 3.23 to 3.25.

Since 1979, high channel scour has been carried out in Heisonglin Reservoir. Relying on a scour flow of 0.2 - 0.3 m^3/s, combined with the operation of clear water impounding and muddy flow releasing, sediment is scoured and storage capacity is recovered. From March 1955 to September 1979, the residual capacity at the normal high-water level of Heisonglin Reservoir has been maintained at about 5.2 million m^3, with scour and deposition in balance.

The procedure of high channel scour is as follows: by utilizing the transverse gradient of reservoir deposits, leading upstream water to scour the deposit face and relying on water erosion and gravity erosion, the deposited sediment will be scoured and discharged. The high channel scour features high dredging efficiency and less water consumption, utilizes no machinery or power consumption, and is relatively low cost.

Muddy water irrigation

Sediment discharged from the reservoir is used for irrigation, reclamation, soil improvement and enrichment. These make sediment discharge profitable, and no longer a problem for downstream areas. In more than ten years, due to muddy water use, the muddy irrigation area in Heisonglin Reservoir increased to 30 million m^2 from 10 million m^2, and the average yield of grain increased (Figure 3.25).

3.4.1.1. Epilogue

The sediment treatment technology of Heisonglin Reservoir consists of high channel scour, clear water impounding, muddy flow releasing and muddy water irrigation. The technology won the third prize of the national scientific and technological progress award and was selected for the "Nine Five" key popularized project of the national scientific and technological achievements by the China National Ministry of Science and Technology. Heisonglin Reservoir has opened up a new way to solve the problem of reservoir sediment deposition in a heavily silt-carrying river. The technology can be used in the sediment treatment of similar reservoirs and in the planning and design of new reservoirs. But the result is not perfect, and further improvement is needed.

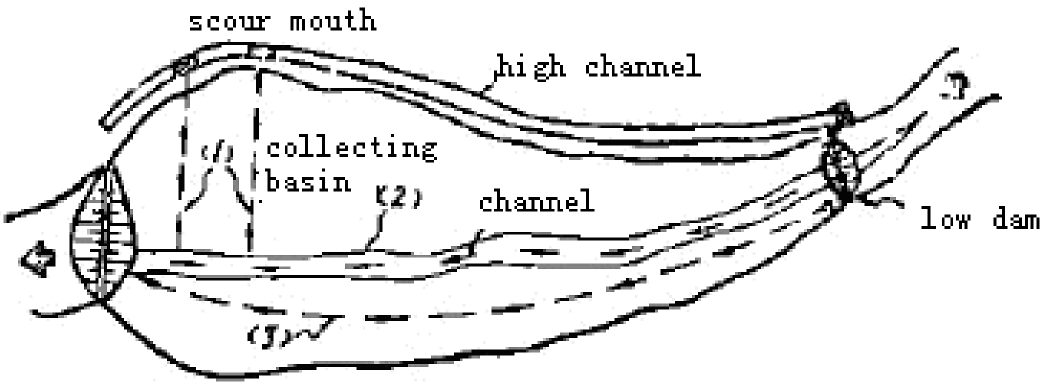


Fig. 3.23
Diagram of high channel scour

Fig. 3.24
Artificial lateral erosion channel F (left) & lateral erosion channel (right)

Fig. 3.25
Grain irrigated by muddy water

HEISONGLIN

Location: China (Yeyuhe River)
Cost of sediment management: Unknown
Management option: Sediment Sluicing

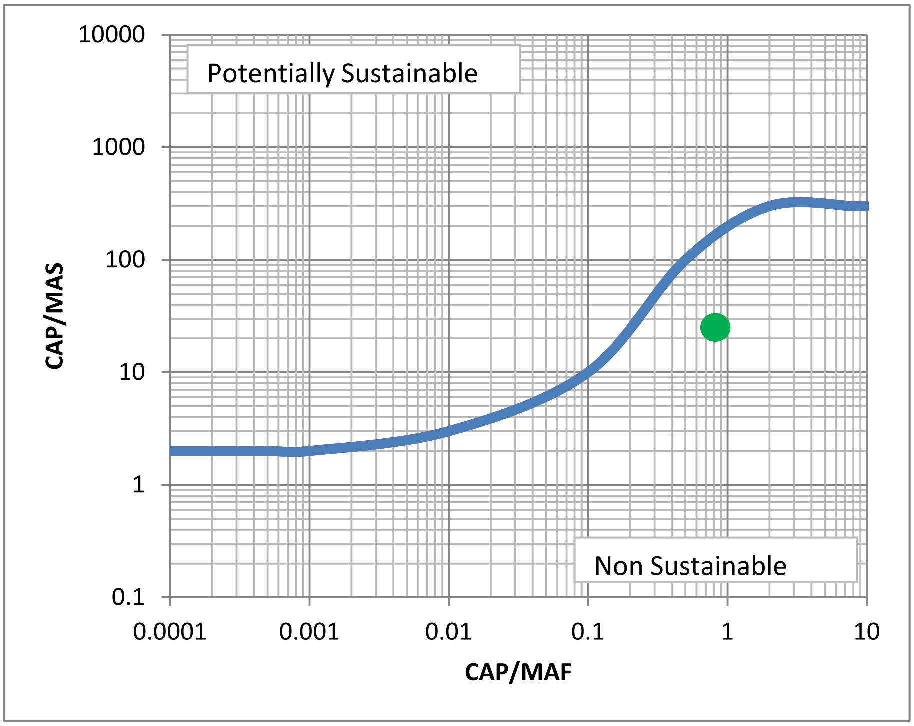
Reducing sediment inflow	
⇨ Sediment Sluicing	
Preventing deposition	
Not applicable	
Removing sediment	
Not applicable	

Main characteristics

Uses	Irrigation and Flood Control
Dam Type	Earth
Dam height (m)	46
Dam length (m)	220
Gross storage (m^3)	14 300 000
Catchment area (km^2)	358
Design discharge(m^3/s)	0.6

Key features

CAP (m^3)	14 300 000
MAF (m^3/y)	17 050 000
MAS (m^3/y)	531 000
CATCHMENT (km^2)	358
CAP/MAF (year)	0.839
CAP/MAS (year)	26.930



3.4.2. China – Xiaolangdi: Xiaolangdi Reservoir

3.4.2.1. Foreword

Xiaolangdi Reservoir is a comprehensive utilization project and its development mission is oriented to flood control (including ice jam prevention), sedimentation reduction, balanced water supply, and irrigation and hydropower generation.

Xiaolangdi Reservoir is located at the last gorge mouth of the middle Yellow River. (Figure 3.26). The ownership of Xiaolangdi Dam project belongs to the People's Republic of China; the reservoir dispatching belongs to the Yellow River Conservancy Commission and the Yellow River Flood Control headquarters; the power generation scheduling belongs to Henan Province Electric Power Company; and the operation management belongs to Xiaolangdi Dam Water Conservancy Construction Management Bureau.

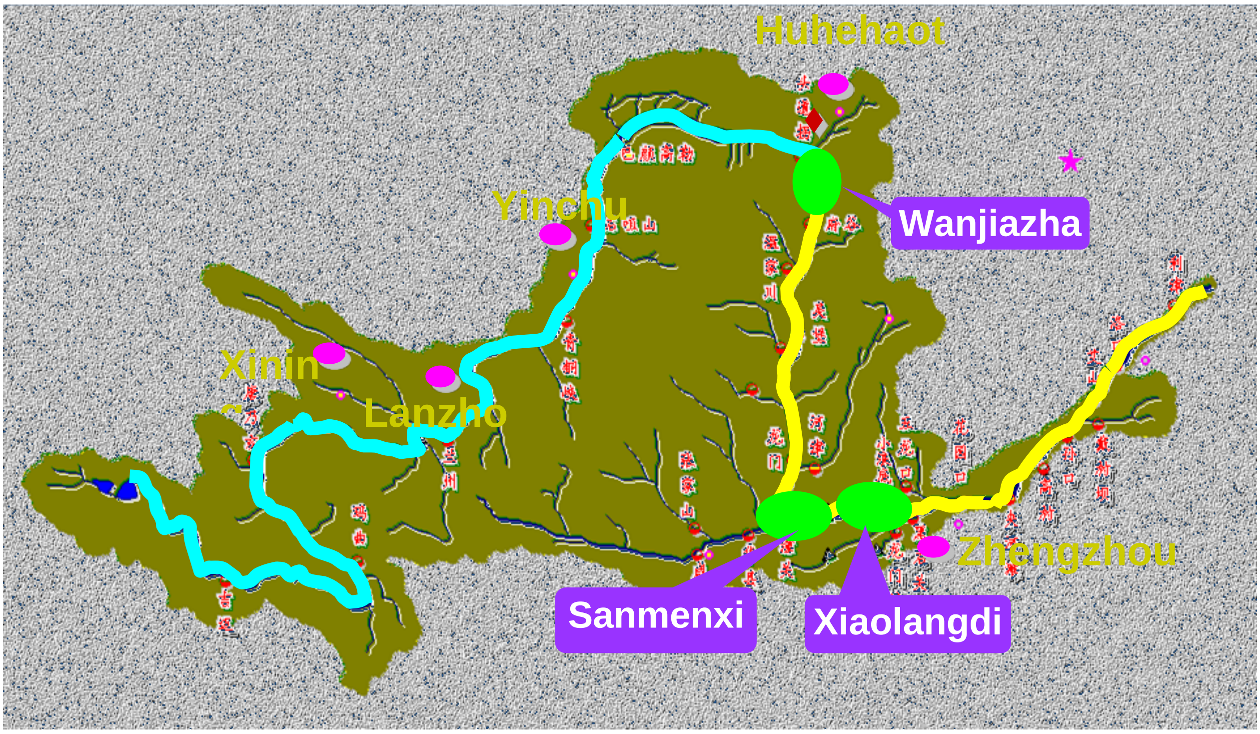


Fig. 3.26
Location map of the Xiaolangdi Dam

3.4.2.2. Basic situation of the reservoir

The Xiaolangdi Dam project was built in September of 1994, closure was in October of 1997, the impoundment was in October of 1999, and the first power was generated at the end of 1999. In May 2000, the reservoir was formally put into use, and all work was completed on December 31, 2001. The controlled basin area of Xiaolangdi Reservoir is 694 000 km^2 and accounts for 92.3% of the basin area of the Yellow River. The highest operational water level is 275 m. The initial storage capacity is 12.65 billion m^3, the storage capacity of water and sediment is 1.05 billion m^3, and the long-term effective storage capacity is 5.1 billion m^3.

The Xiaolangdi project consists of a dam, flood releasing structure, water diversion and a power generation system. Xiaolangdi Dam is a sloping core rockfill dam. The maximum design height of the dam is 154 m, the length of the dam top is 1 667 m, and the width is 15 m. The flood releasing structure includes ten intake towers, three flood discharging tunnels, three desilting tunnels, three free flow tunnels, one spillway, one irrigation tunnel, and three water stilling ponds. The water diversion and power generation system includes six water diversion tunnels, the underground powerhouse, the main transformer chamber, a gate chamber, and three tail water tunnels. Six sets of 300 000 kW water turbine generators are in the underground powerhouse, with a total installed capacity of 1 800 000 kW.

Xiaolangdi Reservoir has many tributaries; there are 18 large tributaries, with most of them located in the middle and lower reaches of the reservoir. Xiaolangdi Reservoir is also a gorge reservoir, with the upstream portion narrow and the downstream portion wide as shown in Figure 3.27. According to the plan morphology, Xiaolangdi Reservoir can be divided into two sections. The upstream reach is from the Sanmenxia hydrological station to the mouth of Banjian River. The reach length is about 62.4 km, and the width of the valley bottom changes between 200 and 400 m. The downstream reach is from the mouth of the Banjian River to the dam. Its length is about 61 km, and the width of the valley bottom changes between 800 and 400 m.

Fig. 3.27
Plan of Xiaolangdi Reservoir

3.4.2.3. Reservoir operation

Xiaolangdi Reservoir regulates water flowing into the Lower Yellow River downstream. The annual inflow and outflow water are 22 293 billion m^3 and 23 524 billion m^3. In flood season, the inflow and outflow volumes are 10 681 billion m^3 and 8 278 billion m^3 respectively. Water inflow and outflow are shown in Figure 3.28.

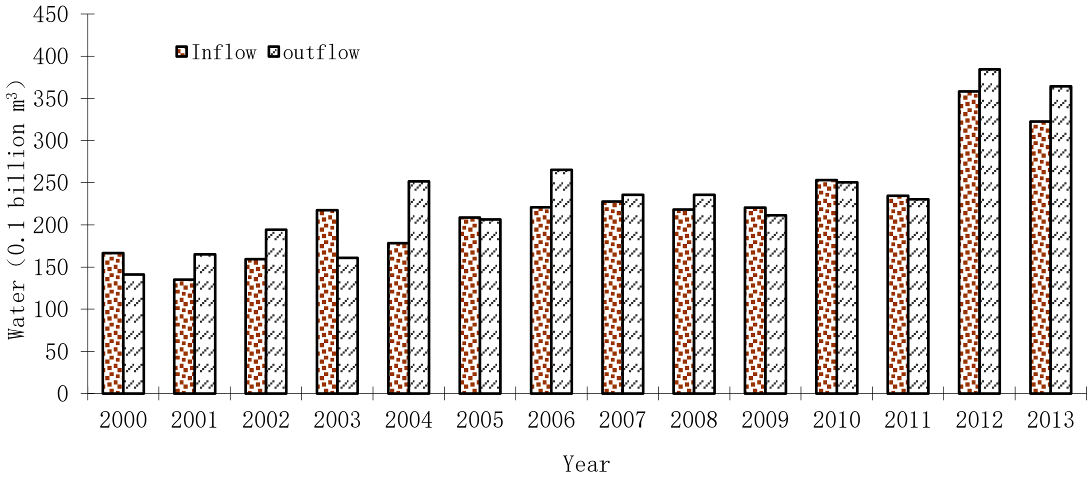


Fig. 3.28
Inflow and outflow water of Xiaolangdi Reservoir from 2000 to 2013

Since put into use in 2000, the amount of deposition in Xiaolangdi Reservoir has increased every year. From 1999 to 2013, the total sediment inflow was 4.6366 billion tons. The proportions of fine sand (particle size less than 0.025 mm), medium sand (particle size between 0.025 mm and 0.05 mm), and coarse sand (particle size greater than 0.05 mm) were 47.9%, 25.6% and 26.5% of incoming sediment, respectively. The amount of deposition was 3.6254 billion tons, and the proportions of fine, medium, and coarse sand were 39.0%, 29.4% and 31.6%, respectively, as shown in Table 3.4. The amount of incoming sediment and deposition are shown in Figure 3.29 and Figure 3.30.

Table 3.4
Amount of Inflow, outflow sediment and deposition from 2000 to 2013

Sum From 2000 to 2013	Amount of inflowing sediment (10^8 t)		Amount of outflowing sediment (10^8 t)		Amount of deposition (10^8 t)		Year inflow sediment component (%)	Year sediment delivery component (%)	Year sediment component (%)
	Flood season	Year	Flood season	Year	Flood season	Year			
Fine sand	20.856	22.194	7.616	8.049	13.240	14.146	47.9	79.6	39.0
Middle sand	10.818	11.885	1.187	1.236	9.631	10.649	25.6	12.2	29.4
Coarse sand	11.191	12.286	0.801	0.827	10.390	11.459	26.5	8.2	31.6
Sum	42.865	46.366	9.604	10.112	33.261	36.254	100	100	100.0

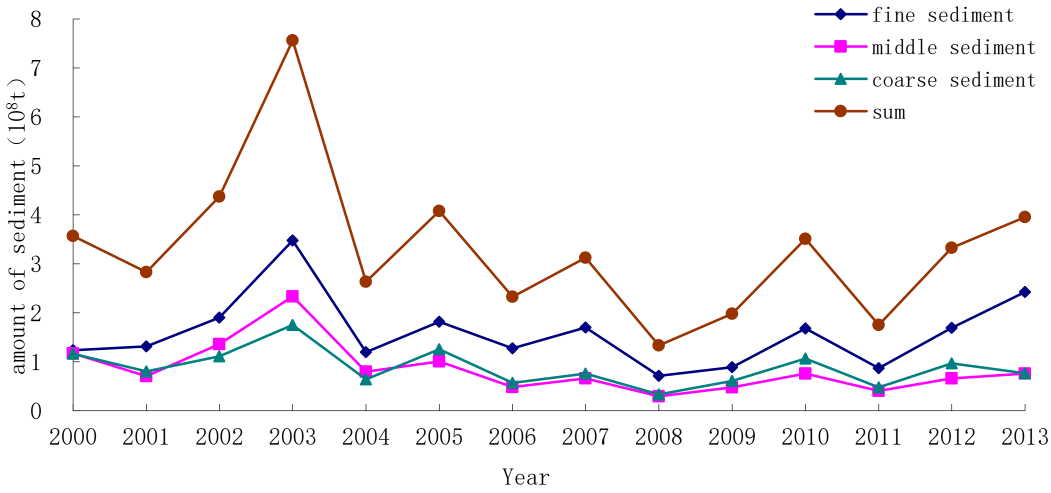


Fig. 3.29
Amount of Inflowing sediment of different sizes in Xiaolangdi Reservoir

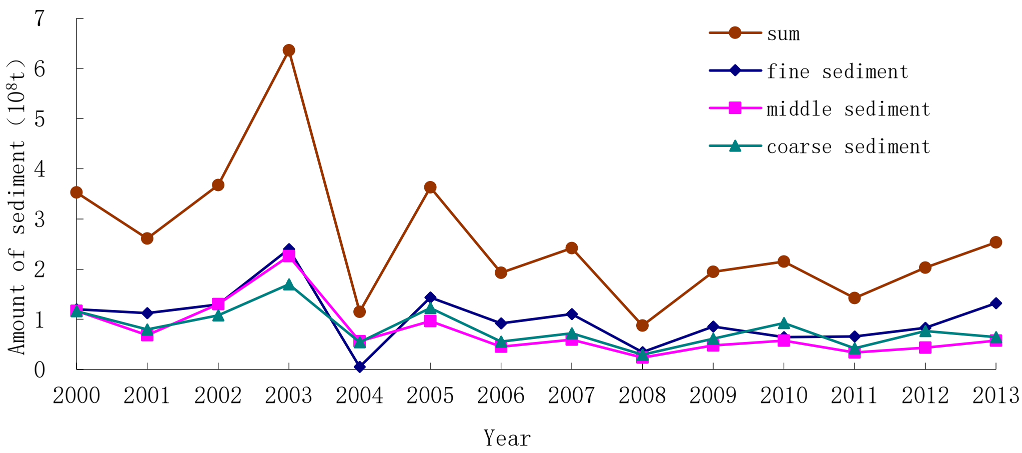


Fig. 3.30
Amount of deposited sediment of different sizes in Xiaolangdi Reservoir

3.4.2.4. Treatment approach of sediment – density current flow

According to the operation rules of the Xiaolangdi project the initial sediment retaining period is complete and the project has entered the later sediment retaining period. In the initial sediment retaining period and the first stage of the later sediment retaining period, the main form of reservoir sediment desilting was by density current flow or turbid water (formed by density current flow) release.

Water and sediment regulations refer to making density current flows by artificial or natural means in flood season or pre-flood season, making full use of the characteristics of sediment transport in the Lower Yellow River, transporting sediment into the sea, and reducing the Xiaolangdi Dam reservoir sedimentation. Pre-flood water and sediment regulations refer to using water storage above the flood control levels of Wanjiazhai Reservoir and Sanmenxia Reservoir, scouring sediment deposited in Sanmenxia Reservoir in the non-flood season and sediment silted in the upper reach of Xiaolangdi Reservoir, and forming density current flow and discharge from Xiaolangdi Reservoir, effectively reducing the deposition of sediment in Sanmenxia Reservoir and the Xiaolangdi Reservoir. By October 2013, the amount of sediment discharged by density current flow and turbid water reservoir formed by density current flow was 1.0112 billion tons. The main type of sediment transported by density current flow was fine sand (0.8049 billion tons) and accounted for 79.6% of all sediment. The process of pre-flood water and sediment regulation is shown in Figure 3.31 and Figure 3.32.

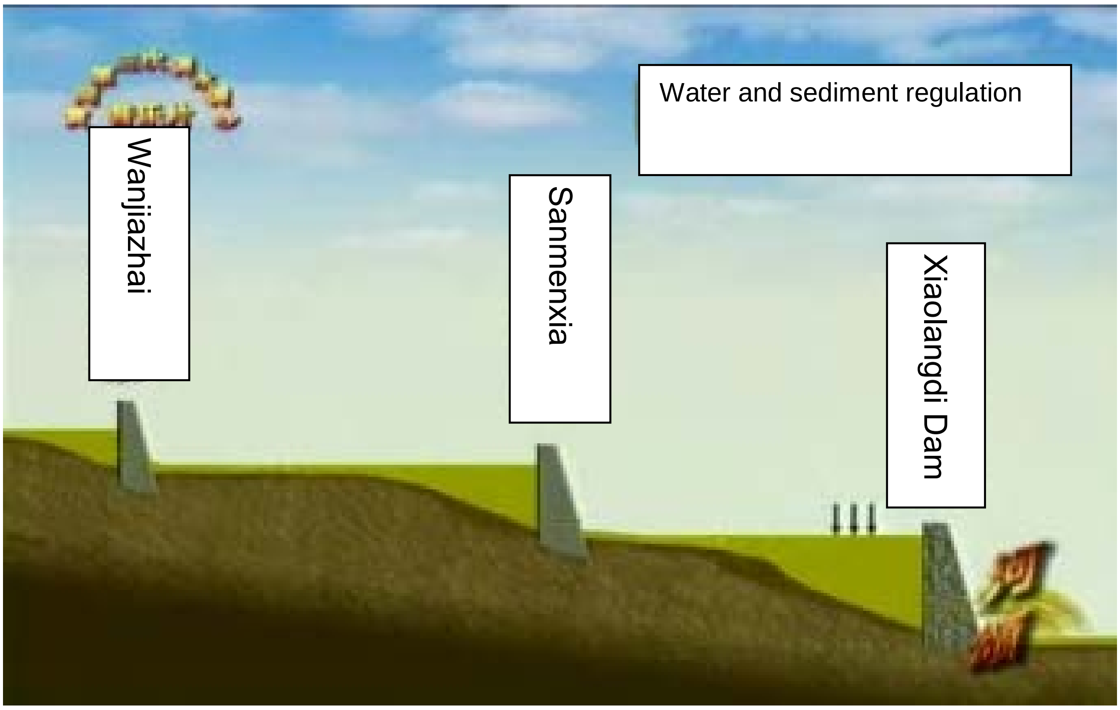


Fig. 3.31
Diagram of density current flow modeled by Wanjiazhai, Sanmenxia and Xiaolangdi Reservoirs

Fig. 3.32
Process of density current flow modeled by Wanjiazhai, Sanmenxia and Xiaolangdi Reservoir

3.4.2.5. Prospect of sediment treatment of Xiaolangdi Reservoir

At present, research into extracting Xiaolangdi Reservoir sediment for construction is carried out by the Yellow River Institute of Hydraulic Research (YRCC). Through a series of analyses and intensive research, the project will eventually allow sediment to be extracted.

In addition, the preliminary research for reservoir sediment treatment and utilization technology is also carried out by YRCC. By means of engineering technology, different particle sizes will be classified and utilized. For example, coarse sediment in the reservoir tail can be directly dredged and used as building material. Using the technology of jet flushing and suction or self-suction pipe flushing, medium and coarse sediment in the middle reach of the reservoir can be transported to the proper site and sorted (coarse sediment can be directly used as building materials), and fine sediment can be used for soil improvement or in the production of large stones. Fine sediment at the dam can be discharged into the sea or can be used as a soil improvement by artificial density current flows or mechanical methods.

3.4.2.6. Prospect of operation mode in later sediment retaining period

Based on the scour and deposition regime on the Lower Yellow River, and potential future changes including impacts from operation of Sanmenxia Reservoir and Henshan Reservoir, the operation of Xiaolangdi Reservoir should persist in the operation mode of “multi-year sediment regulation and man-made precipitation washout at the right occasion” making full use of natural flood discharge sediment, and, when necessary, carrying out flushing and keeping as large a storage capacity as possible, with a certain degree of flexibility. In the meantime, the study of regulating water and sediment should be strengthened and solutions should be found for some of the current technical problems.

XIAOLANGDI

Location: China (Yellow River)
Cost of sediment management: Unknown
Management option: Density Current Routing

Reducing sediment inflow
Not applicable

Preventing deposition
⇨ Density Current Routing

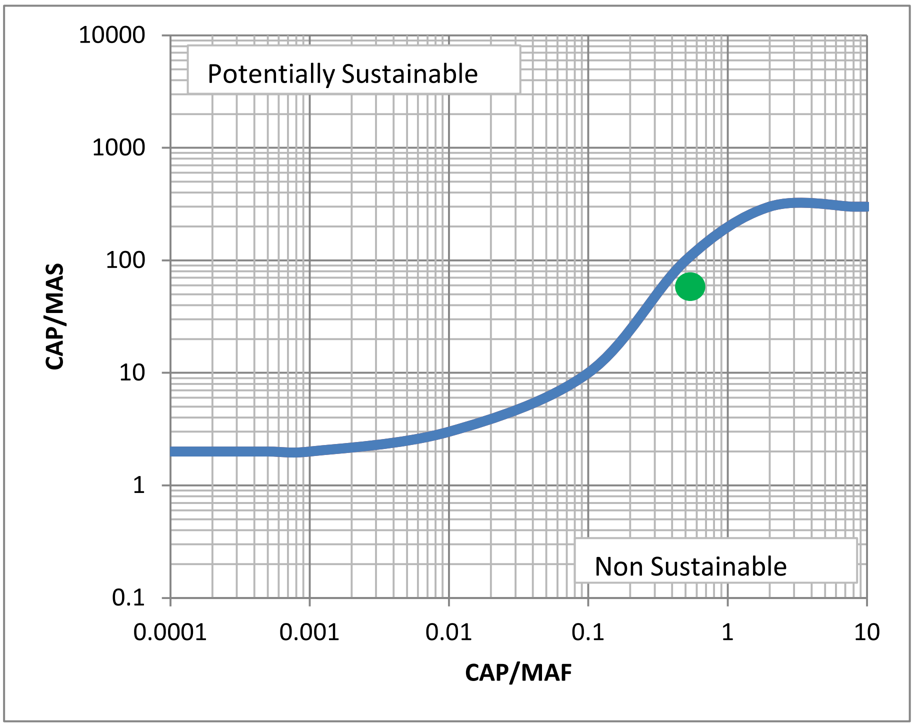
Removing sediment
Not applicable

Main characteristics

Uses	Flood Control
Dam Type	Rock Fill
Dam height (m)	160
Dam length (m)	1 667
Gross storage (m^3)	12 650 000 000
Catchment area (km^2)	699 124
Design discharge(m^3/s)	878.7

Key features

CAP (m^3)	12 650 000 000
MAF (m^3/y)	21 518 000 000
MAS (m^3/y)	215 800 000
CATCHMENT (km^2)	699 124
CAP/MAF (year)	0.588
CAP/MAS (year)	58.619

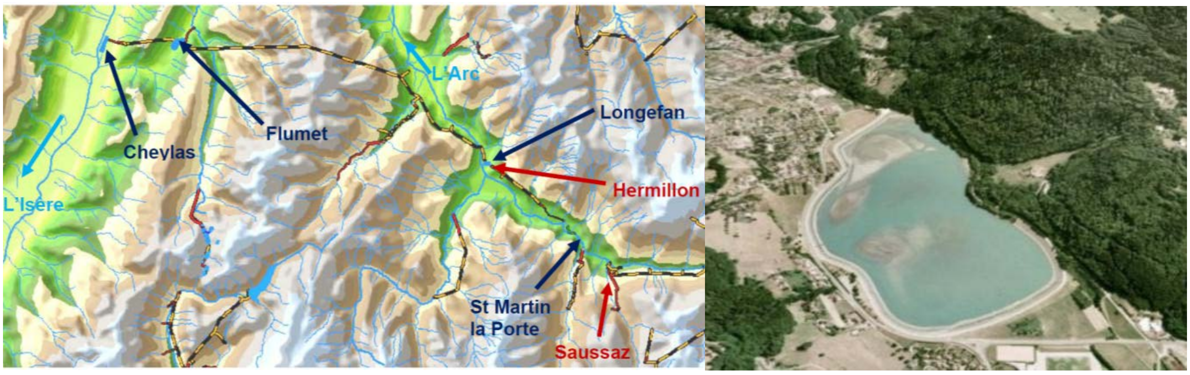


3.4.3. France – Flumet: Management of Sediments in the Flumet Reservoir

Provided by Electricité de France (EDF), E Valette, J Pralong

3.4.3.1. Introduction

Built between 1975 and 1978, the Flumet-Cheylas pumped storage plant is part of a whole hydropower system located along the Arc and Isère rivers in the Southeast of France (French Alps). This project was designed with the aim to minimize the cost of sediment management. In both of these rivers there is a high siltation rate upstream, which has a negative impact on the quality of downstream dam operations. This system is an off channel scheme. The water, derived at the St Martin la Porte Dam from the Arc River, runs through the turbines of a first plant (Hermillon). A regulating reservoir (Longefan) controls flow from Hermillon hydropower plant (HPP) toward the 20 km long Belledonne pipe which leads to the Flumet reservoir (upper reservoir of the pumped storage plant). The lower reservoir (Cheylas) is connected to the Isère River. The situation of the project is shown in Figures 3.33 and 3.34.



Reservoirs in blue, power plant in red

Fig. 3.33
Situation of the Flumet Reservoir (left); aerial view of the reservoir (right)

3.4.3.2. Owners

This entire hydroelectric scheme is owned by the Electricité De France (EDF) Company who drives the power plants according to the upstream and downstream HPPs.

3.4.3.3. Hydrology

The mean annual flow in the Arc River is around 40 m^3/s and the Isère River is around 180 m^3/s. The natural catchment of the Flumet reservoir is only 8.45 km^2, the annual rain is estimated to be 1200 mm/year. Waters come from the derivation of the Arc River flow through the Belledonne adduction. The maximal capacity of the derivation is 70 m^3/s.

3.4.3.4. Basic dam and reservoir data

Flumet Reservoir has an initial capacity of 5.1 hm^3 and an area of 68 ha at the normal operating level (499 m asl). The minimal operating level is 491 m asl. The Flumet Dam is a 600 m long earth fill dam. The Cheylas plant is equipped with two pump-turbines. Each turbine of 240 MW each is able to pass a discharge of 110 m^3/s in turbining mode and 85 m^3/s in pumping mode.

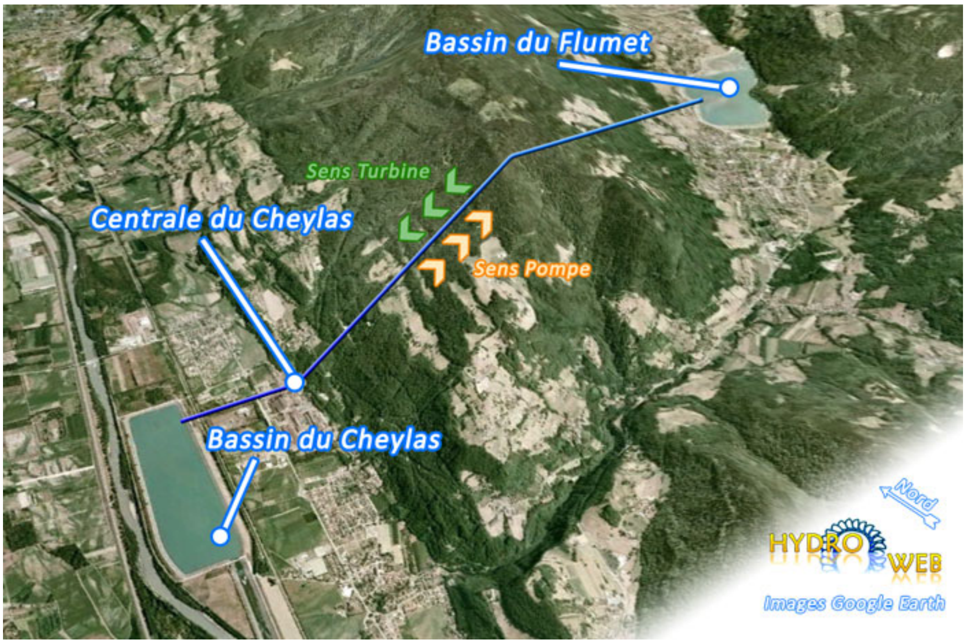


Fig. 3.34
3-D view of the Flumet-Cheylas system (Google earth image)

3.4.3.5. Plot of capacity versus mean annual flow

The Flumet Reservoir has a capacity of 5.1 hm^3. The mean annual flow (Arc River at St Martin La Porte) is around 1200 hm^3.

3.4.3.6. Political issues

The reservoir is built in an urbanized and steep zone, served by mountain roads. EDF could not put too much sediment in the Isère River, so they had to find a solution to reduce the annual sediment inflow. To remove the sediment, EDF had to consider the urban area and its population, so they found a solution for the sediment issue which was dredging and release of sediment in the Isère River.

3.4.3.7. Regulatory constraints

There are no particular regulatory constraints for this reservoir.

3.4.3.8. Sediment data of the site

The Flumet upper reservoir had a 1.7 hm^3 sediment deposit volume in 2014 compared to 5.1 hm^3 of total original capacity. An estimated residual non avoidable siltation flux of 50 000 m^3 a year of new incoming sediment continues building up sediment and represents 60% of all the incoming sediment. This residual incoming flux has already been reduced over time and “optimized” through additional measures taken at upstream facilities of the hydropower system.

3.4.3.9. Classification of sediment management

The Flumet Reservoir is already an off-channel reservoir and techniques to route sediments through the reservoir (turbid density currents, sluicing) or drawdown flushing are not available here.

Some intakes are closed during high sediment production events but this solution is very limited. Thus EDF needed to create an inflow solution.

Two main categories of solutions were envisioned: (1) Extracting and managing sediment “out of water”; or (2) extracting and managing sediment “underwater” (dredging and release of sediments in rivers). Category 1 solutions are not possible to resolve all of the 1.7 hm^3 sediment deposit volume for the following reasons:

- It would generate about 200 000 truck rotations (in a urban zone and on long distances) to transport extracted sediments, and about 25 000 truck laps every 5 years for removing new sediment load;
- Sediments would require specific treatment (drainage, drying, etc.) before any transport and/or use;
- No available space was found at a reasonable distance for long term storage.

The best type of solution which could be set up is removing sediment or preventing its deposition by using the flow. EDF studied four core solutions:

- Dredging and releasing in another catchment
- Dredging and releasing through a local bypass of existing power unit
- **Dredging and releasing sediment further downstream in the Isère River by a new pipe.**
- **Dredging and releasing directly through powers units**

EDF choose to study the feasibility of the last two (in bold).

3.4.3.10. Planned sediment release operations

Dredging and releasing sediment further downstream in the Isère River by a new pipe

To determine the pipe size, EDF had to answer certain questions, such as “what are acceptable release conditions in the downstream river?” and “which release procedure needs to be implemented?”

Hence, a conduit was designed with the following characteristics:

Table 3.5
Flumet Reservoir Key features

Feature	
Length of the conduit	6 600 m
Diameter	From 800 to 600 mm
Transit duration	24-h
Concentration after dilution in the Isère river	0.5 g/l
Head flow	2m^3/s
When	April-August

Dredging and releasing sediment directly through the power units

The maximum acceptable concentration for the units is not precisely known, despite some existing new guidance in the turbine industry (IEC, 2013). Potential impacts on units are: runner erosion, and clogging of unit filters. In the pre-feasibility study, a precautionary maximum concentration value of

0.05 g/l has been prescribed by mechanical engineers; however, this would result in 20+ years to evacuate the sediment, which is unrealistic.

EDF is continuing investigations and started several full-scale tests on different power plants at high sediment concentrations. Flumet-Cheylas is planned to be tested in 2018.

FLUMET

Location: France on the Arc/Isère River

Cost of sediment management:

Management option:

Reducing sediment inflow

Not applicable

Preventing deposition

Not applicable

Removing sediment

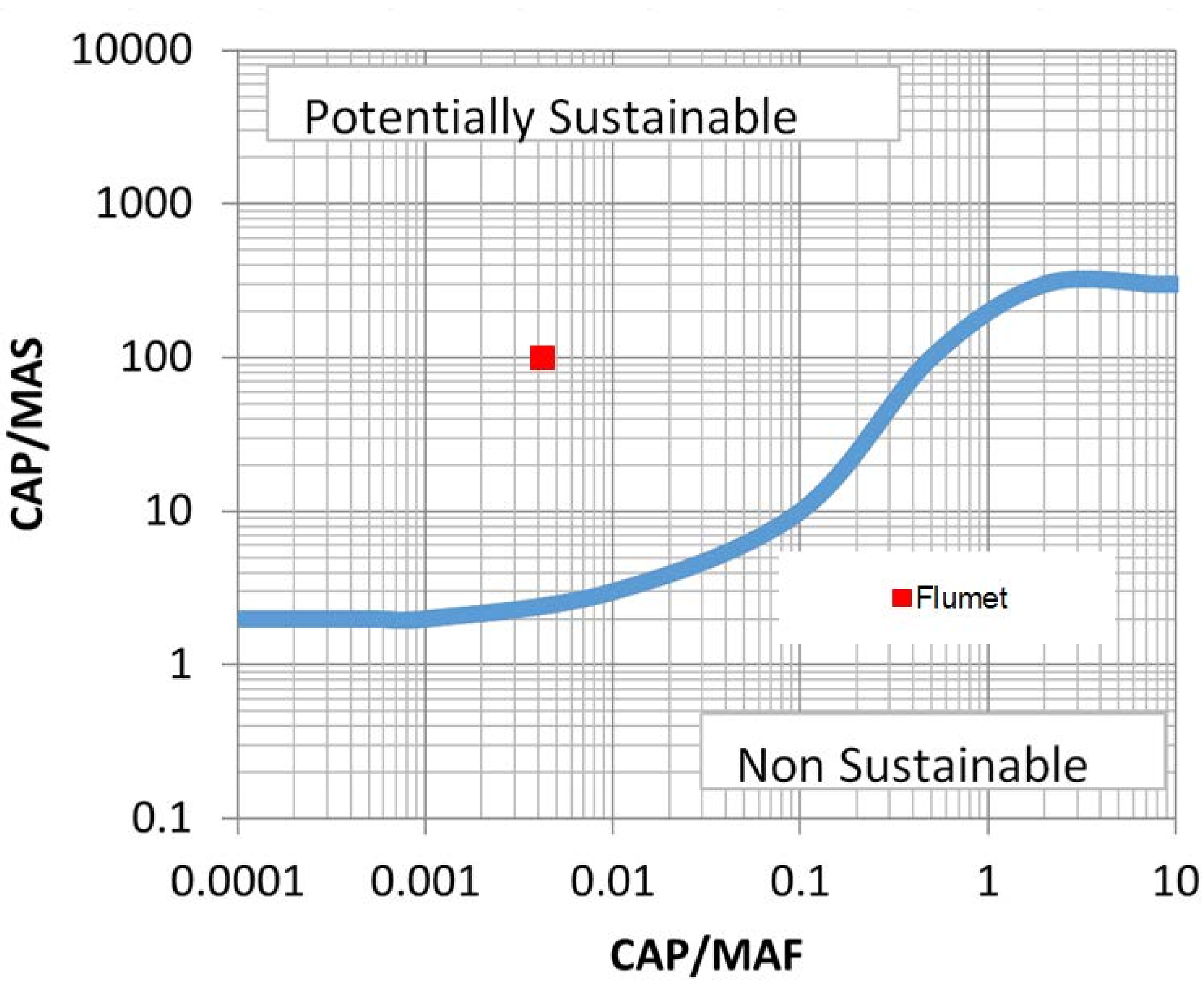
⇨ Dredging

Main characteristics

Dam type	Earth fill dam
Function	Power generation
Dam height (m)	16
Dam length (m)	600
Gross storage (m^3)	5 060 000
Catchment area (km^2)	8.45
Design discharge(m^3/s)	60

Key features

CAP (m^3)	$5.1x10^6$
MAF (m^3/y)	$1\ 200x10^6$
MAS (m^3/y)	50 000
CATCHMENT (km^2)	8.45
[redacted]	
CAP/MAR (year)	$4.25x10^{-3}$
CAP/MAS (year)	101


10000
1000
100
10
1
0.1
Potentially Sustainable
CAP/MAS
Flumet
Non Sustainable
0.0001
0.001
0.01
0.1
1
10
CAP/MAF

3.4.4. France & Switzerland–Management of Sediments on the Upper Rhône River

3.4.4.1. Introduction

The Rhône River originates from the Swiss Alps and flows through France down to the Mediterranean Sea (Figure 3.35). In its upper part, most of the sediments eroded from the steep surrounding mountains settle into Lake Geneva (Figure 3.36a), such that only clear water is released at the impoundment outlet. Further downstream, the main sediment supplier is the torrential Arve River which joins the Rhône River in Geneva (Figure 3.35 and Figure 3.36b).

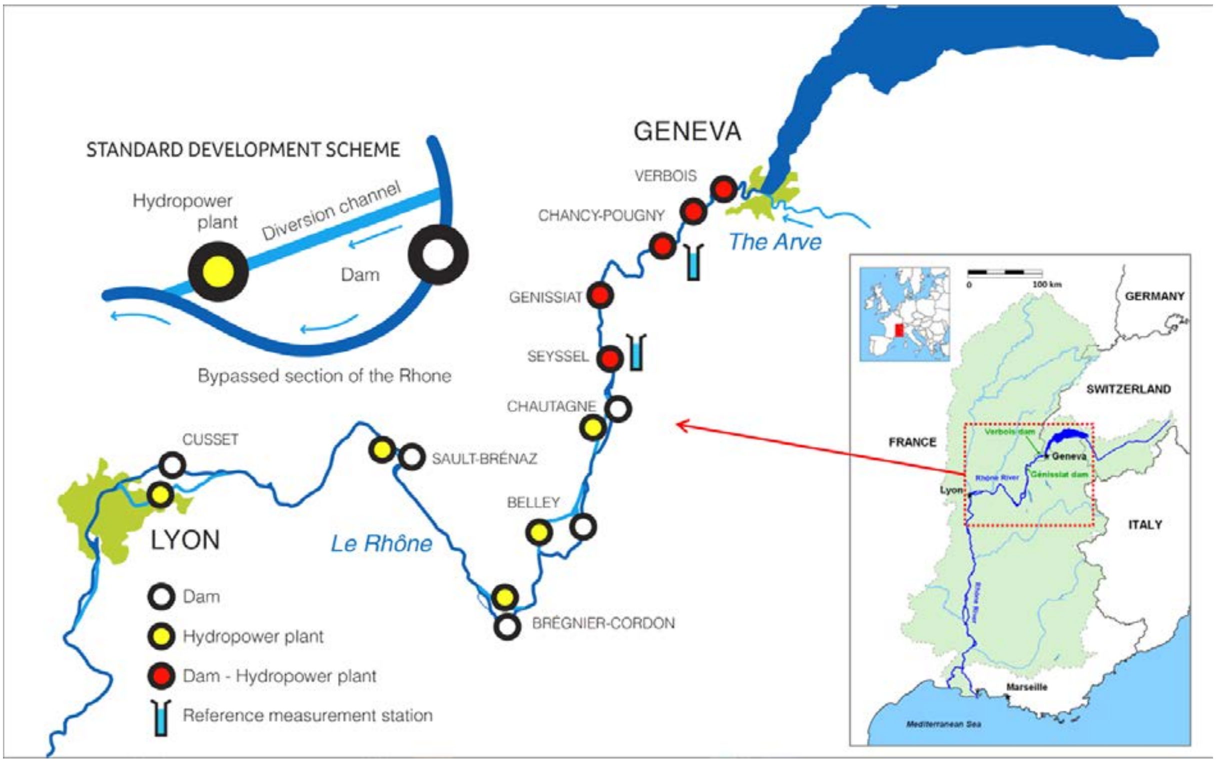


Fig. 3.35
Schematic overview of the Upper Rhone River Basin

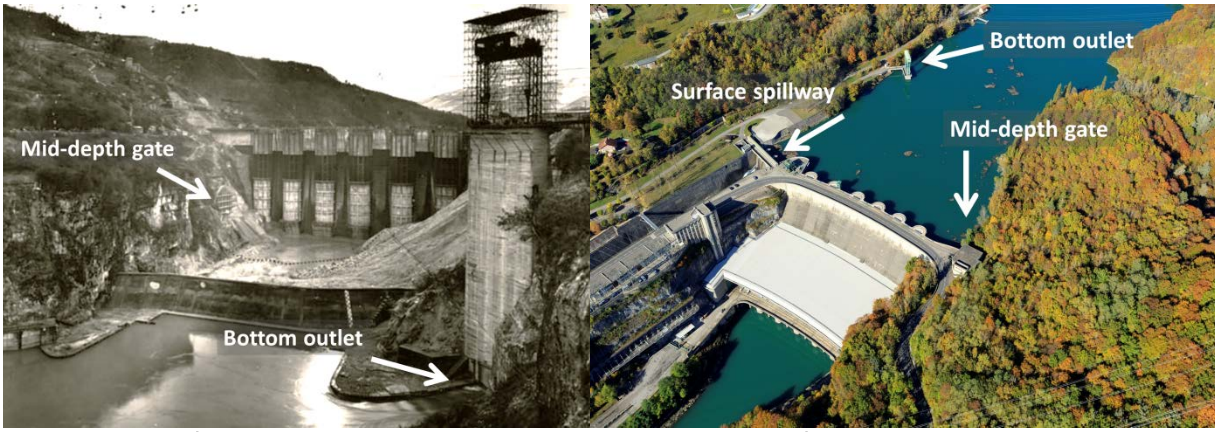
Downstream of the confluence, two successive dams are operated within Swiss territory (Figure 3.35). The upstream-most one is the Verbois Dam presently operated by SIG (Figure 3.36c). It was built in 1942 to replace the Chèvre Dam, an outdated development commissioned in 1896. The downstream-most project is the Chancy-Pougny Dam. It was completed in 1926 and is currently operated by SFMCP.

On the French section of the river, several hydropower developments were built by the Compagnie Nationale du Rhône (CNR). On the Rhône River below Lake Geneva, the upstream-most dam operated by CNR is the Genissiat Dam, which is also the oldest and highest one, (Figure 3.36d and 3.36e). Its construction lasted from 1937 to 1948. Further downstream, the Seyssel Dam was completed in 1951. Four more run-of-river developments (Chautagne, Belley, Brégnier-Cordon and Sault-Brenaz) were also put into operation by CNR between 1980 and 1986 (Figure 3.35). Downstream of Lyon, 13 additional hydropower plants also operated by CNR complement this cascade on the Lower Rhône River (Figure 3.37).

(a) – Rhône River at Lake Geneva inlet

(b) – Confluence between the Rhône and Arve Rivers

(c) – Verbois dam operated by Swiss operator SIG



(d) – View of Génissiat dam from upstream during construction works (CNR)

(e) – Aerial view of Génissiat dam showing the location of the water and sediment release facilities (CNR)

Fig. 3.36
Photographs of the Rhône River and its dams

3.4.4.1. Owners

CNR (Compagnie Nationale du Rhône) is a French company that was entrusted in 1934 by the French State with the concession of the Rhône River in order to develop it and fulfil three missions for the benefits of the national community: hydroelectricity production, navigation development and management, and irrigation for agricultural uses. CNR is France's leading producer of 100 % renewable energy (water, wind, sun). In 2016, the total installed capacity is 3 553 MW. The company produces 25% of France's hydroelectricity, and manages a concession covering 27 000 hectares in the Rhone Valley and 330 km of wide gauge navigable waterway. CNR has conceived a distributive model based on the River Rhône management combining green electricity production with territorial development.

SIG (Services Industriels de Genève) was founded in 1896. It is a Swiss cantonal distribution company providing local services. As of 2016 it supplies water, gas, electricity and thermal energy to 228,000 customers in the canton of Geneva. It processes wastewater, recycles waste and provides services in the fields of telecommunications and energy.

SFMCP (Société des Forces Motrices de Chancy-Pougny) is a French-Swiss company that was entrusted in 1918 with the concession of a short transboundary stretch of the Rhône River extended from Avully (Switzerland) on the left bank to Challex (France) on the right bank. The Chancy-Pougny hydropower plant is the only development operated by the company. SIG and CNR are the two shareholders of SFMCP.

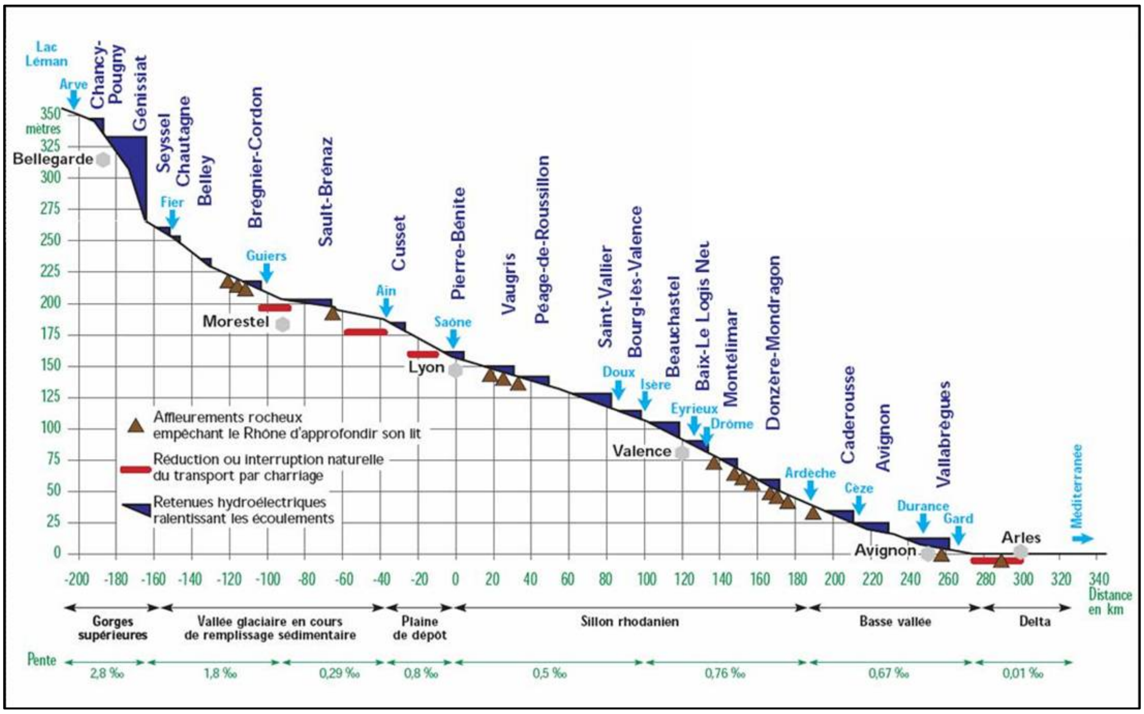


Fig. 3.37
Profile and location of dams built on the Rhône River

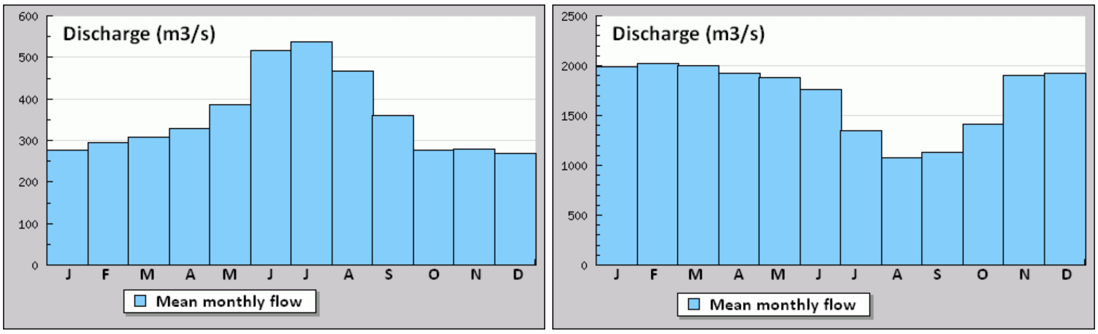


Fig. 3.38
Mean monthly flow downstream Génissiat Dam (left) and at Beaucaire close to basin outlet (right).

3.4.4.2. Hydrology

At Génissiat Dam, the catchment area of the Rhône River is about 10 910 km² and the mean annual flow is 359 m³/s. In this part of the basin, the hydrological regime is strongly influenced by snow and ice melt, and by the flow regulation through Lake Geneva (Figure 3.38). The reference discharges of the Rhône River at the Génissiat and Verbois Dams are also summarized in Table 3.6.

In the Upper Rhône River basin, the sediment flow is mostly supplied by the Arve River (Figure 3.36b). Annually, the average total solid flux has been estimated around 715 000 m³/year, including around 15 000 m³/year corresponding to bedload. According to ongoing surveys, those estimates may be on the high side.

As a reminder, the catchment area at the outlet of the Rhône River Basin is about 95 500 km² and the mean annual flow is 1 700 m³/s. The hydrological regime is completely different but also more complex due to the very diverse features of tributaries and to the heterogeneous distribution of precipitation (Figure 3.38).

Table 3.6
Reference discharges of the Rhône River at Génissiat and Verbois Dams for different return periods

Dam	Reference discharges at dam site			
	Mean annual flow	Q_{10}	Q_{100}	Q_{1000}
Verbois	337 m^3/s	1 050 m^3/s	1 460 m^3/s	1 800 m^3/s
Génissiat	359 m^3/s	1 447 m^3/s	1 915 m^3/s	2 375 m^3/s

3.4.4.3. Basic dam and reservoir data

Only data concerning Verbois and Génissiat Dams are presented in the next paragraphs, as they are the most directly concerned and impacted by the sediment management of the Upper Rhône River.

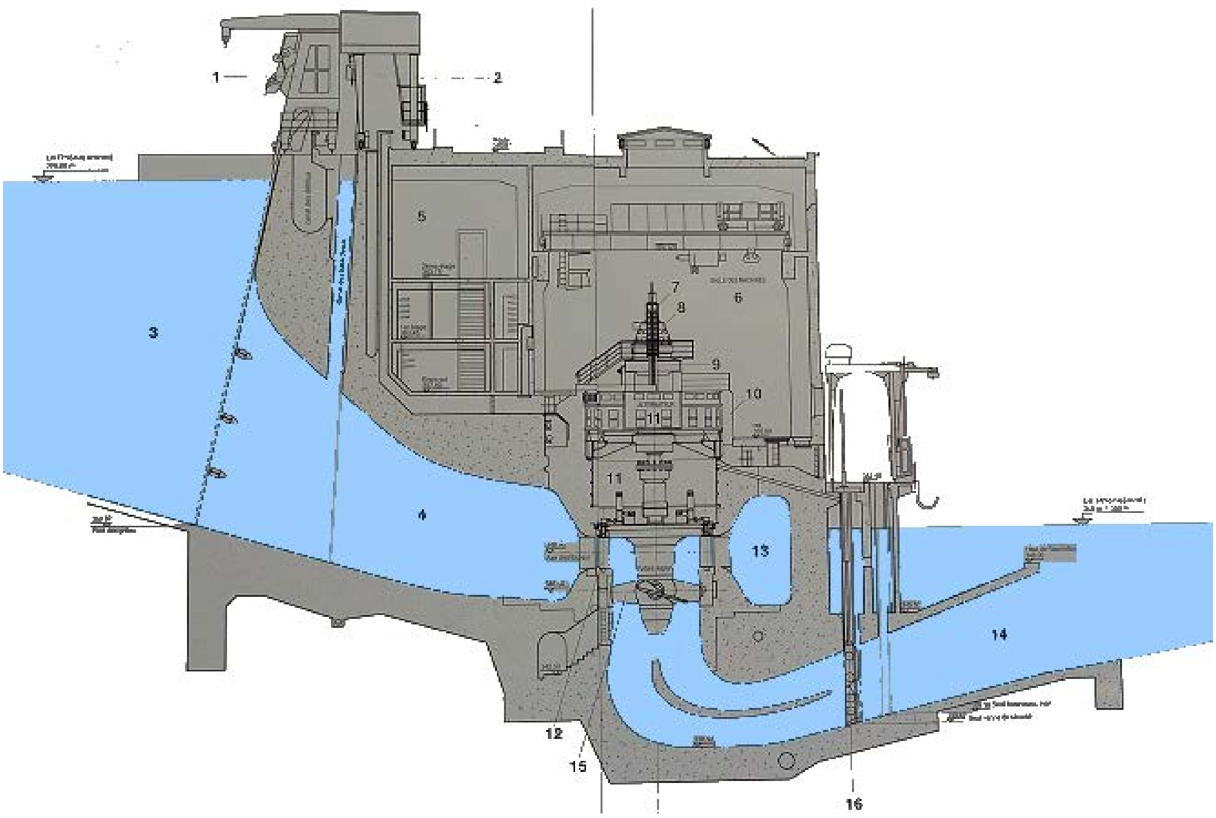


Fig. 3.39
Cross section of the Verbois powerplant

Verbois Dam

The Verbois Dam is a gravity dam 34 m high and 410 m long. The power plant is located on the right bank and is equipped with 4 Kaplan turbines of 25 MW each able to pass a total discharge of 620 m^3/s (Figure 3.39). The maximum head on the turbine is around 20 m and the total capacity of the power plant is 100 MW. The management of floods is performed by using 4 gated spillways and 4 bottom outlets (Figure 3.40). The initial storage capacity of the reservoir was 13 Mm^3 at the normal operating level. The reservoir length is around 12 km long.

Fig. 3.40
Verbois spillways and outlet gates

<u>Genissiat Dam</u>

The Génissiat Dam is a gravity dam made from 670 000 m^3 of reinforced concrete. The dam is 99.7 m high, 165 m long, 57 m wide at the base and 9 m wide at the crest. The power plant is located at the dam toe and is fully integrated to it. It is equipped with six Francis turbines of 66 MW each able to pass a total discharge of 750 m^3/s. The maximal head over the turbine is 67 m and the total capacity of the power plant is 420 MW. The management of floods and sediments discharge is performed by using 3 different facilities (Figure 3.36d and 3.36e, and Figure 3.47):

- A gated spillway located at 316.80 m on the right bank and able to evacuate 1 600 m^3/s,
- A mid-depth gate at 285.90 m on the left bank and able to evacuate 1 500 m^3/s,
- A bottom gate at 262.60m on the right bank and able to evacuate 700 m^3/s.

The initial storage capacity of the reservoir was 54 Mm^3 at the normal operating level (330.70 m asl) and could be increased up to 56 Mm^3 by raising the water level 1 m higher in case of a major flood. The reservoir length is around 22 km.

3.4.4.4. Plot of capacity versus mean annual flow

Table 3.7
Capacity versus Mean Annual Flow at Génissiat and Verbois Dams

Dam	Mean annual flow	Storage Capacity	
Verbois	337 m^3/s	Initial	13 Mm^3
		Current	10 Mm^3
Génissiat*	359 m^3/s	Initial	56 Mm^3
		Current	36 Mm^3

*The volume of Génissiat Reservoir is calculated for a water level at the dam site of 331.70 m NGFO.

3.4.4.5. Political issues

The main challenge on the Upper Rhône River is to ensure a consistent and cooperative management of sediment issues in a transboundary basin where three different operators subject to two distinct regulatory constraints operate a cascade of dams.

3.4.4.6. Regulatory constraints

On the French section of the Upper Rhône River, CNR has to cope with many constraints, including in particular (Figure 3.41):

- Regulating the concentration of fine suspended sediments released from Swiss dams during flushing operations in order to limit the impact on aquatic life (since 2016)
- Preserving natural sections of the Rhône River recently restored for ecological purposes
- Avoiding the obstruction of a water intake used for cooling a nuclear power plant,
- Preventing adverse impacts on well-fields providing drinking water to the city of Lyon (2.106 million inhabitants)
- Preserving bathing water areas located along the river
- Limiting as much as possible sediment deposition in the reservoirs managed by CNR and avoiding in particular the obstruction of the bottom gate of Génissiat Dam by sediment.

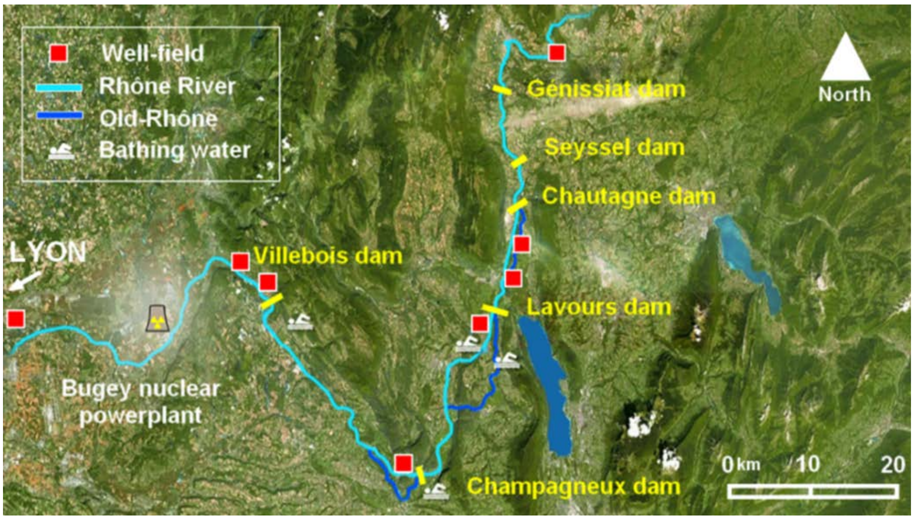


Fig. 3.41
Locations of constraints on sediment releases

This situation implies that the fine suspended sediment concentration released from the Génissiat Reservoir has to be strictly controlled and must remain below critical thresholds in order to avoid adverse impacts, especially on downstream aquatic life. The maximum acceptable limits are:

- Average concentration during the entire flushing operation: below 5 g/l,
- Average concentration for a continuous period of 6 hours running: below 10 g/l,
- Average concentration for a continuous period of 30 minutes running: below 15 g/l.

On the Swiss section of the Rhône River, regulatory constraints regarding environmental issues were very limited before 2016. As a result, suspended sediment concentrations reaching values up to 40-50 g/l were frequently released from the Swiss dams during flushing events. This led CNR to cope with a challenging situation to regulate solid fluxes in Génissiat Reservoir to satisfy the above listed requirements.

After the 2012 flushing event, a technical committee was launched. It was composed of the three industrial operators (SIG, SFMCP and CNR), and the French and Swiss authorities. This binational committee defined and evaluated different sediment management scenarios. A wide consultation with the different stakeholders was then carried out through several public meetings in order to facilitate the emergence of the most consensual sediment management scheme.

The sediment management plan defined for the Upper Rhône River has to comply with several regulations. The Espoo Convention defines the international legal framework on environmental impact assessment in a transboundary context. The convention obliges states to notify and consult each other on all major projects under consideration that might have adverse environmental impacts across borders. At a national scale, the Swiss legal framework applies to the Swiss operator SIG and to the Franco-Swiss operator SFMCP, while French rules apply to French operator CNR and to SFMCP again.

To implement the new sediment management plan, SIG, SFMCP and CNR presented a general operating procedure at the request of French authorities. It includes in particular a hydraulic program to support partial lowering of the Verbois Reservoir. According to this program, Swiss operators also have to comply with the same constraints as the ones respected by the French operator CNR for several decades. This means in particular that the fine suspended sediment concentration released from the Verbois Reservoir also has to remain below the stated values which are potentially critical for aquatic life. This procedure resulted in an in-depth environmental impact assessment study, containing multiple measures to preserve ecological integrity, and a specific file on protected species.

Following an examination of the project by the competent governmental departments and a public inquiry covering all riparian municipalities concerned, operators were authorized to implement the supporting measures by two inter-Prefectural rulings signed in March 2016. Moreover, both countries agreed to deliver a 10-year authorization to implement the new mixed scheme, leading to an administrative simplification for following operations until 2026. During the sediment management operations, the three operators set up an important monitoring program in the field. A steering committee, under the joint aegis of Swiss and French authorities, is responsible for validating and controlling the efficient execution of these different monitoring tasks.

3.4.4.7. Sediment data of the site

Verbois Dam

The initial storage capacity of the reservoir was 13 Mm³ at the normal operating level. However, owing to the Arve River sediment supply, the Verbois Reservoir experiences adverse sedimentation processes affecting mainly sand and silt fractions. They potentially cause an average storage loss of 360 000 m³ annually (around half of the inflowing load) and induce possible flooding hazards for the population of Geneva due to bed aggradation (Figure 3.42). As a result, those deposits have to be removed regularly. This requirement is satisfied with regular flushing operations performed by the Swiss operator SIG. As a result, the storage capacity loss of Verbois Reservoir is currently limited to only 3 Mm³ since the dam completion, and the flooding hazards have been significantly lowered (Figure 3.43).

Before 2016, those flushing operations were performed without paying attention to the environmental issues at stake downstream of Swiss dams. Since the new French-Swiss agreement signed in 2016, Swiss operators have to comply with the same constraints as the ones respected by the French operator CNR for several decades, meaning that the fine suspended sediment concentration released from reservoirs has to remain below critical values in order to avoid adverse impacts on the aquatic life and other uses (see paragraph on “Regulatory constraints”).

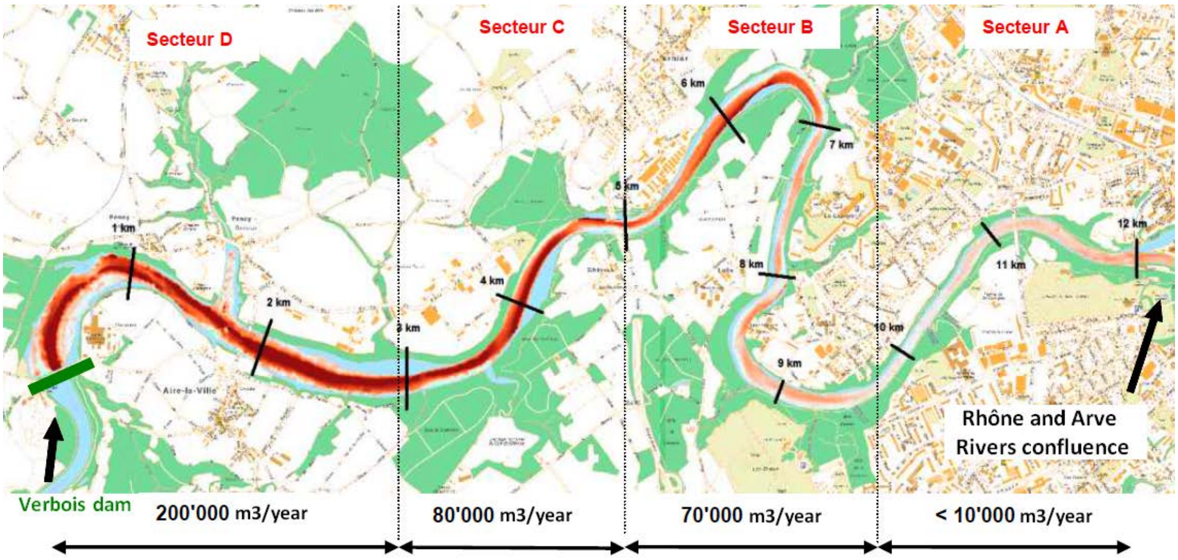


Fig. 3.42
Distribution of deposits in the Verbois reservoir

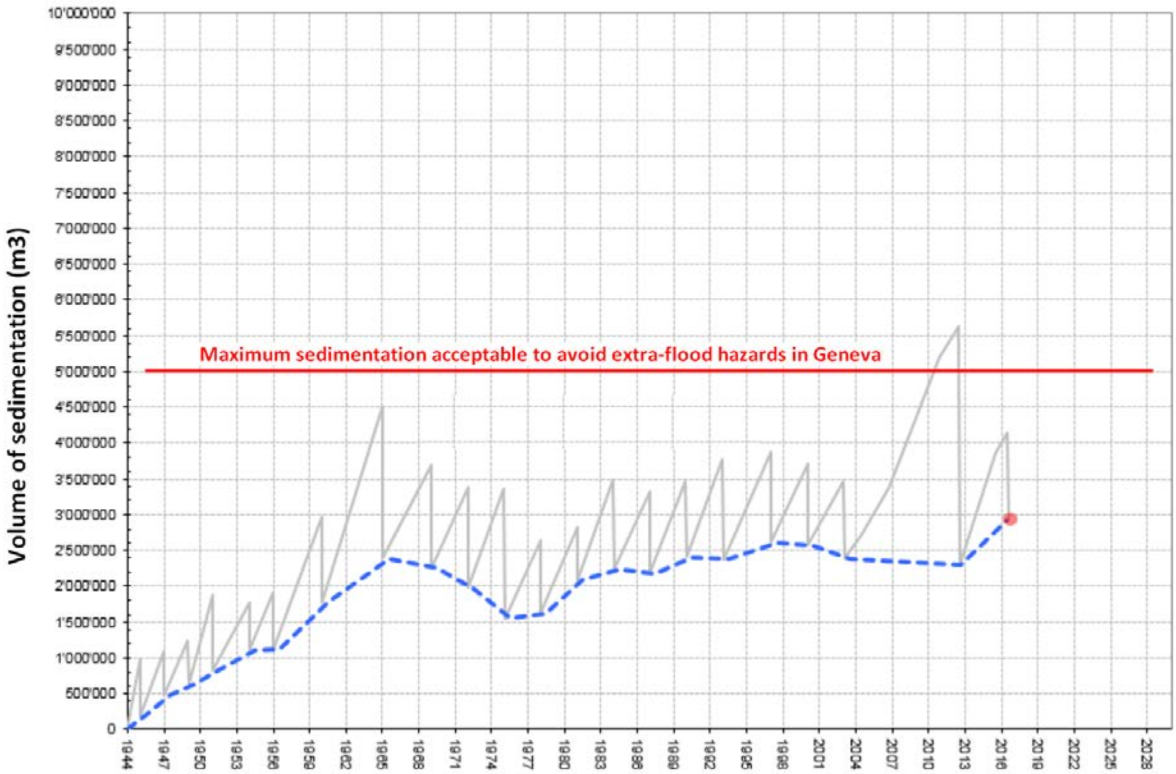


Fig. 3.43
Historical evolution of sedimentation in the Verbois reservoir

Genissiat Dam

The initial storage capacity of the reservoir was 56 Mm³ at a water level of 331.70 m NGFO at the dam site. However, this volume has decreased by 20 Mm³ due to sedimentation (Figure 3.44). Those deposits are mainly composed of silt and sand, as well as gravel to a lesser extent. Their distribution shows a clear longitudinal fining from upstream to downstream (Figure 3.45).

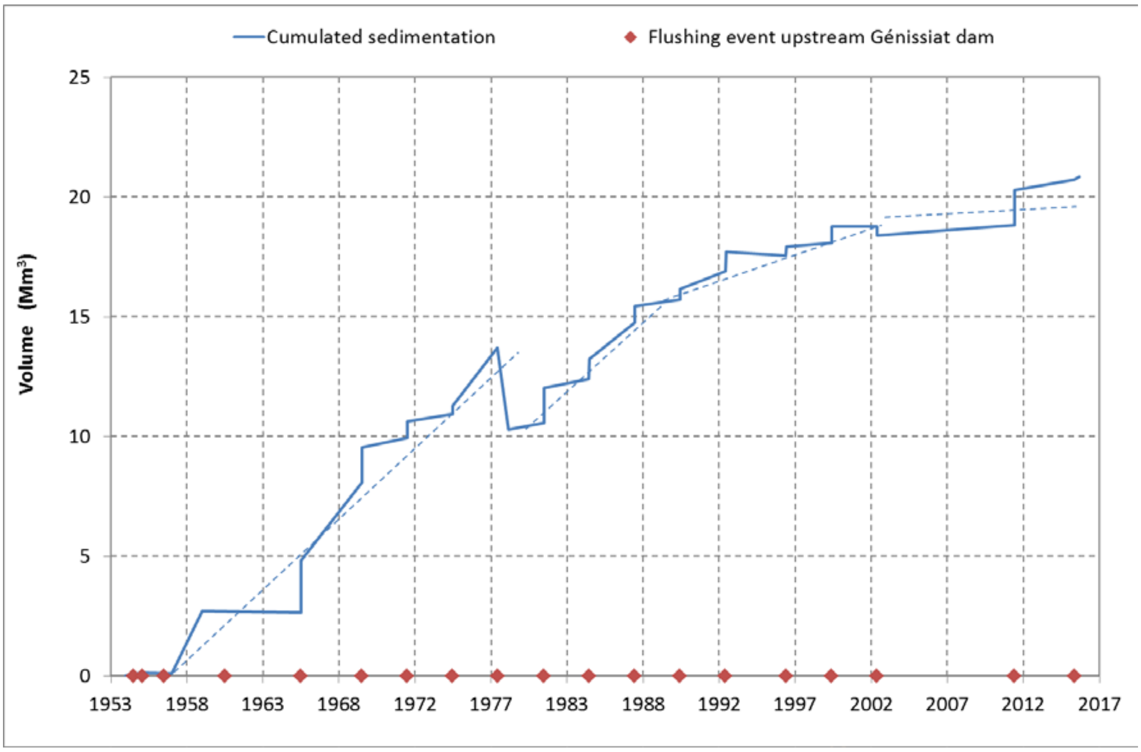


Fig. 3.44
Historical evolution of sedimentation in the Génissiat Reservoir

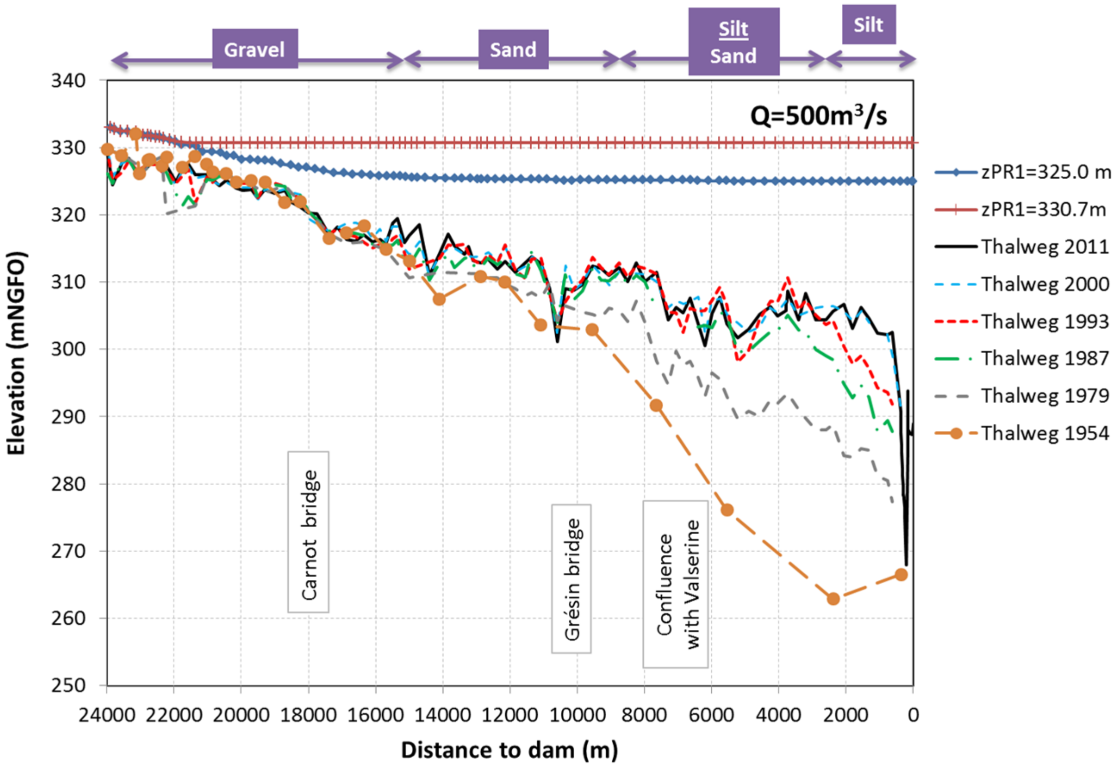


Fig. 3.45
Historical evolution of reservoir bottom in the Génissiat Reservoir

During the last 25 years, the sedimentation in Génissiat Reservoir has been mainly due to the flushing operations organized by Swiss operators (80% of total accumulation of the period). This situation resulted from the French regulatory constraints that required, downstream of Génissiat Dam, to reduce drastically the fine suspended sediment concentrations released from Swiss reservoirs in order to preserve the environmental and industrial issues at stake in the lower sections of the river.

Comparatively, the contribution of flood events affecting the Arve River basin during the same period is less significant (20%) thanks to the quasi-equilibrium profile progressively reached along the reservoir (Figure 3.45). This profile favors a more efficient transfer of inflowing sediments compared to the situation prior to the 1990's.

Since 2016, Swiss and French operators have to comply with the same constraints. As a result, the volume of sedimentation in Génissiat Reservoir during the 2016 flushing operation was only 140 000 m^3 (Figure 3.44). By comparison, historical values were five times greater on average, and some operations, such as the ones organized in 1965, 1969, 1981 and 2012, led to extreme deposits reaching up to 1,4 Mm^3.

3.4.4.8. Classification of sediment management

The following classification of sediment management techniques considers the mean annual inflows of water and sediment in the reservoir. The graph below shows the situation of the Verbois and Génissiat Reservoirs at their initial state in comparison with many other cases worldwide.

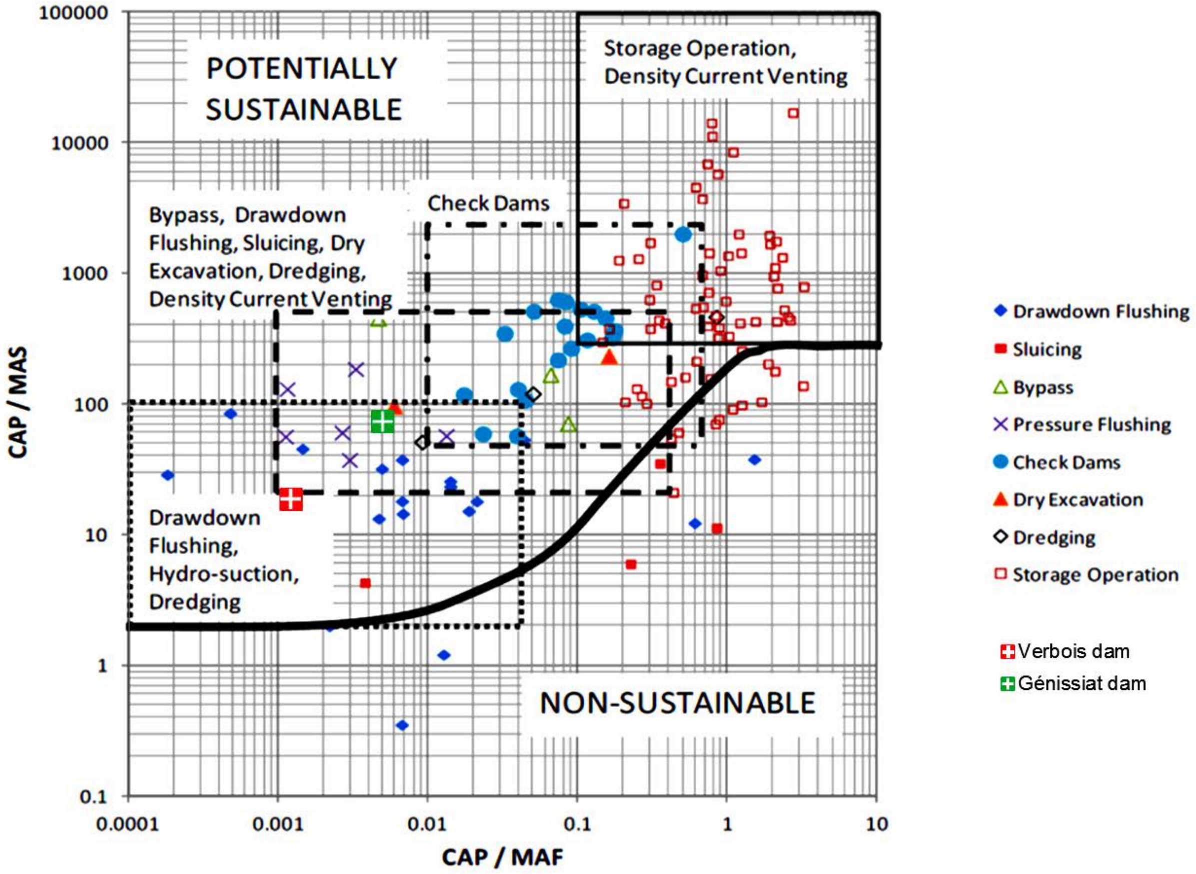


Fig. 3.46

Classification of sediment management approaches and situation at Verbois and Génissiat Dams considering the initial state of the reservoirs

3.4.4.9. Considered management methods

Before 2016, no specific management was performed in Swiss reservoirs to favor the sediment routing during high flows and flood periods. This situation caused a partial but systematic deposition of inflowing particles upstream of successive dams. Those fine sediment accumulations may have induced extra flood hazards for people in Geneva. Historically, the remobilization of deposits was performed later, thanks to full drawdown flushing of reservoirs supported by extra discharge released from Lake Geneva. Those operations used to be organized by Swiss operators every 3 years and led to a discharge, in only a few days, of 1 to 2 Mm^3 of fine sediments into the river system. As no constraints existed regarding the suspended sediment concentration (SSC) released from the reservoirs, they had extremely harmful impacts on aquatic life.

Following the 2016 agreement, Swiss operators now have to consider a new sediment management scheme consisting of a threefold procedure:

- During flood conditions: facilitation of Arve River sediment routing through Swiss reservoirs by discharging additional flow from Lake Geneva. The sluiced volumes expected may be between 30 000 and 50 000 m^3/year.
- During flushing events organized every 3 years (see Figure 3.47 for 2016 event): partial drawdown flushing of Verbois Reservoir supported by additional discharge from Lake Geneva and control of gate openings. A real time control is performed at Pougny monitoring station in order to check that the fine suspended sediment concentrations released from Verbois Dam remain below values potentially critical for aquatic life and other uses. For each operation performed every 3 years, flushed volumes expected may range from 0.8 to 1.5 Mm^3.
- During normal conditions: optional dredging depending on current requirements. This may result in volumes between 10 000 and 50 000 m^3/year.

On the French section of the Upper Rhône River, CNR has to cope with many environmental and industrial constraints during the flushing operation organized by Swiss operators (see paragraph on Regulatory constraints).

At Génissiat Dam, this requires satisfying two opposing goals. The first one is to control the suspended sediment concentration released from Génissiat Dam to regulate the fine suspended sediment discharge from Swiss reservoirs and remain below critical values for aquatic life and other river users. The second one is to favor as much as possible the routing of inflowing sediments to limit sedimentation processes in Génissiat Reservoir.

During those operations, the Génissiat Reservoir water level is first lowered at precise levels to be able to remobilize the sediments previously deposited and ensure the routing of inflowing sediments coming from the upper Swiss reservoirs (Figure 3.47 and Figure 3.48). Inflowing sediments could settle if the reservoir water level is too high, while huge sediment concentrations may be released if the reservoir water level is too low. Secondly, an appropriate gate opening and mixing of the sediment-laden flows released by each of the three hydraulic facilities allows obtaining a suitable solid concentration further downstream thanks to real time monitoring performed at the dam site and the Seyssel monitoring station. As a vertical gradient of concentration for suspended sediments characterizes the flow, the bottom gate (BO) discharges highly concentrated water, the mid-depth gate (MDG) releases less concentrated flows and the surface spillway (SS) passes even more clear water (Figure 3.47). The efficiency of such a gate arrangement and of the associated operation rules have been demonstrated over decades and allow CNR to conduct eco-friendly flushing operations with very limited impacts to aquatic life and other river users.

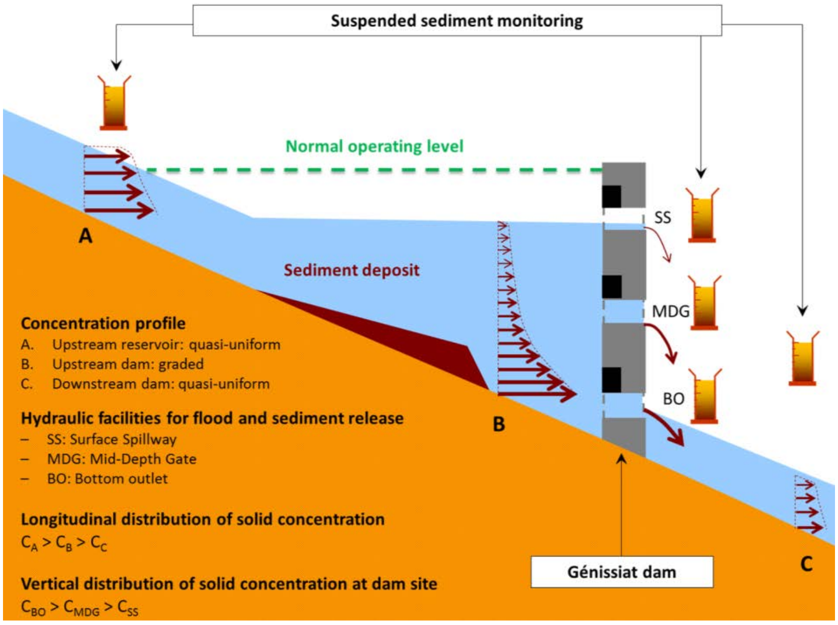


Fig. 3.47
Principle of eco-friendly flushing operations conducted at Génissiat Dam (CNR).

Downstream of Génissiat Dam, the water level of the five other reservoirs operated by CNR are progressively and partially lowered to favor sediment transfer (Figure 3.49). Moreover, all the diversion dams are almost entirely closed in order to route the sediment through the headrace channels and hydropower plants, rather than the natural course of the Rhône (Figure 3.50). This situation preserves the Old-Rhône sections from fine suspended sediment inflows but induces a huge sedimentation upstream of the concerned dams (Figure 3.51).

To achieve an efficient lowering operation, real time monitoring is implemented in the field by Swiss and French operators 24 hours a day. This operation involves hydraulics experts and field teams working with a dense measurement network located on both sides of the border. Moreover, real-time data exchange systems enable fine adjustments of dam operation in order to control the evolution of the suspended sediment concentrations released to the river system.

Some of the monitoring activities are performed by mixed teams composed of representatives from both countries. This example emphasizes the high-level of cooperation between French and Swiss operators, as well as the mutual trust between companies in the framework of this sediment management operation. In addition, besides synchronizing communication plans and joint press releases, SIG/SFMCP and CNR representatives attended each one of the prior public meetings organized to present these operations, in Switzerland as well as in France.

Sediment management on the upper Rhône River lead to important costs for SIG, SFMCP and CNR. In particular, the hydroelectric production of power plants is stopped during the event and the dense monitoring network requires many human and logistical resources. Each operator contributes to the funding of these operations.

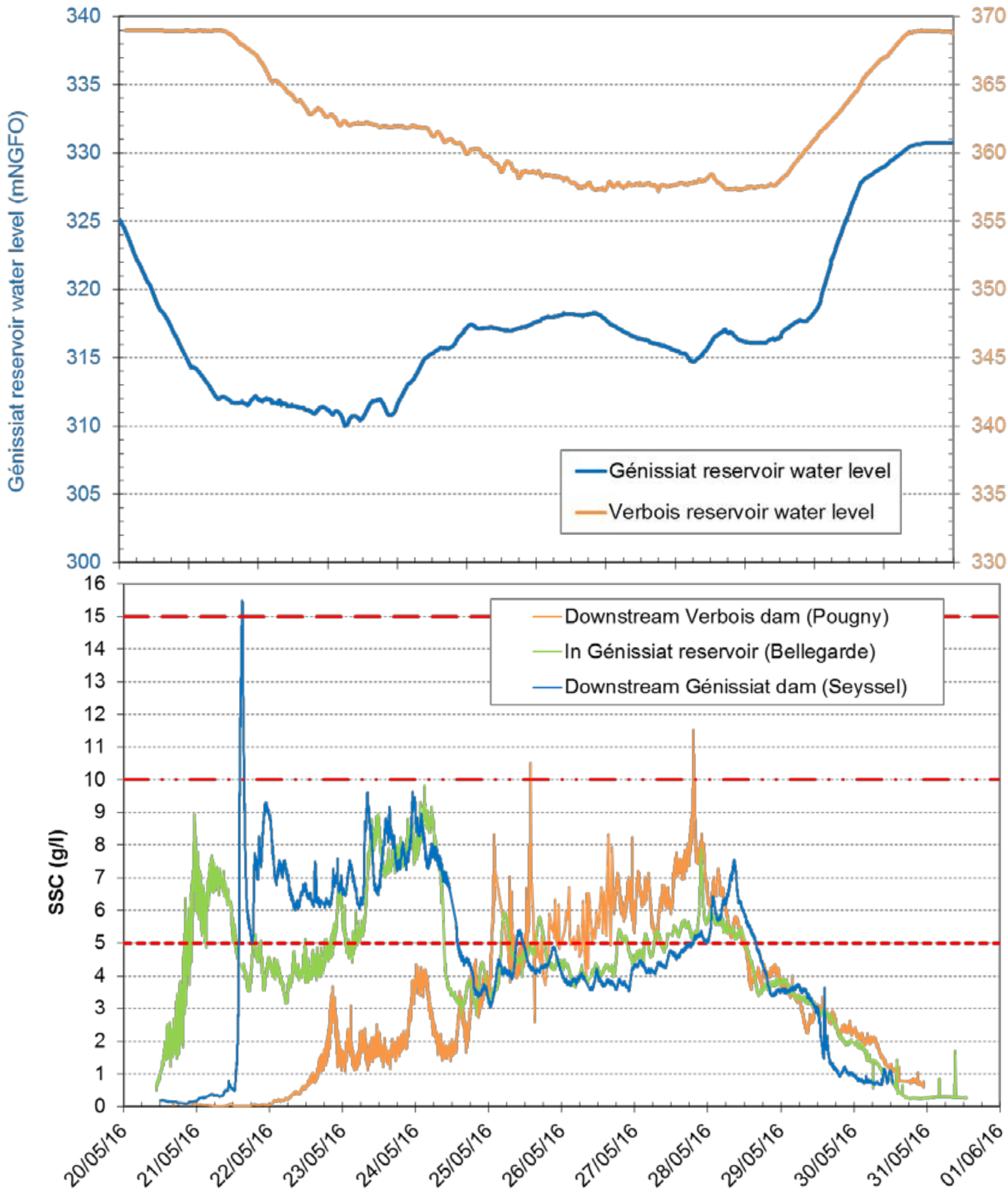


Fig. 3.48
Reservoir water level and suspended sediment concentrations at reference sites during 2016 operation.

Fig. 3.49
Seyssel Dam and Reservoir in normal conditions (left) and during flushing operation (right)

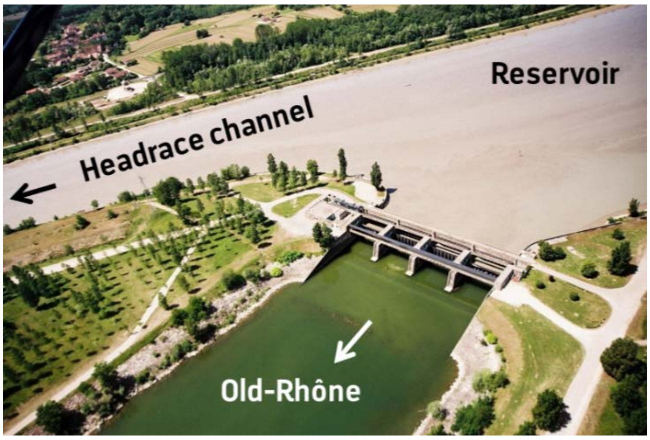


Fig. 3.50
Management of downstream hydropower developments during flushing operations

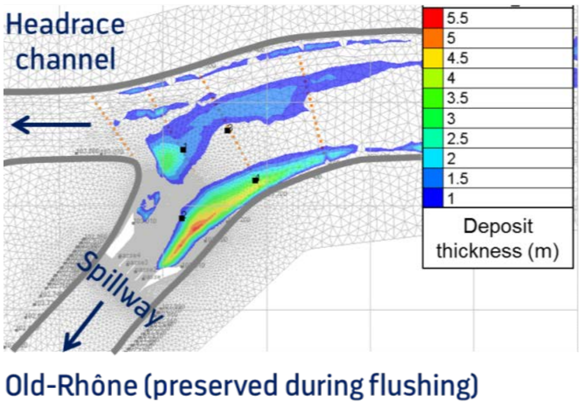


Fig. 3.51
Thickness of deposits due to flushing operations in downstream hydropower developments

VERBOIS

Location: Rhône River (Switzerland)

Cost of sediment management: several millions euros

Management options: sediment sluicing during floods, partial drawdown flushing and local dredging

Reducing sediment inflow

Not applicable

Preventing deposition

⇨ Sediment sluicing

Removing sediment

⇨ Partial drawdown flushing

⇨ Dredging

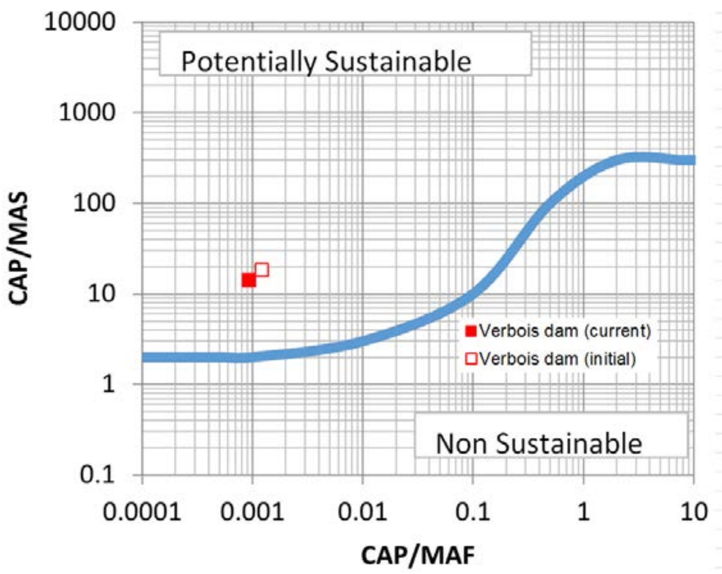
Main characteristics

Dam type	Concrete
Function	Power generation
Dam height (m)	34
Dam length (m)	410
Gross storage (m^3)	13 000 000
Catchment area (km^2)	10 175
Design discharge(m^3/s)	2 700

Key features*

CAP (m^3)	13 000 000
MAF (m^3/y)	10.63×10^9
MAS (m^3/y)	715 000
CATCHMENT (km^2)	10 175
[redacted]	
CAP/MAF (year)	1.22×10^{-3}
CAP/MAS (year)	18.2

*Values presented correspond to initial state



GENISSIAT

Location : Rhône River (France)

Cost of sediment management: several million euros

Management options: sediment sluicing during floods, partial drawdown flushing and local dredging

Reducing sediment inflow

Not applicable

Preventing deposition

- ⇨ Sediment sluicing

Removing sediment

- ⇨ Partial drawdown flushing
- ⇨ Dredging

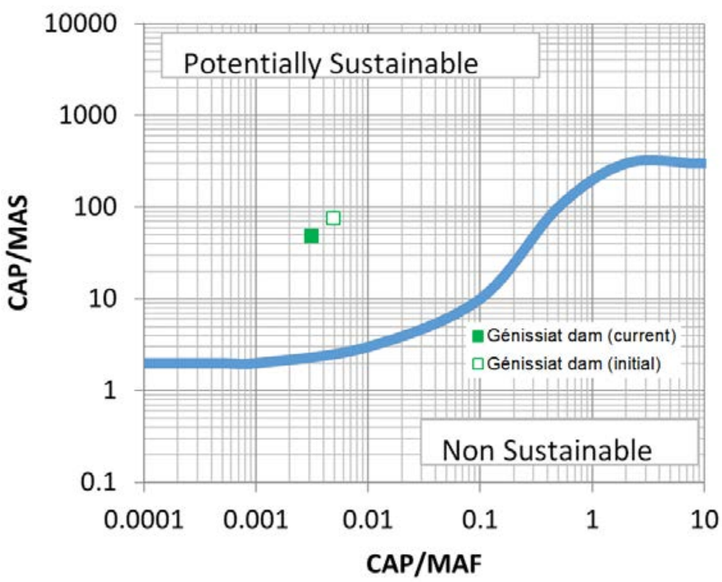
Main characteristics

Dam type	Concrete
Function	Power generation
Dam height (m)	99.7
Dam length (m)	165
Gross storage (m^3)	56 000 000
Catchment area (km^2)	10910
Design discharge(m^3/s)	3 800

Key features*

CAP (m^3)	56 000 000
MAF (m^3/y)	11.32×10^9
MAS (m^3/y)	765 000
CATCHMENT (km^2)	10 910
[redacted]	
CAP/MAF (year)	4.95×10^{-3}
CAP/MAS (year)	73.0

*Values presented correspond to initial state



3.4.5. France – St Egrève: Management of Sediments in the Saint Egrève Reservoir

Provided by Electricité de France (EDF), E Valette

3.4.5.1. Introduction

The Saint Egrève Reservoir was built in the late 1980's in France and became operational in 1991. This reservoir is located on the confluence of the Isère and Drac Rivers. The reservoir is located near Grenoble in the French Alps (Figure 3.52).

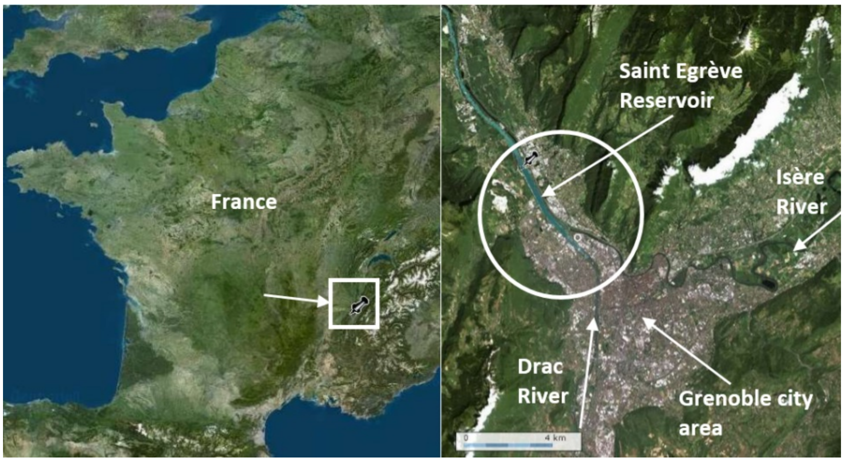


Fig. 3.52
Location of Saint Egreve Reservoir (France)

At this dam there is a sediment accumulation on the left bank of the reservoir. The siltation could potentially exacerbate flood hazards.

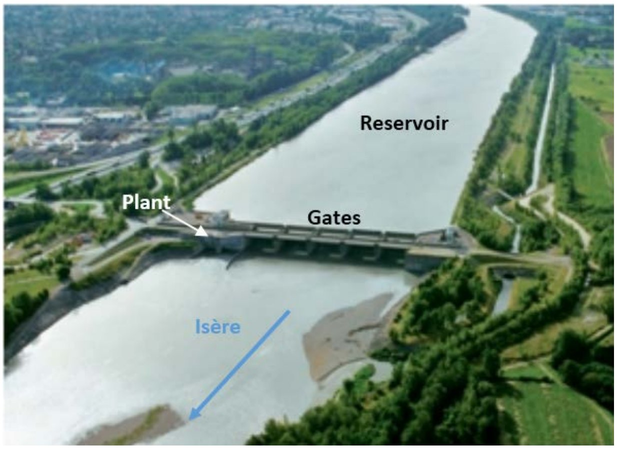


Fig. 3.53
Aerial view of the St Egrève Dam (1992)

3.4.5.2. Owners

This reservoir belongs to Electricité De France (EDF), which also operates this run-of-river hydroelectric station.

3.4.5.3. Hydrology

The Saint Egrève Dam is located on the Isère and Drac River confluence. The catchment area at this point is 9720 km² and the average annual flow entering the reservoir is around 290 m^3/s.

The river has a seasonal regime with high flows during spring periods (snow melt in the Alps) and a smaller secondary peak in autumn (strong Mediterranean rains) and low water during winter.

Table 3.8 presents the natural peak flood discharges of the Isère River at the dam location for different return periods.

Table 3.8
Natural Peak flood discharges of the Isère River at St Egrève for different return periods

Saint Egreve		
Return period	10	100
Peak flood discharge	1 510 m^3/s	2 680 m^3/s

3.4.5.1. Basic dam and reservoir data

The St-Egrève Dam is a run-of-river power station. The dam comprises five identical openings with overflow flaps, and a 25-meter wide Tainter gate with 6 meters of lifting height and a weir at elevation 196.50 m NGF. The normal reservoir level during operation is 205.50 m NGF. The power plant is equipped with 2 bulb turbines of 23 MW each able to pass a total discharge of 540 m^3/s.

For safety reasons, a security distance of 1 meter with respect to the crest of the reservoir embankment must be guaranteed for a flood of 3000 m^3/s (historical flood in Grenoble) downstream of the Isère/Drac River confluence. The dam itself is able to pass more than the 1000-year return period flood at the normal reservoir level.

In 1992, the total capacity of the reservoir was estimated to 6.1 hm^3 and the capacity downstream of the confluence to be 3.86 hm^3 (determined with bathymetric surveys).

3.4.5.2. Plot of capacity versus mean annual flow

There is very little gravel inflow to the reservoir (due to dredging of the Isère and Drac Rivers in the last century for urban development and concrete production needs). Gravel accumulation is not a problem yet even if gravel inflow increases in the Drac River upstream of the reservoir. The mean annual sediment inflow (from clay to sand) is estimated as 2 000 000 t/yr on average with a variability between 1 to 9 million tons per year. In 2016 the total volume was equal to 5.21 hm^3 (6.1 initially) and the volume downstream of the confluence was equal to 3.4 hm^3 (3.86 initially).

3.4.5.3. Political issues

In order to protect the urban area from the flood hazard, EDF has to maintain the sediment stock as low as possible, especially on the left bank which is particularly impacted by the sediment deposit.

3.4.5.4. Regulatory constraints

EDF has to respect the European Union law as it pertains to environmental considerations. Dredging periods and increases of sediment concentration must be approved by the authorities before operations commence.

3.4.5.5. Sediment data of the site

The evolution of the capacity of the reservoir downstream of the confluence is plotted in Figure 3.54. The sediment volume could reach 1.45 hm^3 on the left bank if the bar continues to silt up. In 2010 the elevation of the left bank was 204.5 m NGF. In this case, the cross section for the flow was reduced to 250 m^2 over a 2 500 m length so that the free volume was around 0.6 hm^3.

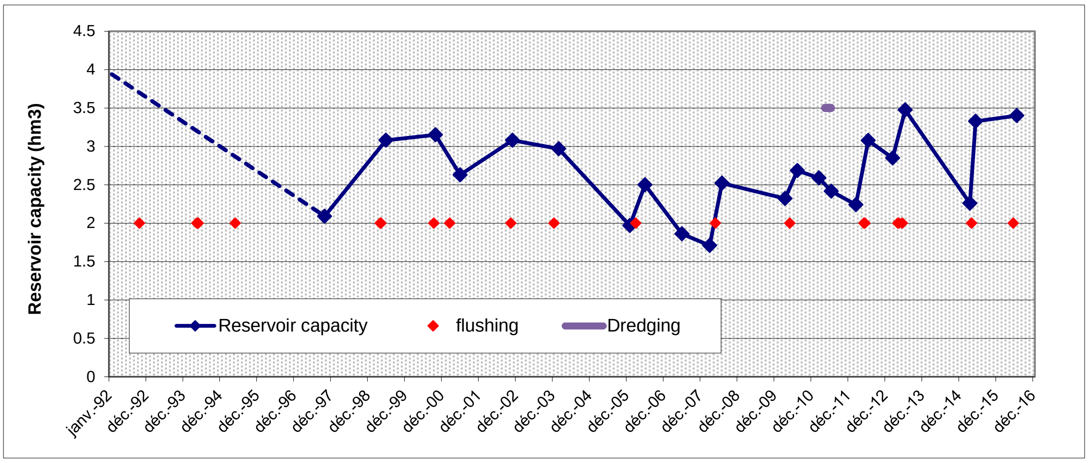


Fig. 3.54
Capacity of the Saint Egreve Reservoir downstream of the confluence

The St-Egrève Reservoir shows a sediment accumulation on the left bank that continues to silt up (see Figure 3.55). In 2010 its elevation was 204.5 m NGF on average, i.e. one meter below the FSL and the volume of sediment in the bank was estimated to 1 hm^3.

Fig. 3.55
Saint Egrève Reservoir during a flushing event

This bank was located close to the left gates of the dam with a possible limitation of the flow capacity through the dam during floods. A 2D hydraulic model was used to predict velocity and shear stress upstream of the dam. The aim of this model was to define the surface of dredging required to have a good conveyance at the left gate during a flood and to develop a strategy to maintain it. The preferential use of the left gate during floods to flush sediment is recommended.

Dredging of the bank was realized in 2011 to limit its elevation and improve flow upstream of the left gates. The dredging volume was 120 000 m³. The remaining channel has a variable topography in its cross sections: its minimum area in the absence of flushing can be estimated at 250 m², i.e. a volume of about 0.6 hm³ downstream of the confluence. The channel is deepened during floods with flushing operations. The preferential use of the left gates since 2010 increases the maximum reservoir capacity that can be reached from 3 hm³ to 3.5 hm³ in the channel downstream of the confluence.

3.4.5.6. Modeled flushing scenarios

Numerical modeling (1D) was used to determine reservoir bed evolution during floods and flushing operations. The objective was to verify that when starting with a high degree of siltation, the erosion at the beginning of flushing is sufficient to guarantee the preservation of the 1-meter freeboard with respect to the crests of the dikes. This model was calibrated with the May 2008 flushing operation and validated with the May 2010 flushing (Figure 3.56). Bathymetric surveys helped to determine three sediment layers:

1. Top layer ➔ slightly consolidated sediment (easily remobilized)
2. Recently deposited sediment (few years)
3. Sediment layer as the most consolidated sediment

In this model, there is a cross section every 100m.

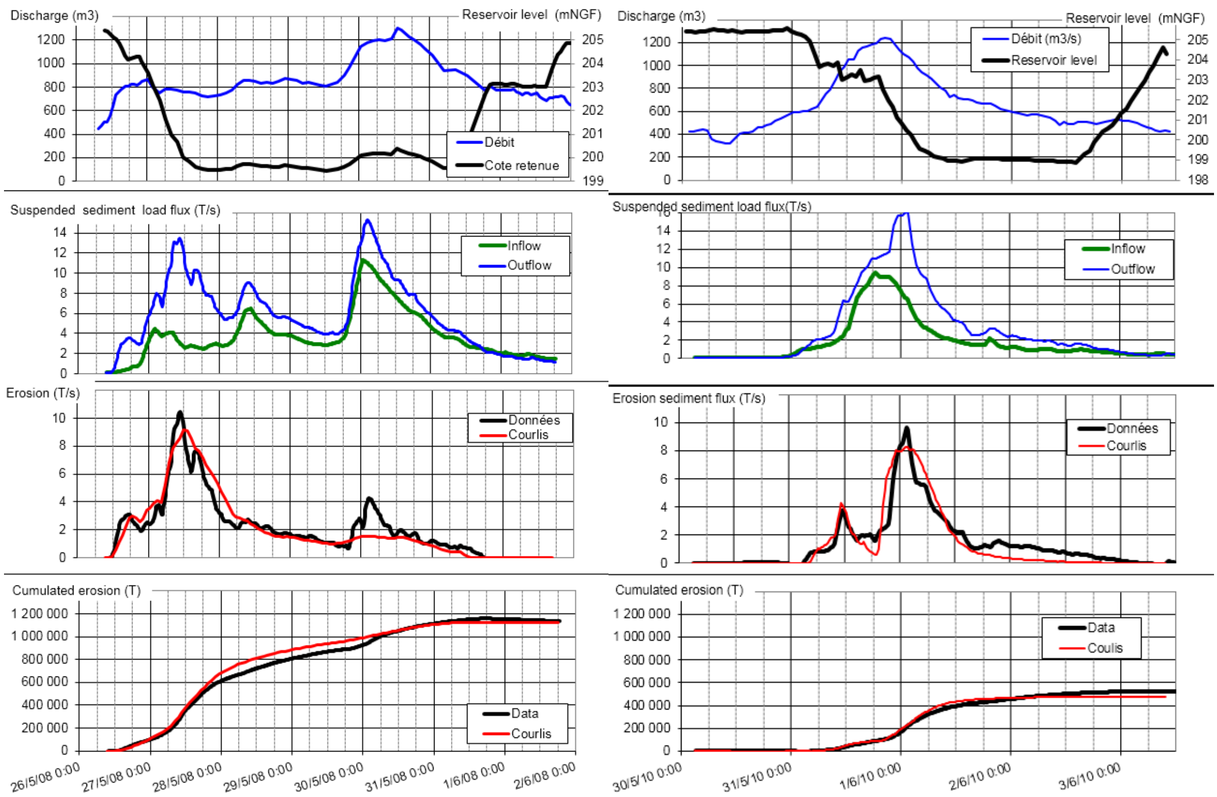


Fig. 3.56

Model calibration and validation through comparison against 2008 (left) and 2010 (right) flushing measurements

The erosion stress, the surface erosion rate and the number of layers are the main parameters of the erosion module and have a strong influence on the results.

3.4.5.7. Classification of sediment management

Channel deposition is managed by flushing. The mascaret-courlis model helps EDF to demonstrate the efficiency of flushing for the design flood and specified levels of siltation. A Telemac 2D model helps EDF to specify the limit of siltation allowed upstream of the left gate of the Dam. The preferential use of the left gate during flood at the end of flushing allows EDF to maintain this part of the reservoir and generate a slow but efficient lateral erosion of the left bank. Dredging is also used to limit the elevation of the left bank (no vegetation is allowed on the bank).

In addition, sluicing occurs during intermediate flows with high concentrations of sediment (around 40 sluicing events occurred between 2010 and 2015). During this operation, the water level is down around the minimal operating level (204.5 m asl), and electricity production is not stopped.

SAINT EGREVE

Location: France on the Arc/Isère River

Cost of sediment management:

Management option:

Reducing sediment inflow

Not applicable

Preventing deposition

- ➩ Flushing
- ➩ Sluicing

Removing sediment

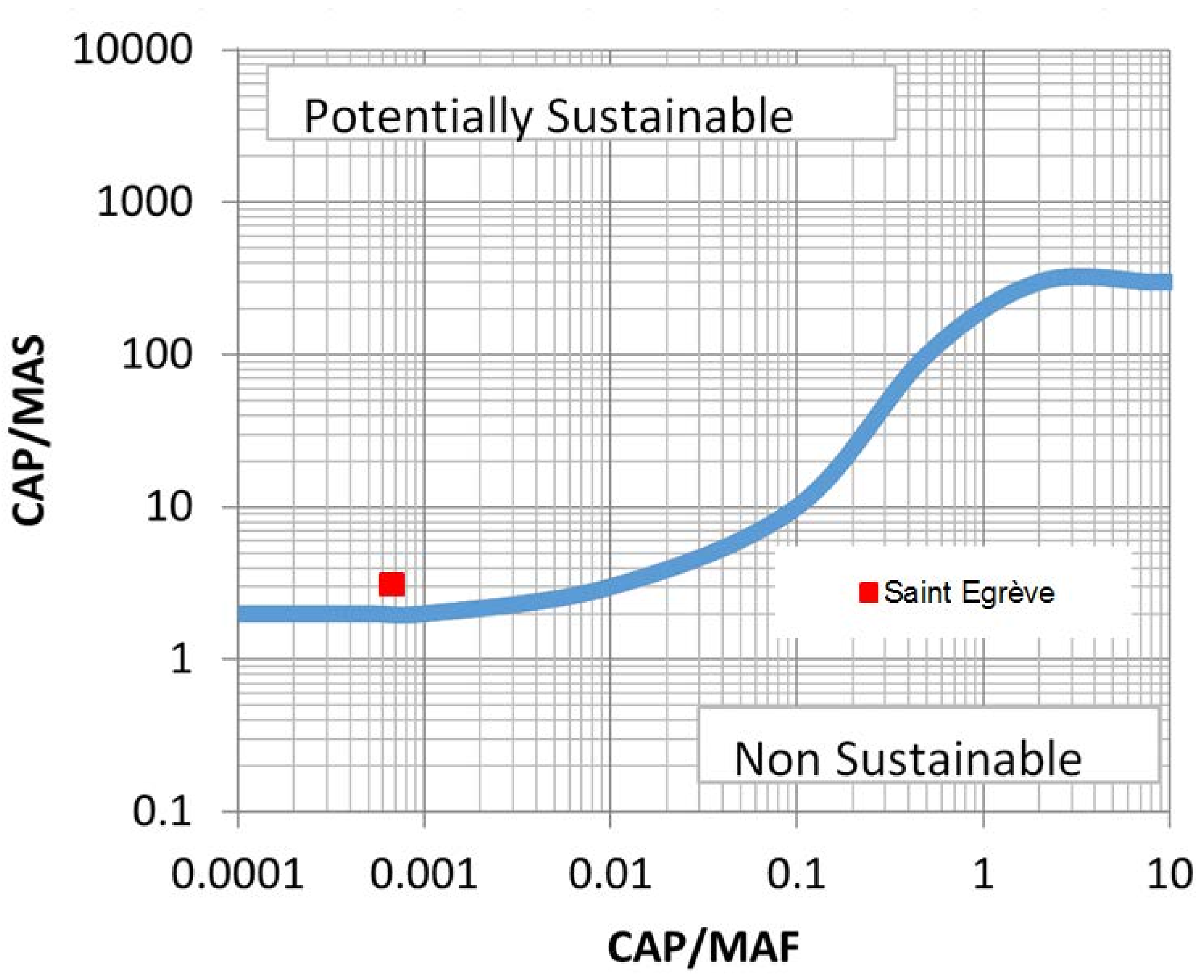
- ➩ Dredging

Main characteristics

Dam type	Barrage
Function	Power generation
Dam height (m)	10.5
Dam length (m)	141
Gross storage (m^3)	6 100 000
Catchment area (km^2)	9 720
Design discharge(m^3/s)	3 000

Key features

CAP (m^3)	$6.1x10^6$
MAF (m^3/y)	$9\ 151x10^6$
MAS (m^3/y)	$2x10^6$
CATCHMENT (km^2)	9 720
[redacted]	
CAP/MAR (year)	$6.67x10^{-4}$
CAP/MAS (year)	3.05


10000
1000
100
10
1
0.1
CAP/MAS
Potentially Sustainable
Saint Egrève
Non Sustainable
0.0001
0.001
0.01
0.1
1
10
CAP/MAF

3.4.6. Indonesia – Bakaru: Management of Sediments at the Bakaru Dam

According to Suprianto, A.Sufiantoro; ICOLD, 2014

3.4.6.1. Introduction

The Bakaru Dam was implemented in 1991. This dam is located on the Mamasa River (Sulawesi Island – Figure 3.57). This is a run of river type dam with a pond.

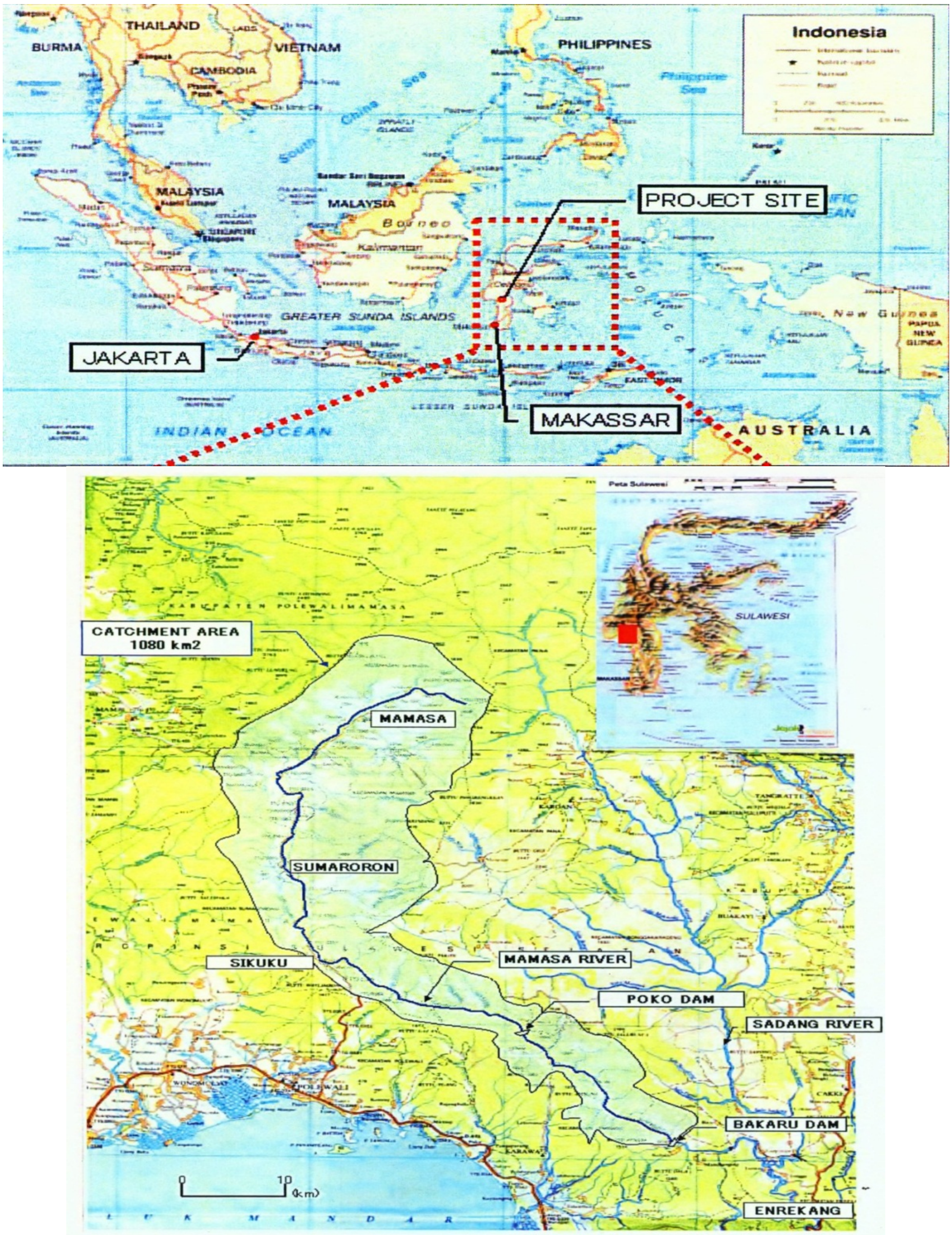


Fig. 3.57
Location of the dam

This dam is impacted by high erosion issues due to the catchment land use being dominated by crops. During the rainy season there is a huge amount of sediment produced, which reduces power supply and impacts water quality.

3.4.6.2. Owners

This dam is managed by Perusahaan Listrik Negara (PNL) in order to produce energy, although the power supply scheme is not yet fully completed:

- First Stage: Two units are operational (2x63 MW)
- Second Stage: Two units are still pending

3.4.6.3. Hydrology

The annual discharges for the latest available five years are shown below:

Table 3.9
Flow events

Return period	Discharge (m^3/s)
2011	34.33
2012	33.93
2013	36.77
2014	31.76
2015	28.71

The dam is located on a 1 080 km^2 catchment. The Mamasa River is around 126 km long.

3.4.6.4. Basic dam and reservoir data

Basic information about the dam and reservoir are provided in the table below.

Table 3.10
Structural characteristics of the Bakaru Dam

Bakaru Dam	
Dam type	Run of River with small impound
Function	Power generation
Dam height (m)	16.5
Dam length (m)	122.5
Gross Storage (m^3)	2 000 000
Catchment area (km^2)	1 080

Design discharge (m^3/s)	45
Crest elevation (mdpl)	615.53
Storage area (ha)	209.82
Type of spillway	2 sand drain gate: 10.5W x 10H 4 spillway gate: 10.5W x 8H 2 regulating gate: 4W x 4H

Fig. 3.58
Bakaru Dam

3.4.6.5. Plot of capacity versus mean annual flow

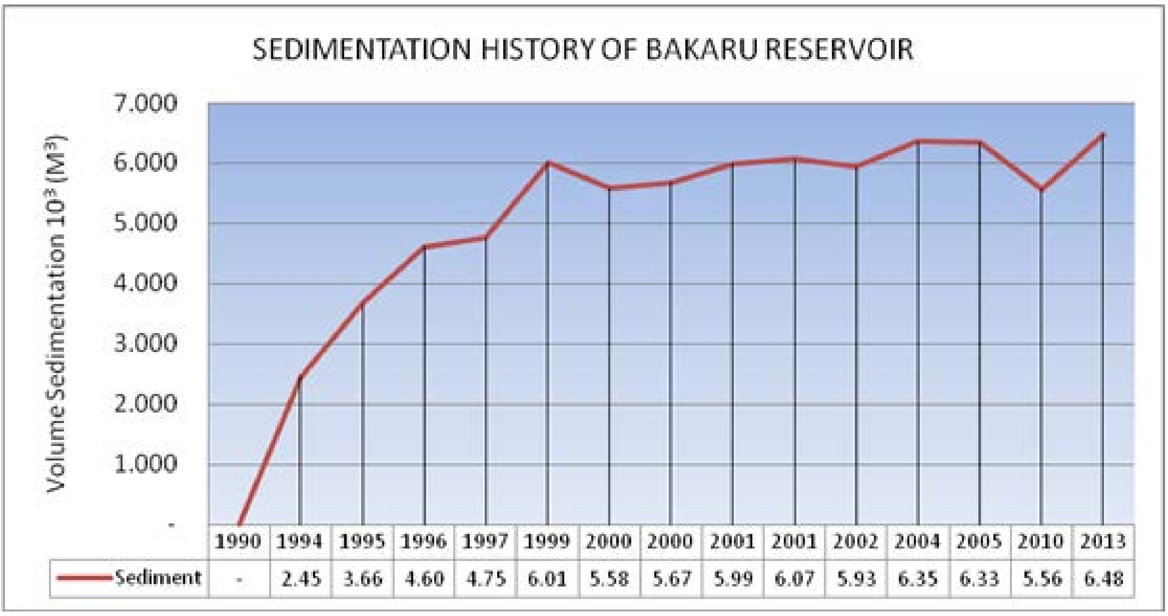


Fig. 3.59
Change in sediment volume

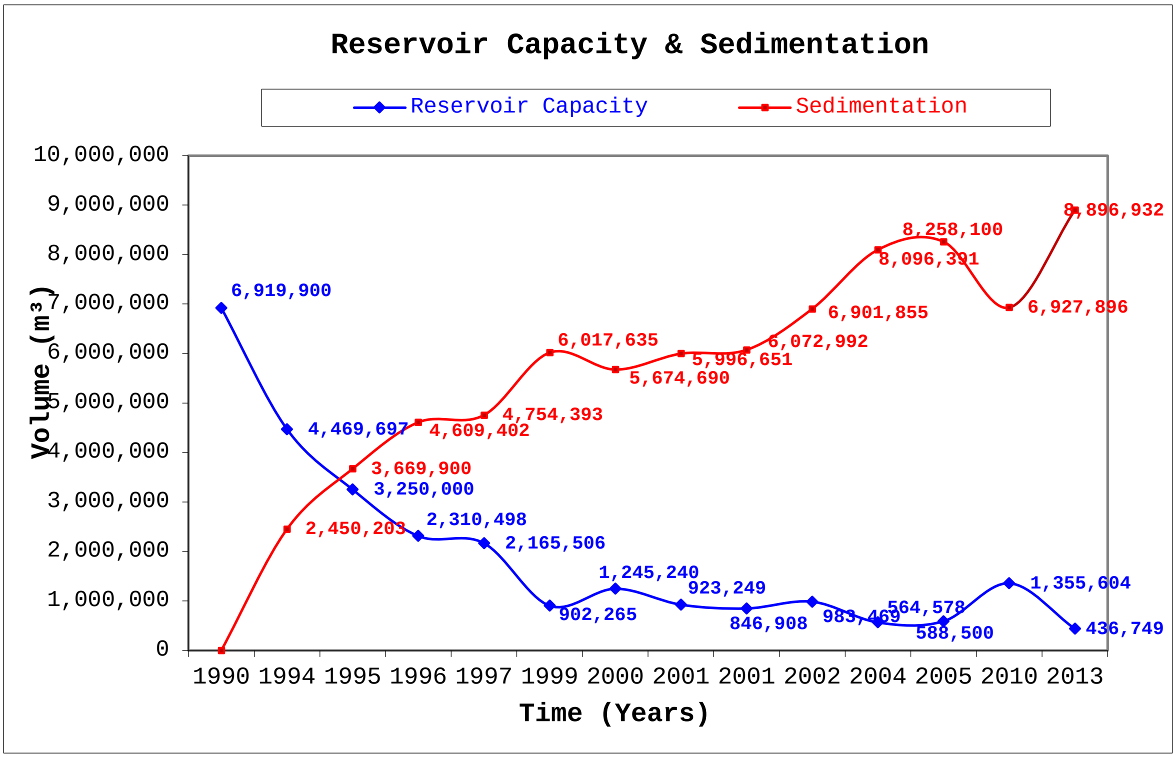


Fig. 3.60
Change in reservoir storage capacity

3.4.6.6. Regulatory constraints

The main purpose of this dam is to supply peak time water supply: (6 h with 45 m^3/s/stage[3]). This required an impoundment of 2 000 000 m^3 in case of emergency.

3.4.6.7. Sediment data of the site

The sediment flow design was calculated at 133 000 m^3/y but the actual annual sediment flow is estimated around 760 000 m^3/y. For this reason PLN had to initiate dredging operations.

During the basic design stage of the Bakaru Hydroelectric Power Project (HEPP), riverbed gravels were sampled and analyzed. The grain size distribution analysis was conducted to estimate the sediment load. According to the results, the mean grain diameter was reported as approximately 16.23 mm and natural sand for concrete was taken from the bed of the Mamasa River, about 1 km to 2 km upstream of the dam site.

However, the actual sediment properties are rather different from the ones estimated during the design stage. Sediment was extracted from the river (bottom sediment sampling and drill exploration) and was laboratory tested for the study. The results show that most of the sediment consists of sand with diameters ranging from 0.075 mm to 4.76 mm. This means that actual sediments are smaller than those estimated during the design stage. Figure 3.61 shows a picture of sediment in the reservoir.

Fig. 3.61
Picture of sediment at reservoir

This dam is also equipped with a raking system as shown in Figure 3.62 below.

[3] The second stage is still pending so only half the storage is used at the moment.

Fig. 3.62
Raking system in Bakaru intake

3.4.6.8. Modeled dumping scenario

This sediment discharge scenario uses a flushing method. The flushing method uses the principle of potential energy by taking advantage of the height difference between the water level in front of and behind the dam. Flushing is implemented by emptying the reservoir water, while the water flow into the reservoir is maintained and the sediment is flushed out through the sand drain gate in the dam. The flushing in Bakaru Reservoir was done by maneuvering the gates of the dam.

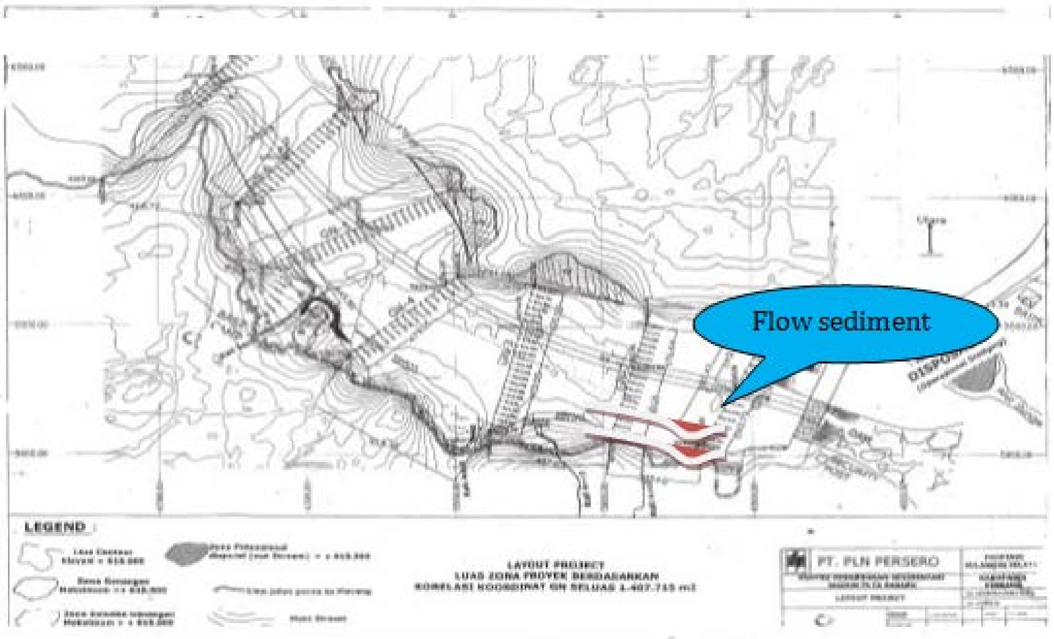


Fig. 3.63
Picture of dumping scenario

The water flow direction is controlled by maneuvering the gates of the dam, which also regulates the removal of sediment. The steps to implement flushing of the reservoir are as follows:

1. Close the Intake Gate. It is intended that the rapid flow of water from the pipe is not included in the reservoir area and maintains the elevation surge tank under normal conditions.

2. Sample the water at some point in the inundation area and the drainage area using a measuring cup, then still the water and precipitate the sediment according to the time required to determine the percentage of sediment contained in the outflow.
3. Lower the elevation of the reservoir by maneuvering the floodgates so that the flow of water can erode sediment.
4. After flushing, fill the reservoir up to a maximum elevation of 615.53 m.

3.4.6.9. Classification of sediment management

Sediment management methods for this dam were chosen from these three solutions:

- Reducing the sediment inflow with check dam and the basin management plan
- Sediment routing and preventing deposition with flushing operations
- Sediment removal with dredging operations

3.4.6.10. Sediment management

When discussing solutions regarding the reservoir sedimentation issues, the first aim was to find a short-term solution to restore reservoir capacity that would meet the power demand in the constrained power balance of the South Sulawesi Power System. Second, the plan was to evaluate the effects of potential development on the upstream area, downstream area and the power network.

A proposed study will identify two options that can be applied to the sedimentation problem of the Bakaru Reservoir, i.e., short term, long term and alternative measures for the mechanical and generating facilities.

For the short-term solution, there are four measures to restore the active storage:

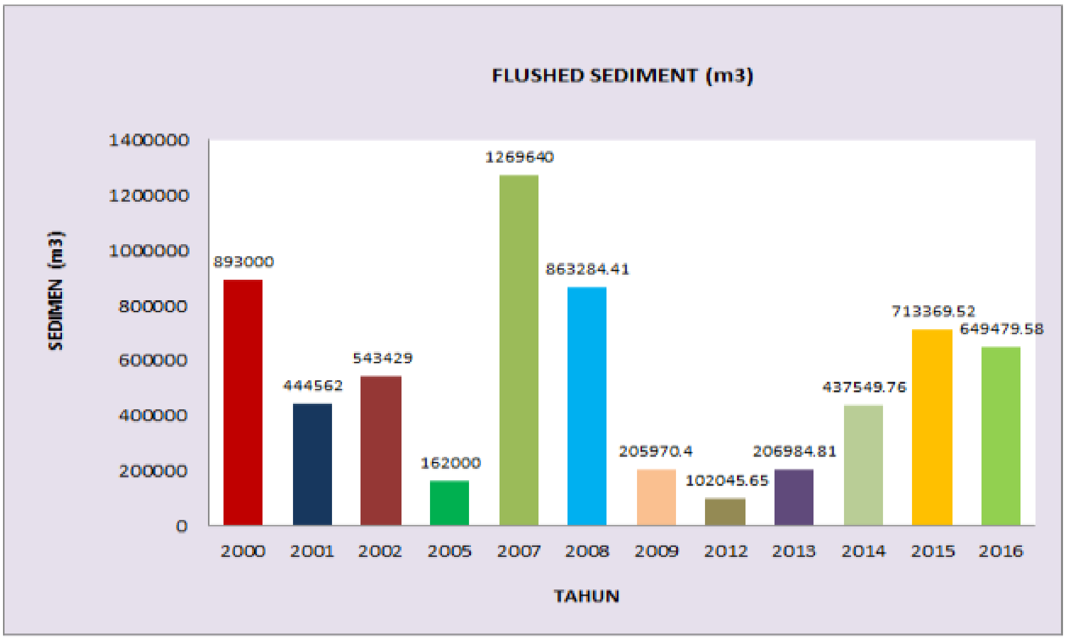
- Flushing by improving the Standard Operation Procedure (SOP)
- Dredging thereby improving the sedimentation profile
- Combination of two options above
- Improving water cooling system

<u>Flushing by improving Standard Operation Procedure (SOP)</u>

The original SOP for the operation of the dam gates included a flushing gate, which was used from 1990 to 2002, and is based on the following principles:

- Holding the water level at a maximum of 615.5 m
- Releasing excessive water through the regulating gates whose thresholds are higher than the ones of the spillway gates and the flushing gates
- Opening the flushing gates **only** during emergency flood conditions when inflow exceeds 400 m^3/sec

According to the reservoir inflow records, floods with discharges over 200 m^3/sec occurred almost every year from 1990 to 2016, consequently there are flushing opportunities almost every year (Figure 3.64).



Noted: at year 2003, 2004, 2006, and 2011, discharge inflow to the reservoir was insufficient for opening the flush gate.

Fig. 3.64
Flushing sediment using SOP modification

Sedimentation was measured in the reservoir almost every year between 1994 and 1997 and between 1999 and 2016. The measurements showed sedimentation at a higher elevation than expected. The storage capacity of DAM PLTA BAKARU was increased significantly over the three years following the flushing events described in Table 3.11 below.

In order to maintain and increase the volume of the reservoir, PLN implemented many methods, including flushing, sluicing, and continuous sediment dredging.

Table 3.11
Storage Capacity Dam PLTA Bakaru

No	Uraian	Waktu Pengukuran	Vol Waduk el. 615,50 (m^3)	Vol Sedimen el 615,50 (m^3)
1	Penggenangan NEWJEC	September 1991	6,919,900	-
2	Pengukuran PLN SBKR	Februari 1994	4,469,697	2,450,203
3	Pengukuran PLN PST	Oktober 1995	3,250,000	3,669,900
4	Pengukuran PLN SBKR	September 1996	2,310,498	4,609,402
5	Pengukuran PSL UNHAS	Oktober 1997	2,165,506	4,754,394
6	Pengukuran PSL UNHAS	April 1999	902,265	6,017,635
7	Pengukuran PLN SBKR	Maret 2000	1,335,563	5,584,300
8	Pengukuran PSL UNHAS	November 2000	1,245,210	5,674,690
9	Pengukuran LPPM UNHAS	April 2001	923,249	5,996,651
10	Pengukuran PLN SBKR	Desember 2001	846,908	6,072,992
11	Pengukuran PLN SBKR	Desember 2002	983,469	5,936,431
12	Pengukuran LPPM UNHAS	Mei 2004	564,579	6,355,321
13	Pengukuran PLN SBKR	Juni 2005	588,500	6,331,400
14	Pengukuran LPPM UNHAS	Juni 2010	1,355,604	5,564,296
15	Pengukuran LPPM UNHAS	November 2013	436,749	6,483,150
16	Pengukuran PLN SBKR	Februari 2015	1,102,112	5,817,788
17	Pengukuran PLN SBKR	Februari 2016	984,354	5,935,546
18	Pengukuran PLN SBKR	April 2016	1,222,553	5,697,347

Based on the measurement results, PLN has made efforts to restore the reservoir capacity by dredging on five occasions between 2005 and 2012, and by flushing from 2000 to 2013. PLN also revised the SOP in 1999 with an order to flush when the flood discharge exceeds 200 m^3/s and to lower the reservoir water level to the minimum water elevation of 612 m when flushing. After several flushing tests the SOP was again revised and issued in 2002, with the following guidelines:

- Lower the water level to the normal pool elevation of 613 m in the wet season
- Release excess water through the flush and drain gates or the spillway gates instead of the regulating gates when the inflow reaches 45 m^3/sec to 70 m^3/sec in the wet season
- Carry out sand flushing under normal conditions when the inflow reaches 70 m^3/sec to 200 m^3/sec
- Carry out sand flushing under flood conditions when the inflow exceeds 200 m^3/sec

Table 3.12

Dredging of Bakaru Reservoir

		Sediment Removal (m^3)	
No.	**Contract Schedule**	**Planned (M^3)**	**Actual (M^3)**
1.	15 Nov 2005 to 22 April 2006	820 000	80 000
2.	29 Dec 2006 to 05 Sept 2007	994 600	696 220
3.	28 Dec 2007 to 22 Nov 2008	700 000	700 000
4.	31 Dec 2008 to 24 April 2010	1 400 000	1 400 000
5.	29 Dec 2011 to 27 Dec 2012	725 000	725 000

Dredging

Dredging is a simple method used to remove sediments; however, continuous dredging activity for the lifetime of the dam is apparently required, since the annual sediment inflow is estimated at ± 700 000 m^3/year.

The dredging area is located from the dam to a point about 2 km upstream and the depth of dredging is about 3.5 m below the high water operation level of 615.5 m, i.e., elevation 612 m. In order to increase effective sluicing of sediments, several channels below the low operation level of 612 m will be dredged in the reservoir based on the results from physical hydraulic model tests including the number of channels, cross sectional profiles and longitudinal profiles. The physical hydraulic model test was proposed and agreed to and was finished in 2008.

If dredging is based on the results of the channel profile from the physical hydraulic model test, the sedimentation flushing and the duration of the dredging period will hopefully be optimized.

A physical hydraulic model test was also created to study sedimentation removal with the use of a gravity-powered suction pipe system installed at the base of the sediment plan level. This could be achieved because of the steep slope of the dam, which is perfect for the disposal process of the sediment. The dredging effort was added to the modeling contract in 2008 to 2010 and 2011 to 2012. Although this maintenance process is an important procedure, the cost of dredging the material is expensive. In 2012 the contract price was Rp. 25,004/m^3 and it has only become more expensive since then.

Therefore, PLN decided to buy the Dredger (Figure 3.65) with a flow rate capacity of 390 m^3/hour (slurry water).

Fig. 3.65
Dredger for Bakaru Reservoir

Combination of dredging and flushing

In order to remove the sediment in the reservoir, an alternative solution was proposed using a combination between the dredging and flushing methods; in this case the dredging improves removal of sediments by flushing.

The Standard Operating Procedure (SOP) of the dam gate operation is based on the results of the best options from the physical hydraulic model tests for sedimentation flushing and flooding.

To solve the sedimentation issue in the long-term, the following solutions are being considered:

1. Regular maintenance by combination of flushing and dredging, implemented in the SOP
2. Upstream protection to reduce sediment inflow
3. Implementation of the Watershed Management Plan
4. Separation of Bakaru reservoir

Regular Maintenance by Combination of Dredging and Flushing

As mentioned above, regarding the short-term solution of the sedimentation issue, the periodic combination of dredging and flushing will restore the effective capacity of the reservoir.

Sediment disposal is an important issue financially, socially and environmentally. If the dam did not exist, sediment would naturally continue directly downstream. Therefore, the combination of dredging and flushing by operation of the dam gates is one option for a long-term solution.

Upstream Protection for Sediment Inflow

Check dams will be constructed upstream of the reservoir approximately nine kilometers from the dam site at the Bone and Selee villages to protect against sediment inflow to the reservoir.

The sediment stored at the check dams will be removed yearly during the dry season. The total capacity of the check dams will be approximately 900 000 m^3 (compared to the average annual sediment inflow of approximately 700 000 m^3).

The Implementation of the Watershed Management Plan

The catchment area of the Bakaru Dam is about 1 045 km^2. From the beginning, the Bakaru Dam project has continuously experienced problems with unexpected excessive sediment deposits in the regulation pond. This accumulated sediment has resulted in the reduction of active storage for regulation and the chronic malfunction of power production operations.

One of the major causes of the excessive sediment deposits is thought to be the deterioration of the upstream watershed of the Mamasa River Basin due to soil erosion and landslides during floods. The situation has been aggravated by illegal logging and other improper socioeconomic activities in the watershed.

For the optimum watershed protection plan these factors should be taken into consideration:

- The Mamasa River Basin needs soil conservation measures in order to reduce sediment production from fields on the slopes, and to maintain and improve agricultural production. Such measures could include reforestation and agro forestry with terracing.
- Regional socio-economic conditions, concerns of farmers, etc., to realistically handle the soil erosion and sediment production.
- Both vegetative and civil engineering measures should be applied to critical areas of soil erosion and sediment production, including the rehabilitation of road networks with proper road side conservation and drainage improvements.
- Implementation of the plan should be realized with the full support and understanding of farmers, local government, PLN (as owner), and other stakeholders.

Separation of Bakaru Reservoir

To operate during the peak 6-hour Bakaru first and second stages, it requires approximately 1.8 million m^3 of water in the pond. Separation of the reservoir into two parts by a coffer dam or sheet pile structure would accomplish this. The first area would be for the overflow of clean water through the spillway structure at elevation 612 m and the other area would be a bypass channel for flushing sediment (Figure 3.66 and 3.67).

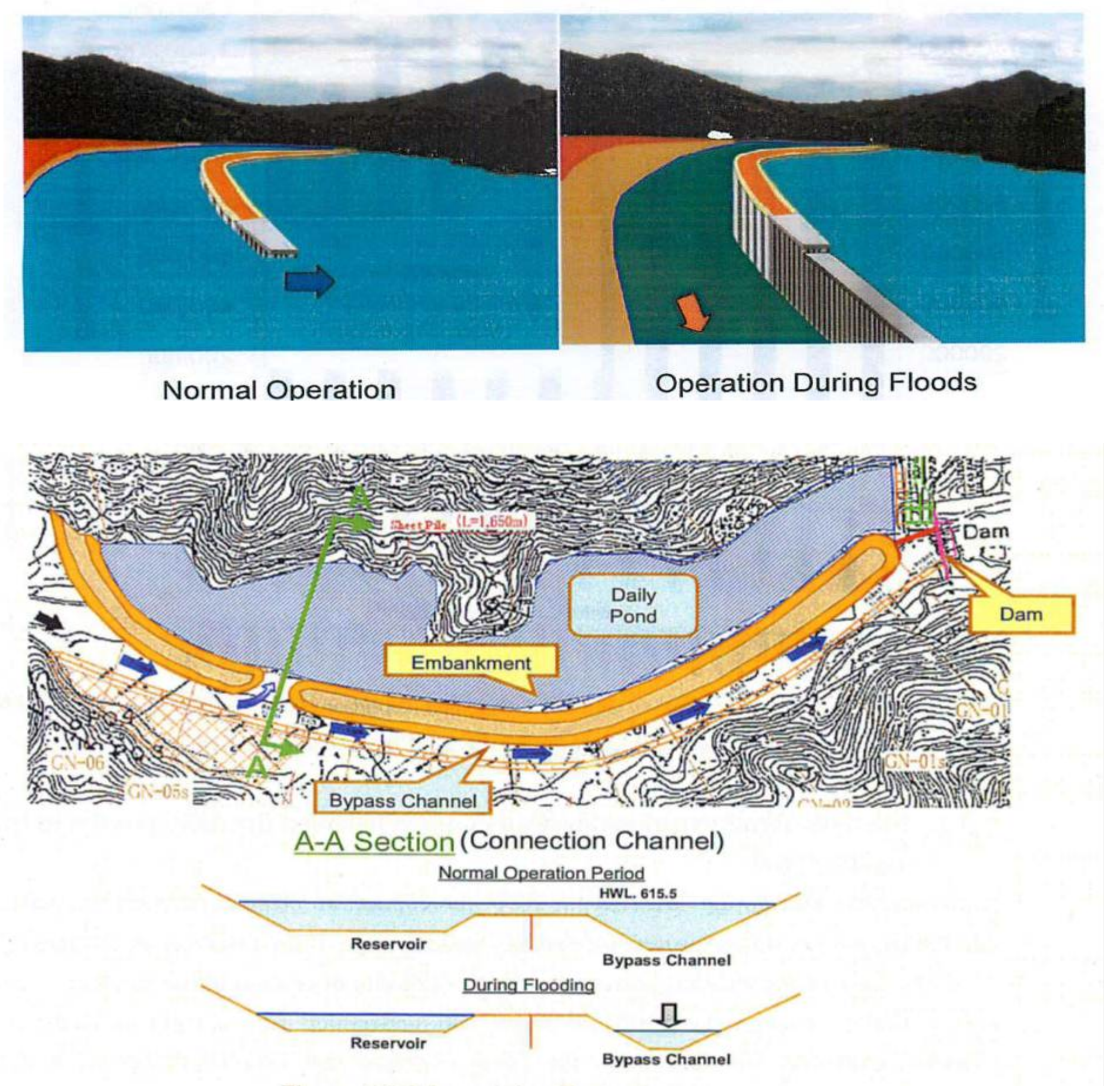


Fig. 3.66
Separation of Bakaru Reservoir

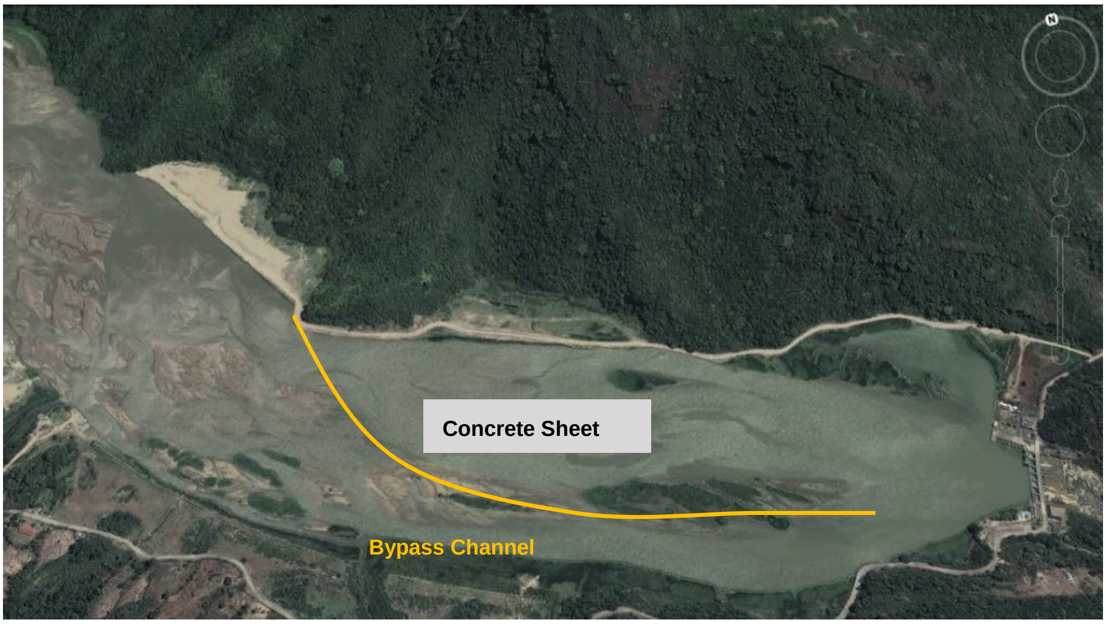


Fig. 3.67
Bypass Channel

3.4.6.11. Conclusion

1. To solve the sedimentation problems which affect reservoir operations at Bakaru Dam, the solution will be a combination of the following:

   - Dredging, which may improve the excavated profile, and flushing without interfering with power production
   - Modification of the Standard Operating Procedure of the dam gates to meet the current conditions of the river with monitoring of the results
   - Remediation and reconditioning of the plant equipment which is adversely affected by the decrease in water quality.

2. For sustainable solutions, preventive remedial work such as reforestation, agro-forestry with terracing, community socialization and consideration of new developments is **a must**. The results of these solutions will reduce the sediment inflow to the reservoir.

Coordination of work and programs between all HEPP stakeholders is necessary for success.

3. To design and operate HEPP in a proper manner is not easy. It requires comprehensive knowledge in design philosophy; good governance in operation and maintenance; and a management system including redesigning, monitoring, recording, analyzing and filing. It is also important that operation staff respect the established SOP. All experiences and records acquired during dam operations and all problem solving should always be taken as a **learning opportunity**.

4. For rivers influenced by deteriorated catchment areas, such as at the Bakaru HEPP, periodic review of the existing, established SOP is **a must**, and should be based on monitoring results and applying past experience to meet current conditions.

BAKARU

Location: Indonesia on the Mamasa River

Cost of sediment management: Rp. 25,004/m³ (dredging, 2012)

Management option:

Reducing sediment inflow

- ⇨ Check dam

Preventing deposition

- ⇨ Flushing
- ⇨ River modification (bypass)

Removing sediment

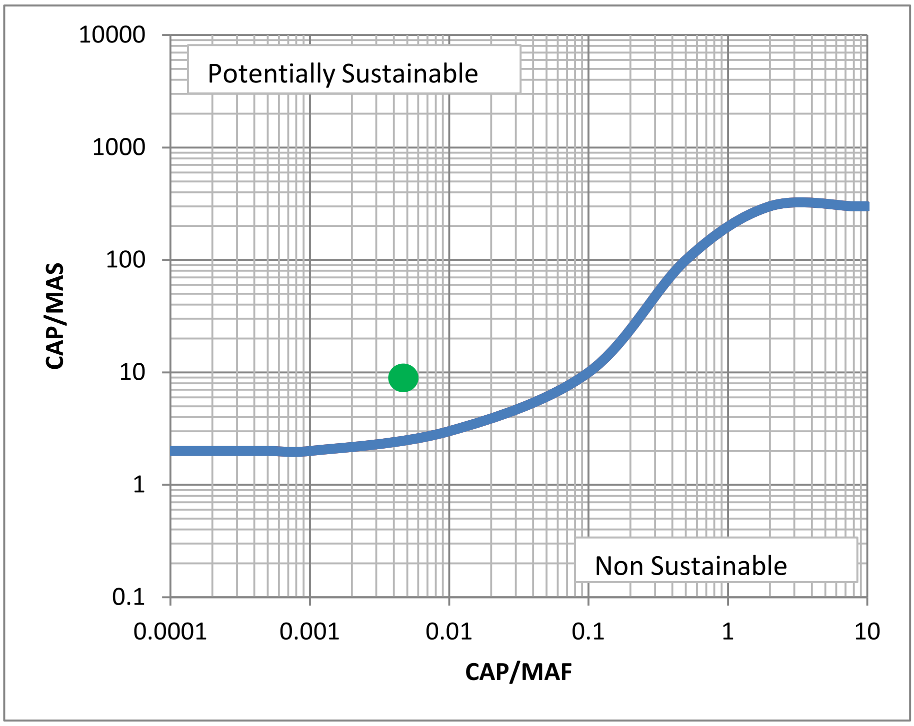
- ⇨ Hydrosuction

Main characteristics

Uses	Power generation
Dam Type	Run of river
Dam height (m)	16.5
Dam length (m)	122.5
Gross storage (m^3)	2 000 000
Catchment area (km^2)	1 080
Design discharge(m^3/s)	45

Key features

CAP (m^3)	6 920 000
MAF (m^3/y)	1 583 107 200
MAS (m^3/y)	750 000
CATCHMENT (km^2)	23.1
CAP/MAF (year)	0.0044
CAP/MAS (year)	9


10000
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Potentially Sustainable
Non Sustainable
CAP/MAS
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0.1
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CAP/MAF

3.4.7. Italy – Simbrivio: Management of Sediments in the Simbrivio River

3.4.7.1. Introduction

The Simbrivio Dam, a concrete gravity dam completed in 1942 (Figure 3.68), is located in the town of Vallepietra in the province of Rome and closes the course of the Simbrivio River, a tributary of the River Aniene (Rome).

Rehabilitation activities of the storage capacity, including restoring the ability to maneuver discharges, began in the summer of 2011 and were completed by the year 2012.

The dam is used for the daily adjustment of the Simbrivio River flow rates for the production of electricity at the hydroelectric Power Plant of Comunacqua.

Fig. 3.68
Location of the catchment area and geographical area

3.4.7.2. Owners

This dam is managed by ENEL (the national power company) with the sole purpose of hydroelectricity generation (the reservoir is not used for water supply).

3.4.7.3. Hydrology

The catchment area is about 33.7 km^2 and the annual rainfall is estimated at 845 mm (Filettino station). The extreme events are described below:

Table 3.13
Simbrivio Extreme Events

Return period	Discharge (m^3/s)
100	18.10
500	21.67
1 000	23.20

When floods occur, it is rare that an overflow of water beyond its normal confines would intersect with secondary paths and municipal roads.

3.4.7.4. Basic dam and reservoir data

The Simbrivio Dam is a gravity dam with a slightly curved axis and height of 10.20 m; the total volume of the reservoir is 60 x 10^3 m^3 and the active storage is 35 x 10^3 m^3. Other information about the dam is provided in Tables 3.14 and 3.15 below.

Table 3.14
Summary of characteristic data of the dam

Dam	Simbrivio
River	Simbrivio
Comune	Vallepietra
Provincia	Roma
Type of dam	Concrete Gravity
Storage capacity	60x10^3 m^3
Max Elevation	695.00 m s.l.m.
Max Regulation	694.00 m s.l.m.
Min Regulation	691.00 m s.l.m.
End of construction	1942
Testing	1987

Table 3.15
Structural characteristics of the dam

Simbrivio	
Dam type	Gravity
Function	Power generation
Dam height (m)	10.2
Dam length (m)	66.5
Gross storage capacity (m^3)	60 000
Catchment area (km^2)	33.7
Design discharge (m^3/s)	118
Crest elevation (m)	695
Storage area (ha)	5 500
Type of spillway	Automatic Tilting Gate

3.4.7.5. Description of the dam

Dam overflows are intercepted by an automatic gate with a fan and a counterweight that allows raising the maximum pool level to elevation 694 m while passing the flood waters.

The dam has a direct type foundation which is composed of an alluvial cover, which is about 4 m thick, after which it reaches a formation of dolomite.

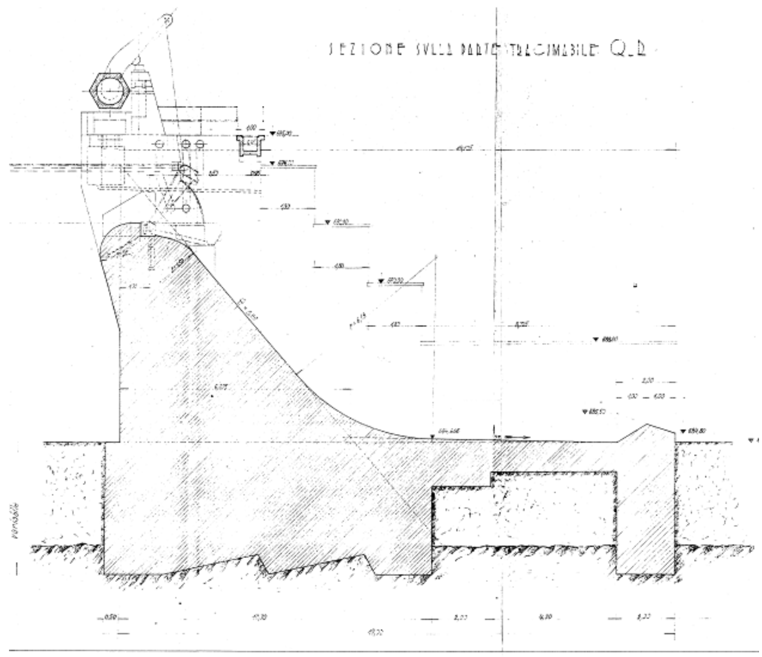

Fig. 3.69
Longitudinal section of the dam

Discharges from the dam are by one spillway and two bottom outlets consisting of two ducts with a rectangular section of 1.05 m x 2.00 m located on either side of the spillway and passing through the entire body of the dam.

Each duct is intercepted by a flat gate with a sill at an altitude of 684.5 m and is capable of a discharge flow rate of 58 m^3/sec (Figure 3.70).

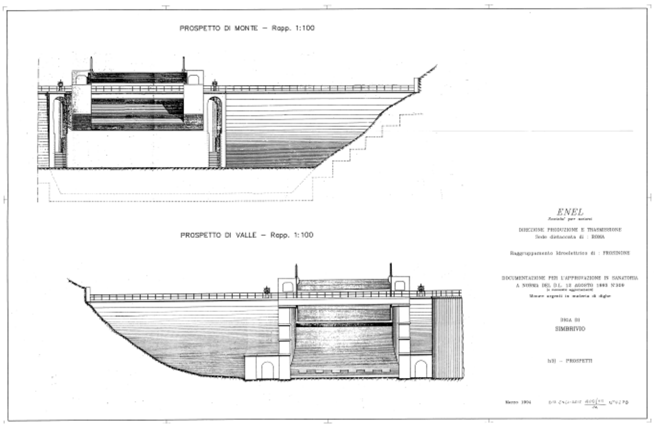

Fig. 3.70
Cross section of the dam

3.4.7.6. The Hydroelectric Power Plant

Schematically the hydroelectric power plant of Comunacqua is composed of the following structures:

- An intake structure situated in the left bank of the river and the dam, which consists of three inlets with two interposed pilings on which rests the building where the operations take place. The three inlets are protected by a single metal grid and are intercepted by three flat gates with electric and manual controls;
- a gravel trap is positioned downstream of the outlet to collect the sediment, which is then intercepted by a flat gate used for unloading operations and sent through a 20m-long tunnel that leads into the Simbrivio River;
- a gallery to derive water pressure, with a 6 km long polycentric section;
- a vertical surge tank built into the rock and covered with concrete, with a capacity of about 100 m^3;
- a penstock which consists of a first section with a diameter of 2 m and a length of 200 m, made of reinforced concrete, and a second section with a diameter of 1.5 m and a length of 27.8 m, made with bolted steel plates.

In Figure 3.71 and Figure 3.72 the vicinity map and profile schematic of the production plant are represented.

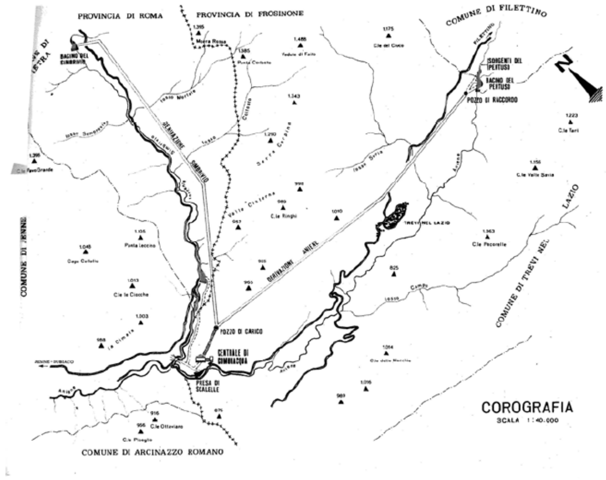

Fig. 3.71
Vicinity map

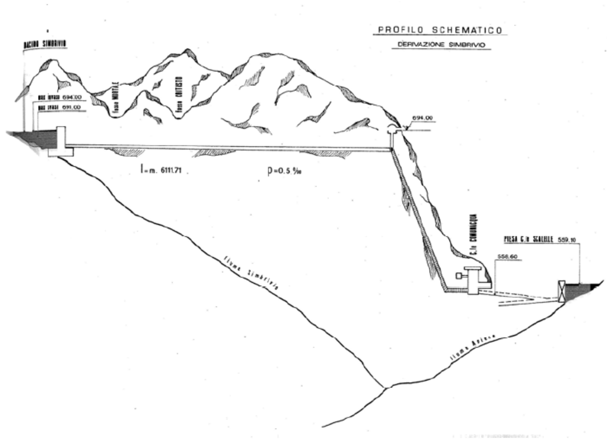

Fig. 3.72
Schematic profile system

3.4.7.7. Plot of capacity versus mean annual flow

The mean annual sediment flow is approximately 1 500 m³ and if nothing had been done, the reservoir would have filled in around 15 years (the last dredging was in 1990).

3.4.7.8. Political issues

The main purpose of this dam is to be a buffer and to allow for daily river flow adjustments. However, if the reservoir is full of sediment, this purpose cannot be fulfilled. Moreover, this type of issue impacts ecological quality and could generate extra costs for the dam/power plant manager. Therefore, it is important for ENEL and the local stakeholders to solve this issue.

3.4.7.9. Regulatory constraints

Before being able to remove sediment from the lake or restore the quarry it was necessary to obtain various permissions. It should be noted that the area of the basin falls within the Regional Natural

Park of Simbruini Mountains inside the Special Protection Area "Simbruini and Ernici Mountains" and is consequently subject to regulations that limit hydrogeological operations. Therefore, besides the authorization of the Project Management Document it was necessary to obtain 17 additional and separate clearances to be able to remove sediment from the lake.

In regards to the abandoned quarry restoration project, it was necessary to obtain a total of 15 additional permissions.

We will not enter into the merits of the complex authorization procedure which was necessary, but we want to emphasize that although there is a need to simplify the process of authorization, the positive end result was achieved thanks to the cooperation of the authorities.

The rehabilitation activities related to storage capacity and the restoration of discharge maneuverability began in the summer of 2011 and was completed by the year 2012. The activities were ongoing in the years 2011 and 2012 with periods of interruption due to the requirements from the authority of the Protected Natural Area and by the limited extension of the intervention areas and communication routes.

3.4.7.10. Sediment data of the site

The storage capacity at the beginning of 2011 was practically nil due to the sedimentary material which even obstructed the deep and surface gates.

Since its creation, the lake of Simbrivio has experienced significant silting. This has resulted in the need to operate the plant with particular attention and, despite following operating rules, it has also necessitated sediment removal in the basin as early as 1990 (Figure 3.73).

Fig. 3.73
Removing sediment in 1990

The silting of the reservoir up to the year 2007 was determined by comparing bathymetric data with the project data, which was compiled at the time of dam construction and was reported in the document: 'Conditions for operation and maintenance'.

From the comparison with the data thus calculated at the maximum level (694 m asl) there was a decrease of the total volume of approximately $58.6x10^3$ m^3 (-98%) and a reduction of the active storage of approximately $33.6x10^3$ m^3 (-96%) (Figure 3.74, Figure 3.75).

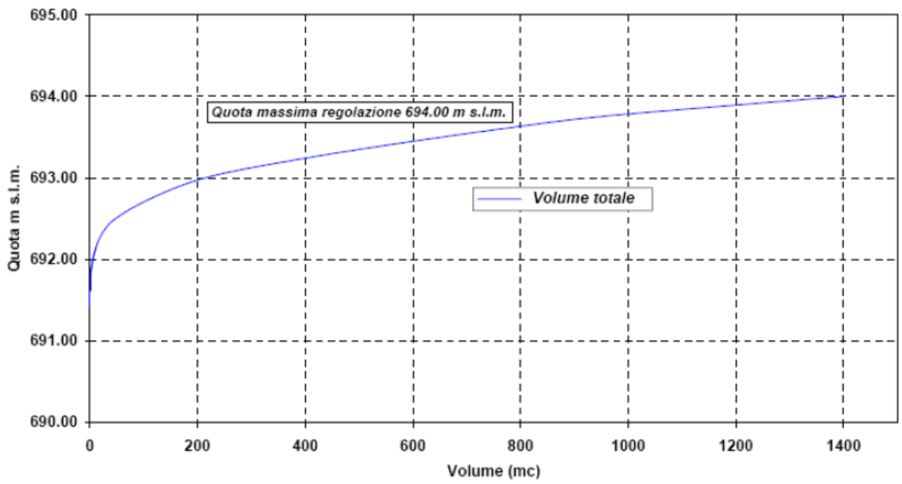

Fig. 3.74
Curve of the total volume and active volume in the basin

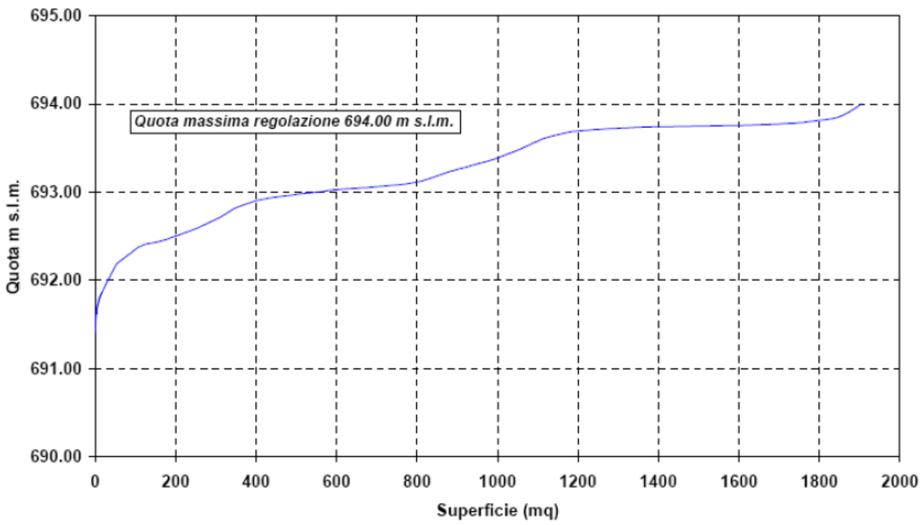

Fig. 3.75
Curve of the surface area of the reservoir as a function of level

This situation implies a current virtually nil storage capacity, and associated problems such as the inability to operate the bottom outlets and substantial limitations on the handling of the spillway flows; therefore, it was necessary to intervene by removing sediment from the lake to restore the functionality of the project.

3.4.7.11. Classification of sediment management

There are three sediment management options available:

- Reducing/increasing sediment deposition
- Preventing deposition
- Removing the sediment

The chosen solution was to apply the third option, consisting in removing sediment from the reservoir and then dumping it in a quarry.

3.4.7.12. Planned sediment management

The removal of sediments was performed in the empty reservoir, which was achieved through the use of a temporary barrier built upstream of the reservoir and a channel which allowed the water to bypass the dam. Construction vehicles carried the sediment to the former quarry where it was appropriately settled and shaped. Civil works and bridges over watercourses were required to improve the mountain roads used by the construction vehicles.

Sediment management project

In accordance with the current regulations, it was necessary to prepare the “Project of sediment management of the Simbrivio Basin” report before proceeding with any sediment removal from the lake (Art. 114 Law 152/2006 and s.m.i.).

Project management for the basin contains guidelines, which were taken into consideration, along with the expected operations of lake drawdowns and / or sediment removal, and all the characteristic data of the lake area available at the time the project was created.

In particular, the guidelines consist of a general framework with characteristic reservoir data, catchment data and hydrological data. There is also data from field surveys, including physical and chemical properties:

These include measurements of sediment volume, and characteristics of water and sediment quality, along with data for downstream sediment.

The guidelines also describe operational management procedures, both for routine maintenance and for removing sediment, including:

- drawdown of the lake for maintenance and / or inspection,
- operations to increase discharges,
- release of water,
- removal of sediment.

Of the management methods listed above, the first two are normally carried out for plant-related reasons (maintenance, inspection and testing of unit functionality and discharge operations) and do not generally involve removal of sediment from the basin. The latter two, however, are related to removing sediment and increasing reservoir capacity.

Finally, we characterized the receiving water body downstream of the lake and defined actions for the prevention, mitigation, and monitoring of the receiving water body.

The analyses of the material in the Simbrivio Basin showed that the sediments consist mainly of coarse-grained material; the sediment material is considered to be "non-hazardous"; and the sediment can be used as landfill or for aggregate production. It is possible to release the sediment downstream through bottom outlets or it can be used to cover commercial and / or industrial sites, environmental renovation works (with the approval of the plans) or in different cycles of industrial production.

The physio-chemical measurements and laboratory tests carried out on the waters of the Simbrivio Basin showed that the water quality corresponds approximately to a “good” ecological status.

Sediment removal project

Once the sediment of the lake had been characterized, we designed remediation measures and verified that in order to restore the functionality of the project it was necessary to remove approximately $30.0x10^3$ m^3 of sediment. The next step was to consider the possibility of sediment reuse.

At this point we started to work closely with the authorities in charge (Region, Province, City) to find an optimal solution for reusing the removed material. Common goals included: achieving a higher environmental value within the area of influence of Simbrivio Lake, satisfying the needs / requirements of the owner and completing the task at a reasonable cost. With this in mind we thought about the possibility of environmentally upgrading the abandoned quarries and giving them back to the community, with the hope that they could find a use for them.

The careful examination of the updated regional mapping of existing quarries has made it possible to find suitable solutions, based on quarry capacity and distance from the Simbrivio basin, i.e. the quarry placed in proximity of Trevi del Lazio (Frosinone), about 20 km away from the lake (Figure 3.76).

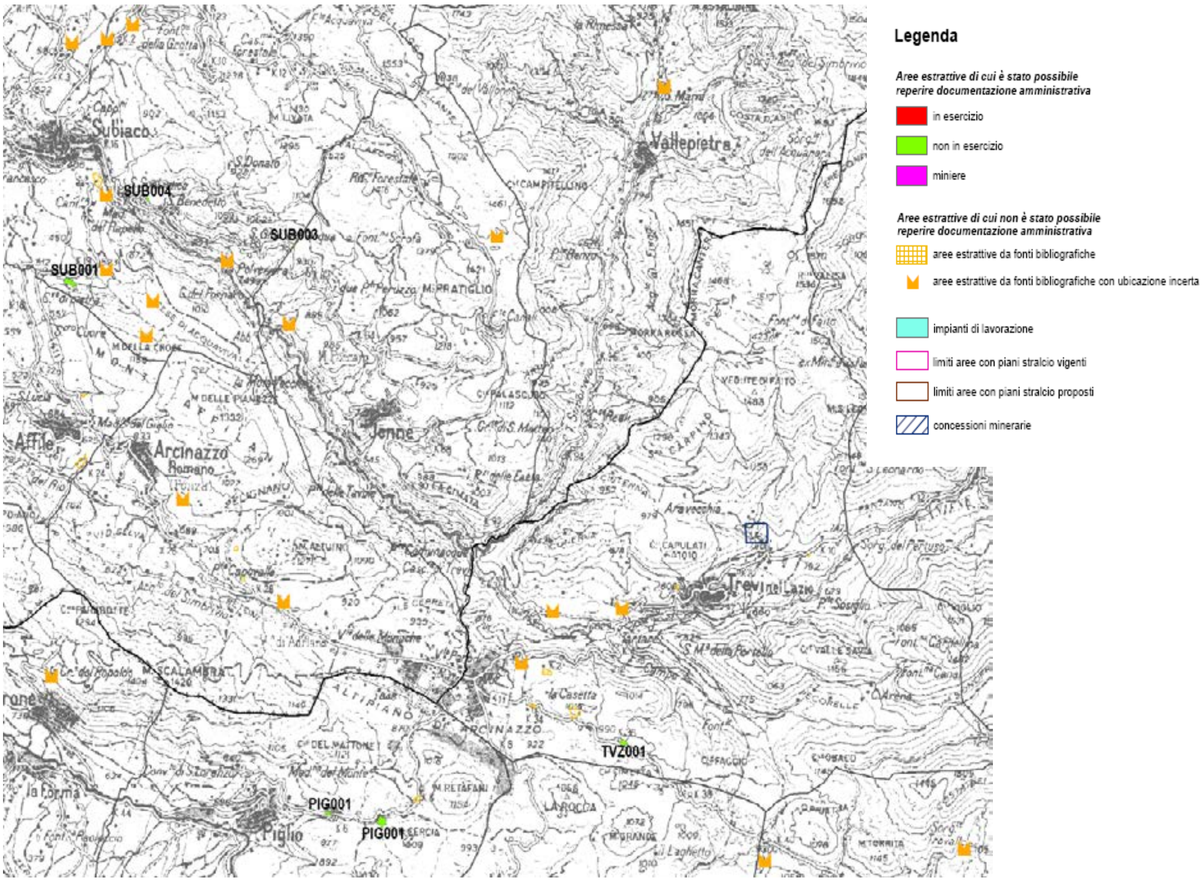

Fig. 3.76
Mapping of regional quarries

The intervention project as a whole was composed of two separate tasks: the first task consisted of the removal of sediment from the lake, prepared in accordance with the principles contained in the project management guidelines; the second task included the environmental rehabilitation of the abandoned quarry site.

Removal of sediment from the lake

The removal of sediment from the lake was executed by mechanical equipment.

The main phases of work consisted of conveying incoming water (to the basin towards the gravel trap and then to the Simbrivio River) through the implementation of a bypass. Thus, excavation was made to restore the volumes of accumulation in correspondence with hydraulic structures. The excavated material was transported with trucks from the basin area to the abandoned quarry site. To transport sediment along the mountain roads, it was required to build river crossings. The work vehicles carried the sediment to the quarry site where it was properly settled and shaped, taking care to consider drainage and consolidation, which was required due to the environmental vulnerability of the area.

Then they replaced the gates at the bottom outlets and proceeded with the full restoration of the sites affected by the project work, including temporary works (construction sites, temporary overpasses). (Figure 3.77, Figure 3.78).

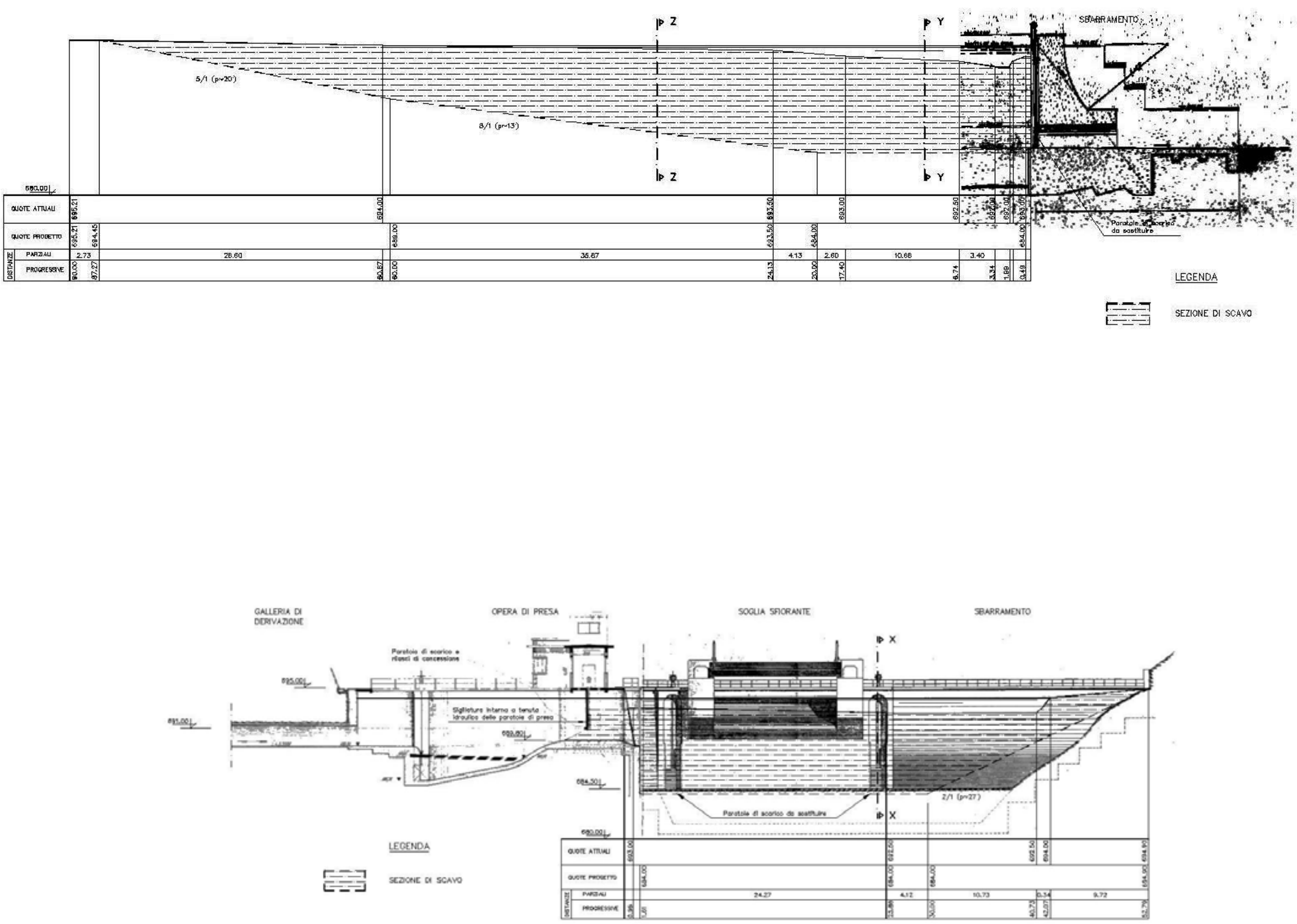

Fig. 3.77

Removal Project I: longitudinal and cross-section

Fig. 3.78
During the removal of sediment

Environmental restoration of the quarry

To use the extracted lake sediment for environmental restoration of the quarry it was necessary to repeat and extend the characterization of the sediment to ensure it was compliant with national and regional recommendations for this type of use.

The proposed restoration of the quarry was evaluated through site visits and specific surveys to better define the environmental characteristics of the restoration sites.

Schematically the project consisted of:

- Recharging and modelling of the area with the materials coming from the Simbrivio Reservoir;
- Covering the slopes with topsoil and plant species common in the area. (Figure 3.79, Figure 3.80, Figure 3.81).

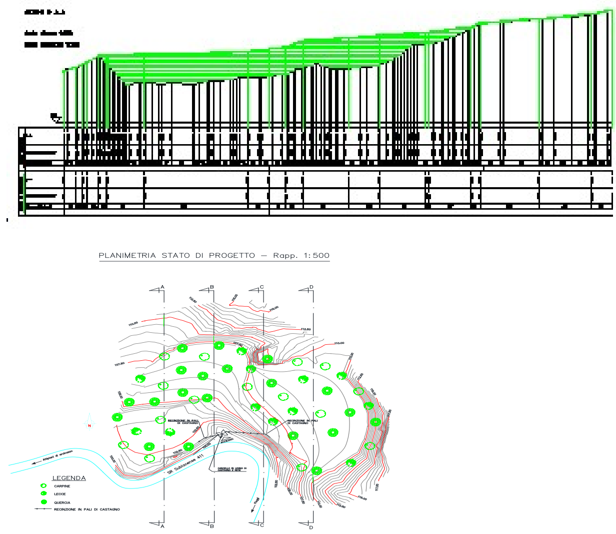

Fig. 3.79
Draft of quarry redevelopment: Plan and cross section

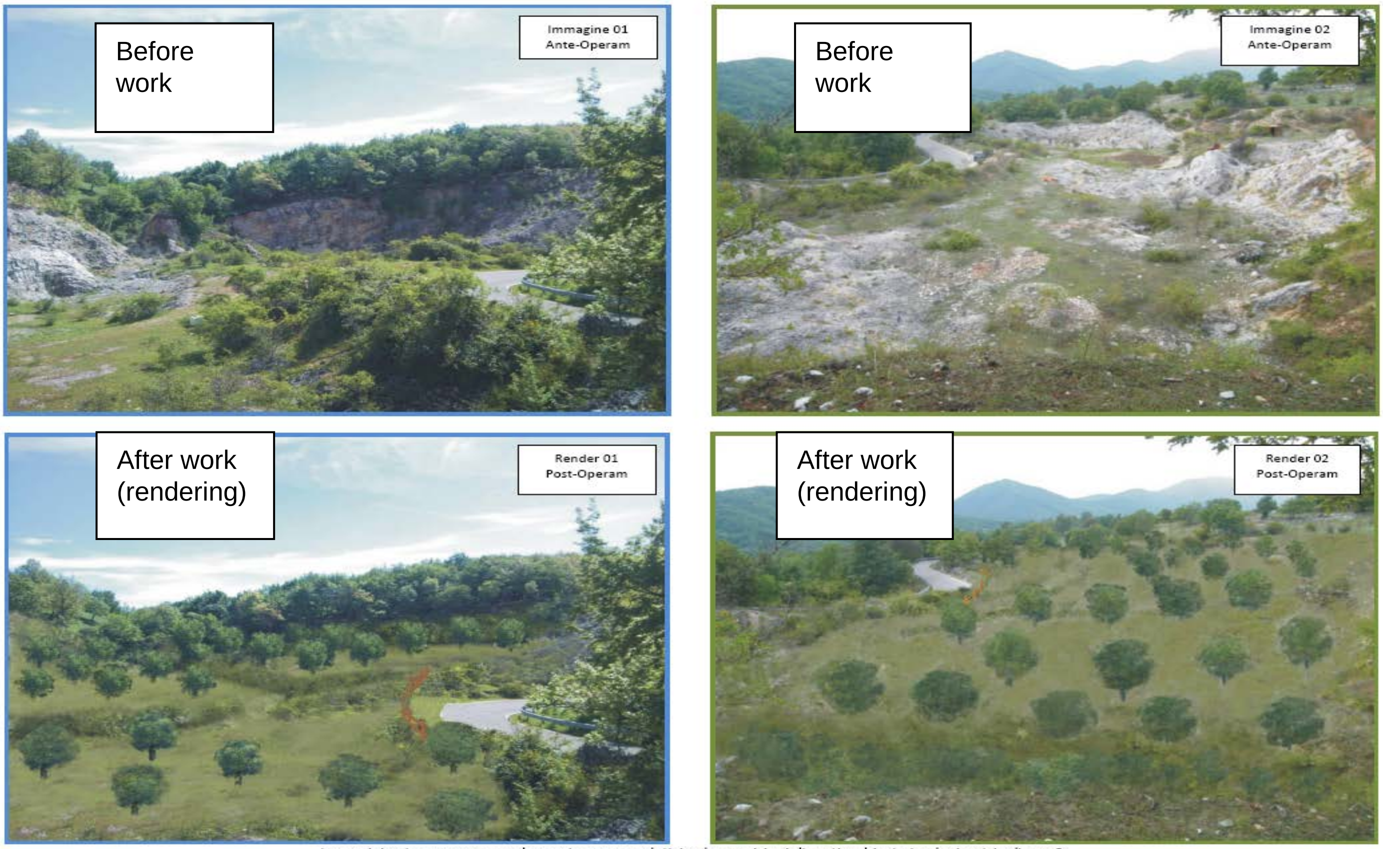

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Fig. 3.80
Above: Photo of the quarry before restoration; Below: rendering of the quarry after restoration

Fig. 3.81
Photo of the quarry area during restoration

Fig. 3.82
Photo of the quarry after the work

3.4.7.13. Conclusions

The restoration of reservoir storage capacity at Simbrivio Dam, the removal and reuse of sediment, the restoration of operational flexibility and the increased safety conditions of the dam have been made possible because of the synergy that has been established between ENEL and the responsible authority, grounded in their mutual interest to restore and manage natural environments and resources to be economically compatible and environmentally sustainable.

This experience has made clear some important issues that represent a starting point for general discussion regarding the removal of sediment from reservoirs. In particular, application of general legislation should not ignore the specificity of individual cases; it is necessary to simplify the process. In order to restore the reservoir to its original active capacity, the volume of sediment that must be removed may be quite large and may be difficult to remove. Therefore, with upcoming projects of similar scope, the legislation should consider maintaining the capacity of the reservoir, rather than restoring it to its original active capacity.

SIMBRIVIO

<u>Location:</u> Sibrivio River (Italy)

<u>Cost of sediment management:</u> 27.5 €/m³

<u>Management option:</u>

Reducing sediment inflow

Not applicable

Preventing deposition

Not applicable

Removing sediment

⇨ Dry excavation

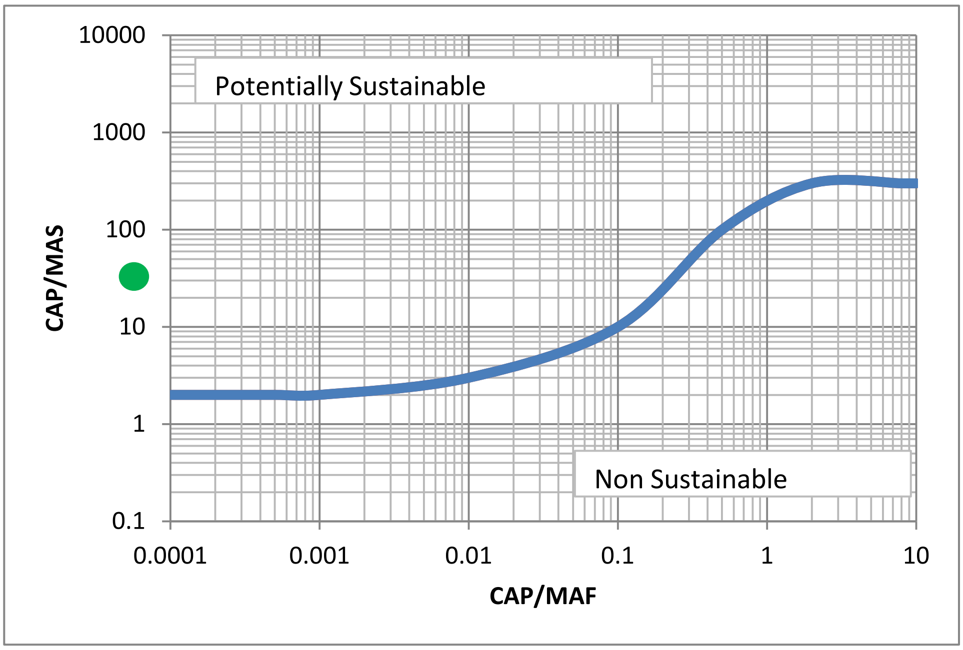
Main characteristics	
Dam type	Gravity
Function	Power generation
Dam height (m)	10.2
Dam length (m)	66.5
Gross storage (m^3)	60 000
Catchment area (km^2)	33.7
Design discharge(m^3/s)	118

Key features

CAP (m^3)	60 000
MAF (m^3/y)	$730x10^6$
MAS (m^3/y)	1 500
CATCHMENT (km^2)	33.7

[redacted]

CAP/MAF (year)	0.00008
CAP/MAS (year)	40



3.4.8. Japan – Asahi: Management of Sediments at the Asahi Dam

According to: Kataoka and Tada (2005), and Auel et al. (2016)

3.4.8.1. Introduction

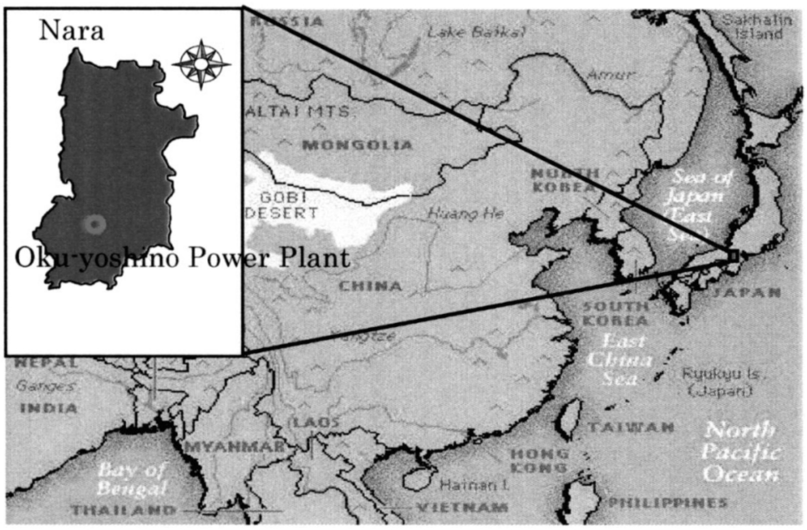


Fig. 3.83
Location of Asahi Dam

The 86 m high Asahi arch dam impounds the lower reservoir of the 1 206 MW Okuyoshino pumped-storage hydropower plant in Nara Prefecture (Fig. 3.83). Operation started in 1978 with an original reservoir volume of 15.5×10^6 m^3. The catchment area is 39.2 km^2 and mostly covered by forest with a maximum altitude of 1 800 m a.s.l. The upstream Asahi River reach is a mountainous gravel bed stream with steep slopes of 2% at the reservoir head up to 3.8% some 1 500 m further upstream. Severe typhoons in 1989 caused large landslides in the catchment leading to high sediment load transported into the reservoir. During subsequent typhoons in 1990 more sediment was entrained causing high turbidity inside and downstream the reservoir (Akiyama 2012). Reservoir sedimentation has continued since then, compromising the power intake and discharge function.

3.4.8.2. Owners

Kansai Electric Power Co. Inc. (KANSAI) constructed this dam between 1975 and 1980 to supply peak demand electricity. The plant supplies 1206 MW. This dam houses a pumped storage type scheme.

3.4.8.3. Hydrology

Asahi Dam is located at the outlet of a 39.2 km^2 catchment and is designed for a flood of 1 200 m^3/s. The annual rainfall is around 2 300 mm. Return period floods are provided in Table 3.16.

Table 3.16
Return period floods at Asahi Dam

Return period	Discharge
1 year	200 m^3/s
5 year	330 m^3/s

This catchment experiences heavy rainfall in the upstream basin which impacts the turbidity of the river. For example, in 1990 four heavy runoff events caused conspicuous prolonged turbidity over a period of 200 days.

Moreover, the area endured some typhoons, such as those in 1989 and 1990, which changed the sediment supply.

3.4.8.4. Basic dam and reservoir data

Table 3.17
Specifications of Asahi Dam

Catchment area	39.2km²	
Design flood	1,200m^3/s	
Power Plant	Name	Oku-yoshino
	Max. output	1,206MW
	Max. discharge	288m^3/s
	Effective head	505m
Dam	Type	Arch
	Height	86.1m
	Crest length	199.41m
Reservoir	Gross storage	* $15.47 \times 10^6 m^3$
	Effective storage	* $12.63 \times 10^6 m^3$
	Available depth	32m

*: when constructed

Table 3.18
Structural characteristics of the dam

Asahi dam	
Dam type	Arch
Function	Power generation
Dam height (m)	86.1
Dam length (m)	199.41
Gross Storage (m^3)	15 470 000
Catchment area (km^2)	39.2
Design discharge (m^3/s)	1 200
Crest elevation (m)	452

Storage area (ha)	56
Type of spillway	Three steel radial spillway gates, 11.5m wide by 8.2m high, one 2m diameter hollow jet discharge valve. Bypass channel: Hood-shaped reinforced concrete tunnel, 3.8m wide by 3.8m high, length of 2.35km

3.4.8.5. Sediment data of the site

Severe typhoons in 1989 caused large landslides in the catchment leading to high sediment load transported into the reservoir. During subsequent typhoons in 1990 more sediment was entrained causing high turbidity inside and downstream the reservoir.

Sediment grain size distributions from the riverbed downstream of the dam over three consecutive years are shown in Figure 3.84.

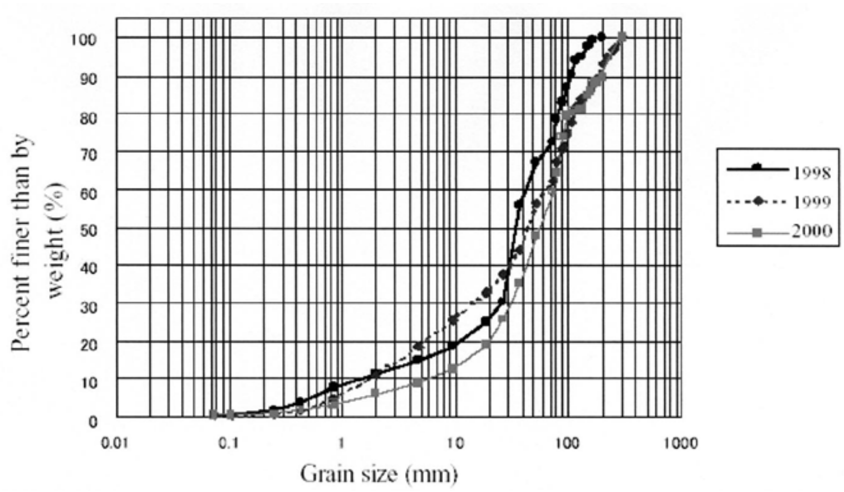


Fig. 3.84
Grain size distribution at the downstream riverbed

3.4.8.6. Plot of capacity versus mean annual flow

The mean sedimentation supply between 1978 and 1988 was about 20 000 m^3/year and between 1989 and 1995 was calculated at approximately 85 000 m^3/year. The differences are likely due to two typhoons which changed the sediment supply in the catchment. To improve the reservoir water quality, KANSAI repaired some collapsed hillsides within company-owned land and installed filtration systems to improve natural filtration into the river. However, reservoir sedimentation progressed compromising the power intake and discharge function. On account of the importance of maintaining sediment continuity, KANSAI needed to set up a new system. After several studies, in 1998 it was decided to implement a sediment bypass system.

The efficiency of the Asahi sediment bypass tunnel is revealed by analysing the annual reservoir sedimentation survey data together with the amount of bypassed sediments. The bypassed sediments were estimated by applying a 1D numerical model for the upstream river reach. Estimated sediment volumes were calibrated with both reservoir sedimentation data and bed elevation survey data downstream of the dam. Fig. 3.85 shows both the actual and accumulated sediment volumes over time from 1989 to 2013.

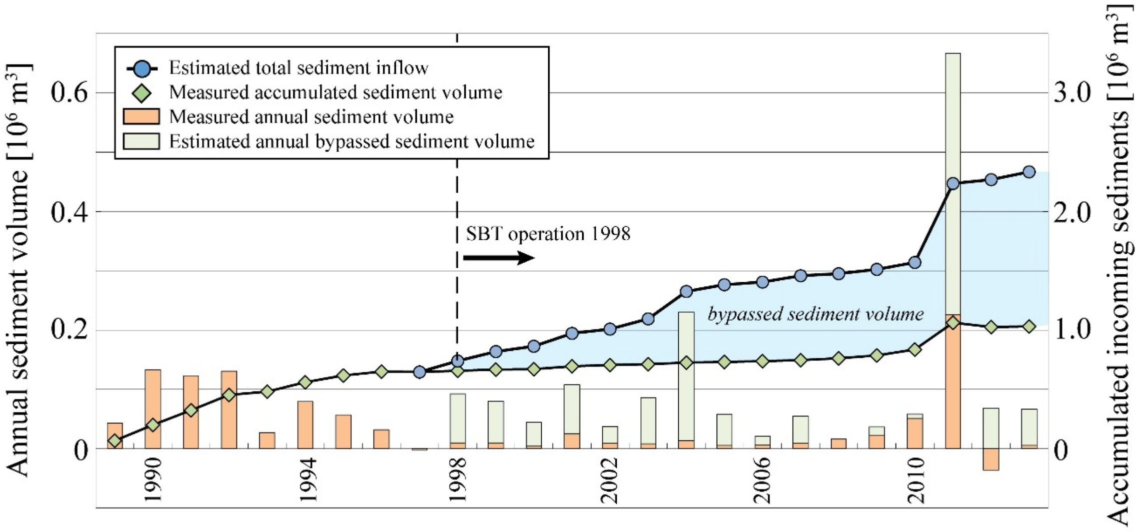


Fig. 3.85
Aggregated and bypassed sediment volume in Asahi Reservoir (Auel et al. 2016)

Since the bypass began operation in 1998, 77% of all incoming sediments have been diverted through the tunnel revealing its high efficiency. The remaining 23% of sediments were deposited in the reservoir during high flood events where the inflow discharge exceeded the tunnel design capacity. Even in 2011, when typhoon Talas hit Japan causing severe landslides in the catchment, still 66% of the sediments were bypassed. Besides the bypass efficiency, positive ecological effects downstream of the dam were observed shortly after commencement of operations. Substantially reduced turbidity, improved water quality, and restoration of bed morphology due to bypassed sediments was reported.

3.4.8.7. Political issues

All studies focused on sedimentation without considering potential impacts on the population and the environment.

3.4.8.8. Regulatory constraints

There is no fixed minimum flow at the dam outlet because Asahi Dam is a lower dam of a pumped storage power plant.

3.4.8.9. Modeled flushing scenario

In 1993, KANSAI made 1D and 2D numerical models in order to evaluate sedimentation evolution. The results showed that if nothing was done, the sediment level would rise to the intake level and would disturb power generation. Because of this fact, KANSAI studied countermeasures that would reduce the turbidity and the advancement of the sediment delta.

3.4.8.10. Applied sediment management

The chosen system was a sediment bypass tunnel (Figure 3.86). The tunnel is opened during flood events to divert the sediments below the dam. The total tunnel length of 2 383.5 m includes a 18.5 m long steel-lined inlet section, a 2 350 m long concrete-lined tunnel and a 15 m long concrete-lined outlet. The tunnel consists of an archway cross section of 3.80 m width and 3.80 m height with a slope of 2.9%. The design discharge is 140 m^3/s corresponding to a three year flood event. Higher floods are partially diverted into the reservoir by means of an overtopping weir. Since its inauguration, the tunnel has experienced severe abrasion up to several decimeters due to high flow velocities of about 12 m/s in combination with coarse bed-load transport. Annual maintenance works are conducted in order to repair the concrete invert.

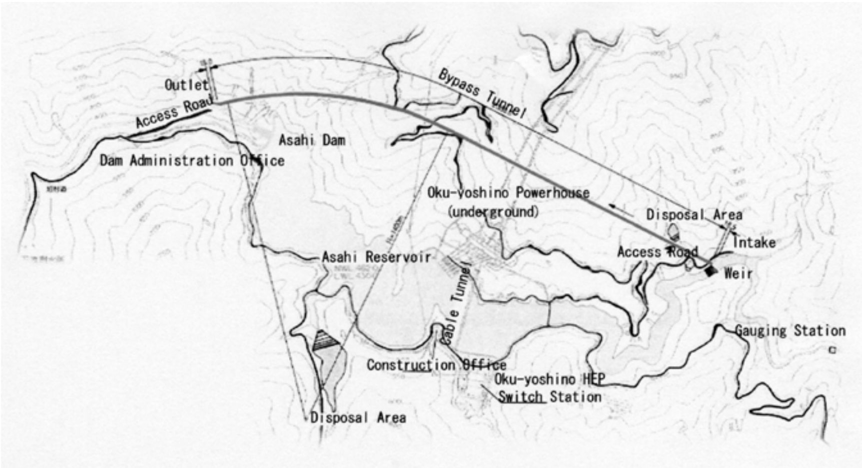


Fig. 3.86
General layout of the bypass system

ASAHI

Location: Japan

Cost of sediment management: Not available

Management option: Sediment Bypass Tunnel

Reducing sediment inflow

Not applicable

Preventing deposition

⇨ Tunnel

Removing sediment

Not applicable

Main characteristics

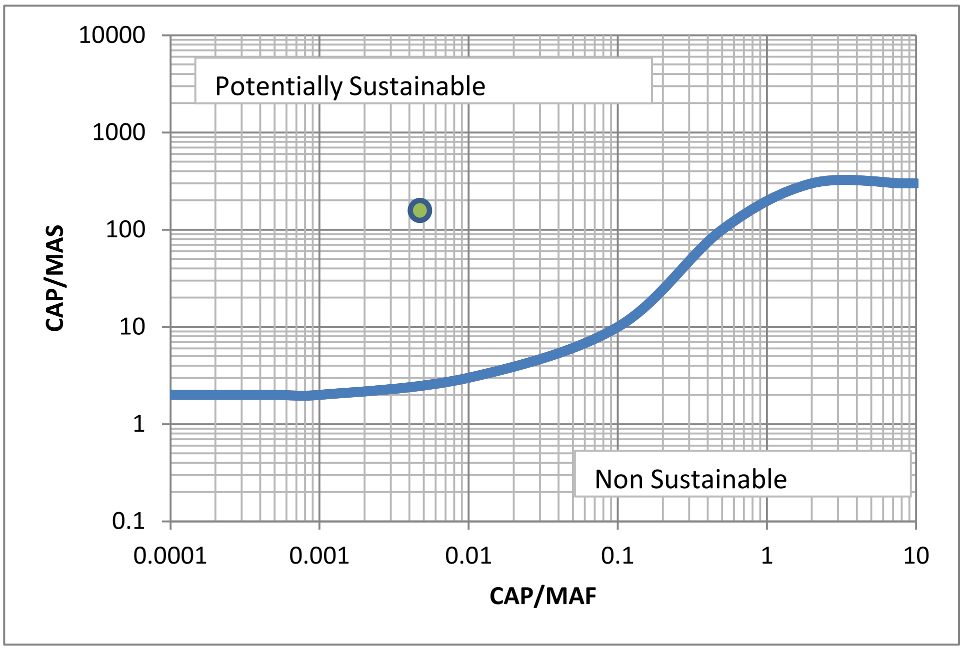
Dam type	Arch
Function	Power generation
Dam height (m)	81.6
Dam length (m)	199.41
Gross storage (m^3)	15 470 000
Catchment area (km^2)	39.2
Design discharge(m^3/s)	1200

Key features

CAP (m^3)	15 470 000
MAF (m^3/y)	813 000 000
MAS (m^3/y)	94 400
CATCHMENT (km^2)	39.2

[redacted]

CAP/MAF (year)	0.00473
CAP/MAS (year)	164



3.4.9. Japan – Dashidaira and Unazuki: Management of Sediments in the Dashidaira and Unazuki Dams

According to: Kanazawa (2005), Sumi & Kanazawa (2006), and Auel et al. (2016)

3.4.9.1. Introduction

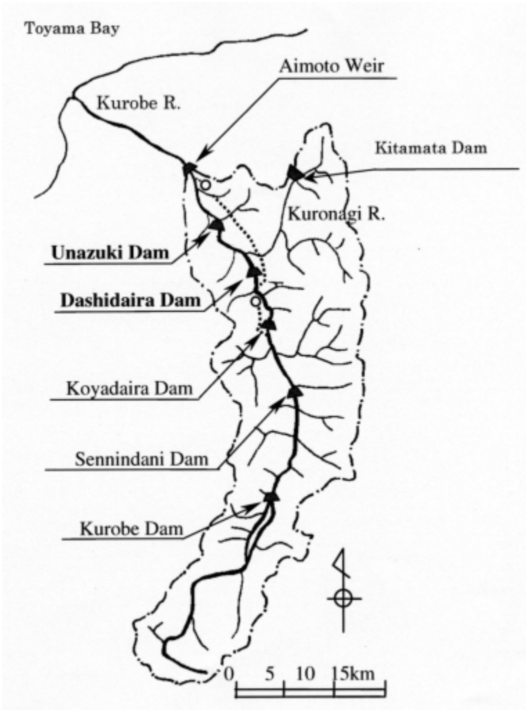


Fig. 3.87
Kurobe River Basin

The Kurobe River is a class A river, managed by the Japanese Ministry of Land, Infrastructure and Transport (MLIT), while class B rivers are managed by the prefecture. The river is located in Toyama Prefecture and is 85 km long (Figure 3.87). It is a torrential river carrying a large volume of sediment. Because of the torrential regime and the large annual rainfall, the owners decided to implement hydroelectric power stations.

Over several thousand years an alluvial fan was formed in the lower reach. This great quantity of sediment could be an issue and it needed to be addressed.

Although built for other purposes (see following sections below), in order to manage sediment coordinated flushing using the Unazuki Dam and Dashidaira Dam in a cascade is performed.

3.4.9.2. Owners

The Unazuki Dam was completed in 2001 and is managed by the MLIT. The dam was built with the purpose of flood control and is the last dam on the Kurobe River.

The Dashidaira Dam was implemented by the Kansai Electric Power Co (KEPCO) in 1985. It was built for power generation.

3.4.9.3. Hydrology

In the Kurobe catchment, the annual rainfall is estimated at 4 000 mm. This is more than double the national annual average rainfall. KEPCO decided to take advantage of the potential power generation of this abundant volume of water and the torrential flow.

For the extreme event, the 100-year return flow was estimated at 7 200 m^3/s. Floods can be severe in this catchment. In 1995, due to heavy rain, a landslide occurred. (6 hm^3 of sediment deposited in the middle course of the Kurobe River and around 3.4 hm^3 near the Dashidaira Dam). The damage to the power plant and the railway was significant (Figure 3.88).

Fig. 3.88
Damage inflicted to the Nekotama Station in July 1995

3.4.9.4. Basic dam and reservoir data

Table 3.19
Structural characteristics of the dams

	Unazuki dam	**Daishidaira dam**
Dam type	Gravity	Gravity
Function	Power generation	Power generation
Dam height (m)	97.0	76.7
Dam length (m)	190	136
Gross Storage (m^3)	24 700 000	9 010 000
Catchment area (km^2)	617.5	461.2
Design discharge (m^3/s)	7 600	6 200

Crest elevation (m)	262	346.7
Storage area (ha)	88	35
Type of spillway	2 Crest Shell Slide Gates 3 Condit Radial Gates 2 Condit Slide Gates 1 Jet Flow Gate	3 Flood Gates 2 Upstream Gates 2 Intermediate Gates 2 Downstream Gates

3.4.9.5. Plot of capacity versus mean annual flow

The mean annual sediment inflow is estimated to be 228 000 m³/yr for the Unazuki Dam and 250 000 m³/yr for the Dashidaira Dam. The gross storage capacity is 24.7 $\times 10^6$ m³ for the Unazuki Dam and 9.01 $\times 10^6$ m³ for the Dashidaira Dam.

Fig. 3.89 shows both the measured deposited and total sediment inflow in Dashidaira reservoir versus time since 1985 (Sumi & Kanazawa 2006). The flushed amount is the difference between these two curves. The flushed sediment is calculated comparing reservoir survey data before and after the event. Consequently the sediment amount which is entrained into the reservoir during the flushing operation is directly sluiced downstream and not considered in the data analysis. The total sediment inflow is therefore even higher.

The data reveal that sedimentation significantly decreased since 1991. Remarkable is the large flood event in 1995 leading to a sediment accumulation of 7.34×10^6 m³ in the reservoir corresponding to almost 82% of the gross storage. One successful flushing operation in November 1995 reduced the volume again to 5.61×10^6 (62% of the total volume). Without flushing, the reservoir would have been filled in 1999. From 1991 to 2014, the aggregated volume increased only by 9% to 4.29×10^6 m³. In total 88% of all incoming sediments were flushed.

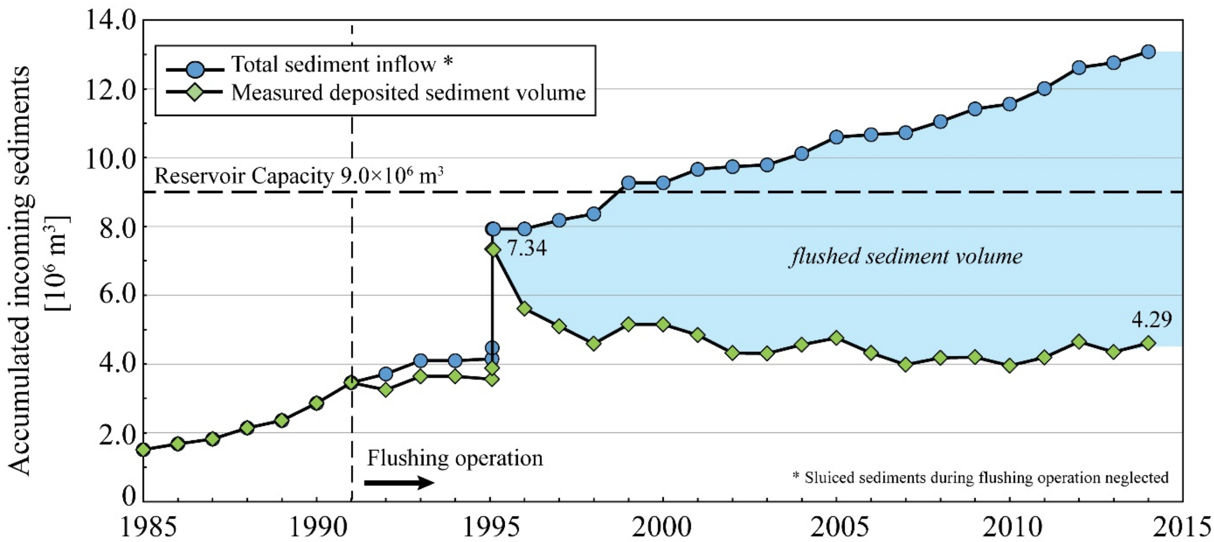


Fig. 3.89
Aggregated volume and total sediment inflow in Dashidaira reservoir versus time (Auel et al. 2016)

3.4.9.6. Regulatory constraints

For the preservation of the riparian ecosystem there is a required minimal discharge of 1.76 m³/s.

3.4.9.7. Sediment data of the site

The Kurobe River carries a large quantity of sediment and if the sediment supply mechanism were to become obstructed, various problems could occur. On the downstream river section, the channel becomes unstable and there is degradation of the riverbed.

The coast in this area has receded about 200 m over the last 100 years. Therefore, a continuous sediment supply from the river needs to be maintained. If there is no human intervention, earthflow disasters, such as the one that occurred in 1995, may continue to occur.

Each year, around 1.4 hm^3 of sediment is supplied by the catchment.

3.4.9.8. Classification of sediment management

In this catchment, there are several ways to manage the sediment issue:

- Silt sabo dam in the upstream part to reduce the sediment supply
- Sediment routing with sluicing and flushing operations
- Facilities on the coast in order to prevent beach drifting
- Sand bypass for beach nourishment

In this basin, all the management options are based on reducing sediment inflow, preventing deposition and removing the sediments.

3.4.9.9. Planned sediment management

In this catchment, in order to maintain sediment continuity the different stakeholders foster synergies to reduce the impact of the dams. They coordinate flushing in order to release the sediments as naturally as possible at the end of each flood (Figure 3.90).

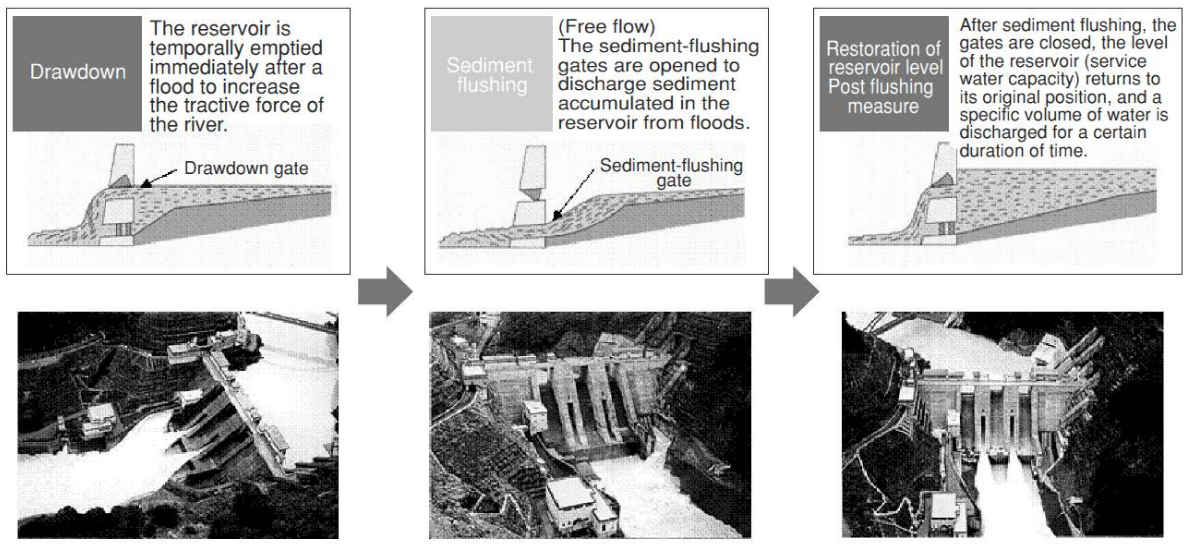


Fig. 3.90

Sediment flushing procedure in "comprehensive sediment management in the Kurobe River"

For this purpose, they set up the following procedure for the release of sediment:

1. Flush sediment between June and August in order to maintain the riverbed as low as possible in case of a flood or overflow

2. Open the drawdown gate for lowering the water level at the final stage of a flood
3. Open the sediment flushing gate in order to restore the natural pre-impoundment condition
4. Take post-flushing measures to wash down sediment in the downstream channel with a limited discharge for refilling the reservoir

UNAZUKI DAM

Location: Kurobe River (Japan)

Cost of sediment management: Cannot be easily separated from the total project cost.

Management option: Drawdown Flushing

Reducing sediment inflow

- ⇨ Silt Sabo

Preventing deposition

- ⇨ Flushing
- ⇨ Sluicing
- ⇨ Sand bypass

Removing sediment

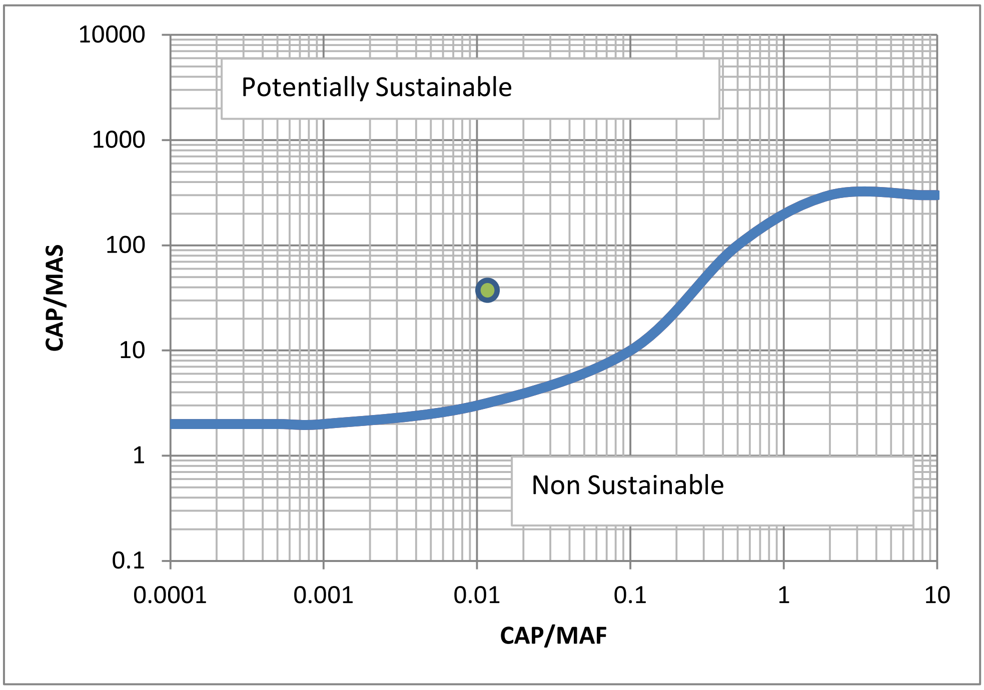
- ⇨ Drawdown flushing

Main characteristics

Dam type	Gravity
Function	Power generation
Dam height (m)	97.0
Dam length (m)	190
Gross storage (m^3)	24 700 000
Catchment area (km^2)	617.5
Design discharge(m^3/s)	7 600

Key features

CAP (m^3)	14 500 000
MAF (m^3/y)	1 212 610 000
MAS (m^3/y)	362 500
CATCHMENT (km^2)	617.5
CAP/MAF (year)	0.012
CAP/MAS (year)	40



DASHIDAIRA

Location: Kurobe River (Japan)

Cost of sediment management: Not available

Management option: Drawdown flushing

Reducing sediment inflow

- ⇨ Silt Sabo

Preventing deposition

- ⇨ Flushing
- ⇨ Sluicing
- ⇨ Sand bypass

Removing sediment

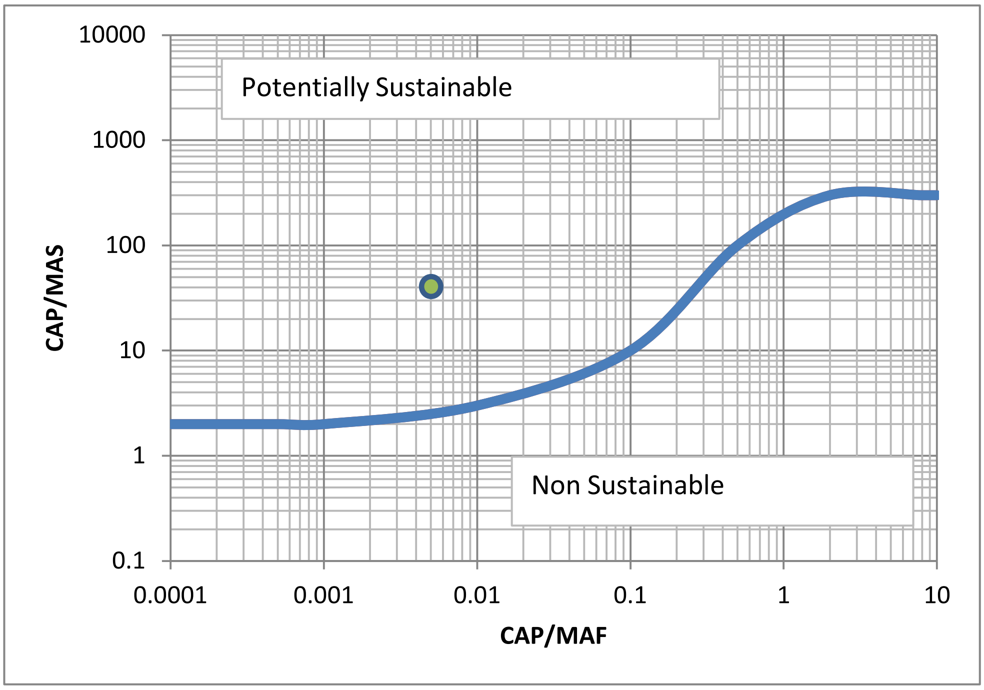
- ⇨ Drawdown flushing

Main characteristics

Dam type	Gravity
Function	Power generation
Dam height (m)	76.7
Dam length (m)	136
Gross storage (m^3)	9 010 000
Catchment area (km^2)	461.2
Design discharge(m^3/s)	6 200

Key features

CAP (m^3)	9 010 000
MAF (m^3/y)	1 839 000 000
MAS (m^3/y)	250 000
CATCHMENT (km^2)	461.2
CAP/MAR (year)	0.0049
CAP/MAS (year)	36



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CAP/MAS
Potentially Sustainable
Non Sustainable
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CAP/MAF

3.4.10. Japan – Mimikawa: Management of Sediments in the Mimikawa Reservoir

According to: T. Sumi, T. Yoshimura, K. Asazaki, M. Kaku, J. Kashiwai, T. Sato; ICOLD; 2015

3.4.10.1. Introduction

The Mimikawa River is a class B river, managed by the prefectural governor, as opposed to a class A river managed by the Japanese Ministry of Land, Infrastructure and Transport (MLIT). The river is located on Kyushu Island (Figure 3.91). Between 1920 and 1960, the Kyushu Electric Power Company (KEPCO) set up seven dams and hydro power stations. After Typhoon 0514 (September 2005) they became aware of the necessity to manage sediment. The typhoon had a return period of 50 years.

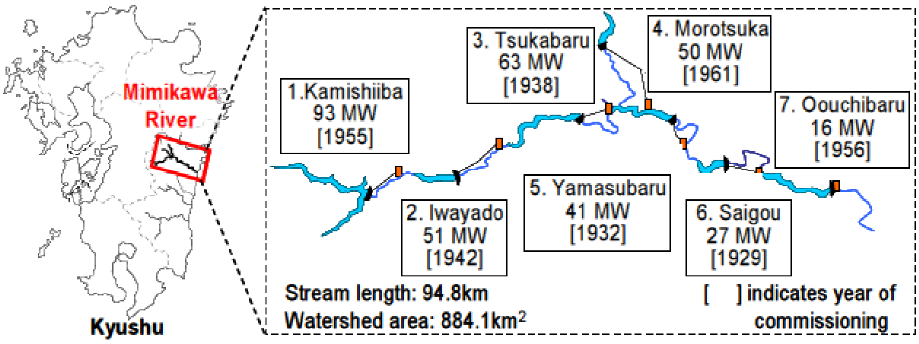


Fig. 3.91
Mimikawa River basin in "Approaches for integrated sediment flow management at dams in the Mimikawa River Basin"

Table 3.20
Mimikawa Key features

Mimikawa River and hydro power station	
Catchment	884.1 Km²
Length	94.8 km
Generating power	340 MW
Output	900 million kWh

3.4.10.2. Owners

KEPCO is the owner of the hydro power station on the Mimikawa River. The KEPCO dams had been impacted by several typhoons and Typhoon 0514 supplied a huge quantity of sediment which flowed into the river and reservoirs in the Mimikawa River basin. KEPCO is a stakeholder for sediment management at the dam and contributed to the "Mimikawa River basin integrated sediment flow management plan".

3.4.10.3. Hydrology

The average annual rainfall is estimated as 2 900 mm. Return period flows are shown in Table 3.21 while design floods and estimated flows at different projects on the river for historical typhoons are shown in Figure 3.92.

Table 3.21
Typhoon Characteristics

Typhoon/return period	Rain/discharge
100-year return period in Yamasubaru and Saigou dam	More than 5 000 m^3/s
50-year return period in Yamasubaru and Saugou dam	More than 3 000 m^3/s
Typhoon 0514	1 300 mm

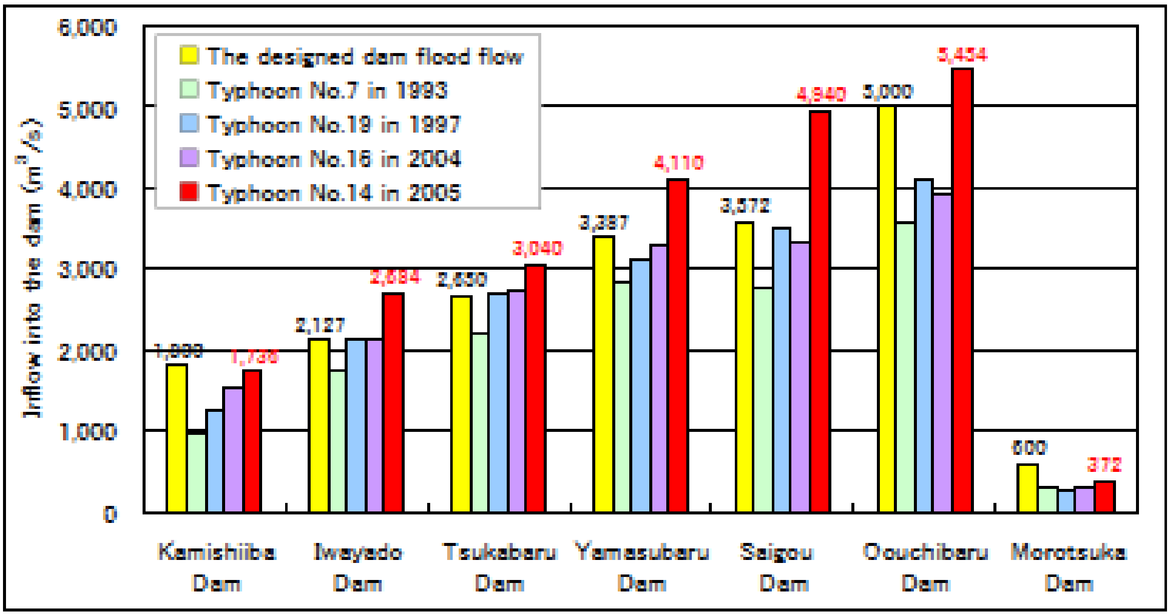


Fig. 3.92
Inflow during typhoons

3.4.10.4. Basic dam and reservoir data

Table 3.22
Key characteristics of dams in the Mimikawa River Basin

Reservoir sedimentation of dams in the Mimikawa River Basin

Dam Name	Total Storage Volume CAP (10^3m^3)	Annual Runoff Volume MAR (10^6m^3)	Total Sedimentation Volume (10^3m^3)	Year of Operation	Annual Sedimentation Volume MAS (10^3m^3)	CAP/MAR	CAP/MAS
Kamishiiba	91600	672	12600	58	217.8	0.136	420
Iwayado	8310	876	5560	72	77.2	0.00948	108
Tsukabaru	34300	1071	6890	75	91.8	0.032	374
Morotsuka	3480	151	1060	52	20.3	0.0231	172
Yamasubaru	4190	1410	2590	81	32	0.00297	131
Saigo	2450	1610	1010	84	12	0.00152	204
Ouchibaru	7490	1830	1930	57	33.8	0.00409	222

Table 3.23
Structural characteristics of the dams

	Kamishiiba	**Iwayado**	**Tsukubaru**	**Morotsuka**	**Yamasubaru**	**Saigo**	**Ouchibaru**
Dam type	Arch	Gravity	Gravity	Hollow	Gravity	Gravity	Gravity
Function	Power generation	Power generation	Power generation	Power generation	Power generation	Power generation	Power generation
Dam height (m)	110.0	57.5	87.0	59.0	29.4	20.0	25.5
Dam length (m)	341.0	171.0	215.0	149.5	91.1	84.5	152.6
Gross Storage (m^3)	91 550 000	8 309 000	34 326 000	3 484 000	1 642 000	1 508 000	7 488 000
Catchment area (km^2)	Dam cascade 1/7 223.6	Dam cascade 2/7 355.7	Dam cascade 3/7 430.7	Dam cascade 4/7 109.1	Dam cascade 5/7 598.6	Dam cascade 6/7 647.8	Dam cascade 7/7 884.1
Design discharge (m^3/s)	1800	2127	2650	600	3387	3572	5000
High Water elevation (m)	480	326.4	235.5	360	123.33	80	50
Storage area (ha)	266	39	122	18	41	40	88
Type of spillway	4 Radial Gates 9.0m W x 8.0m H	8 Radial Gates	8 Radial Gates 7.0m W x 5.9m H	1 Radial Gate	7 Radial Gates	6 Roller Gates	6 Roller Gates

3.4.10.5. Plot of capacity versus mean annual flow

The mean annual sediment inflow and siltation rates in the most downstream three dams are: Yamasubaru Dam: 10.5, 2.6 m^3/yr; Saigo Dam: 11.2, 1.2 m^3/yr; Ouchibaru Dam: 15.8, 3.2m^3/yr

3.4.10.6. Political issues

In order to foster the communication between all the stakeholders, the Miyazaki Prefecture decided to establish the Mimikawa River Basin Integrated Sediment Flow Management Technical Committee (Committee).

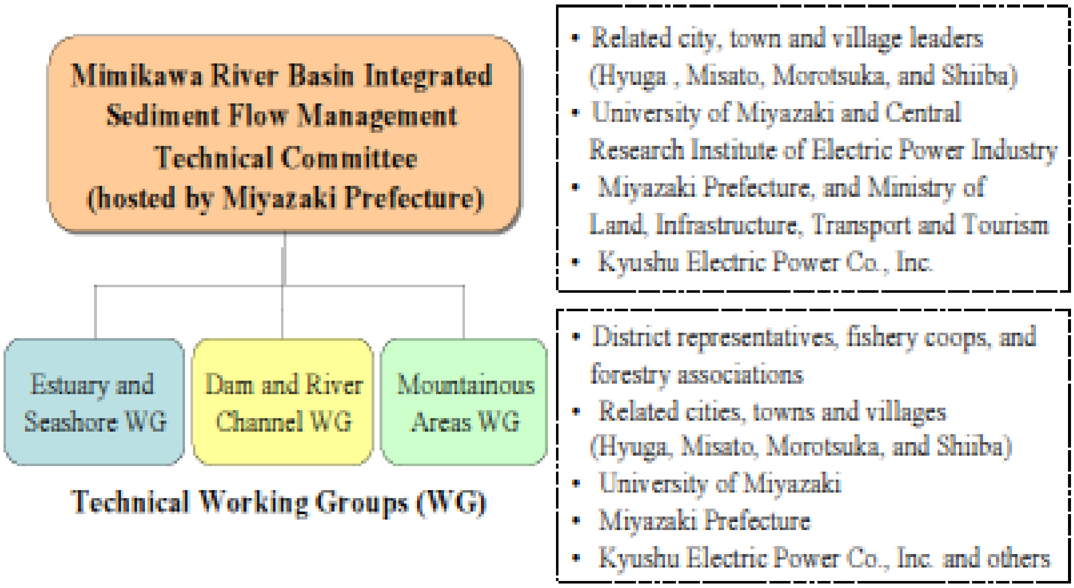


Fig. 3.93
Framework for the technical committee

The structure of the committee is shown in Figure 3.93; the committee is divided into three technical working groups.

3.4.10.7. Regulatory constraints

Due to environmental policy, all the dams have to release more than around 0.18 m^3/s to maintain good conditions in the downstream river.

3.4.10.8. Sediment data of the site

Successive typhoons are the major impact on sediment supply from the catchment. For example, with the 0514 typhoon, 10 hm^3 of sediment flowed into the river and half of this amount was deposited in the reservoir. More than 26.4 hm^3 flowed into the river (Figure 3.92).

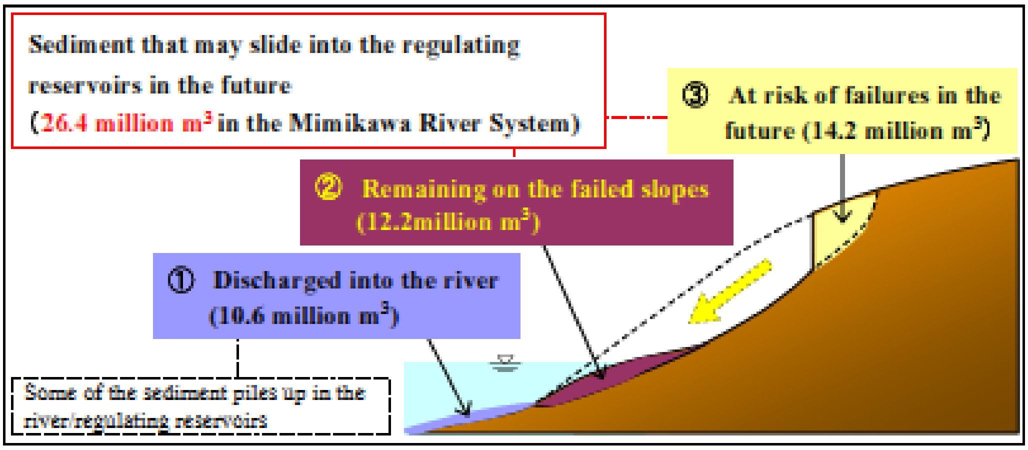


Fig. 3.94
Quantity sediment due to mountain slope failures

3.4.10.9. Modeled flushing scenario

In order to forecast the effects of sediment sluicing under the conditions shown in Table 3.24, a one-dimensional analysis of riverbed fluctuations over the approximate 58 km between Yamasubaru Dam upstream and the river estuary was conducted. The simulation results confirmed that if nothing is done, the sediment level is going to increase (Figure 3.95); therefore, sluicing operations were considered.

Table 3.24
Investigation conditions*

Investigation conditions			Yamasubaru Dam upstream	Saigou Dam upstream	Oouchibaru Dam upstream	Oouchibaru Dam downstream river
Initial riverbed conditions			Riverbed survey after Typhoon 0514			
River flow rate conditions			Actual flow rates at each dam 1994-2004			
Post-calculation conditions			Calculation until dam-regulating reservoir riverbed stabilization confirmed			
Sediment inflow conditions	First 10 years ($m^3/km^2/year$)		1,092	1,056	791	791
	From year 11 ($m^3/km^2/year$)		606	742	521	521
Water level conditions	Case1	Existing operation case	Reflects dam operation results			
	Case2	Sluicing of sediment case	Using actual flow rates, while flow rate at each dam exceeds $200m^3/s$, calculate water level during sluicing of sediment (all gates free flow)			

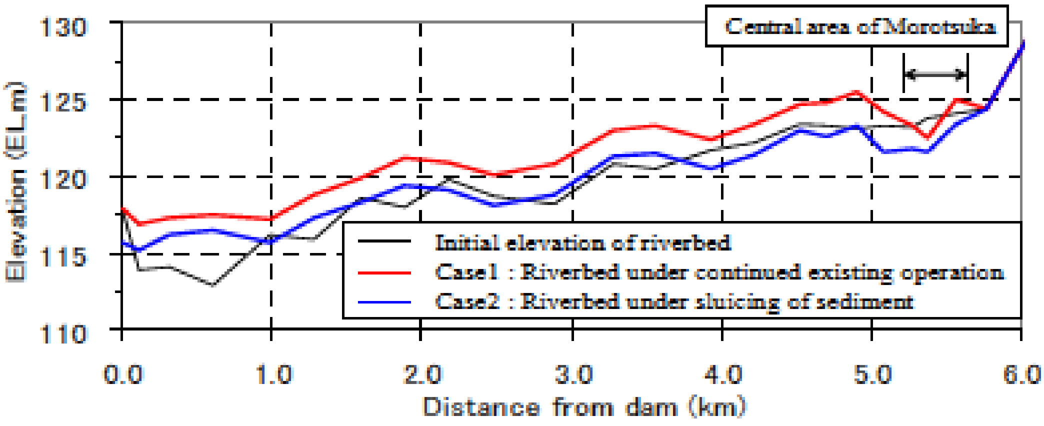


Fig. 3.95
Result of riverbed fluctuation analysis

Some changes in the riverbed were too complex to be modelled with numerical modeling, so a physical model was implemented to simulate changes in sediment levels (Figure 3.96).

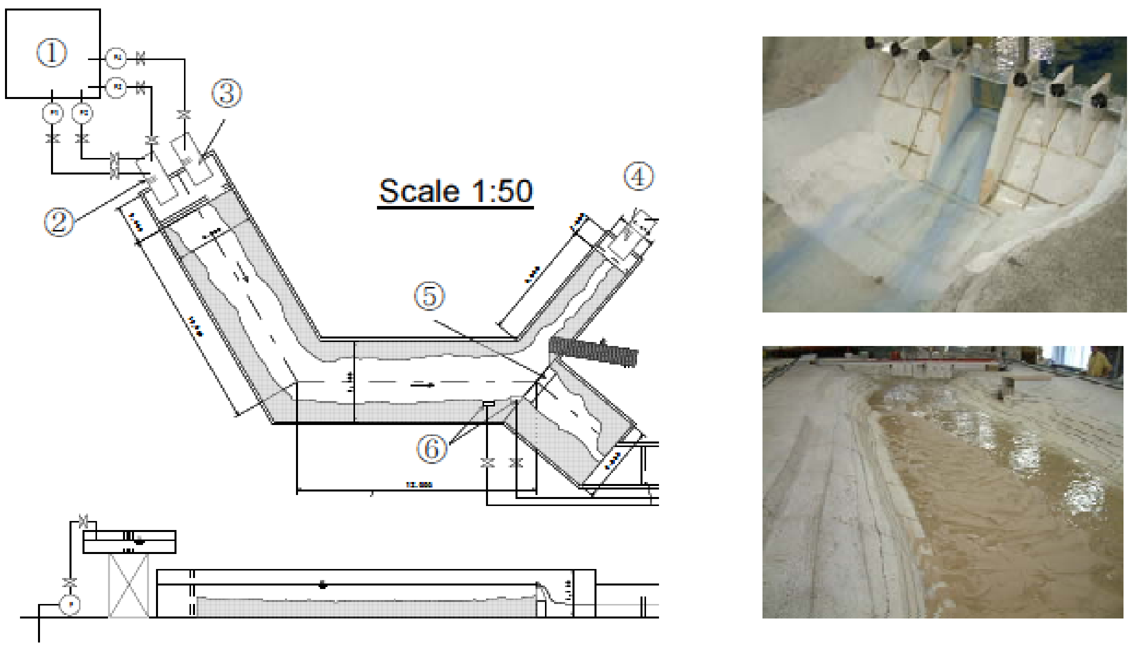


Fig. 3.96
Plan and cross-sectional view of hydraulic model and photographs of experiment in progress (Yamasubaru Dam)

3.4.10.10. Classification of sediment management

In order to restore sediment continuity, KEPCO implemented the sluicing sediment management method for the prevention of sediment deposition. This type of sediment management method avoids setting up a dredging system and having to manage the sediments during a flood due to a typhoon.

Before the dams could be retrofitted for sluicing, some advance dredging was required as confirmed by the physical model.

3.4.10.11. Planned sediment management

The integrated sediment flow management plan for the Mimikawa River Basin incorporated lowering spillway crests or removing spillways on four dams (Figure 3.97). This plan restored the sediment continuity between the dams.

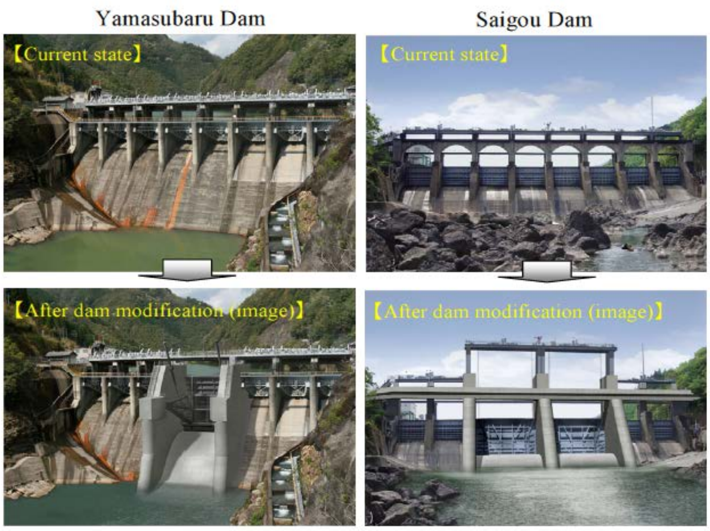


Fig. 3.97
Modifications on two dams

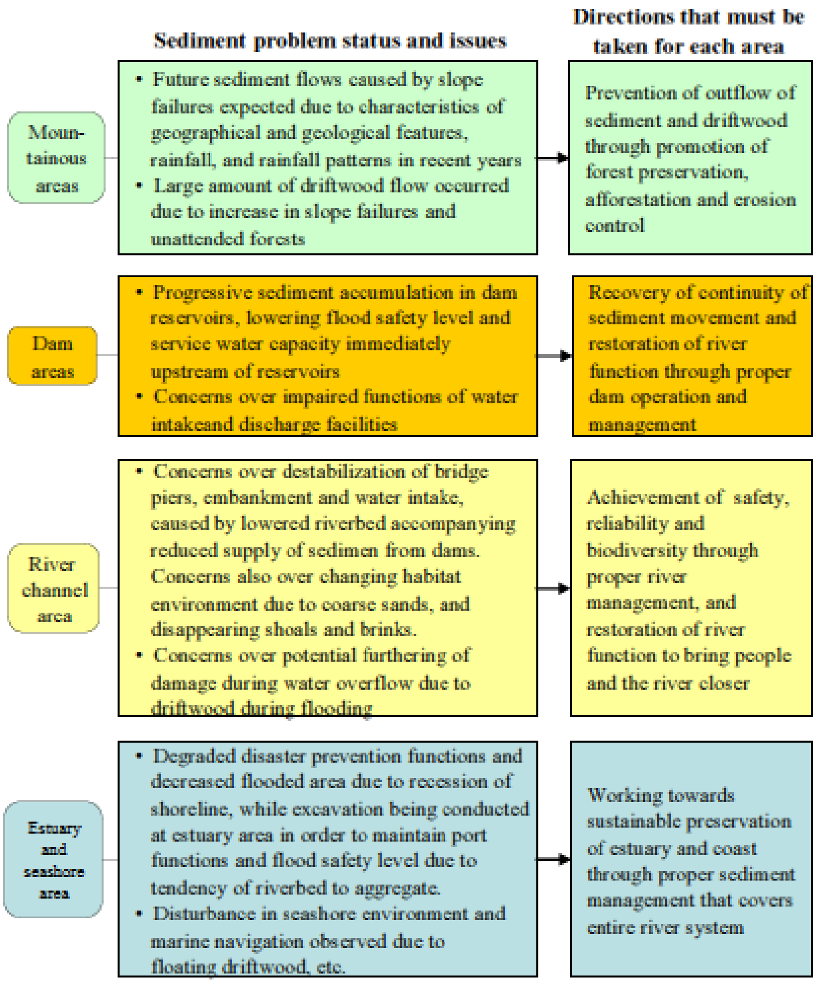


Fig. 3.98
Direction that must be taken for each area

Along with the dam retrofitting work, KEPCO implemented dredging operations to relocate the existing accumulated sediment.

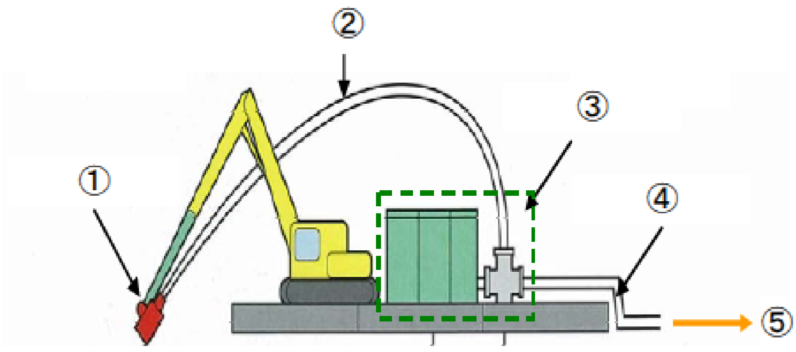


Fig.16
Schema of special ejector pump system
Schéma du système de pompe avec éjecteur spécial

①Sediment intake (Crusher)
②Sediment suction pipe
③Ejector pump
④Sediment conveying pipe
⑤Discharge outlet

① Alimentation de sédiments(Concasseur)
② Tuyau de succion de sédiments
③ Pompe d'éjecteur
④ Tuyau de transport de sédiments
⑤ Décharge de sédiments

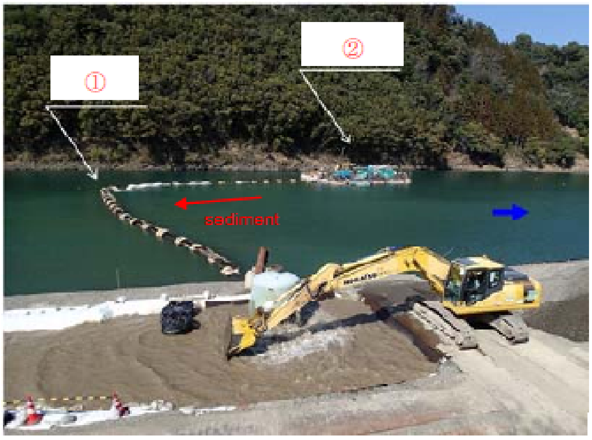


Fig.17
Work being carried out at Saigou Dam in 2013
Travaux en cours au barrage de Saigou en 2013

①Sediment conveying pipe
②Special ejector pump

② Tuyau de transport de sédiment
② Pompe avec éjecteur spécial

Fig. 3.99
Dredging operation

KAMISHIIBA

Location: Japan, on the Mimikawa River

Cost of sediment management: Not available

Management option: None presently

Reducing sediment inflow

Not applicable

Preventing deposition

⇨ Flushing

Removing sediment

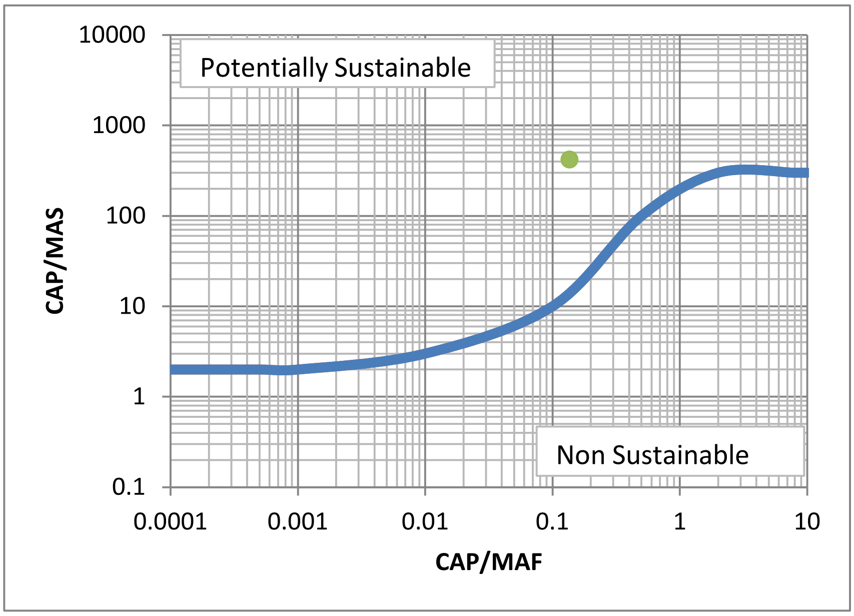
⇨ Hydro suction

Main characteristics

Dam type	Arch
Function	Power generation
Dam height (m)	110
Dam length (m)	341
Gross storage (m^3)	91 600 000
Catchment area (km^2)	223.6
Design discharge(m^3/s)	1 800

Key features

CAP (m^3)	91 600 000
MAF (m^3/y)	672 000 000
MAS (m^3/y)	217 800
CATCHMENT (km^2)	223.6 dam cascade 1/7
CAP/MAF (year)	0.136
CAP/MAS (year)	420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Non Sustainable
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IWAYADO

Location: Japan, on the Mimikawa River

Cost of sediment management: Not available

Management option: None presently

Reducing sediment inflow

Not applicable

Preventing deposition

- ⇨ Flushing

Removing sediment

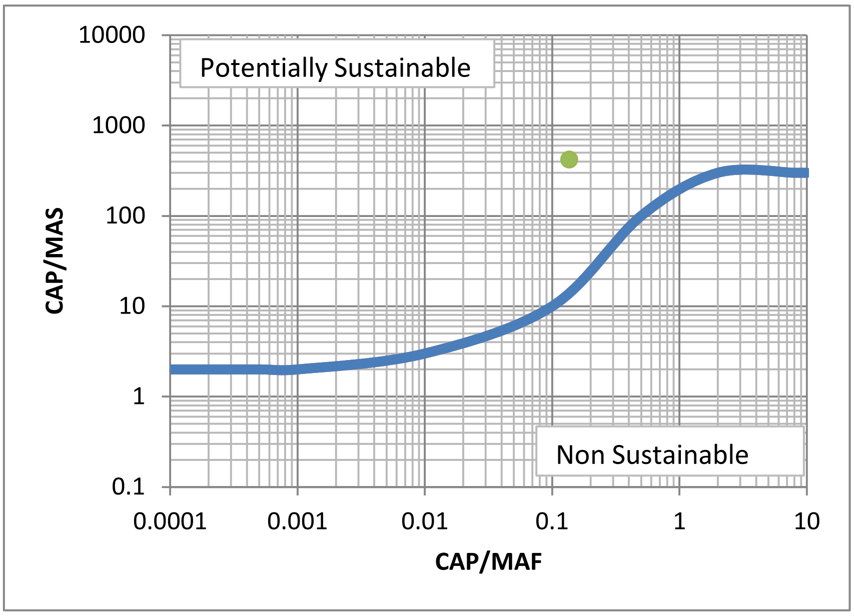
- ⇨ Hydro suction

Main characteristics

Dam type	Gravity
Function	Power generation
Dam height (m)	57.5
Dam length (m)	171
Gross storage (m^3)	8 310 000
Catchment area (km^2)	355.7
Design discharge(m^3/s)	2 127

Key features

CAP (m^3)	8 310 000
MAF (m^3/y)	876 000 000
MAS (m^3/y)	772 000
CATCHMENT (km^2)	355.7 dam cascade 2/7
CAP/MAF (year)	0.00948
CAP/MAS (year)	108


Potentially Sustainable
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TSUKUBARU

Location: Japan, on the Mimikawa River

Cost of sediment management: Not available

Management option: None presently

Reducing sediment inflow

Not applicable

Preventing deposition

- ⇨ Flushing

Removing sediment

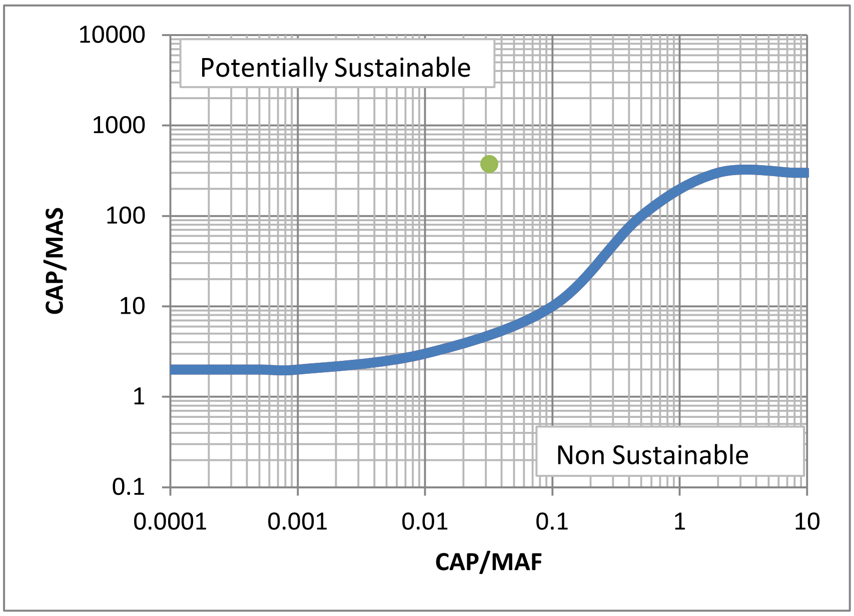
- ⇨ Hydro suction

Main characteristics

Dam type	Gravity
Function	Power generation
Dam height (m)	87
Dam length (m)	215
Gross storage (m^3)	34 300 000
Catchment area (km^2)	430.7
Design discharge(m^3/s)	2 650

Key features

CAP (m^3)	34 300 000
MAF (m^3/y)	1 071 000 000
MAS (m^3/y)	91 800
CATCHMENT (km^2)	430.7 dam cascade 3/7
[redacted]	
CAP/MAF (year)	0.032
CAP/MAS (year)	374



Potentially Sustainable
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MOROTSUKA

Location: Japan, on the Mimikawa River

Cost of sediment management: Not available

Management option: None presently

Reducing sediment inflow

Not applicable

Preventing deposition

⇨ Flushing

Removing sediment

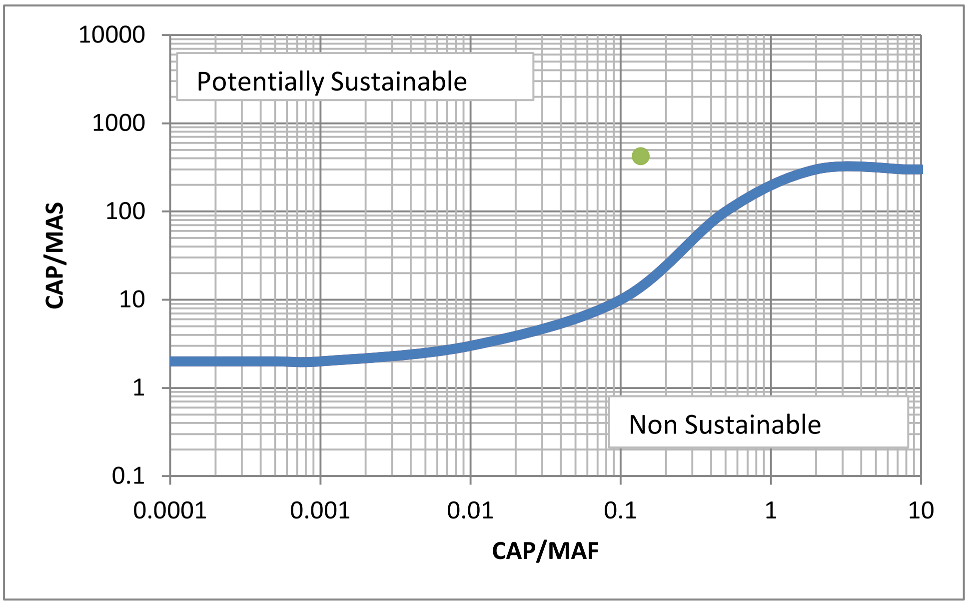
⇨ Hydro suction

Main characteristics

Dam type	Hollow
Function	Power generation
Dam height (m)	59
Dam length (m)	149.5
Gross storage (m^3)	3 480 000
Catchment area (km^2)	109.1
Design discharge(m^3/s)	600

Key features

CAP (m^3)	3 480 000
MAF (m^3/y)	151 000 000
MAS (m^3/y)	20 300
CATCHMENT (km^2)	109.1 dam cascade 4/7
CAP/MAF (year)	0.0231
CAP/MAS (year)	172



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Potentially Sustainable
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CAP/MAF

YAMASUBARU

Location: Japan, on the Mimikawa River

Cost of sediment management: Not available

Management option: Sediment sluicing

Reducing sediment inflow

Not applicable

Preventing deposition

⇨ Flushing

Removing sediment

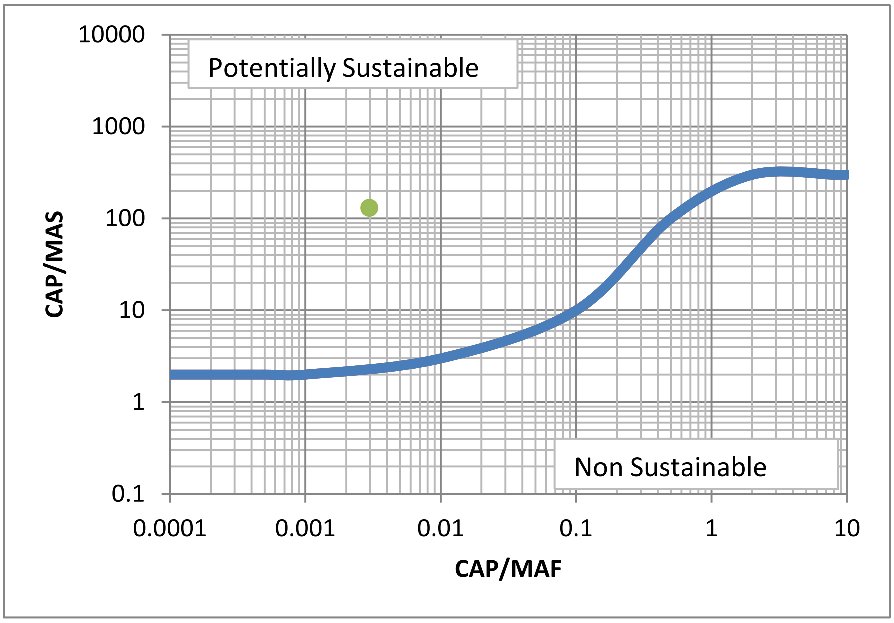
⇨ Hydro suction

Main characteristics

Dam type	Gravity
Function	Power generation
Dam height (m)	29.4
Dam length (m)	91.1
Gross storage (m^3)	4 190 000
Catchment area (km^2)	598.6
Design discharge(m^3/s)	3 387

Key features

CAP (m^3)	4 190 000
MAF (m^3/y)	1 410 000 000
MAS (m^3/y)	32 000
CATCHMENT (km^2)	598.6 dam cascade 5/7
CAP/MAF (year)	0.00297
CAP/MAS (year)	131



Potentially Sustainable
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CAP/MAF

SAIGO

Location: Japan, on the Mimikawa River

Cost of sediment management: Not available

Management option: Sediment sluicing

Reducing sediment inflow

Not applicable

Preventing deposition

⇨ Flushing

Removing sediment

⇨ Hydro suction

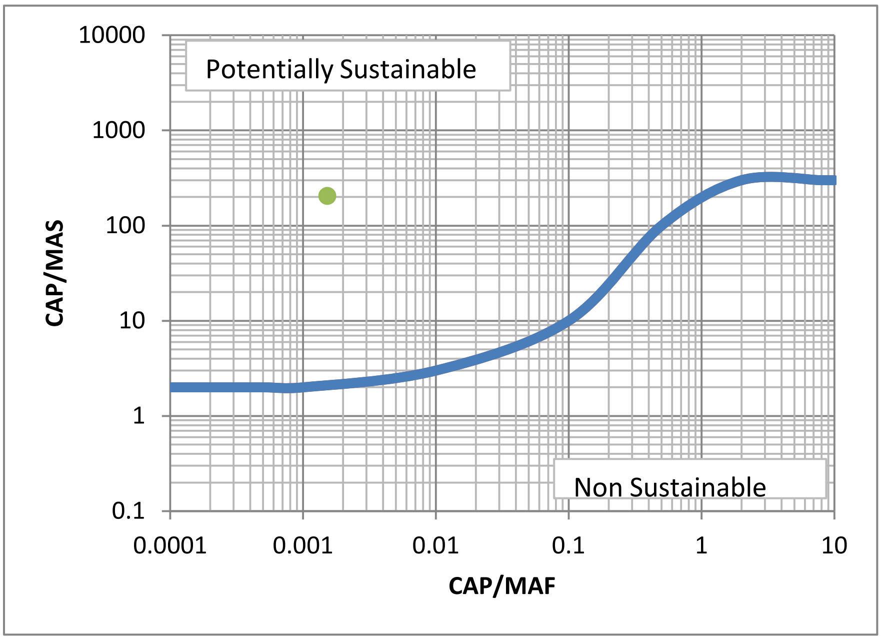
Main characteristics

Dam type	Gravity
Function	Power generation
Dam height (m)	20
Dam length (m)	84.5
Gross storage (m³)	2 450 000
Catchment area (km²)	647.8
Design discharge(m³/s)	3 572

Key features

CAP (m³)	2 450 000
MAF (m³/y)	1 610 000 000
MAS (m³/y)	12 000
CATCHMENT (km²)	647.8 dam cascade 6/7

CAP/MAF (year)	0.00152
CAP/MAS (year)	204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OUCHIBARU

Location: Japan, on the Mimikawa River

Cost of sediment management: Not available

Management option: Sediment sluicing

Reducing sediment inflow

Not applicable

Preventing deposition

- ⇨ Flushing

Removing sediment

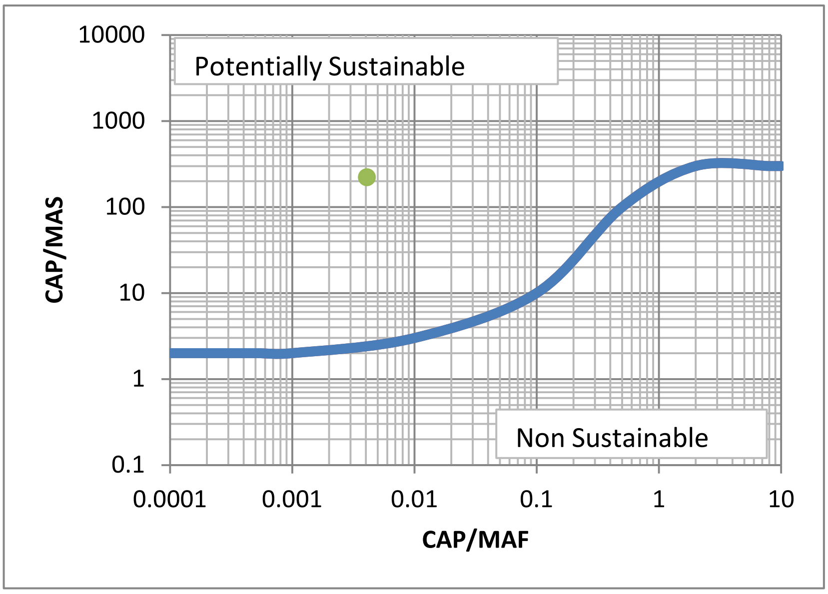
- ⇨ Hydro suction

Main characteristics

Dam type	Gravity
Function	Power generation
Dam height (m)	25.5
Dam length (m)	152.6
Gross storage (m^3)	7 490 000
Catchment area (km^2)	884.1
Design discharge(m^3/s)	5 000

Key features

CAP (m^3)	7 490 000
MAF (m^3/y)	1 831 000 000
MAS (m^3/y)	33 800
CATCHMENT (km^2)	884.1 (dam cascade 7/7)
CAP/MAF (year)	0.00409
CAP/MAS (year)	222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CAP/MAF

3.4.11. Japan – Miwa: Management of Sediments at the Miwa Dam

According to: Y. Enomura; EADC (2005).

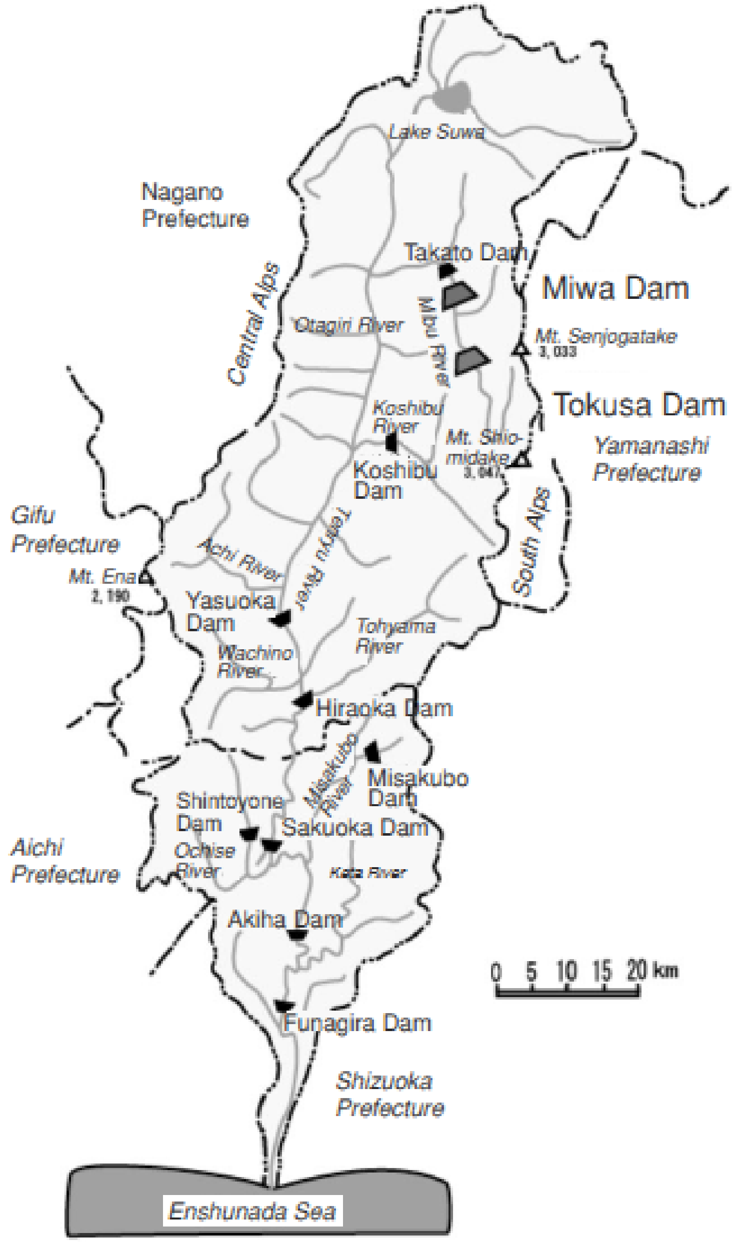


Fig. 3.100
Location of the Tenryu River

3.4.11.2. Introduction

The Miwa Dam is located on the Tenryu catchment (southwest of Honshu Island, Figure 3.100). It was completed in 1959 for the purposes of flood control, irrigation and power generation.

Until the present, excavated sediment from the reservoir has been used in public works as banking material for relocated roads and farmland consolidation. But this dam needs a permanent solution for sediment management.

3.4.11.3. Owners

This dam is owned and managed by the Ministry of Land Infrastructure and Transport (MLIT).

3.4.11.4. Hydrology

The catchment drained by the Miwa Dam is around 5 090 km². The Tenryu River is located in a steep mountainous area.

3.4.11.5. Basic dam and reservoir data

Table 3.25
Structural characteristics of the dam

Miwa Dam	
Dam type	Gravity
Function	Flood control, hydropower
Dam height (m)	69.1
Dam length (m)	367.5
Gross Storage (m^3)	30 000 000
Catchment area (km^2)	311.1
Design discharge (m^3/s)	1 200
Crest elevation (m)	817.6
Storage area (ha)	179
Type of spillway	1 Condit Gate 5.0m W x 6.4m H 2 Tainter Gates 5.0m W x 6.3m H

The Miwa Dam supplies electricity to 43 000 households and provides water to 2 500 ha of downstream paddy fields.

3.4.11.6. Plot of capacity versus mean annual flow

The accumulation of sediments decreases the capacity to control flooding and water supply distribution.

3.4.11.7. Political issues

Sediment management at this dam is important, since it affects rice production; each flood event impacts the paddy fields as well.

3.4.11.8. Regulatory constraints

A diversion weir is needed and built during the dry period (between October and March) to avoid the possibility of construction being impacted during flood periods. Moreover, the reservoir level has to be lowered for construction to take place.

On account of the environmental policies, a discharge of 0.96 m^3/s must be provided at all times.

3.4.11.9. Sediment data of the site

The average annual sediment supply varies yearly (Figure 3.101), with the worst years for rice cultivation also being the years with the highest volume of sediment supply. Consequently, an efficient sediment management policy is required.

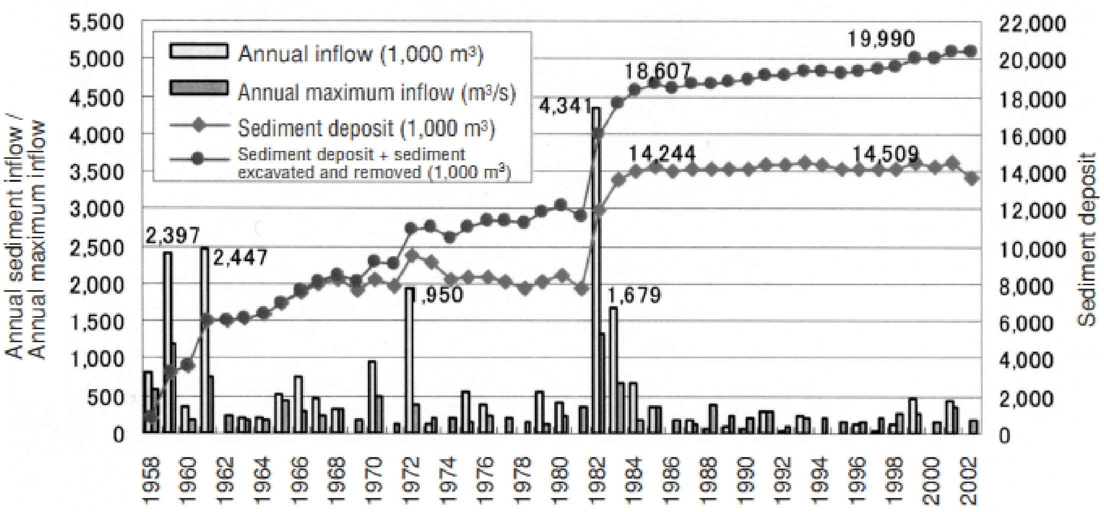


Fig. 3.101
Yearly sediment change

The surveys on grain size indicate that most of the wash load could be trapped before flowing to the river. The mean annual sediment inflow is estimated to total around 685 000 m^3.

3.4.11.10. Classification of sediment management

Sediment removal was conducted as needed before new construction; however, local stakeholders wanted to improve sediment management with permanent devices. As a result, now there are systems in place to prevent deposition (bypass tunnels) and to reduce inflow (check dams).

3.4.11.11. Planned sediment management

In order to reduce the sediment accumulation, three systems have been implemented (Figure 3.102):

- Check dam to trap the sediment upstream (coarse grained soil) **(1)**
- Diversion weir to trap the sediments (fine grained soil) **(2)**
- Flood bypass tunnel **(3)**

Surveys were conducted to evaluate the effectiveness of these new system components.

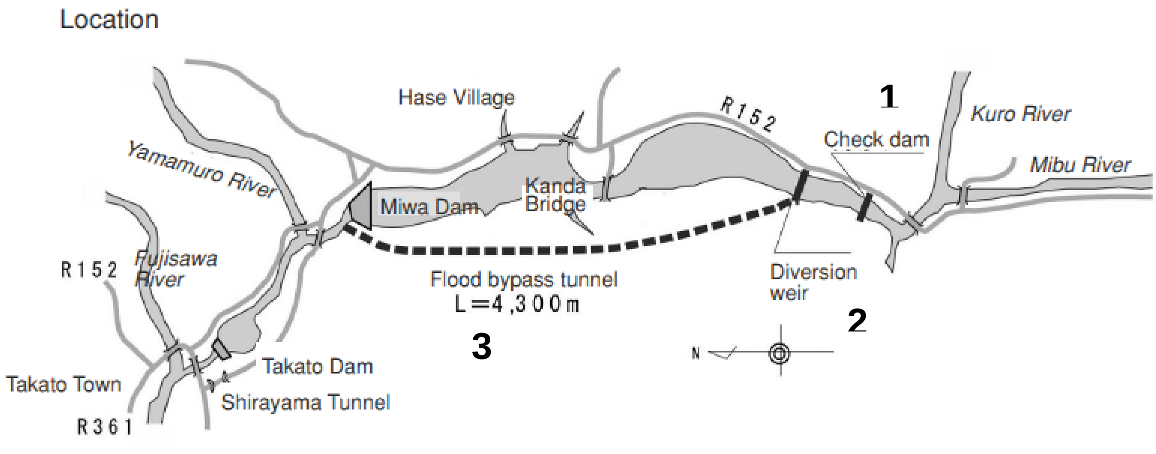


Fig. 3.102
Plan of the project

As mentioned earlier, a portion of the sediment is excavated for use as construction material. Figure 3.103 summarizes the annual expected volume of sediment deposits.

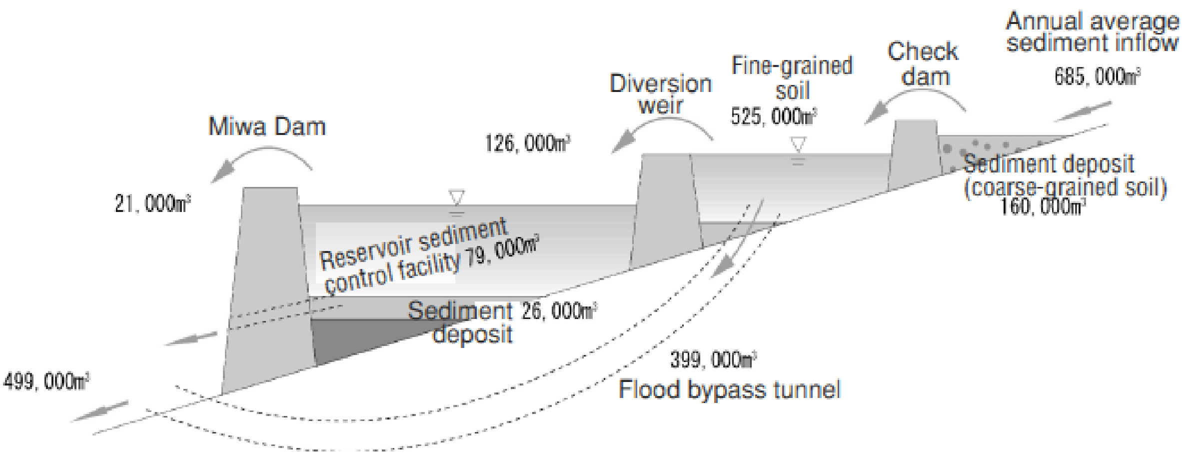


Fig. 3.103
The profile of the sediment control measures

MIWA

Location: Japan, on the Tenryu River

Cost of sediment management: About 50 billion JPY

Management option: Sediment bypass tunnel and excavation

Reducing sediment inflow

- ⇨ Check dam

Preventing deposition

- ⇨ Tunnels

Removing sediment

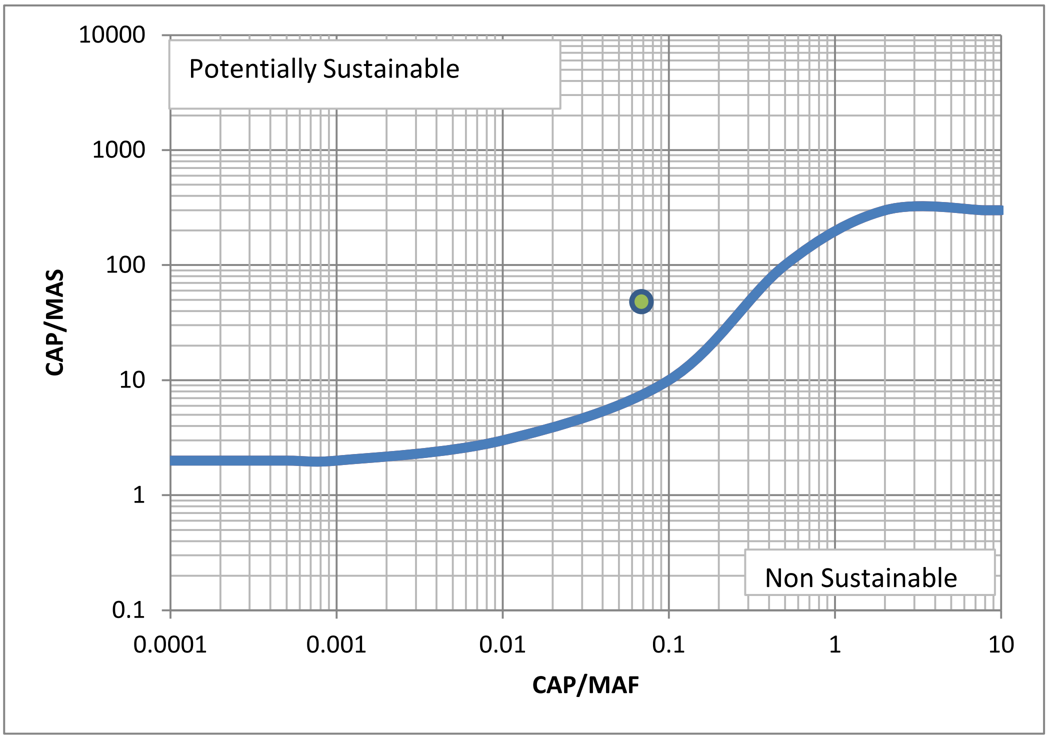
- ⇨ Dry excavation

Main characteristics

Dam type	Gravity
Function	Flood control, hydropower
Dam height (m)	69.1
Dam length (m)	480
Gross storage (m^3)	29 952 000
Catchment area (km^2)	311.1
Design discharge(m^3/s)	1 200

Key features

CAP (m^3)	29 952 000
MAF (m^3/y)	408 825 000
MAS (m^3/y)	685 000
CATCHMENT (km^2)	311.1
CAP/MAF (year)	0.0732
CAP/MAS (year)	44


10000
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1
0.1
CAP/MAS
Potentially Sustainable
Non Sustainable
0.0001
0.001
0.01
0.1
1
10
CAP/MAF

3.4.12. Japan – Shimokubo: Management of Sediments at the Shimokubo Dam

According to: H. Ogawa, A. Kanayama; EADC (2005)

3.4.12.1. Introduction

The Shimokubo Dam is located on the Kanna River (Figure 3.104). It has a 323 km² catchment. Sediment transport continuity was cut off by the dam. In order to solve the riverbed degradation issue, some sediment transport measures have been implemented. Around 1.5 km of the downstream reach has a particularly beautiful landscape (the Sanba Seki Kyo).

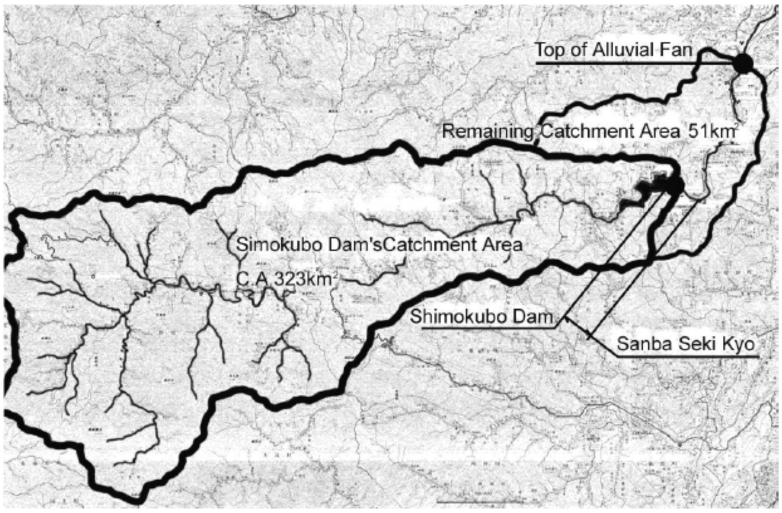


Fig. 3.104
Catchment area of the Shimokubo Dam

The landscape deterioration is due to the riverbed degradation, diminished sandbars and weakened cleansing effect caused by the interruption of sediment transport downstream of the dam.

3.4.12.2. Owners

This dam is managed by the Japan Water Agency. The Kanna River is classified as an A/B river, which means that it is managed by both the Ministry of Land Infrastructure and Transport (MLIT) and the prefecture. The Shimokubo Dam has many functions, including flood control, river discharge maintenance, water supply (for industrial and domestic uses) and hydropower generation.

3.4.12.3. Hydrology

The annual rainfall is estimated as 1300 mm. The extreme flow event is described in Table 3.26 below:

Table 3.26
Extreme flow events

Return period (years)	Discharge (m^3/s)
200	2 000

3.4.12.4. Basic dam and reservoir data

Table 3.27
Structural characteristics of the dam

Shimokubo	
Dam type	Gravity
Function	Power generation, irrigation
Dam height (m)	129
Dam length (m)	626
Gross Storage (m^3)	130 000 000
Catchment area (km^2)	322.9
Design discharge (m^3/s)	500
Crest elevation (m)	300.0
Storage area (ha)	327
Type of spillway	2 Radial Gates, 2 Tainter Gates

3.4.12.5. Plot of capacity versus mean annual flow

The mean annual sediment inflow is estimated to be 200 000 m^3/y. The change in sediment volume at the project is shown in Figure 3.105.

3.4.12.6. Political issues

Riverbed degradation has a detrimental impact on the landscape. All study results on riverbed degradation were periodically communicated to the area residents and to the Kanna River Sediment Transport Committee, who would like to see the riverbed restored.

3.4.12.7. Regulatory constraints

Due to the water supply function, the Shimokubo dam has to be able to provide up to 16 m^3/s; a minimum flow of 0.323 m^3/s must be released at all times for environmental purposes.

The Sanba Seki Kyo is an important landscape feature for this catchment and its deterioration could impact economic activities like tourism. In order to spare the water, the flushing operation should be done in the flood season and the dumping operation should be done any time before the flood season.

3.4.12.8. Sediment data of the site

The Shimokubo Dam intercepts 87% of the Kanna mountainous catchment (407 km^2) and creates sediment issues for the downstream part of the river. Indeed the dam interrupts sediment continuity. At the end of 2004, around 8 hm^3 of sediment was accumulated in the reservoir which is 81% of the reservoir’s design capacity.

Some river sections have been degraded almost 5 m deeper than before the construction of the dam and the riverbed material in the river immediately downstream of the dam has become coarser. The mean size of the sediment is more than 50 mm.

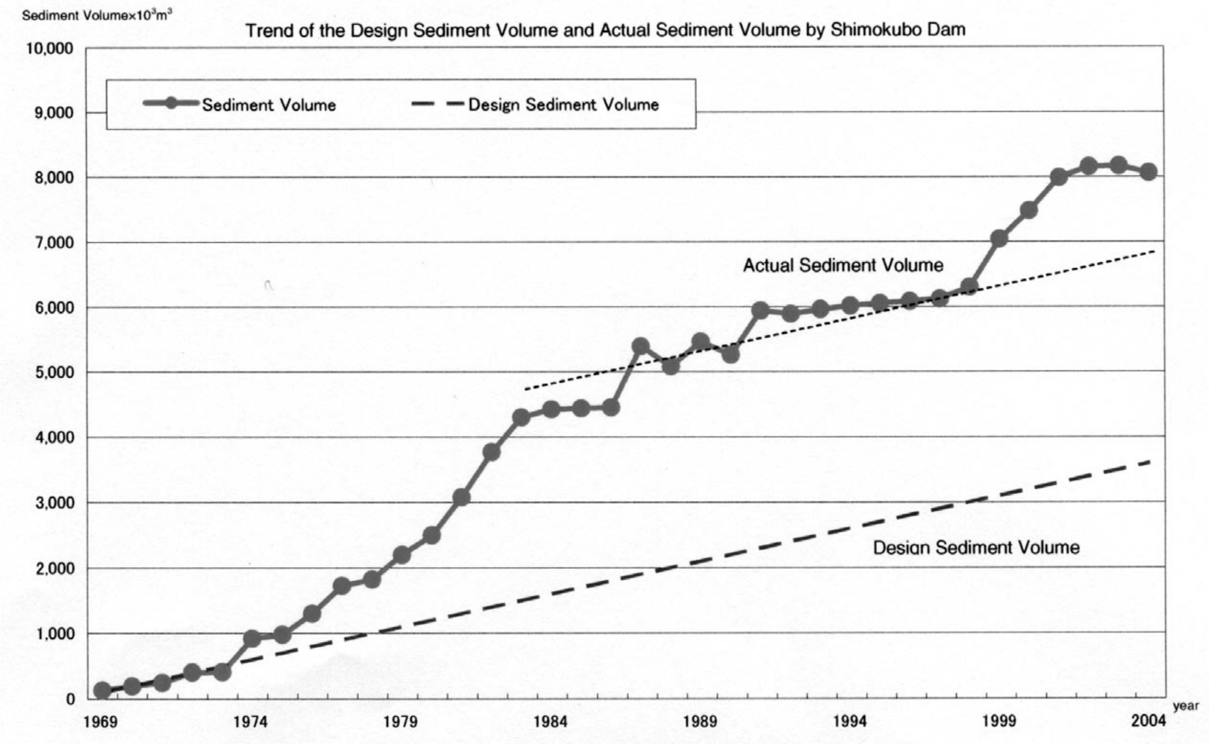


Fig. 3.105
Change in sediment volume

3.4.12.9. Modeled dumping scenario

In order to release a good quantity of sediment and to lead the sediment policy, some transport experiments have been set up in the upstream reach of the river. Since 2003, the sediment which is deposited in a sediment trap located 8.5 km before the dam is dumped by truck into the river downstream from the dam. Then, the dumped sediment is washed away by discharge from the reservoir. The best conditions for this experiment occur during the flood season (July-September).

3.4.12.10. Classification of sediment management

Between the three types of sediment management (reducing inflow, preventing deposition and removing sediment), it is “removing sediment” which has been applied to the Shimokubo dam.

This solution needs trucks in order to dump the sediment and stakeholder coordination before each release operation. The components of this management strategy are:

- Trapping sediment before the dam
- Gathering sediments from the upstream reach
- Releasing sediments in the downstream reach
- Releasing the wash flood (fixed discharge/ fixed time)

3.4.12.11. Planned sediment management

The initial studies began in 2003. Now the sediment operation is conducted on a regular basis. More details about the actual releasing operation is reported in Sakurai and Hakoishi (2013).

SHIMOKUBO

Location: Japan, on the Kanna River

Cost of sediment management: Not available

Management option: Sediment excavation and replenishment

Reducing sediment inflow

Not applicable

Preventing deposition

Not applicable

Removing sediment

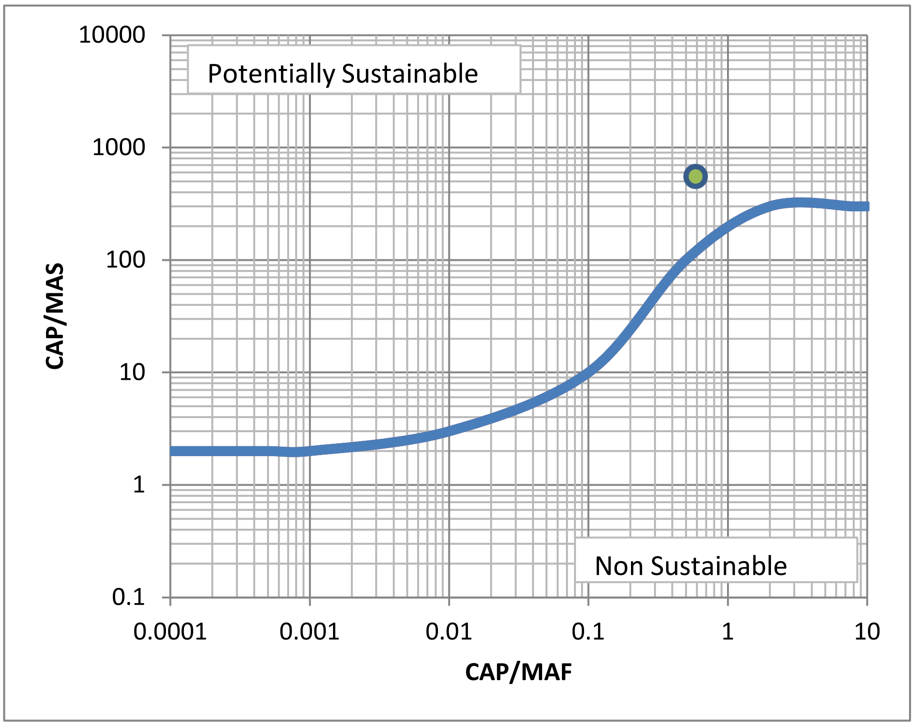
⇨ Dry excavation

Main characteristics

Dam type	Gravity
Function	Power generation
Dam height (m)	129
Dam length (m)	626
Gross storage (m^3)	130 000 000
Catchment area (km^2)	322.9
Design discharge(m^3/s)	500

Key features

CAP (m^3)	130 000 000
MAF (m^3/y)	216 260 000
MAS (m^3/y)	217 180
CATCHMENT (km^2)	322.9
CAP/MAF (year)	0.601
CAP/MAS (year)	599



10000
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CAP/MAS
0.0001
0.001
0.01
0.1
1
10
CAP/MAF
Potentially Sustainable
Non Sustainable

3.4.13. Nepal – Kali Gandaki: Management of Sediments in the Kali Gandaki Reservoir

Provided by Mr. Gregory Morris, GL Morris Engineering

3.4.13.1. Introduction

The Kali Gandaki River in western Nepal originates in the high Himalaya. Its upper watershed includes glaciers and three of the world's 14 mountain peaks exceeding 8 000 m in elevation, including Annapurna. The northern watershed limit defines the border between Nepal and Tibet. In the upper reach, above about 2 500 m elevation, the river is generally braided with evidence of high lateral input of sandy sediment as evidenced by fans of sediment deposits associated with the lateral tributaries. At about 2 500 m the river enters a gorge which extends to and beyond Kali Gandaki dam. The watershed area tributary to the dam is 7 618 km^2.

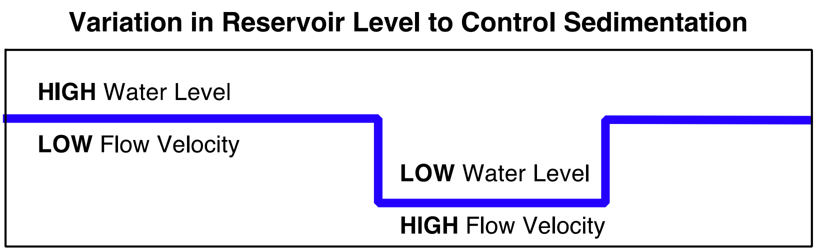
The Kali Gandaki hydropower plant dam and intake facility is owned by the Nepal Electricity Authority, and is located about 50 km southwest of Pokhara, just below the confluence with the Andhi Khola River (lat. 27°58'44" N, long. 83°34'50" E). The 44 m tall dam was designed to continuously divert 141 m^3/s to a 144 MW run-of-river hydropower plant operating three Francis turbines with 115 m gross head, while retaining approximately 3.1 Mm^3 of storage for six hours of daily power peaking. The Kali Gandaki River sediment yield averages about 43 Mt/yr, of which about 50% is sand, which is sufficient to completely fill the reservoir multiple times in a single monsoon season.

The original total reservoir capacity was 7.7 Mm^3, but the dead storage below the spillway crest, comprising about half the total volume, was filled with sediment before the project began operating. The project has been operated for sustainable sediment management since the initiation of power production in 2002, and has successfully sustained the regulating storage volume by seasonal reservoir drawdown (seasonal sluicing) with only a minor loss in volume despite the high sediment load. However, due to high rates of abrasion to hydro-mechanical equipment by sediment, the World Bank funded a project to analyze the project's sediment handling capacity through a review of the operational data, field measurements, plus both numerical and physical modeling, and based on this, to design and construct rehabilitation work both at the headworks and the powerhouse. Headworks modifications focused on improving the hydraulic configuration of the intake and the desander to improve sediment removal efficiency.

This project provides an example of using seasonal sluicing to sustain storage for power peaking, despite extremely high sand loads. Experience at this site is relevant not only to projects designed for run-of-river operation, but it will also be relevant to those storage projects which will lose their seasonal storage capacity due to sedimentation, and may eventually modify their structures and operational rule to practice sediment sluicing to sustain daily or weekly power peaking capacity, while otherwise operating in run-of-river mode.

3.4.13.2. Hydrology and Sediment Transport

Streamflow in Nepal is highly seasonal, with high flows during the summer responding to a combination of snow and glacier melt plus the monsoon. Flow and suspended sediment seasonality at the Kali Gandaki dam may be seen in Figure 3.106. The suspended sediment concentration increases dramatically as soon as the reservoir level is lowered for sluicing, due to mobilization of the bed sediment.



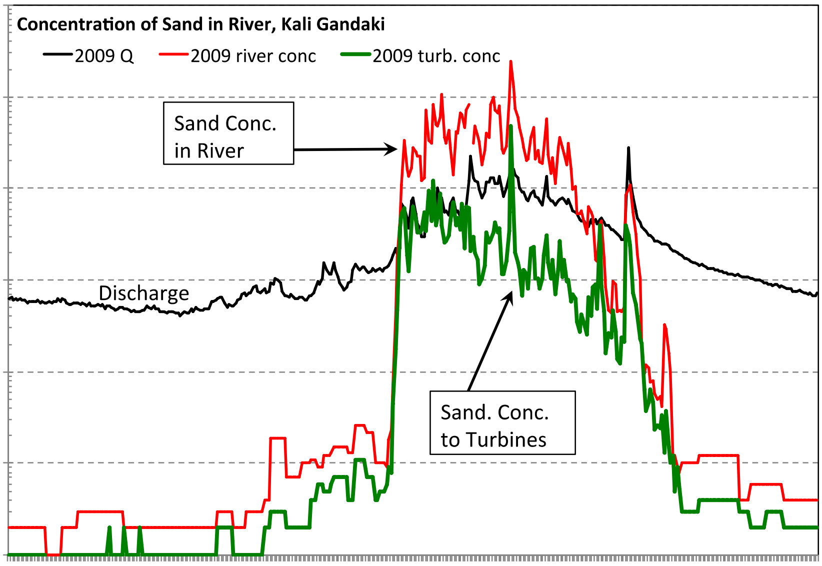


Fig. 3.106

TOP: Seasonal variation in operational water level. BOTTOM: Seasonality of streamflow and suspended sediment concentration for year 2009. River concentration is measured immediately upstream of the power intake and the turbine concentration is measured in the draft tube.

Bed material in the Kali Gandaki River consists of cobbles (d_{50} = 110 mm). The annual suspended load is approximately 40 Mt/yr, and sampling during 2008 – 2009 showed that between 50% and 60% of the suspended load consists of sand (d_{50} = 0.9 mm). For a bulk density on the order of 1.5 t/m^3 for sand, and given an annual sand load of approximately 20 Mt/yr, just the sand fraction of the suspended load would occupy 13 Mm^3 of volume, sufficient to fill the reservoir completely several times during a single monsoon. The specific suspended sediment yield from the 7618 km^2 watershed is on the order of 5 000 t/km^2/yr. Based on sampling of the well-mixed water in the draft tubes exiting the turbines, the suspended sediment load on the turbines averages about 1.7 Mt/yr, of which 43% is sand. About 99% of all sediment is discharged during the monsoon, from May 16 to October 31. Approximately 60% of the sand-sized sediment consists of angular and highly abrasive quartz.

3.4.13.3. Project Configuration and Operating Rule

<u>Project Description</u>

The Kali Gandaki reservoir is about 5 400 m long but occupies a narrow gorge and along most of its length is somewhat less than 100 m wide. During the dry season the reservoir level varies between 524 and 518 m for power peaking operation. However, during May when inflow begins to exceed about 300 m^3/s and the power plant will be operating continuously at full power, the water level is lowered to 518 m for continuous sediment sluicing. As soon as the water level drops the suspended sediment concentration immediately increases as the bed material is mobilized (Figure 3.106). Even though the intake weir has been placed at a high level, a considerable amount of sand continues to enter the intake during the sluicing period, and a desander has been provided to reduce the sand load on the turbines. When flows recede In October, the water level is raised back to 524 m and power regulation for peaking begins when inflow drops significantly below the plant's 141 m^3/s design capacity. A photograph of the site is given in Figure 3.107, and Figure 3.108 illustrates the relevant water and structural levels in the area of the dam. Basic project information is summarized in Table 3.28.

The project's original operating rule contemplated annual flushing of the reservoir, in addition to seasonal sluicing. However, flushing was never implemented because of the need to continuously generate power, since Nepal was operating under a schedule of rolling blackouts due to the lack of generating capacity. Also, it soon became apparent that the sluicing operation was, of itself, sufficient to sustain the desired peaking storage volume. Furthermore, given the high suspended sediment load, flushing would provide only very little additional benefit in terms of storage preservation.

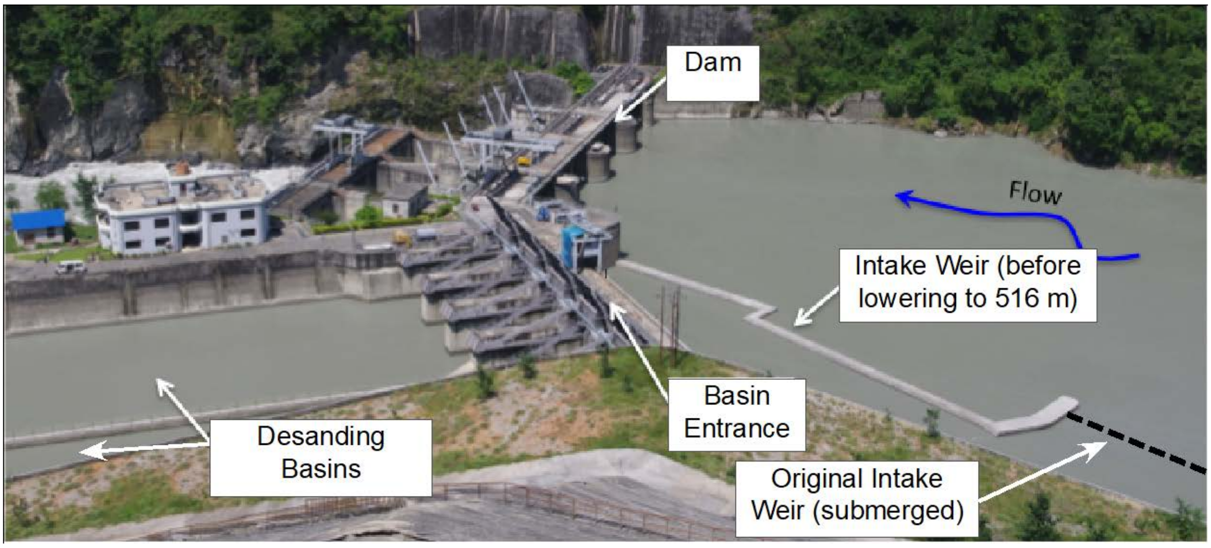


Fig. 3.107
Photograph of Kali Gandaki headworks with river level at 518 m.

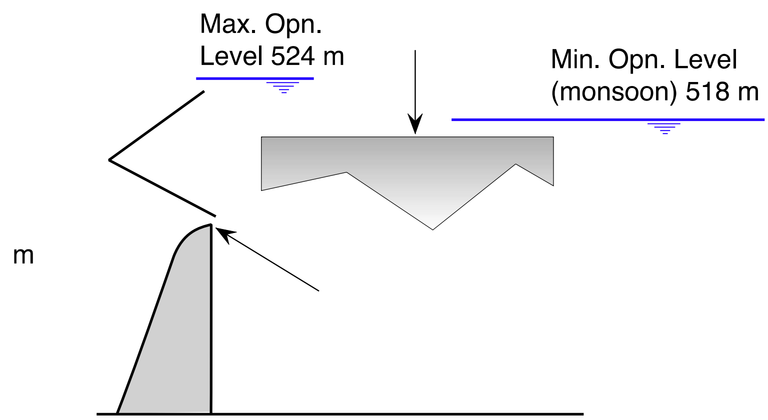


Fig. 3.108
Schematic longitudinal view showing relevant structural and operational levels for Kali Gandaki Dam and intake weir.

Table 3.28

Basic project information

Total reservoir volume	7.7 Mm^3 at construction, 3.77 Mm^3 in Dec. 2010
Regulating volume (between el. 518 to 524 m)	3.1 Mm^3 at construction, 3.0 Mm^3 in Dec. 2010
Watershed area above dam	7618 km^2
Began operation	May 21, 2002 per daily operational report
Surface area of the reservoir	65 ha at construction and 65 ha in Dec. 2010
Maximum & minimum operational levels	524 m and 518 m
Gated outlets in river channel	3 radial crest gates, sill elev. 505 m, 6400 m^3/s capacity for 1000-year design flood
Turbines	3 Francis @ 48 MW, 47 m^3/s each for 141 m^3/s design discharge at 115 m gross head
Mean annual river flow (2002-2012)	306 m^3/s = 9,637 Mm^3/yr
Average Power Generation	842 GWh/year
Total sediment load in river	37 Mt/yr (1993 pre-construction data) 43 Mt/yr (2006-2009 data)
Sediment passed through turbines	1.7 Mt/yr (2006-2009), of which 43% is sand

3.4.13.4. Proposed Modifications

The headworks modifications that will be undertaken under this project financed by the World Bank include the following key components:

1. The intake structure will be modified to improve its performance. Currently there is a short intake weir which delivers water in to a forebay at the entrance to the desander (as seen in Figure 3.107). This weir entrains a large volume of sand and the hydraulic configuration results in flow imbalances between the two desander basins. The intake weir will be modified by lowering and straightening the long wall visible in Figure 3.107, and eliminating the current intake weir, to thereby generate a more uniform flow pattern entering the desanders. A skimming wall will be added to deflect floating debris and improved trash rack cleaning will also be provided, to better control debris clogging.
2. The desander entrance will be modified to reduce the impact of turbidity flows that carry sediment-laden inflow along the bottom of the desander and directly to the outlet. This flow pattern was observed by field measurements, and the solution was developed through physical modeling.
3. A LISST laser-diffraction instrument will be installed to continuously monitor suspended sediment grain size and concentration, to identify periods of high suspended sediment concentration exiting the desanders and periods when power generation should be reduced or halted to protect the equipment from high rates of abrasion.

The project will additionally include development of an updated operational manual and operator training.

3.4.13.5. Management Suitability Graph

Based on the annual inflows of sediment and water, and the volume to be sustained for regulating storage (taken as 3.5 Mm^3), the following parameters can be calculated:

CAP:MAF ratio = 3.5/9637 = 4E-4

Reservoir Life (yrs): CAP/MAS = 3.5/(40/1.5) =3.5/26.7 = 0.13

These values are plotted in the management suitability classification graph (Figure 3.109) for different types of sediment management techniques, showing that this reservoir is classified as "non-sustainable". However, operation of this site is clearly sustainable based on sluicing operations, showing that the "sustainable" range may extend beyond that shown in the chart.

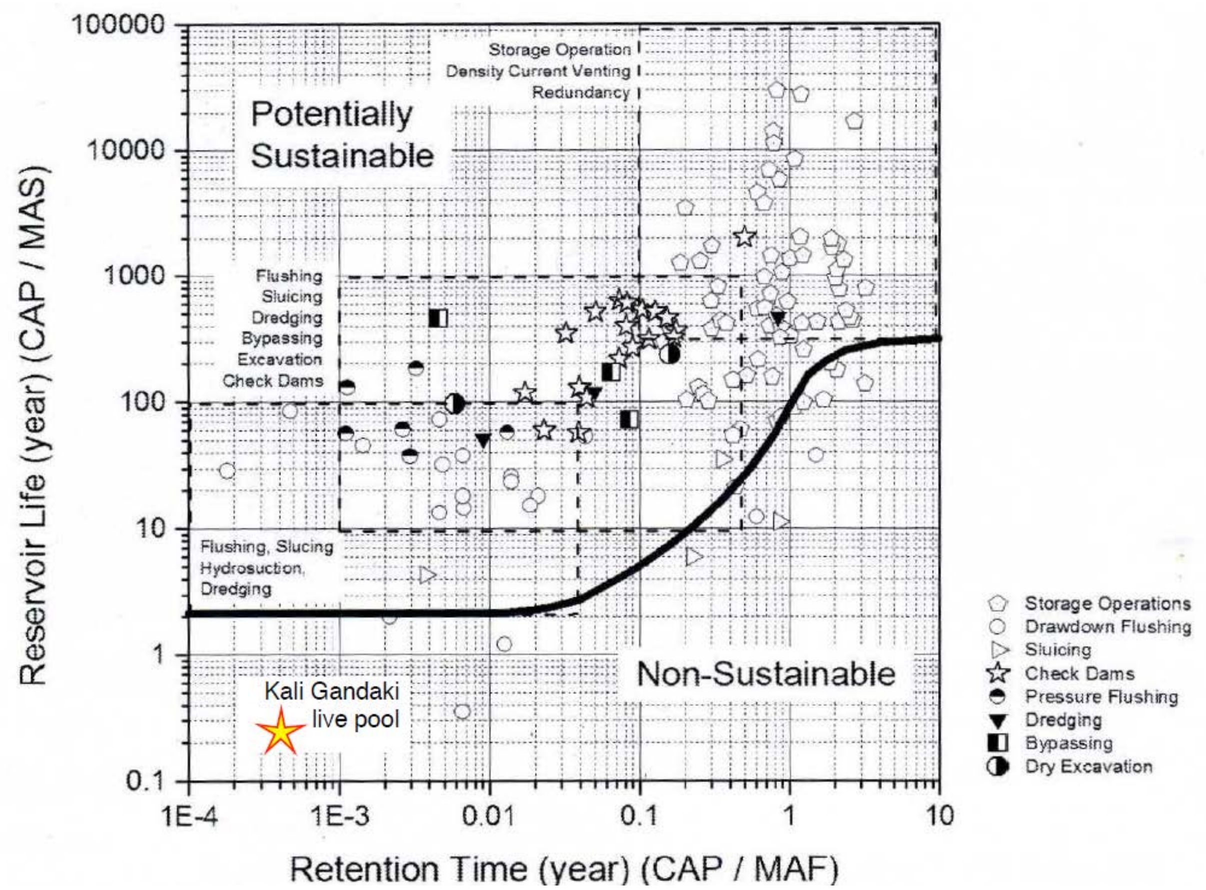


Fig. 3.109
Suitability classification of different sediment management techniques.

3.4.13.6. Economics/Sustainability

The project is clearly sustainable and its operation is highly economical, producing electric power for Nepal at a very low cost. Hydropower plants have high initial costs, but have the proven ability to generate power for periods in excess of 100 years without major rehabilitation work. Even at sites where turbine abrasion is significant, the cost of annual turbine repair has been found to be small in comparison to the value of power produced. The work that is being undertaken at Kali Gandaki should reduce the plant's susceptibility to abrasion damage, and the data collected to date together with numerical modeling indicate that the facility should be able to continue to operate indefinitely.

The major hazard faced by the facility is landslide hazard from the steep walls on either side of the reservoir, including an active slide area that is currently threatening the access road to the headworks. Stabilization of this unstable area is included as part of the rehabilitation package.

3.4.13.7. Regulatory Issues

There are no regulatory issues which impede sediment management operations at this site. It is also pertinent that the sluicing operation maintains both the natural flow hydrograph and sediment discharge during the monsoon season, and as such the suspended sediment concentration below the dam is not significantly different from that upstream of the dam.

3.4.13.8. Operational Issues

Sediment-guided Operation

Episodic events of high suspended sediment concentration can produce high rates of abrasion to hydromechanical equipment such as turbine runners. It makes little sense to operate turbines during short periods of high abrasion potential, when the damage from abrasion exceeds the income from power, especially considering that the loss or runner efficiency due to abrasion damage will continuously exert a drain on power production until the runner is removed for repair. **Sediment-guided operation** seeks to identify the periods of high abrasion potential, and to reduce or stop power operations during those periods.

Suspended sediment concentration generally increases with discharge, but the relationship is not direct and the highest suspended sediment concentrations do not necessarily coincide with the peak discharge. The rate of turbine abrasion is sensitive to both the concentration and the grain size of sediment, and events which deliver higher concentration and grain sizes to turbines will cause a disproportionate amount of damage. Therefore, at Kali Gandaki a real-time laser diffraction monitoring system (LISST) is being installed to track both concentration and grain size distribution of the sediment delivered to turbines, thereby enabling the operator to identify periods with the highest abrasion potential. During these periods power production may be reduced, to similarly reduce the hydraulic loading rate on the desanders and increase their sediment removal efficiency, or the plant may be temporarily shut down.

Operational Monitoring and Feedback

The experience at the Kali Gandaki plant also illustrates the importance of reviewing operational data and providing feedback to operators. Figure 3.110 presents data on the sediment removal efficiency of the headworks (intake and desander), showing a significant reduction in removal efficiency associated with a change in operator. There was no change in the stated operational rule or in the structures or their equipment, but there was less control over water levels during the period of lower sediment removal efficiency. These data demonstrate that sediment management is not simply a matter of installing appropriate equipment, but is also dependent on how the facility is operated.

This underscores the need to continuously monitor operation of sediment management facilities, to display and interpret the data, and to provide feedback and training to operators to achieve the highest performance level. Performance cannot be optimized absent effective operational monitoring, feedback and training.

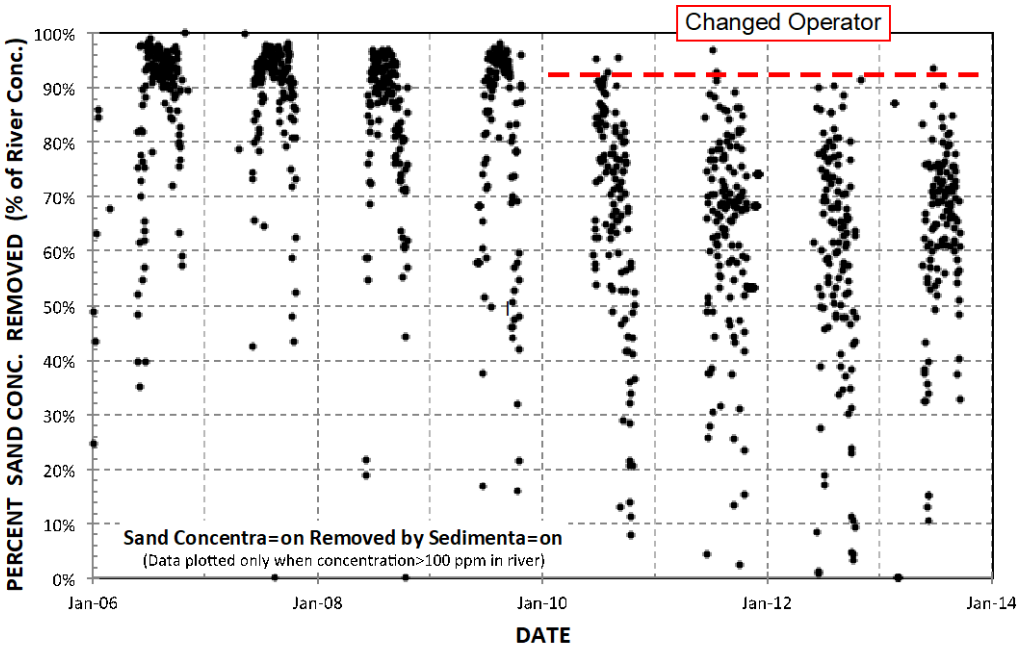


Fig. 3.110
Reduction in sand removal efficiency correlated to a change in operator.

3.4.13.9. Upstream and Downstream Issues

There is a flooding issue at the upstream limit of the reservoir which affects the lower portion of a village as well as a pilgrimage site. This is discussed under "Political Issues".

The reservoir is capturing coarse sediment (cobbles) and there has been bed incision below the dam, but this has not been studied or documented. However, there is a problem of low tailwater elevation at the powerhouse which results in turbine cavitation (and damage), and this is probably related to the reduced supply of coarse sediment (cobbles) and channel incision.

3.4.13.10. Political Issues

The principal political issue associated with the project is the problem of increasing flood levels at the village of Seti Beni, which also affects the Holy Stone, a large stone (about 10 m in diameter) which is a popular Hindu pilgrimage site. It was previously accessible only by footpath but is now accessible via boat along the reservoir during the dry season when the reservoir level is high. Seti Beni is located at the upstream limit of the reservoir and is affected by a gradual increase in the bed level as coarse bed material (cobbles) accumulates in this area. There is no visible delta at the upstream limit of the reservoir, and the accumulation of coarse bed material has occurred very slowly. Coarse sediment is also discharged into the reservoir at this location by a steep lateral tributary. Due to inaccessibility, the removal of bed material by heavy equipment is not considered a feasible option. Rather, the recommendation at this time is to relocate several susceptible small structures to higher levels, and to improve the foundation to the Holy Stone to protect against erosion of its base during flood flows.

3.4.13.11. Summary

The Kali Gandaki project demonstrates that storage for daily hydropower regulation can be sustained even under extreme sediment loads. It also demonstrates the essential role that operational monitoring and optimization play in the management of sediment.

KALI GANDAKI

Location: Nepal
Cost of sediment management: Unknown
Management option: Operational sluicing

Reducing sediment inflow
Not applicable

Preventing deposition
Not applicable

Removing sediment
⇨ Sluicing

Main characteristics

Uses	Hydropower
Dam Type	Concrete gravity
Dam height (m)	44
Dam length (m)	5400
Gross storage (m^3)	7 700 000
Catchment area (km^2)	7618
Design discharge(m^3/s)	141

Key features

CAP (m^3)	3 500 000
MAF (m^3/y)	9 637 000 000
MAS (m^3/y)	26 700 000
CATCHMENT (km^2)	7618
CAP/MAF (year)	0.0004
CAP/MAS (year)	0.13

See Figure 3.109 for the CAP/MAF to CAP/MAS plot.

3.4.14. Sudan – Khashm El Girba: Management of Sediments in the Khashm El Girba Reservoir

3.4.14.1. Introduction

The Khashm El Girba (KEG) dam was built between 1960 and 1964 on the Atbara River in Sudan (one of the main tributaries of the Nile - Figure 3.111). The objectives covered by this project include flood regulation, irrigation of the Halfa area and hydroelectricity production using the water diverted for irrigation.

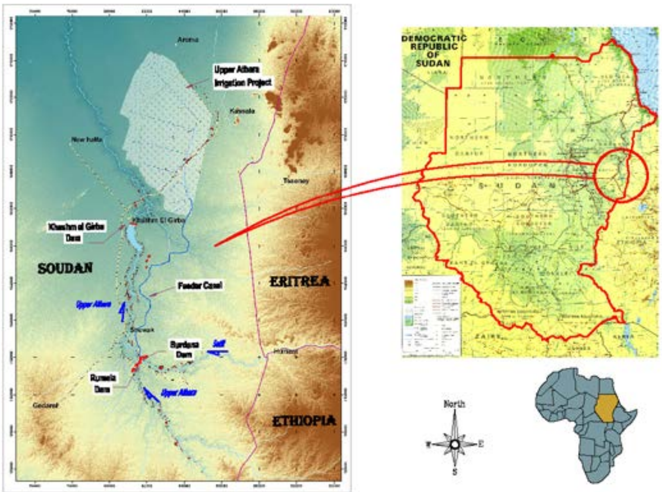


Fig. 3.111
Localization of the Khashm El Girba dam

3.4.14.2. Owners

The KEG dam belongs to the Sudan Ministry of Irrigation and Hydroelectric Power. From 1959 to 1964 Sogreah delivered complete engineering services from preliminary studies through to final commissioning (including scale model studies).

3.4.14.3. Hydrology

The KEG reservoir is located on the Atbara River, about 200 km downstream of the Ethiopian border. It collects the waters from the Setit and Upper Atbara rivers with catchment areas of about 70 000 km² and 30 000 km² respectively. The average annual volume of water entering the reservoir is about 12 billion m^3, with 60% of that volume coming from the Setit River.

The river has a highly seasonal regime since the major part of the discharge is concentrated in the summer months with large floods in August (up to 5 000 m^3/s for a two-year return period). Beyond this period, the river is limited to a thin trickle. Table 3.29 presents the annual yields of each branch for various return periods (values between brackets represent exceptionally dry years). We can see that the partition of the runoff is about 60%/40% regardless of the return period.

Table 3.29

Annual yields of Upper Atbara and Setit Rivers for various return periods

UPPER ATBARA DAM COMPLEX - Upper Atbara and Setit Rivers : Annual Yields (Mm³)									
Return period (Years)	(100)*	(50)*	(20)*	(10)*	2	10	20	50	100
Upper Atbara – Kubur	1400	1700	2200	2700	4900	7800	8750	9800	10500
Setit - Wad El Heliew	2250	2600	3400	4050	7100	11000	12200	13600	14700
			Percentage Upper Atbara and Setit						
Upper Atabara	38%	40	39	40	41	41	42	42	42
Setit	62%	60	61	60	59	59	58	58	58

* values between brackets = dry years

Figure 3.112 below shows the discharge in both rivers for each year for the 1965-2005 period. The “wet” season appears clearly between July and September.

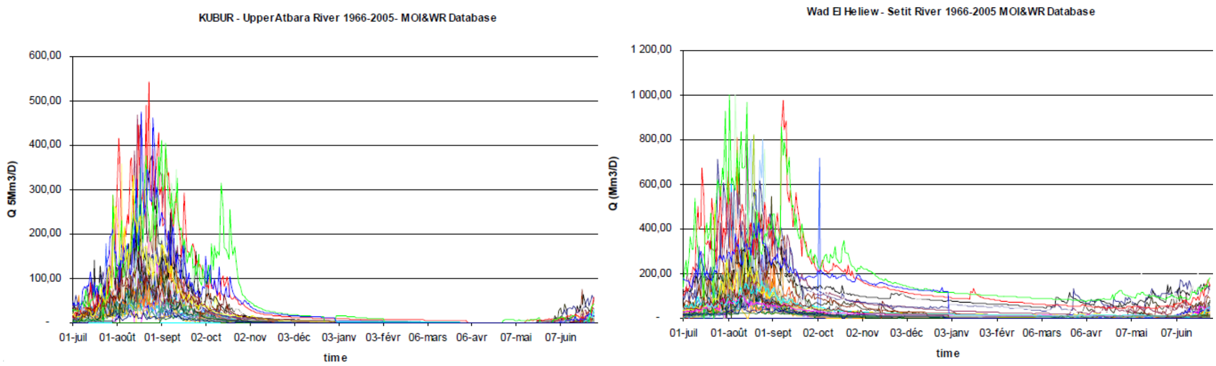


Fig. 3.112

Discharge in Upper Atbara (left) and Setit (right) rivers for each year in the 1965-2005 period

The flood regime of each river is specified in Table 3.30 below. Values have been updated thanks to a new study taking into account the 1956-1993 sampling period. Generally, the peak flood discharges have increased compared with the 1974 hydrology report.

Table 3.30

Peak flood discharges of Upper Atbara and Setit Rivers for various return periods

Upper Atbara river – peak flood discharges (Mm3/day and m^3/s) from 1956-93 sample					
Return period	2 years	10 years	100 years	1000 years	10000 years
Mm^3/day	170 Mm^3/d	300	465	625	790
m^3/s	1970 m^3/s	3475	5380	7250	9150
Previous study(*)	*1800 m^3/s*	*2800*	*4100*	*5400*	*8500*

Setit river – peak flood discharges (Mm3/day and m^3/s) from 1956-72 sample					
Return period	2 years	10 years	100 years	1000 years	10000 years
Mm^3/day	270 Mm^3/d	490	760	1040	1320
m^3/s	3100 m^3/s	5700	8800	12000	15300
Previous study(*)	*3700 m^3/s*	*5800*	*8200*	*10500*	*16000*

(*) Note Mougin 1/3/76 + SOGREAH report R 11728 feb 1974

3.4.14.4. Basic dam and reservoir data

The main concrete buttress dam is 67 m high and 490 m long (Figure 3.113). Additionally, about 3.5 km of earth fill embankments (18 m high) allow storing 1.3 billion m^3 of water for irrigation and hydropower. The normal operating water level was set at 473 m asl and the maximum reservoir level for a 1/5000 year flood was fixed at 474.5 m asl, 1.5 m higher.

The spillway has seven bottom radial gates 7.00x7.30 m able to evacuate 7700 m^3/s at the nominal water level and five surface sliding gates 7.00x7.10 m with an additional discharge of 1000 m^3/s also at 473 m asl.

The downstream power plant is equipped with two Kaplan turbines of 3.9 MW each and three bulb units (3x2 MW) working either as pumps or as turbines depending on the irrigation needs and on the reservoir level. An additional pumping station equipped with four vertical axis pumps (4x1.8 MW), each having a minimum discharge of 5 m^3/s, operating at the maximum head of 20 m, enables the water supply to flow into the irrigation channel when the water level in the reservoir falls below 450 m asl.

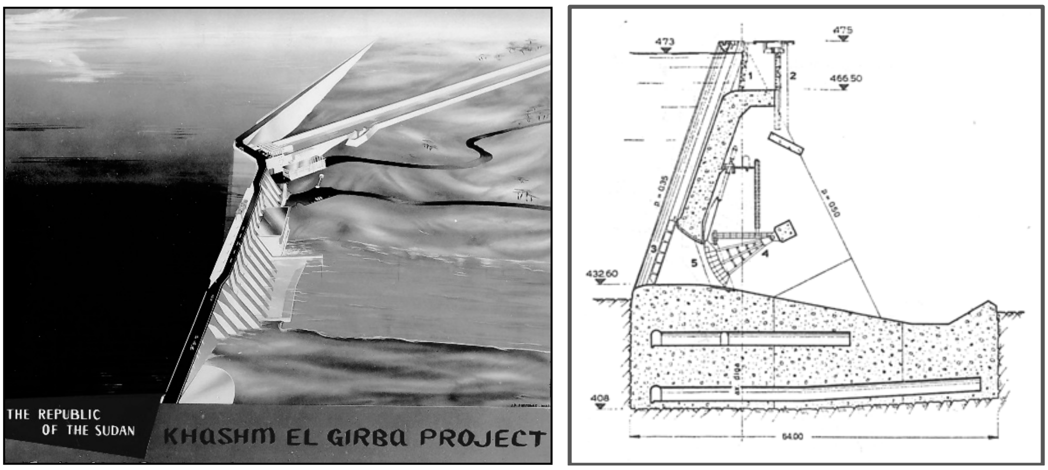


Fig. 3.113

General view and longitudinal section of the dam

3.4.14.5. Plot of capacity versus mean annual flow

Due to the large sediment transport rate during the summer floods, the reservoir volume has decreased constantly since the dam was built. As shown in Figure 3.114, it has lost about half of its capacity in twenty years (1964-1985).

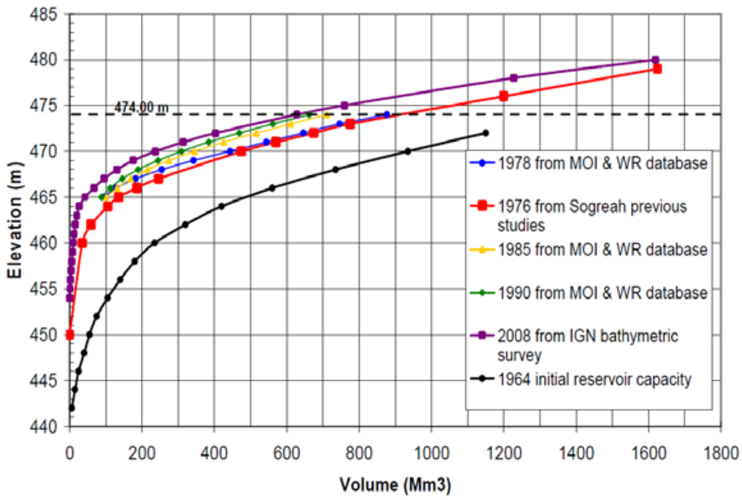


Fig. 3.114
Khashm El Girba reservoir capacity curves

3.4.14.6. Political issues

The dam is close to two major towns in eastern Sudan: Kassala is 75 km east of the dam near the Eritrean and Ethiopian borders and Gedaref is 120 km south of the dam. Both cities are governorates of eastern Sudan and have a significant role in this part of Africa as they have welcomed refugees from Ethiopia both after a large drought in the eighties and after the war between Eritrea and Ethiopia.

Moreover, the dam was originally designed as a single purpose project for irrigation of the New Halfa scheme. The aim of that project was to house the Halfawi Nubian families who had lost their homes and lands as a result of the Aswan Dam construction in Egypt which flooded more than 150 km of the Nile valley in Sudan.

3.4.14.7. Regulatory constraints

There is no particular disposition concerning environmental issues except the need for a constant supply of water for irrigation in the New Halfa area. By now, the water supply of about 100 Mm^3/year provided to the population of the New Halfa area is the only constraint assigned to the owner of the reservoir.

3.4.14.8. Sediment data of the site

A campaign to measure suspended particles was carried out in the 1970's on both the Setit and Upper Atbara Rivers, a few kilometers upstream of their confluence. The results revealed that the average yearly volume of sediment entering the reservoir was about 65 Mm^3 (56 Mm^3 coming from the Setit River and 9.6 Mm^3 from the Upper Atbara River). Sediment transport of the Setit River is considerably higher than that of the Atbara River which is consistent with the sediment yield of each branch.

These sediments are mainly made up of fine sand, silt and clay. They consist of material eroded from the catchment during the wet season and washed away during the rainy season.

Figure 3.115 presents the particle size distribution (in terms of mass) in the Atbara River upstream of the reservoir. The different curves represent various sampling depths but they show the same trend. About 20% of the sediments are 0.08 to 1 mm (sand), 30% are from 1 mm to 20 mm and

50% are larger than 20 mm (large gravels and some cobbles). The river bed composition of the Upper Atbara and Setit are rather similar: fine sand and gravels.

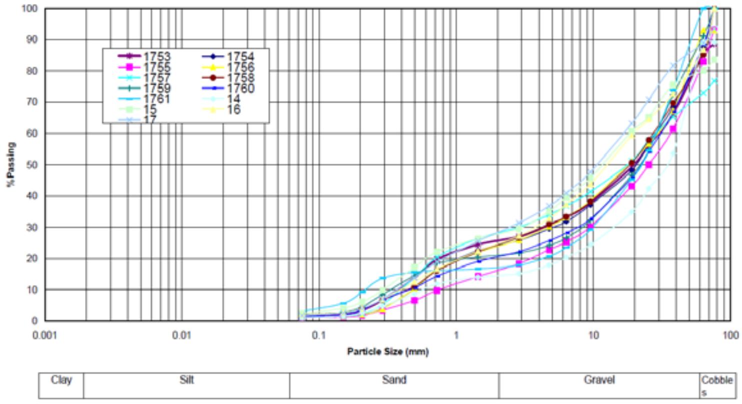


Fig. 3.115

Particle size distribution in the Upper Atbara River

Regarding the bed load component, no specific measurement was carried out on either the Upper Atbara or Setit Rivers. Nevertheless, on the basis of the sediment investigation at Roseires Dam (Gibb and Coyne et Bellier, 1996) the bed load component could be assessed as some 25% of the suspended load.

The following table summarizes the annual average sedimentation expected in the present condition for the Setit and Upper Atbara Rivers close to their confluence (at the entrance of Khashm El Girba reservoir). The computations are based on reconstituted series of discharges (10 day-discharges) over the 1956-1995 period. Volumes are larger than the estimation done in the 1970's.

Table 3.31

Annual average long-term sediment load (1956-1995 period)

	Suspended load volume	**Total sediment volume**
Upper Atbara River	11 Mm^3/year	14 Mm^3/year
Setit River	65 Mm^3/year	81 Mm^3/year

3.4.14.9. Classification of sediment management

The classification of the sediment management techniques is done considering the mean annual inflows of water and sediment to the reservoir. Figure 3.116 below shows the situation of the KEG reservoir in comparison with many other cases. We can observe it is close to the limit between being potentially sustainable and non-sustainable and the flushing method seems to be applicable here.

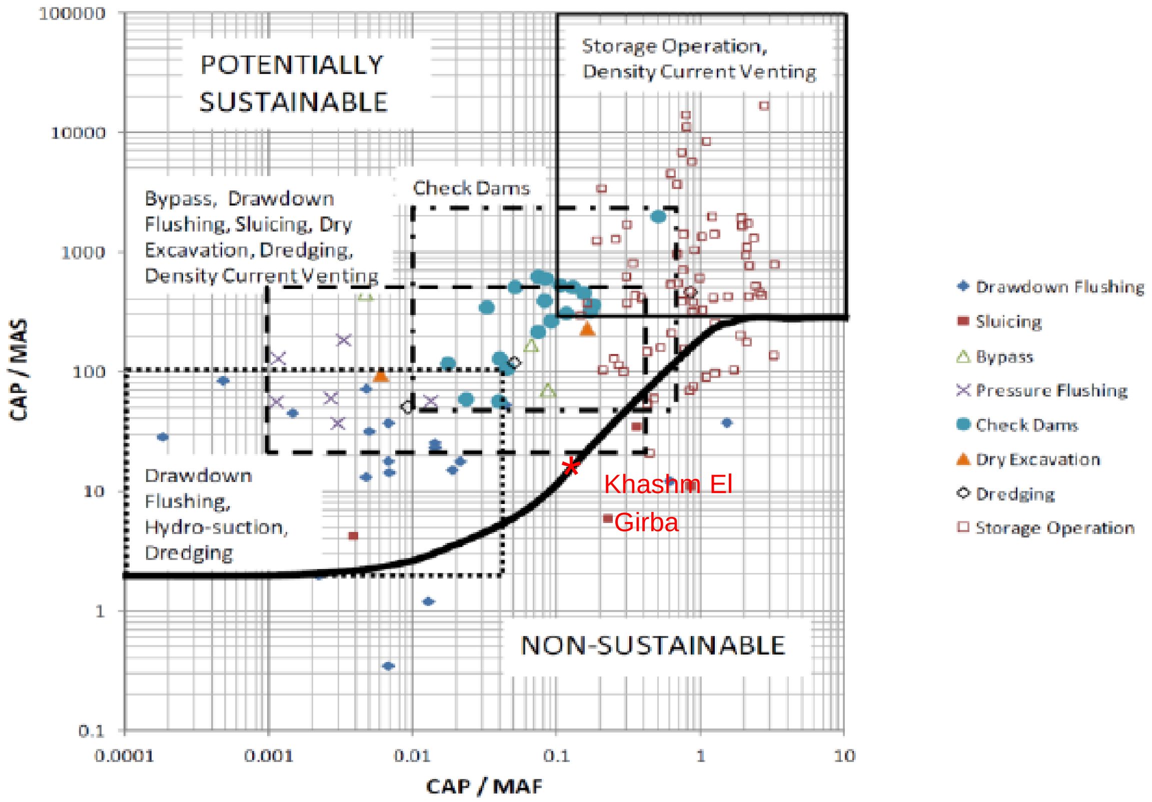


Fig. 3.116

Classification of sediment management approaches and situation of KEG reservoir

3.4.14.10. Experimental sediment flushing operations

Modification of the dam and reservoir for sediment management would have been inefficient. Thus, it was decided to plan flushing sequences to evacuate the accumulated sediments through the bottom gates.

This operation was programmed on the basis of analysis from Sogreah after the two experimental operations in 1971 and 1973. The program was adjusted in accordance with comments and requirements from the Ministry of Irrigation.

The initial flushing program proposed by Sogreah in 1974 was developed to evacuate part of the sediments from the reservoir. The idea was to organize two or three flushing events during the flood period in August. Prior to each flushing, the removal of accumulated timber was completed by raising the water level and spilling the water, along with the timber.

To respect the constraints of irrigation it was decided in accordance with the Ministry of Irrigation to split the flushing operation into two periods and to fill the irrigation channel before the operations. The flushing sequences done in July and August 1974 are shown in Figure 3.117, in terms of reservoir water level and outflow.

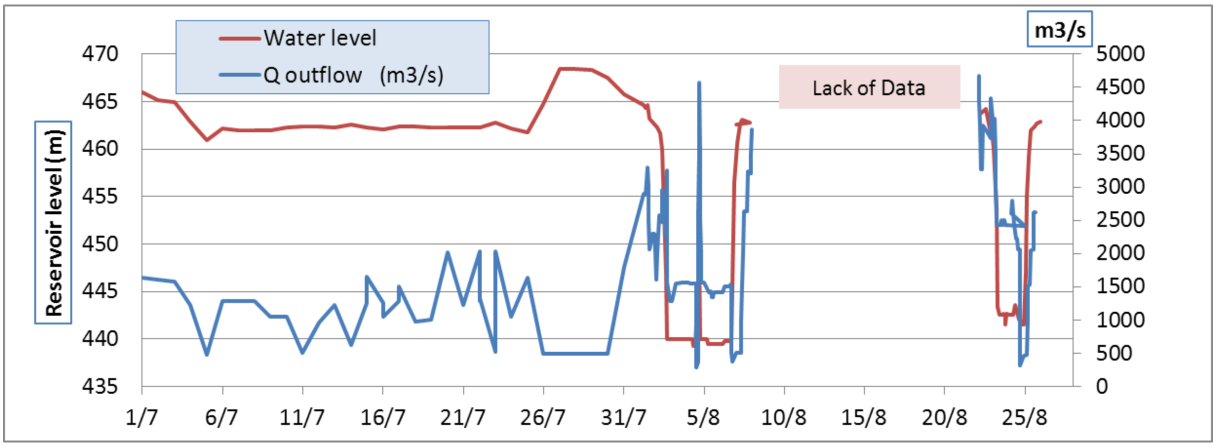


Fig. 3.117
Experimental flushing program as executed: reservoir water level and outflow discharge

The flushing sequences followed these steps:

1. By July 5, 1974, the reservoir was lowered to normal flood operating level at 462 m asl;
2. On July 25 the level was raised for timber spilling before lowering for flushing;
3. The drop was started on August 2 and the level was kept down longer than proposed in the initial program, in accordance with the program modification;
4. On August 4, a visit was made to an accessible reach of the river at Manaba (7 km upstream of the dam) and revealed the lateral limit of the scour into the deep deposits. It also revealed the presence of slump and potential slips in the steep sediment faces;
5. After raising the pool on August 6, the normal operating level was maintained. An exceptional flood occurred from August 10 to August 14. The outflow from the dam reached 6 500 m^3/s between August 12 and August 13.

This flood brought large quantities of floating timber to the reservoir (Figure 3.118). New flushing operations were impossible before timber removal; consequently, the water level was raised to 469 m by August 17, in order to spill the timber through the surface sluice gates. On August 19, lowering started for the second flushing operation. The second flushing operation was carried out on August 23 and August 24.

Fig. 3.118
Aerial view of the dam (left) and typical timber accumulation at the turbine entrance (right)

3.4.14.11. Efficiency of the flushing operation

The amount of sediment passing through the reservoir from July 1 to August 26 was evaluated as 37x10^6 tons. No measurements of sediment inflow were available for the period, but the estimated sediment transport of the river was clearly below the measured outflow. That suggests that a large part of this sediment load corresponded to the erosion of the previous year's deposits which were exposed to erosion when the reservoir was dropped to the normal flood season operating level.

The evolution in the sediment outflow from the dam during the flushing operation from August 1 to August 7 and during that from August 22 to August 25 is similar. The sediment concentration was very high at the beginning of the operation but tailed off rapidly as shown in Figure 3.119.

The stabilization value, towards the end of the six-day period of the first flushing sequence, was very similar to the measured and estimated average sediment inflow rates at that time. The rapid fall off in sediment concentration indicated the lack of usefulness in prolonging the low-level period.

The total recorded sediment outflow from the dam for the two flushing periods was estimated at 85.5 M tons. Unfortunately, no sediment outflow measurements were available for the period between the two flushing operations. Yet the estimated average annual sediment inflow was considered to be about 85 M tons (from measurements up to 1973 and statistical analysis).

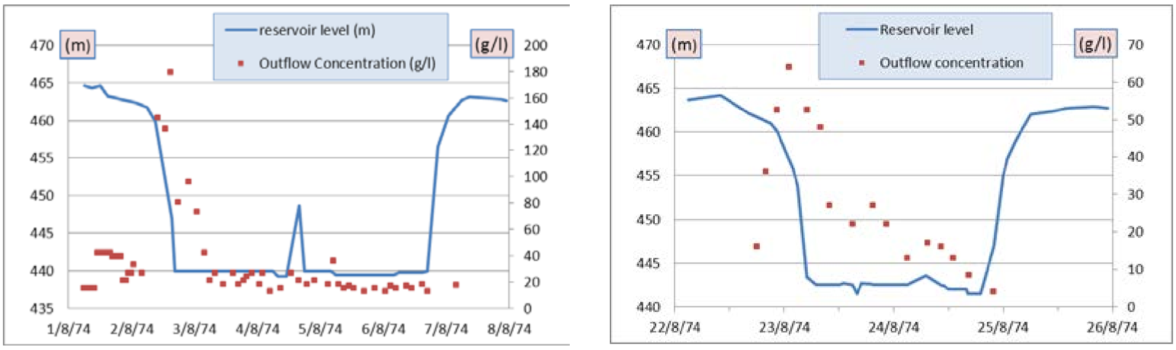


Fig. 3.119

Details of the first and second flushing sequences (reservoir level and outflow concentration)

It seemed reasonable to expect that two flushing operations, of three days duration each per year, could be sufficient for maintaining an optimal state of reservoir sedimentation equilibrium.

The two flushing operations ensured that the main stream in the vicinity of the dam was kept clear from bed deposits (figure 3.120). To maintain a deep main channel it is probably beneficial to concentrate the deposit of fine sediment into the channel during operations at a level of 462 m, during flood season. This deposit could be removed by subsequent low-level operations.

The timing of the first operation at the beginning of August and the second towards the end of August appeared to be the best arrangement with regards to sediment removal, as well as for satisfaction of irrigation requirements.

For timber removal the only reliable method available seemed to be to raise the water level along with the timber, and then to spill the timber over with the water.

The methods developed for operation of electro-mechanical equipment during flushing operations appeared satisfactory.

Fig. 3.120
Upstream (left) and downstream (right) views of the flushing operation

3.4.14.12. Long term results of the sediment flushing operations

The flushing program has been followed closely by the KEG management. Figure 3.121 shows the typical variation of water level compared with the revised reservoir operating scheme for silt flushing from 1974 up to 2007:

- Beginning in July, the reservoir is set to a normal flood operating level of 462 m asl;
- When a flood occurs (mid-July), the gates are closed and the water level is raised to 468.5 m asl for timber spilling;
- The water level is lowered at a rate corresponding to a constant emptying discharge of 1 000 m^3/s for sediment flushing until it reaches 440 m asl;
- The level is raised to 462 m asl by closing the gates to refill the irrigation system before starting a new flushing sequence.

It has been reported by several sources that many problems related to sedimentation have been identified after a few years of operation of the KEG Reservoir. A delta was created at the tail of the reservoir above the normal level of the reservoir (i.e. 473.5 m). Nevertheless, the sedimentation rate in the reservoir has fallen drastically from about 50 Mm^3/year to 10 Mm^3/year after 1974 (when the flushing operations began).

Figure 3.122 shows that the reservoir volume and the sedimentation rate have decreased since flushing operations started in 1974.

3.4.14.13. Upper Atbara Project, Rumela and Burdana dams

Two new dams are planned upstream of the KEG reservoir with a new evaluation of the hydrology and sediment data. The goals are to develop new irrigated zones, produce electricity and above all control the siltation of the KEG reservoir. The new dams would be located on the Setit River (Burdana) and Upper Atbara River (Rumela) a few kilometers upstream of the confluence. We can expect that these two reservoirs would behave similar to the KEG Reservoir in terms of sedimentation. Table 3.32 summarizes the data for each reservoir:

To handle the potential siltation problems of these two new reservoirs, the same flushing plan as that of the KEG reservoir will be adopted immediately after the construction of the dams. Well-coordinated flushing events at the three reservoirs should keep a good equilibrium in terms of siltation for many years.

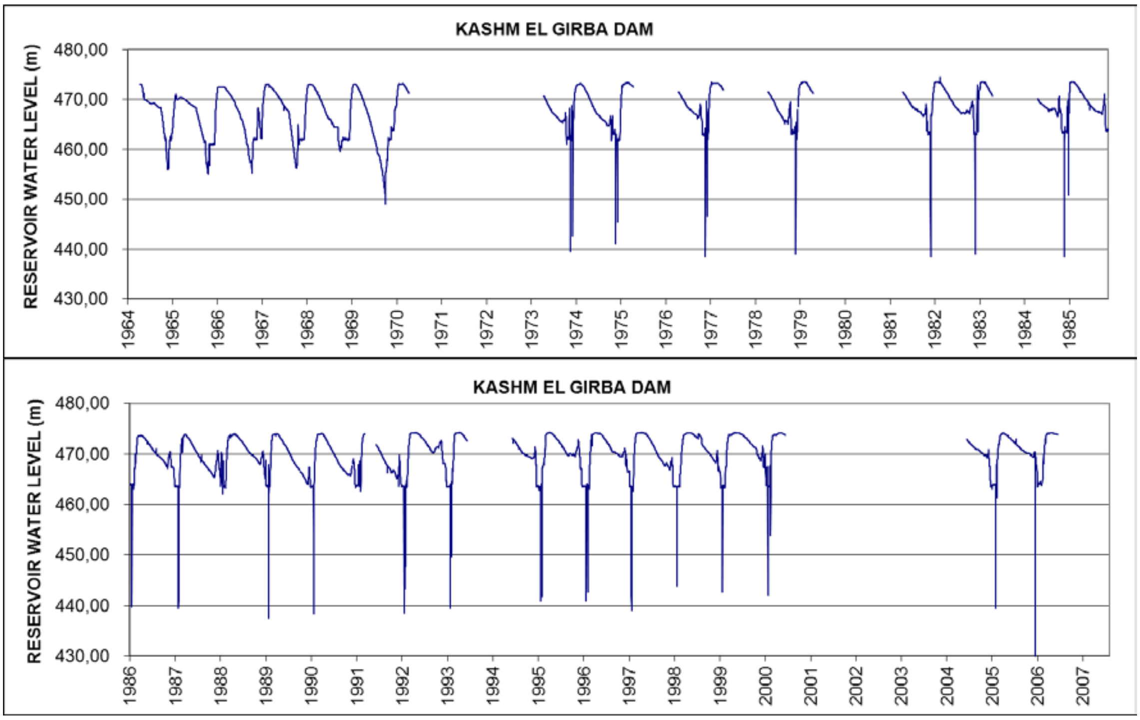


Fig. 3.121
Water level in the reservoir since 1964

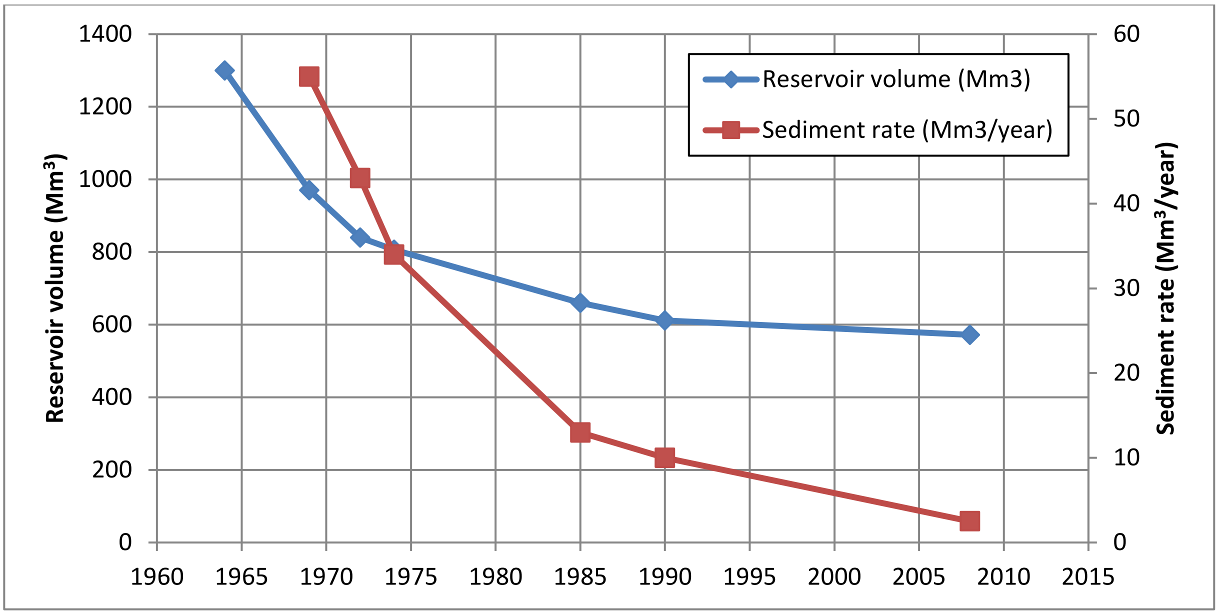


Fig. 3.122
Reservoir volume and sediment rate evolution since the dam was built

Table 3.32
Yield data per year for the Upper Atbara project dams

	Annual inflow (Mm³)	Annual sediment load (Mm³)
Khashm El Girba (Atbara)	11 800	95
Burdana (Setit)	7 100	81
Rumela (Upper Atbara)	4 900	14

KHASHM EL GIRBA

Location: Sudan, Atbara River
Cost of sediment management: Unknown
Management option: Operational flushing

Reducing sediment inflow
Not applicable
Preventing deposition
Not applicable
Removing sediment
⇨ Flushing

Main characteristics

Uses	Irrigation and Hydropower
Dam Type	Concrete buttress
Dam height (m)	67
Dam length (m)	490
Gross storage (m^3)	1 300 000 000
Catchment area (km^2)	100 000
Design discharge(m^3/s)	Unknown

Key features

CAP (m^3)	1 300 000 000
MAF (m^3/y)	11 800 000 000
MAS (m^3/y)	95 000 000
CATCHMENT (km^2)	100 000
CAP/MAF (year)	0.11
CAP/MAS (year)	13.7

See Figure 3.116 for the CAP/MAF to CAP/MAS plot.

3.4.15. United States – Spencer Reservoir: Management of Sediments in Spencer Reservoir

3.4.15.1. Introduction & Owners

The Niobrara River Basin covers approximately 35 060 km^2 (13538 square miles) of northern Nebraska, southern South Dakota, and eastern Wyoming in the United States (Figure 3.123). The Niobrara River drains the northern portion of the sandhills physiographic region in Nebraska and South Dakota. Land use within the basin is primarily agricultural (ranching and farming). There are no major impoundments on the main stem, but a number of minor impoundments exist including Box Butte Dam and Spencer Dam. These and other similar impoundments have affected channel morphology in the Niobrara River Basin significantly over time (Buchanan, 1981). Development within the basin has been primarily related to center pivot irrigation. Over the nearly 900 km (560-mile) course of the Niobrara River, the channel elevation drops from approximately 1 676 m (5 500 feet) to 372 m (1 220 feet) above mean sea level for a total elevation difference of roughly 1 305 m (4 280 feet) (Alexander et al. 2009).

Most flows in this sand-bed river are fed by groundwater and tributary inflows. The Niobrara joins the Missouri River in northeast Nebraska near the town of Niobrara. The confluence is just upstream of the headwaters of Lewis and Clark Lake, which is the most downstream reservoir on the Missouri River main stem system. The Niobrara River supplies 55 to 60% of sediment that enters Lewis and Clark Lake. The delta formed at the confluence is causing increased surface water flooding, increased groundwater levels, water quality and water supply problems for municipal water intakes, recreation access problems, and impacts to endangered species habitat. Cities, counties, landowners and local businesses, as well as the Santee Sioux Tribe have expressed an interest in managing Niobrara River sediments as a means of minimizing delta related impacts (Ayres, 2008).

Spencer Dam is located on the Niobrara River about 60 kilometers (40 miles) upstream from its confluence with the Missouri River. The main purpose of the project is to generate electricity. The reservoir experiences serious sedimentation issues due to the high sediment concentration inflows from the upper Niobrara basin (Nebraska Sandhills region) that fill the operational pool in a few months. Therefore, for the last 60 years, operators have flushed the reservoir twice annually to keep an operational pool open.

The Spencer Dam and hydropower project (“Spencer hydro”) is owned by the Nebraska Public Power District. The Spencer hydro project has been operating since 1927. Its two Westinghouse generators have a combined maximum capacity of 3000 kilowatts per hour. The Spencer hydro project is the only hydroelectric plant on the Niobrara River. Spencer’s peak generation year was 1957 when it produced 15 059 MWh of electricity.

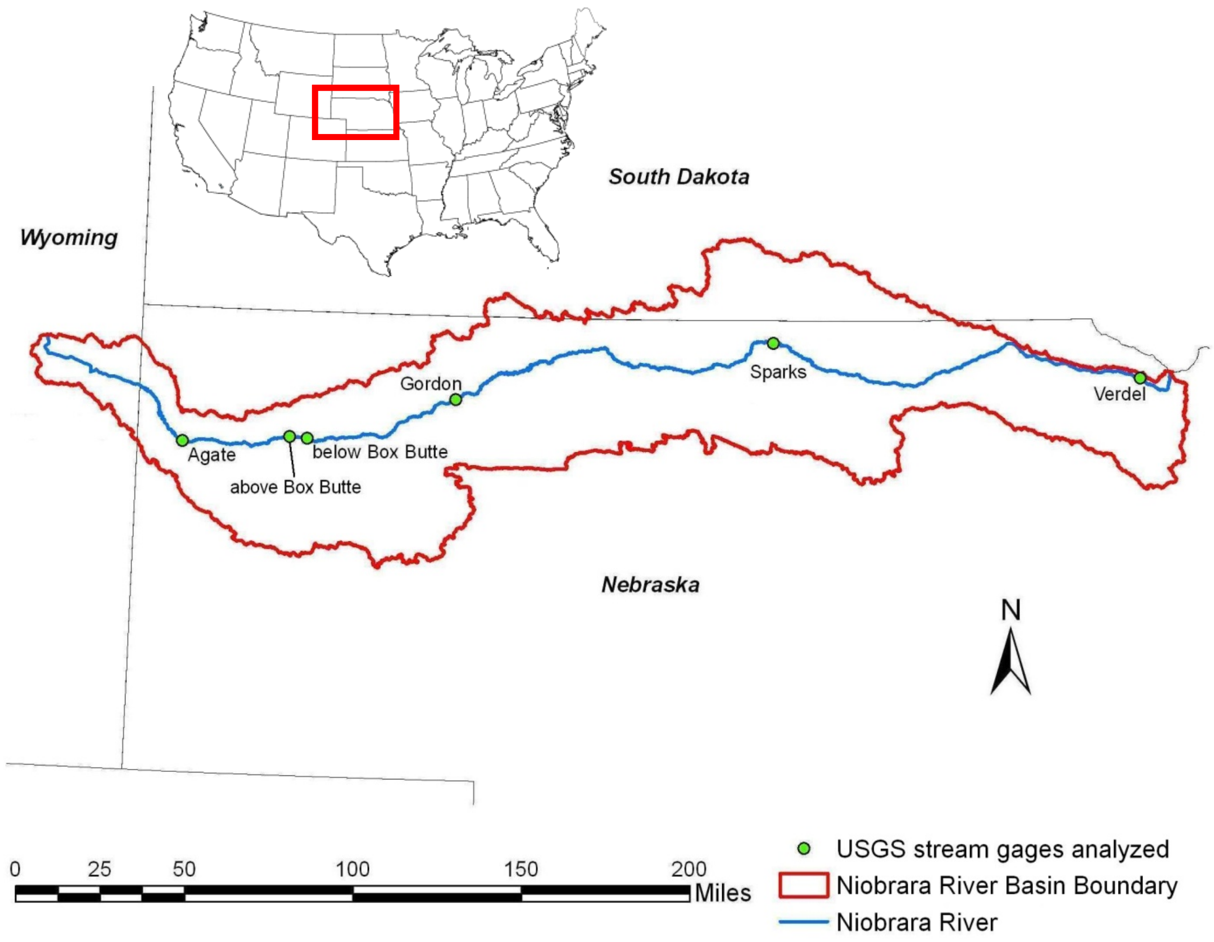


Fig. 3.123
Niobrara River Basin location map and primary USGS stream gaging stations

3.4.15.2. Hydrology

The Niobrara River near Verdel, Nebraska stream gage (#06465500) is located approximately 24 km (15 miles) upstream of the confluence with the Missouri River. The gage has been active since 1938 and had a total of 71 annual peak flows recorded at the time of the analysis (WEST, 2010b).

Spencer Dam is located on the Niobrara River approximately 60 kilometers (40 miles) upstream of the confluence and although used primarily for hydropower generation does provide a limited amount of flood regulation. Guidelines from IACWD Bulletin 17B (Interagency, 1982), which recommend the use of the Log Pearson Type III distribution as a base method for flood frequency studies, were used to determine frequency flows. The distribution requires estimating of three moments: the mean, standard deviation and skew, with the skew parameter being the most sensitive to extreme events. The recommendations are typically considered applicable only to streams with unregulated flows; however, because Spencer Dam provides only a minor amount of regulation for high flow events that are of interest in this study, Bulletin 17B procedures were still considered applicable. For the flood frequency analysis for the Niobrara River, the computed station skew value of 1.197 was taken as the adopted skew without weighting with the regional skew. Table 3.33 summarizes the results of the frequency analysis based on the computed frequency and expected probability curves.

Table 3.33
Flood Frequency Estimate for Niobrara River near Verdel, Nebraska

Return Period (years)	**Computed Frequency Discharge (m^3/s)**	**Computed Frequency Discharge (ft^3/s)**
500	1 930	68 210
100	1 035	36 620
50	785	27 750
10	400	14 030
5	290	10 160
2	175	6 210

A flow duration curve was obtained from the WEST (2010a) study and is shown in Figure 3.124. It was created by using the daily mean discharge information for the period of record (May 1938 – July 2009) at the Niobrara near Verdel, Nebraska, gage #06465500. The daily mean flow values were sorted in decreasing order and ranked sequentially. Based on this analysis, the mean annual flow is 43 m^3/s (1510 ft^3/s).

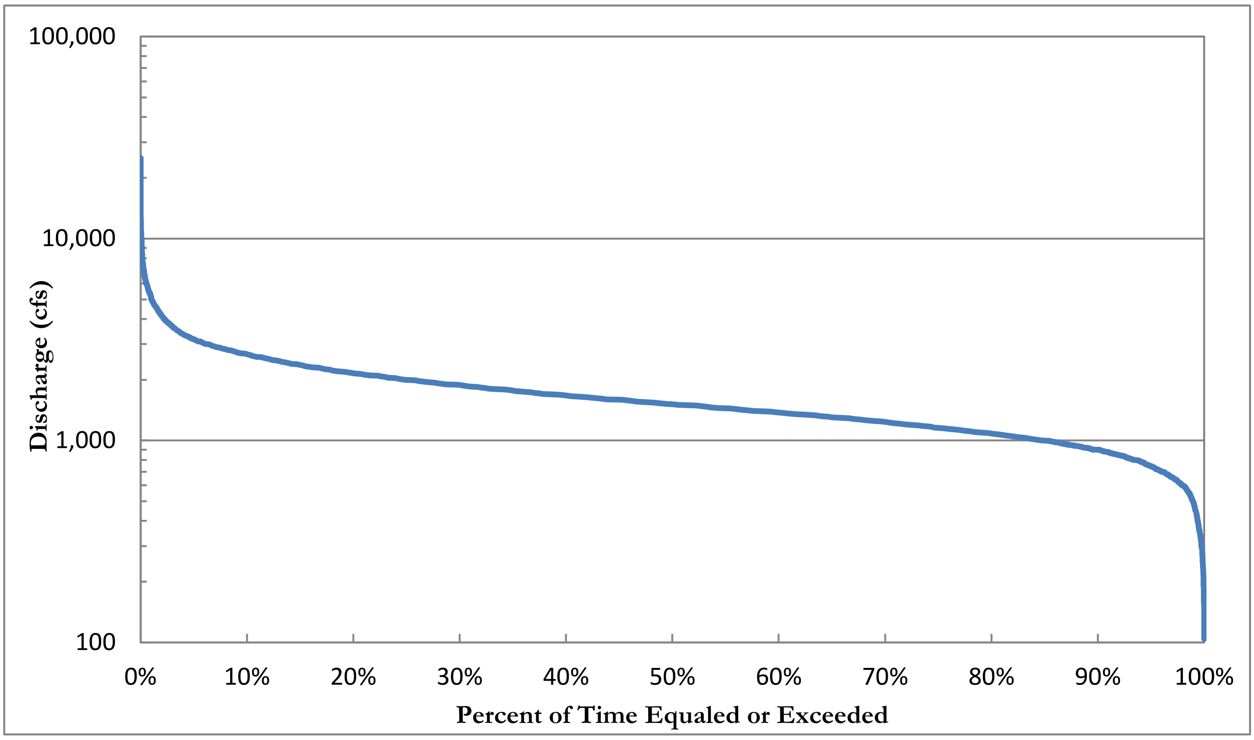


Fig. 3.124
Flow Duration Curve for Niobrara River near Verdel Gage #06465500

3.4.15.3. Basic Dam / Reservoir Data

Spencer Reservoir was formed in 1927 by the construction of Spencer Dam. The project was built to develop hydroelectric power by the use of the relatively uniform discharge through a head of about 20 feet created by the dam. The reservoir is kept full except for the short periods when it must be flushed to remove sediment which has encroached to the point that it is going through the turbines, or to regain storage capacity.

The dam is an approximately 10 m (30 ft.) high structure consisting of a concrete section with Tainter (radial) gates and stop logs across the original channel along the left side of the valley, and an earth-fill section extending across the floodplain to the right side of the valley. The Dam has four Tainter gates and one ice sluice gate. A photograph of the spillway and powerhouse taken from downstream of the dam is shown as Figure 3.125. To the left of the photograph one can observe five 10 m (33 feet) wide bays containing wooden stop logs inserted in H beams which are normally left in place except in instances of large flood events. Basic information about the dam is given in Table 3.34.

Fig. 3.125

Downstream face of Spencer Dam spillway and powerhouse (public domain photograph)

Table 3.34

Spencer Dam Information (NID, 2015).

Item	Description
U.S. National Inventory of Dams ID	NE00628
Dam Height (top of the dam to the lowest point along the downstream toe)	10 m (29 feet)
Dam Length	1 128 m (3700 feet)
Structural Height (top of the dam to the lowest point of excavation during construction)	13.7 m (45 feet)
Hydraulic Height (from the maximum designed reservoir level to the lowest point along the downstream toe	7.9 m (26 feet)
Normal Storage (below the lowest spillway opening)	6.54 x 10^6 m^3 (5,306 acre-feet)
Max. Storage (at the maximum reservoir elevation)	20.34 x 10^6 m^3 (16,487 acre-feet)
Storage Area (at normal pool)	350 ha (864 acres)
Drainage Area	28 670 km^2 (11070 square miles)
Maximum Recorded Flow (design discharge unknown)	560 m^3/s (19,7700 cubic feet per second) on 22 July 2010
Head	~6 m (20 feet)
Turbines	2 Kaplan turbines
Year Constructed	1927

Table 3.35
Structural characteristics of the dam

Spencer	
Dam type	Earth with concrete spillway section
Function	Power generation
Dam height (m)	8.8
Dam length (m)	1,128
Gross Storage (m^3)	6.54 x 10^6 m^3
Catchment area (km^2)	28 700
Design discharge (m^3/s)	Unknown
Storage area (ha)	350
Type of spillway	4 Tainter (Radial) Gates: 4m (13 feet) high, 10.2m (33.5 feet) wide 1 Sluice Gate: 3m (10 feet) wide, 5.5m (18 feet) high 5 bays with stoplogs – 10m (33 feet) wide

3.4.15.4. Capacity versus Mean Annual Flow

As described earlier, mean annual flow is approximately 43 m^3/s. Over a year this yields a volume of 1.348 * 10^9 m^3. The maximum reservoir storage is 20 116 415 m^3, while the normal storage is 6 544 855 m^3. Thus, the maximum capacity/mean annual flow ratio is 0.015 while the normal capacity ratio is 0.005. The estimated annual sediment load at the dam is 1.5 M t/y (WEST 2010a). Using a submerged specific gravity of 1.65, this can be converted to an annual volume of 1.08 million m^3 (29.13 M ft^3). This gives a maximum storage capacity to sediment inflow ratio of approximately 18.6. According to Sumi's (2013) analysis of sediment management of dams in Japan, flushing should be a reasonable sediment management option for the Spencer project (Figure 3.126).

3.4.15.5. Political Issues

There are no known political issues associated with this project. This is most probably due to a) the length of time that the project has been operating with the periodic sediment flushing and b) the relatively sparsely populated area near the project.

3.4.15.6. Regulatory Constraints

Periodic flushing of sediments at Spencer Dam is recognized as causing temporary high flows and sediment concentration in the released waters although these are limited in both space and time. Past environmental studies have investigated various aspects of the releases (dissolved oxygen, turbidity, suspended solids, etc.) and their impact on fauna (Hesse & Newcomb, 1982; Gutzmer et al., 2002). Early April and early October were chosen as the usual flushing times due in part to the least impact on fish due to their downstream migration patterns at these times.

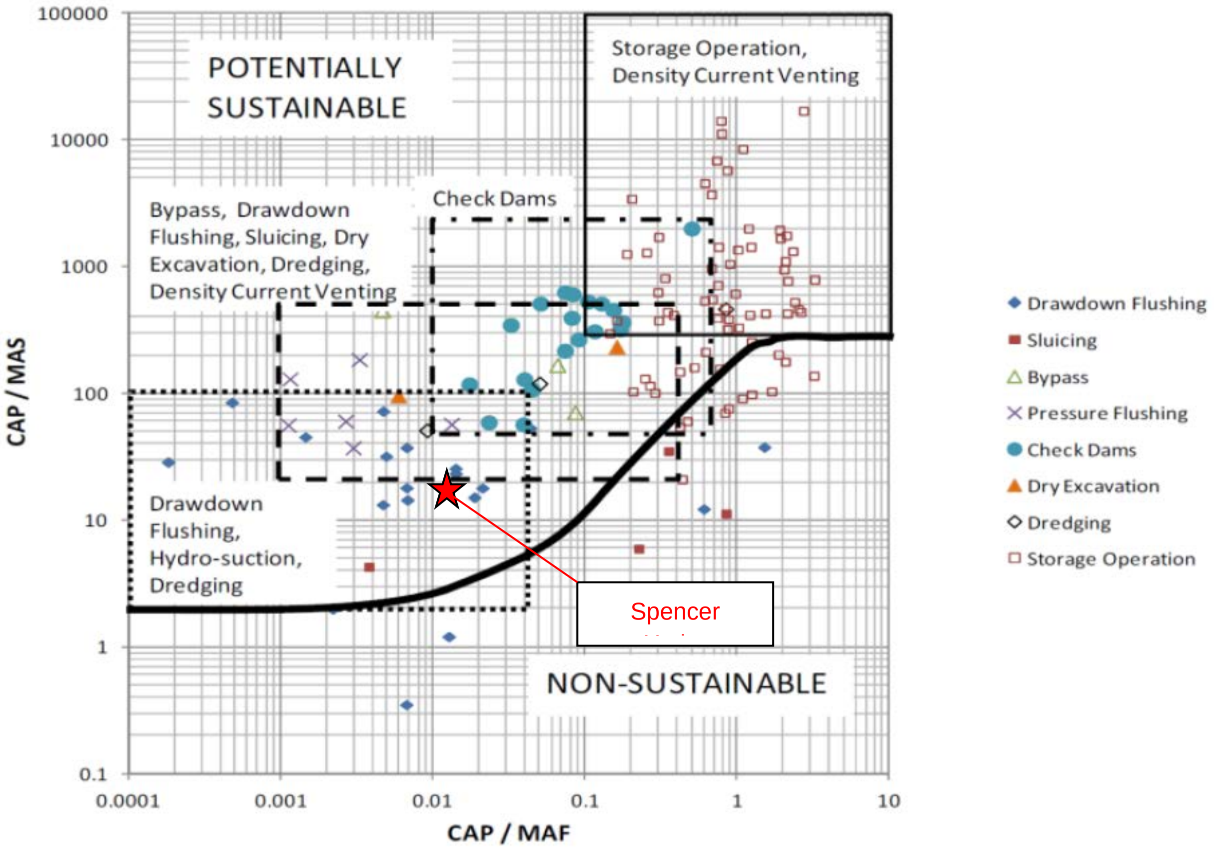


Fig. 3.126

Classification of sediment management approaches with Spencer hydro added

Although the project operated for many years without a permit, recently it has obtained a permit to discharge sediment per provisions of United States Federal Law. Specifically, a permit issued by the U.S. Army Corps of Engineers (USACE) under Section 404 of the Clean Water Act (United States Code of Federal Regulations, Title 33, Section 1344, also written as 33 CFR 1344) allows:

> “opening the gates to flush accumulated sediment (sluicing) through the Spencer Dam Hydro Facility to allow for continued operations of the dam and hydro plant. Sluicing is conducted twice a year (spring and fall). Each sluicing event passes approximately 176,000 cubic yards of material for a total of 352,000 cubic yards per year. Planned sluicing events are conducted outside of the spawning period for fish species to minimize impacts and to avoid tern and plovers nesting. A permit will be valid for five years if issued and a reevaluation will be conduct at the end of a five-year period. The applicant will be required to notify the USACE 30 days prior to a sluicing event.”

Section 401 of the Clean Water Act (33 CFR 1341) also applies which requires that all discharges of fill material must be certified by the appropriate state agency as complying with applicable effluent limitations and water quality standards before a Department of the Army permit can be issued. Certification expresses the state's opinion that the discharge will not violate applicable water quality standards.

Other considerations included in the permit application were:

- AVOIDANCE, MINIMIZATION, AND MITIGATION: The applicant provided avoidance and minimization measures for impacts. The applicant also had to provide alternatives to the proposed project which consisted of no action, and hydraulic dredging with disposal to containment facilities.
- CULTURAL RESOURCES: To receive the permit, the project must demonstrate that it is in compliance with the National Historic Preservation Act of 1966 and its amendments, as well as the procedures set forth in 33 CFR 325. The National Register of Historic Places was checked, and there are no known National Register sites in the vicinity. As part of the public notice issued by the Corps, they solicited input from the State Historic Preservation Office, Native American Tribes, and the public.
- ENDANGERED SPECIES: In compliance with the Federal Endangered Species Act, a preliminary determination was made that the work would not affect species designated as threatened or endangered or adversely affect critical habitat. The Corps solicited comments from the U.S. Fish and Wildlife Service and other interested agencies and individuals on this determination.
- FLOODPLAIN: This activity was reviewed in accordance with Executive Order 11988, Floodplain Management, which discourages direct or indirect support of floodplain development whenever there is a practicable alternative. Comments were requested from individuals and agencies that believe the described work will adversely impact the floodplain.

For the Spencer Dam sediment flushing project, no comments were received within the 21-day window after release of the public notice in May, 2014. The "section 404" permit was issued in September 2014 and is valid for five years. The Nebraska Public Power District is required to notify the U.S. Army Corps of Engineers 30 days prior to a sluicing event.

3.4.15.7. Sediment Data

According to Spencer Dam personnel, the only source of sediment data for Spencer Reservoir is from a study conducted by Hotchkiss and Huang (1994) to determine the feasibility of installing a hydrosuction sediment removal system at Spencer Dam (WEST, 2010a), which included two sediment samples from Spencer Reservoir. The sample located in the middle of the reservoir was chosen to represent the sediment size gradation for the Spencer Dam flushing load calculations. The sediment sample included a particle size distribution and net weight within each grain size class. The annual load for each grain size class was calculated by multiplying the percentage of the total weight for each grain class by the total annual sediment load from flushing, 538 200 tons. The sample gradation and load calculations are shown in Table 3.36. As can be seen from the gradation, over 90% of the sample is fine to medium sand.

3.4.15.8. Classification of Sediment Management

The biannual operations at Spencer Dam can be classified as flushing or sluicing. No attempt is made to time the releases with high inflows. Photographs of the reservoir during flushing and at peak storage are shown as Figure 3.127.

The sluicing operation usually consists of the following procedure: The turbine gate is closed. The stop log above the Tainter gate in the small sluiceway next to the powerhouse is completely raised, and the Tainter gate below is opened to its maximum extent. Then either one or two of the spillway

Tainter gates are raised about one meter. Maximum draw-down occurs within about 30 or 40 minutes. The sills of the spillway Tainter gates are set so high (only about 5 m below full pool) that drawdown does not exceed this amount unless the river flow is small enough to be carried entirely by the narrow sluiceway against the powerhouse. Consequently, there is usually a small pool against the dam and powerhouse even when all gates are open. During the period that the pool is drawn down there is considerable bed scouring and banks start sloughing in the channels carrying the major flow. Many of the chunks which fall from the banks do not disintegrate immediately but are rounded into balls of various sizes and are rolled for some distance by the current. Trains of sand waves are constantly forming and breaking. The flow is very muddy from the bank erosion of clays and has a high sand content. The channels are definitely deepened only a few hundred yards upstream from the dam, but the increased slope farther upstream in the main channels causes an accelerated movement of bed material in the form of bars. The effective upstream limit of this activity has not been definitely located. When the gates are closed the pool begins to refill rapidly. The turbine gate is not fully opened until the reservoir has refilled to about 1 m of full pool. There is some accumulation of sediment in the turbine intake channels, resulting from turbulence during sluicing but this sediment is largely flushed out as soon as the turbine gates are opened.

Table 3.36

Sediment Sample from Spencer Reservoir (Hotchkiss and Huang, 1994).

Percent Finer	Particle Size (mm)	Net Weight (lbs)	Percent of Weight	Annual Load (tons)
0.2	0.00-0.08	0.003	0.18%	991
3.0	0.08-0.15	0.046	2.82%	15 198
28.5	0.15-0.25	0.416	25.54%	137 441
90.7	0.25-0.43	1.012	62.12%	334 351
95.6	0.43-0.50	0.080	4.91%	26 431
98.2	0.50-0.60	0.042	2.58%	13 876
99.0	0.60-0.71	0.014	0.86%	4 625
99.4	0.71-0.85	0.006	0.37%	1 982
99.8	0.85-1.18	0.006	0.37%	1 982
99.9	1.18-2.00	0.002	0.12%	661
100.0	2.00-4.75	0.002	0.12%	661
Total Weight		**1.629**	**100%**	**538 200**

Fig. 3.127

Spencer Reservoir (a) During Flush and (b) Near Maximum Pool

3.4.15.9. New Dam Versus Retrofit of Existing Dam

As mentioned in the introduction, Spencer Dam has been operating with its current configuration and periodic sediment flushing since the 1930s. No retrofits are anticipated at this time.

3.4.15.10. Special Items

The Niobrara River feeds into the Missouri River about 60 km below Spencer Dam. The Niobrara feeds a large amount of sediment to the Missouri River at Lewis and Clark Lake which has resulted in the formation of a delta at the upstream end of the lake. Although the loss of storage capacity is not yet a major concern due to the size of the reservoir, the resulting blockage of drinking water intakes, increase in groundwater levels, and increase in water surface elevations upstream of the delta has impacted local populations and crop production. The U.S. Army Corps of Engineers is currently proposing to use Spencer Dam and its sediment flushing to aid in development and calibration of a much larger model of the main stem Missouri River that will be used to examine sediment management alternatives for Lewis and Clark Lake.

3.4.15.11. Economics / Sustainability

Detailed economic data is not available from the private dam owner. The project is sustainable as it temporarily stores sediment coming from the upstream watershed and then releases it during flushing operations twice a year.

SPENCER

Location: United States of America on the Niobrara River

Cost of sediment management: Only minor costs other than lost electricity production

Management option: Sluicing

Reducing sediment inflow

Not applicable

Preventing deposition

Not applicable

Removing sediment

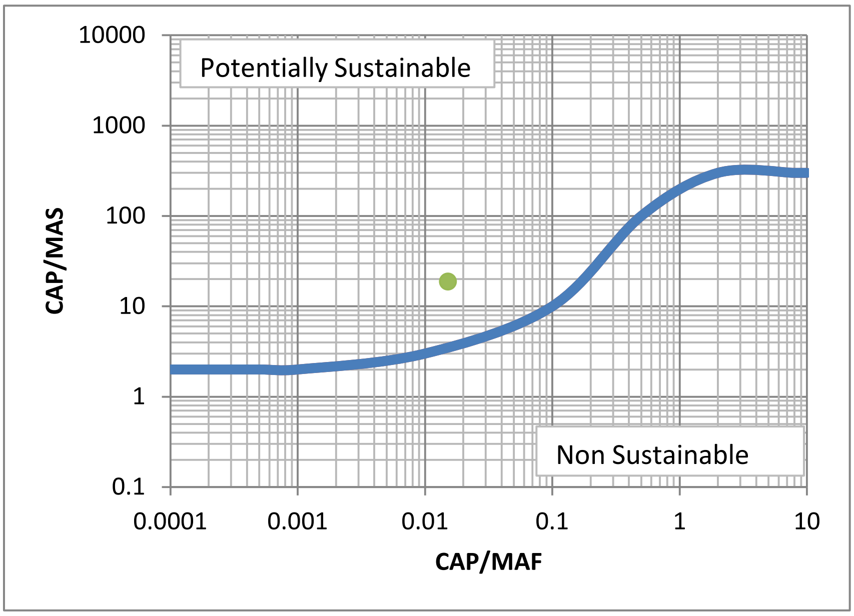
- ⇨ Flushing
- ⇨ Sluicing

Main characteristics

Dam type	Earth with concrete spillway section
Function	Power generation
Dam height (m)	8.8
Dam length (m)	1 128
Gross storage (m^3)	6.54 x 10^6
Catchment area (km^2)	28 700
Design discharge(m^3/s)	Unknown

Key features

CAP (m^3)	5 100 000
MAF (m^3/y)	1 348 000 000
MAS (m^3/y)	1 080 000
CATCHMENT (km^2)	28 700
CAP/MAF (year)	0.015
CAP/MAS (year)	19


Potentially Sustainable
Non Sustainable
CAP/MAS
CAP/MAF
10000
1000
100
10
1
0.1
0.0001
0.001
0.01
0.1
1
10

3.5. SYNTHESIS OF CASE STUDIES

The case studies presented herein form only a small subset of projects where sedimentation is an issue and/or is actively being managed. However, we hope that the reader will gain from the experience of others an idea of the studies and management techniques that have been tried and are currently being used to create a more sustainable project.

The samples can generally be divided into two groups. In the first, flushing or sluicing sediment is used where appropriate from technical, environmental and legal perspectives. The second group includes technical solutions such as dredging, addition of structural elements, or adaption of existing installations. In some cases there is combination of techniques from the two groups.

For some of the case studies the sedimentation rate is only reduced, with overall reservoir sedimentation still progressing. This will prolong the life of the project although it does not provide a sustainable solution for the long term. Other case studies provide truly sustainable solutions, preserving or even restoring active reservoir volume. Of course, the aim of all of the case studies is to reduce sedimentation issues while subject to local regulatory, logistical, and financial restrictions. Given the variability in project types and environmental settings, sediment management needs to be examined for each project individually. The case studies within this bulletin show there is no one-size-fits-all solution available.

The case studies do provide information from a technical perspective and in some cases include budgetary information, although the latter was harder to come by. Information on the commercial benefit of the proposed or executed solutions is generally not included as operators tend to restrict distribution of information about value of water losses or power production.

The case studies demonstrate that each operator is required to find an individual optimum according to their demands and constraints. The case studies may lead an operator to consider different options and also be open to adaptive management as results of the management techniques become apparent over time. Also, some of the cases show that it is wise to critically check earlier concepts or designs, as a number of earlier studies did not meet their sedimentation reduction goals when put into practice.

Learning from past experience and using new insights, the sample cases show the wide range of activities that are being employed to reduce the negative impact of sedimentation while maintaining environmental and commercial benefits within a watershed or river system. The samples of muddy water irrigation from Heisonglin Reservoir as well as the sediment campaign along the Rhone River demonstrate the value of sediment continuity. Fine sediment is usually considered a problem for river reaches below a dam, but is proving to be hydromorphologically valuable to preserve river form and function.

The case studies in this bulletin show that the dam community is facing the challenge of dealing with progressing sedimentation in different ways, and that there is room and demand for further innovative approaches. Readers are welcome to share their experiences for future publications.

4. GENERAL RECOMMENDATIONS ON SEDIMENT MANAGEMENT

Best sediment management techniques will vary from project to project and will depend on the sediment loading characteristics (amount, timing, sizes of sediment), the physical setting of the project (influencing delta formation and/or progression of density currents), conditions downstream of the dam, time and budgetary constraints, and the regulatory framework as addressed in Section II. Even with the aid of Figure 3.1, there is no single technique that is “best” for a given project; rather, there are usually several techniques (including combinations of different techniques) that may work within a range of effectiveness and selection will be based on not only economic but environmental and social/cultural factors. It is hoped that this publication will provide an aid to those looking for potential solutions for reservoir sedimentation based on real projects. Where appropriate, general texts on management methods are referenced (e.g., Morris and Fan, 1998).

Dam and reservoir projects represent a significant investment to create storage, which can be lost over time due to sedimentation. In most cases, these projects are not easily replaceable as the number of good dam sites is limited. Reservoirs are increasingly important for benefits such as water supply, flood control, recreation and power production given the growing world population and climate variability. Loss of reservoir volume by sedimentation should therefore be considered one of the most important issues for a sustainable future and measures to either extend the lifetime of a project or make it truly sustainable from a sedimentation point of view in the long term should be of the utmost importance to those working in the profession.

Operators of existing dams in many cases have found that sedimentation either was not considered in the original design, or that sedimentation estimates were inaccurate. This is a challenge that many of the dam owners of the case studies presented in this bulletin are facing. However, for new dam and reservoir projects there exists a clear opportunity for early assessment of sedimentation and selection and design of measures to create a truly sustainable project. This should include a sufficient budget for sustainable reservoir operation and also for retirement or decommissioning of the project in the (hopefully) distant future if sedimentation cannot be held to a sustainable level.

This bulletin shows that the dam community is active in elaborating solutions to sedimentation problems and presents approaches for management around the world. While the focus herein is on the management techniques and is primarily technical in nature, it is important to note that planning for sustainable new projects will also involve economic evaluation approaches that may need to differ from traditional methods (Annandale, 2013).

The general aim of the dam community should be to have sustainable reservoir projects in both planned and existing reservoirs. It is hoped that this publication will provide an aid to those looking for potential solutions for reservoir sedimentation.

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