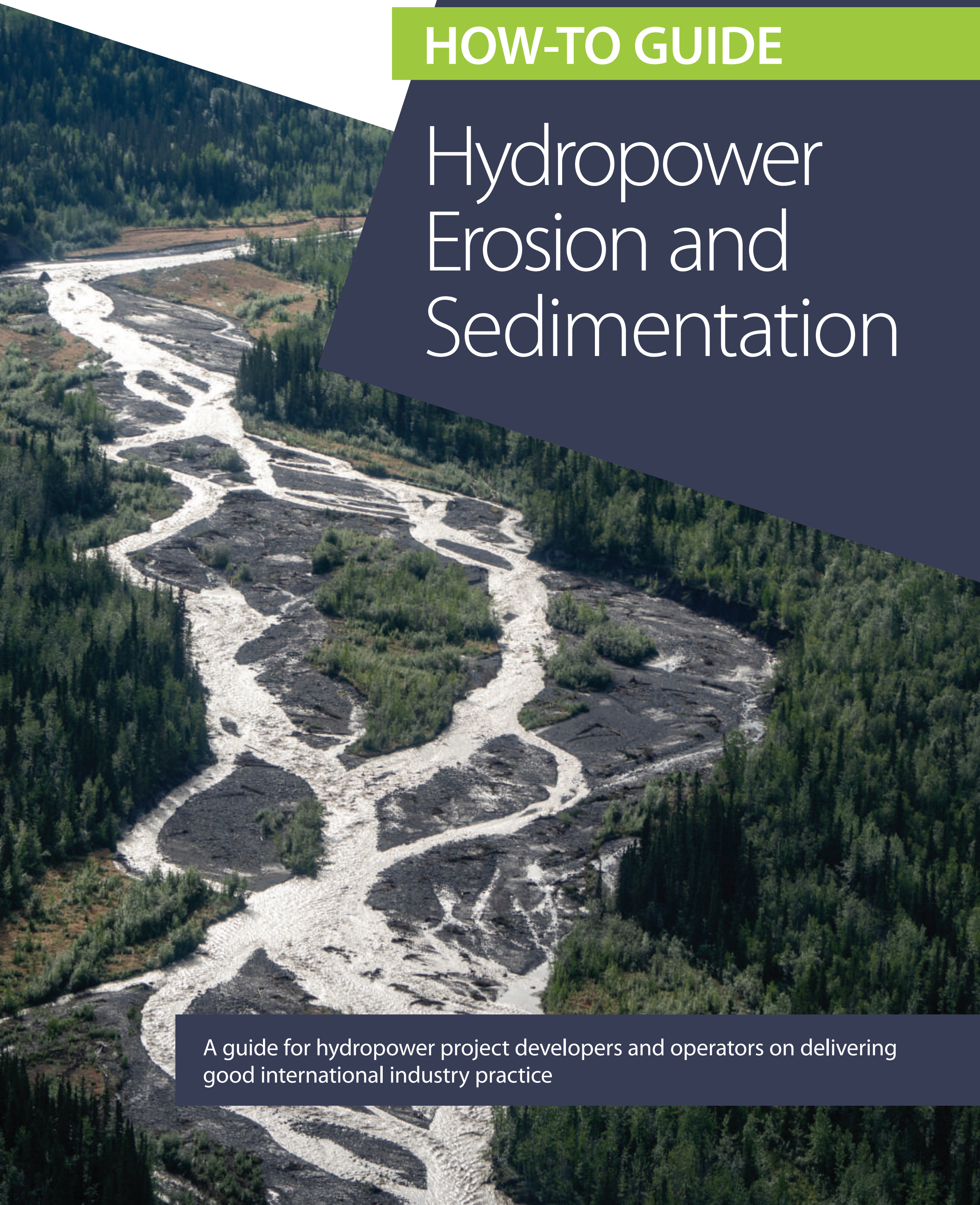
international hydropower association

HOW-TO GUIDE

Hydropower Erosion and Sedimentation



A guide for hydropower project developers and operators on delivering good international industry practice

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Contents

Acronyms

AWARENET	Arab Integrated Water Resources Management Network
CKNet-INA	Collaborative Knowledge Network Indonesia
CAP	Reservoir Gross Storage Capacity
CIWEM	Chartered Institution of Water and Environmental Management
EMP	Environmental Management Plan
EMS	Environmental Management Systems
EPC	Engineering, Procurement and Construction
ESIA	Environmental and Social Impact Assessment
ESG	Environmental, Social and Governance
ESMMP	Environmental and Social Management And Monitoring Plan
DEM	Digital Elevation Model
GCM	Global Climate Model
GHG	Greenhouse Gas
GIS	Geographical Information System
HEC-RAS	Hydrologic Engineering Center's (CEIWR-HEC) River Analysis System
HESG	Hydropower Sustainability ESG Gap Analysis Tool
HGIIP	Hydropower Sustainability Good International Industry Practice Guidelines
HSAP	Hydropower Sustainability Assessment Protocol
IAHR	International Association for Hydro-Environment Engineering and Research
ICE	Institution of Civil Engineers (ICE)
ICH	International Centre for Hydropower
ICIMOD	International Centre for Integrated Mountain Development
ICOLD	International Commission on Large Dams
IHA	International Hydropower Association

IHE	Delft Institute for Water Education (formerly known as UNESCO-IHE)
IRTCES	International Research and Training Centre on Erosion and Sedimentation
ISI	UNESCO International Sediment Initiative
IWHR	Institute of Water Resources and Hydropower Research
LAWETNET	Latin American Water Education and Training Network
LTCR	Long-Term Capacity Ratio
MAF	Mean Annual Runoff
MAS	Mean Annual Sediment Inflow
MOL	Minimum Operating Level
NBCBN	Nile Basin Capacity Building Network
PWG	Participatory Watershed Governance
RESCON	Reservoir Conservation Model
RoR	Run-of-River
SSC	Suspended Sediment Concentration
SWAT	Soil and Water Assessment Tool
TE	Trap Efficiency

Glossary

The following is a selection of key terms. A highly comprehensive glossary of terms is available in the International Glossary of Hydrology, published by the World Meteorological Organsation (WMO) and the United Nations Educational, Scientific and Cultural Organization (UNESCO) in 2012.

Bathymetry	Bathymetry is the study of the underwater depth of the river or reservoir, and is the underwater equivalent of topography.
Bottomset bed	Sediment deposited immediately upstream of the dam. Mainly consists of fine sediment.
Capacity-inflow ratio	Reservoir volume divided by mean annual flow (m^3/(m^3 per year)), used in a Brune curve to determine trap efficiency. It is the same as the retention time expressed in years for the reservoir at full capacity.
Colluvium	Sediment that has moved downhill to the bottom of the slope by gravity, rather than by the effect of running water.
Density current	An in-flowing current of high sediment-density water that may travel along the reservoir bed, without mixing with cleaner reservoir water, and that may reach the dam. Also known as a turbidity current.
Dry bulk density	The dry weight of sediment per unit volume of deposit.
Empty flushing	The opening of a low-level outlet to completely empty the reservoir, thereby enabling the river to scour sediment deposits.
Foreset bed	Sediment deposited at the mid-point of the reservoir, between the pivot point and the bottomset bed. Mainly consists of coarse sediment.
Gully erosion	Erosion occurring in large gullies, formed by running water and the erosion accumulating over time. Gullies may be part of a larger network of rills and gullies.
Pivot point	The edge of the topset bed, where the surface of the sediment deposit turns steeply down towards the foreset bed.
Pressure flushing	Opening of a submerged low-level outlet to release sediment while the reservoir level is high, producing a localized scour cone immediately above the outlet.
Retention time	The length of time that water on average is retained within the reservoir, calculated by dividing reservoir volume by mean annual flow.
Rill erosion	Erosion occurring in small channels of water running down a hill, which may be part of a larger network of rills and gullies.
Sediment bulk density	Mass of sediment per unit volume (kg per m^3).
Sediment delivery ratio	Ratio of the amount of sediment eroded in a catchment to the amount of sediment delivered to a reservoir.
Sediment rating curve	A chart based on field measurements and/or computer modelling that relates sediment concentrations to levels of flow. Rating curves should not be constructed by plotting sediment load against discharge because the total sediment load is related to discharge, resulting in spurious correlation.

Sediment yield	The mass of sediment produced by a catchment area, measured in tonnes of sediment per year (t/yr).
Sheet flow	Sediment moved downhill uniformly by the effect of running water.
Specific sediment yield	The mass of sediment produced by a catchment area, measured in tonnes of sediment per year per unit area of the catchment (t/km^2/yr).
Specific weight	See Dry bulk density.
Topset bed	Sediment deposited at the upstream end of a reservoir, upstream of the pivot point. Mainly consists of coarse sediment.
Trap efficiency	The extent to which a reservoir traps sediment. A reservoir with 90% trap efficiency is one that traps 90% of sediment inflow, whilst 10% passes downstream.
Turbidity current	See Density current.

Runoff gauge downstream from Jirau Hydropower Plant, Brazil
Photo credit: Bernt Rydgren

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Introduction

Introduction

To ensure sustainability in hydropower, developers and operators of hydropower projects need to know how to manage erosion and sedimentation issues. The importance of managing reservoir sedimentation has received increased recognition recently: without sediment management, hydropower projects may not preserve water storage sites as a sustainable renewable resource for power generation, water supply, or flood management in the long-term, and the world's best and most feasible water storage sites could be exhausted. In addition, managing social and environmental impacts that arise from erosion and sedimentation issues continues to be essential to any hydropower developer or operator, not only to avoid business risk but also to act responsibly towards local communities.

Landslide near a hydrpower project in Nepal
Photo credit: Doug Smith

1.1 This How-to Guide

1.1.1 Aim

This How-to Guide aims to contribute to increasing knowledge and understanding of the practical measures that can be undertaken to meet good international industry practice, in conformance with the internationally recognised Hydropower Sustainability Tools (see Box 1.1).

This guide expands upon the Hydropower Sustainability Good International Industry Practice Guidelines (HGIIP) and is designed to provide practical support to practitioners and stakeholders in erosion and sedimentation management in relation to a hydropower project.

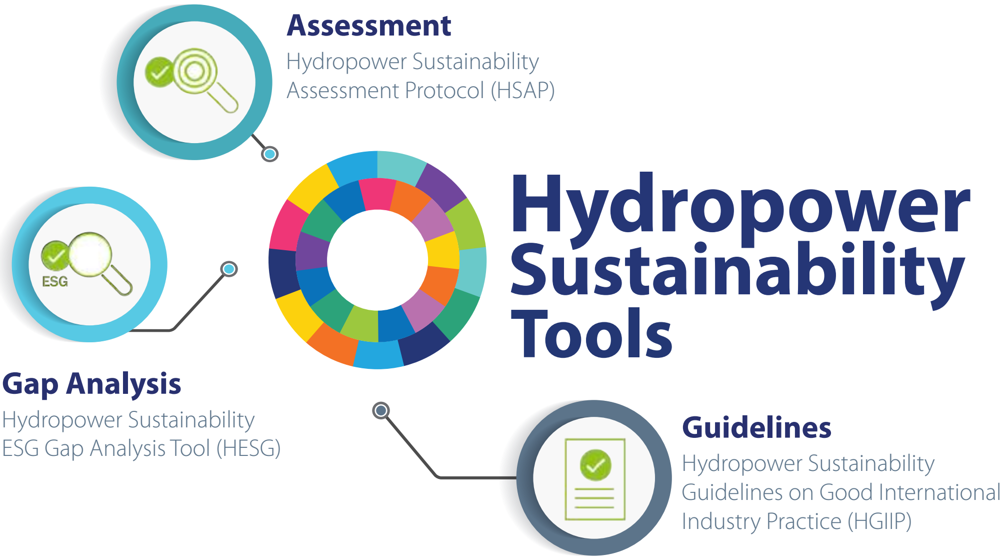
The key decision-makers for erosion and sedimentation management are the hydropower companies that develop, own and operate projects, environmental consultancies, as well as governments. The guide can help developers and operators recognise erosion and sedimentation caused by the project (or 'operating hydropower facility' in the Operation tool), and manage erosion and sedimentation responsibly, thus enhancing project performance and increasing operating efficiency and lifetime.

The urgency of managing these erosion and sedimentation issues is increased by climate change, because:

- Sustainable reservoir storage is necessary for the power generation of hydropower projects to be resilient to increased hydrological variability;
- Sediment inflows may change with climate change-induced increases in hydrological variability and the frequency of extreme events; and
- A project that cannot be sustained due to sedimentation issues will not be able to contribute to the mitigation of greenhouse gas (GHG) emissions, or play a role in climate change adaptation.

1.1.2 Approach and structure

The approach of this guide is to map out the necessary steps or deliverables that the developer or operator must take or prepare in order to meet good international industry practice, in relation to the project life cycle, from early concept through to detailed design, construction, and operation.



Hydropower Sustainability Tools

Assessment
Hydropower Sustainability Assessment Protocol (HSAP)

Gap Analysis
Hydropower Sustainability ESG Gap Analysis Tool (HESG)

Guidelines
Hydropower Sustainability Guidelines on Good International Industry Practice (HGIIP)

The Hydropower Sustainability Tools are governed by the Hydropower Sustainability Assessment Council, a multi-stakeholder group of industry, government, financial institutions, and social and environmental NGOs. The tools are supported by the International Hydropower Association (IHA), the council's management body

Sustainability guidelines

The HGIIP define expected sustainability performance for the sector across a range of environmental, social, technical and governance topics. Released in 2018, the 26 guidelines present definitions of the processes and outcomes related to good practice in project planning, operation and implementation. As a compendium, the guidelines are a reference document for meeting the expectations of lenders, regulators and consumers. Compliance with each guideline can be specified in commercial contracts between financiers and developers, and between developers and contractors. The guidelines are based on the performance framework of the HSAP.

Erosion and Sedimentation

The Erosion and Sedimentation good practice guideline addresses the management of erosion and sedimentation issues with the hydropower project or operating facility. Adherence with this guideline is measured using the HSAP and the HESG.

Assessment protocol

The HSAP offers a framework for objective assessments of hydropower project performance. It was developed between 2007 and 2010 following a review of the World Commission on Dams' recommendations, the Equator Principles, the World Bank Safeguard Policies and IFC Performance Standards, and IHA's own previous sustainability tools. Assessments are delivered by independent accredited assessors and can examine different stages of a project's life cycle. Evidence collected during an assessment is used to create a sustainability profile and benchmark performance against both good and best proven practice. The assessment protocol was updated in 2018 with a new topic covering hydropower's carbon footprint and resilience to climate change.

Gap analysis tool

The HESG enables hydropower project proponents and investors to identify and address gaps against international good practice. Launched in 2018, the tool is based on the assessment framework of the HSAP's environmental, social and governance topics.

It provides a gap management action plan to help a project team address any gaps and is divided into 12 sections that are compatible with both the IFC Environmental and Social Performance Standards and the World Bank's Environmental and Social Framework.

The guide is presented in five chapters and three annexes:

- **Chapter 1** – Introduction
- **Chapter 2** – Understanding erosion and sedimentation in hydropower
- **Chapter 3** – Achieving good international industry practice
- **Chapter 4** – Methodologies and technologies
- **Chapter 5** – Conclusions
- **Annex 1** – Glossary
- **Annex 2** – Bibliography
- **Annex 3** – Project examples

1.2 Erosion and sedimentation in the Hydropower Sustainability Tools

Erosion and
Sedimentation

The hydropower sector now has a suite of sustainability tools to harmonise the understanding of sustainability in hydropower. A separate topic on Erosion and Sedimentation is included in all three of the main HSAP tools that correspond to the project life cycle stage – preparation, implementation, and operation – and requirements on erosion and sedimentation are also set out in the HESG. These provide a definition of good international industry practice in the management of erosion and sedimentation, in relation to criteria on Assessment, Management, Conformance and Compliance, and Outcomes.

The intent of the Erosion and Sedimentation topic is that:

- Erosion and sedimentation caused by the project (or 'operating hydropower facility' in the Operation tool) is managed responsibly and does not present problems with respect to other social, environmental and economic objectives;

- External erosion or sedimentation occurrences which may have impacts on the project are recognised and managed; and

- Commitments to implement measures to address erosion and sedimentation are fulfilled (in the Implementation and Operation tools only).

1.2.1 Objectives of this How-to Guide

The guide:

- Presents how erosion and sedimentation affects the sustainable development, implementation, and operation of hydropower projects;

- Explains the terminology used to describe erosion and sedimentation issues;

- Identifies the steps that are necessary to meet good international industry practice in relation to the project life cycle;

- Maps a range of methodologies and technologies in relation to these steps and the project life cycle; and

- Catalogues these methodologies and technologies, describing further sources of information for each.

The objective is to enable the reader to know how to manage erosion and sedimentation issues, using a range of methodologies and technologies, and to know where to find further expertise and guidance. It is intended for those engaged in the development and operation of hydropower projects, as well as stakeholders with interests in these projects and in the wider hydropower industry.

1.2.2 Scope

The scope of the guide covers:

- The basic good practice requirements for the management of erosion and sedimentation, set out in the HSAP and associated tools;

- All stages of a project's life, from the early stage, through preparation, implementation, and operation;

- Impacts of erosion and sedimentation issues on the project;

- Impacts resulting from erosion and sedimentation caused by the project;

- All scales of erosion and sedimentation issues ranging from large, landscape-scale issues, to localised site-based issues; and

- Storage and run-of-river (RoR) projects.

Although this How-to Guide identifies the potential social and environmental impacts of erosion and sedimentation issues, it does not address the mitigation of or compensation for these impacts other than through the management of the causal erosion and sedimentation issues.

The ability of project civil infrastructure to withstand the erosive capabilities of water is a vital concept in project design, for example the ability of a plunge pool to withstand the volumes of flow spilled in the long-term. This is a consideration of infrastructure design and safety, and is not addressed in this guide.

1.2.3 Key Sources

This How-to Guide draws on a number of key resources that are available on the management of erosion and sedimentation:

- Annandale, G. (2013). *Quenching the Thirst – Sustainable Water Supply and Climate Change.* Charleston: CreateSpace Independent Publishing Platform.

- Annandale, G., Morris, G. and Karki, P. (2016). *Extending the Life of Reservoirs: Sustainable Sediment Management for Dams and Run-of-River Hydropower.* Washington, DC: World Bank.

- Efthymiou N., Palt S., Annandale G. and Karki, P. (2017). *Reservoir Conservation Model, RESCON 2 Beta: Economic and Engineering Evaluation of Alternative Sediment Management Strategies.* Washington, DC: World Bank.

- International Hydropower Association. (2017). *Sediment Management Knowledge Hub.* [online] Available at: https://www.hydropower.org/sediment-management [Accessed 14 Aug. 2019].

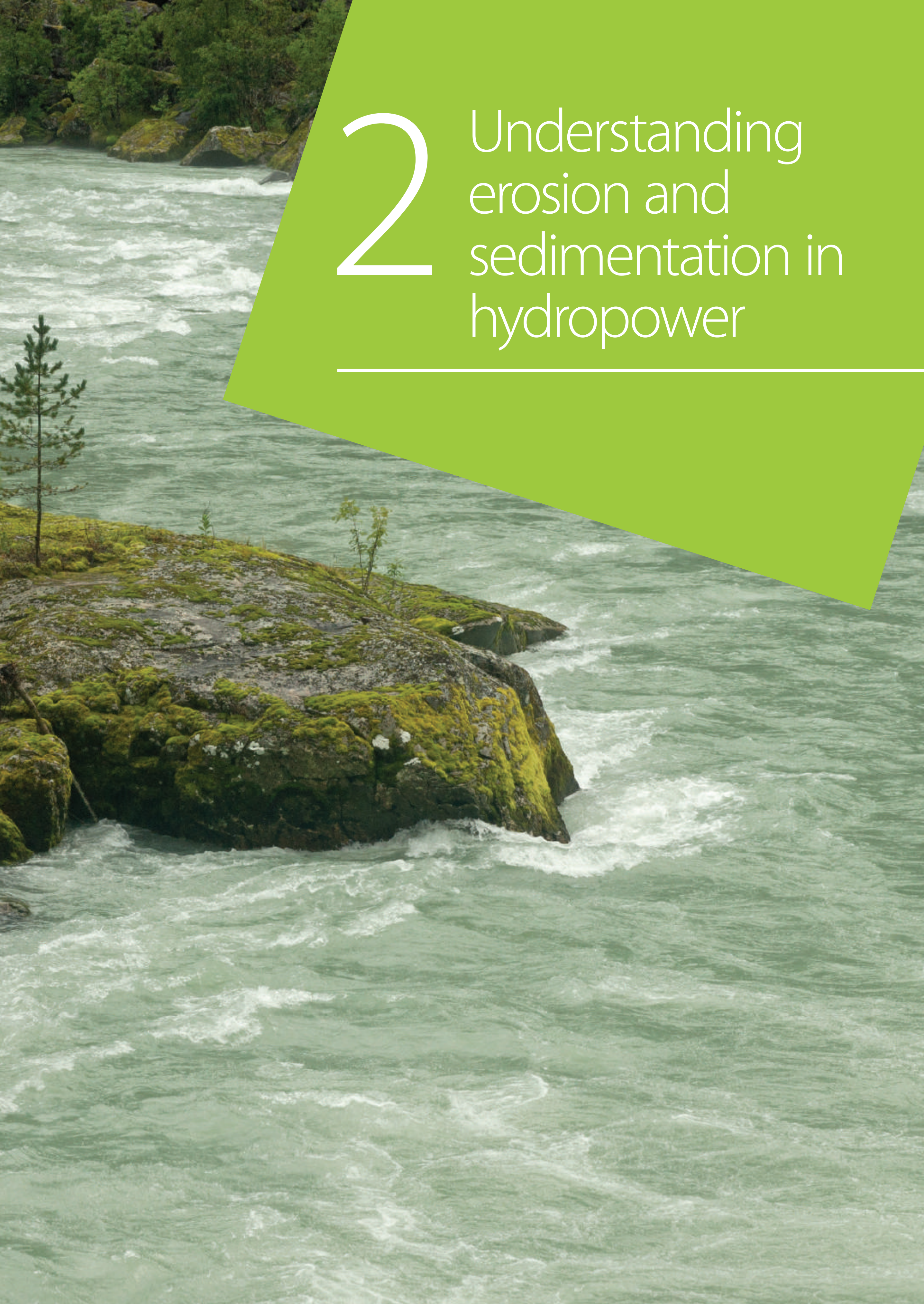
- Morris, G. and Fan, J. (1998). *Reservoir Sedimentation Handbook*. New York: McGraw-Hill Book Co.

- Palmieri, A., Shah, F., Annandale, G. and Dinar, A. (2003). *Reservoir Conservation: The RESCON Approach*. Washington, DC: World Bank.

Sediment-transport measurement station near Jostedal Hydropower Project operated by Statkraft, Norway
Photo credit: Bernt Rydgren

2

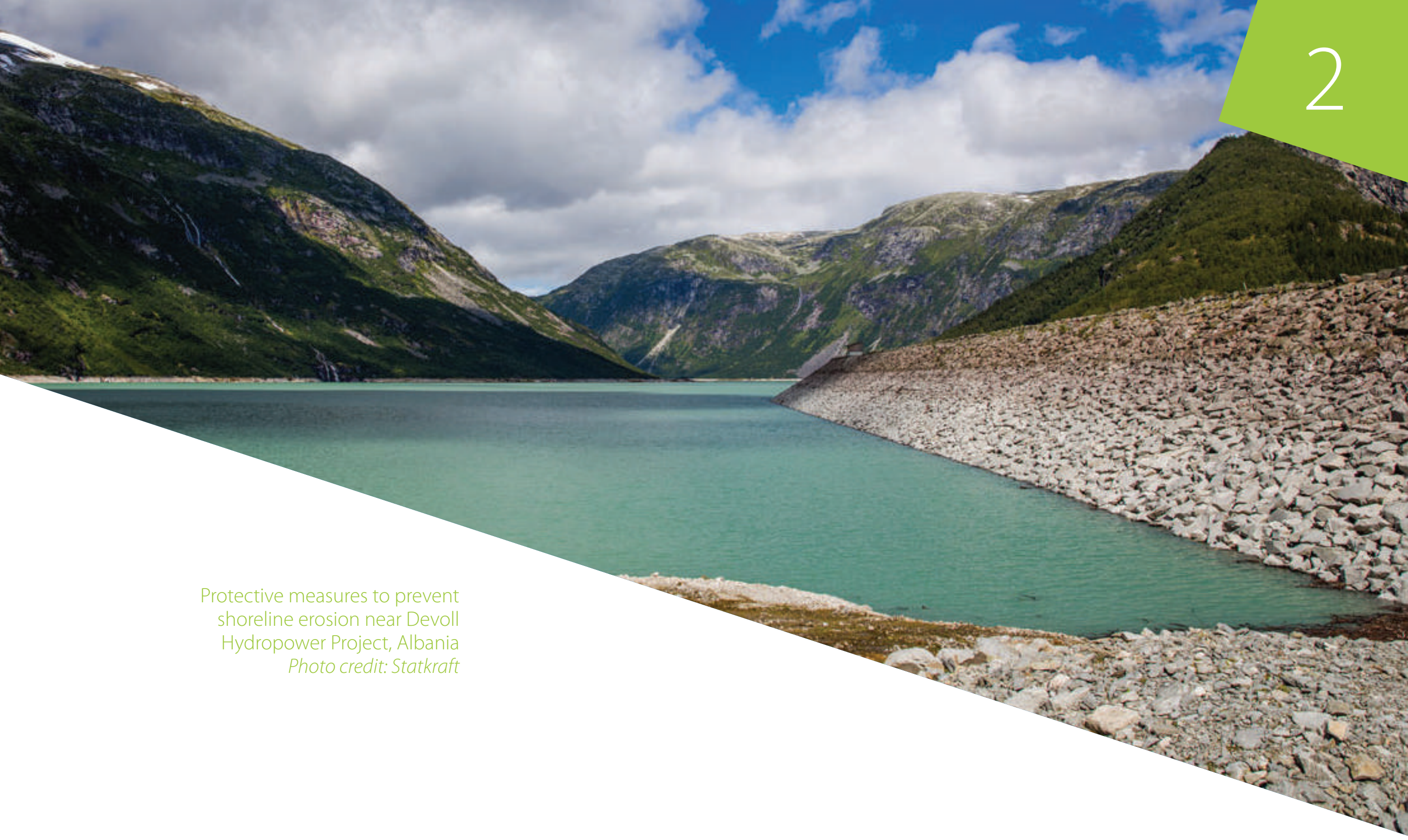
Understanding erosion and sedimentation in hydropower



Understanding erosion and sedimentation in hydropower

Just as rivers carry water, so they carry sediment. Hydropower projects alter the pattern of sediment transport – erosion, suspension, movement, and deposition – in a river basin, because they alter or divert the flows of sediment-carrying water. This has strong implications for the longevity of reservoirs and maintenance costs, as well as social and environmental consequences.

This chapter presents an overview of how erosion and sedimentation affect the sustainable development and operation of hydropower projects, including the associated environmental and social impacts.



Protective measures to prevent shoreline erosion near Devoll Hydropower Project, Albania
Photo credit: Statkraft

2.1 Sediment transport in rivers

Erosion is the removal and transportation of solid material by the action of water, ice, or wind, including abrasion by the sediments they carry. **Sediment** is solid material that is eroded and deposited in a new location by water, ice, or wind. It can consist of rocks and minerals, as well as the remains of plants and animals. It can be as small as silt and clay particles, or as large as a boulder.

Rivers naturally erode, move, and deposit sediments. Box 2.1 below provides further information on river morphology and sedimentation dynamics. The sediments carried in a river are referred to as its **Sediment Load**, and the measured volume or mass of the sediment load is referred to as **Sediment Yield** (in tonnes or m^3 per year). The total sediment load consists of:

- **Bed load**, which consists of coarse particles located on a riverbed, and is pushed by the flowing water so that it rolls or slides along, or saltates. Saltation refers to the lifting of particles from the bed into suspension and their fall back to the bed, where they might hit other particles, making them also saltate;

- **Suspended load**, which consists of the particles that have become suspended in the water. Suspended load normally consists of the finer sediment particles that are light enough for the turbulence of the water to keep them in suspension. The higher the turbulence, the higher the mass of sediments that can be suspended; and

- **Wash load**, which consists of particles that remain in suspension, and usually consists of very fine particles, such as clay or silt particles, with sizes that are not encountered in the riverbed material.

Box 2.1 River morphology

The form or morphology of a river, flow volumes and velocity, and the type of sediment affect patterns of erosion, movement and deposition. A river's morphology is not stable or static, with change occurring over time through a dynamic process. Sedimentation dynamics refers to the movement and balance of sediment erosion and deposition in a river system.

An increase in-channel width, decrease in river gradient, or a decrease in the flow velocity will reduce the movement of bed load, and will reduce turbulence so that suspended load is dropped out of the water column. Terms for different types of fluvial bedforms and landforms include bars, pools, riffles, meanders, oxbow lakes, fluvial terraces, and islands. Fluvial channels (i.e. river or stream courses) may be straight, meandering, or braided. Anastomosed rivers consist of multiple channels that could be either straight, meandering, braided or a combination of these. Alluvium is the sediment that is deposited by a river in the surrounding valley or delta, for example on a floodplain.

2.2 Erosion and sedimentation issues: upstream

The construction of a dam on a river will physically trap some sediment and will slow river flows or turbulence so that suspended load is deposited in the reservoir. The loss of storage capability and the reduction of reservoir lifetime is the first issue discussed below, with resulting social and environmental impacts. Managing inflows of sediment loads may require action to reduce the sediment yield of the catchment, i.e. catchment management, as discussed in Section 2.2.2. The third issue, reservoir shoreline slope stability, may also affect reservoir sedimentation, but is chiefly a concern because of its associated social and environmental impacts. Finally, the transport of abrasive sediments can damage the civil and electromechanical structures of the project even in the initial years of operation.

2.2.1 Reservoir sedimentation and storage loss

Sediment deposition in a reservoir normally begins at the upstream end, i.e. at the reservoir tail, and typically moves downstream in the shape of a delta (other shapes have also been observed, including uniform depositions along the length of reservoir).

The storage in a reservoir consists of **dead storage**, i.e. the reservoir volume that lies below the minimum operating water level, and **active storage** or **live storage**, i.e. the volume that may be used for daily, inter-seasonal or inter-annual storage and released for power generation or water supply, or reserved for flood management.

As shown in Figure 2.1, the delta gradually moves into the active storage volume very early on in the reservoir's lifetime. In contrast to what is commonly, but incorrectly, assumed, sediment deposition in the active storage space is as prevalent as in the dead storage space. Sediment deposition in the active storage space results in the reduction of active storage volume, reducing the ability of the project to meet its performance objectives, in power generation, peaking generation, flood management or water supply.

The **long-term capacity ratio** (LTCR) is the term used for the ratio of the volume of the reservoir in the long-term (with or without sediment management) to the original reservoir volume.

The objective of sediment management in storage projects is to ensure that the storage is maintained sufficiently for the project to meet its power generation, water supply, and flood management objectives. However, the global net amount of reservoir storage has been decreasing because, in the past, reservoir sediment management was

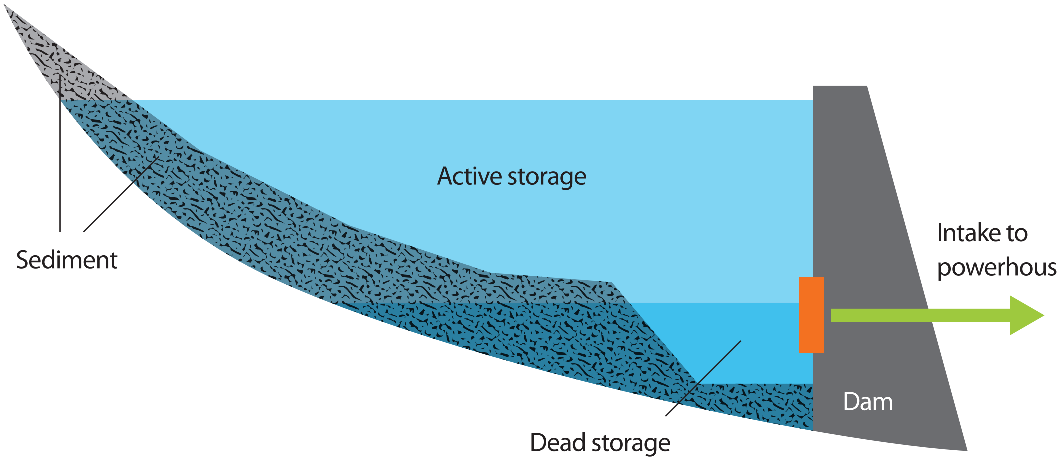


Figure 2.1 Sediment accumulation in reservoirs

Source: Annandale, G., Morris, G. and Karki, P. (2016). Extending the Life of Reservoirs: Sustainable Sediment Management for Dams and Run-of-River Hydropower. Washington, DC: World Bank.

not standard practice. Currently the amount of storage globally lost to sedimentation is greater than the amount of storage added through the construction of new dams. In recent years, there has been a shift away from a "design life" approach in which reservoir sedimentation is accepted as a *fait accompli* towards managing reservoir sediment to ensure that the project can continue to generate economic and social benefits in the long-term. Sustaining hydropower projects beyond a short design life is also important to preserving the value of the world's stock of water storage sites, avoiding the social and environmental costs of developing replacement projects at other sites, and avoiding the cost and environmental impacts of decommissioning.

RoR projects, i.e. projects where the storage of water beyond a short period is not required, and storage projects will need different sediment management approaches[1]. For most RoR projects, sediment management will focus on the prevention of sediment damaging project structures and equipment or on downstream issues, as discussed below. However, RoR projects that store water on a daily basis for daily peaking still need to preserve sufficient storage in the headpond to perform daily peaking during dry months.

Sediment deposition may also cause social and environmental impacts upstream of reservoirs. Principally, the sediment deposited at the reservoir tail could create or exacerbate upstream flooding, as it will raise the backwater effect of the river during high flows, and it may restrict navigation from the river into the reservoir. Navigation may also be affected by sediment in other parts of the reservoir. It may affect infrastructure such as bridges, by reducing the size of the flood the bridge can withstand. In addition, the benefits that a reservoir can bring over time – in recreation and fisheries, for example – may be affected by sediment deposition, and there may be environmental issues such as visual impacts, the accumulation of solid wastes washed from upstream, the creation of habitat for vectors of disease, colonisation of the sediment by invasive species, and sedimentation of pools used for spawning. Wind erosion from the drawdown area can also be a significant issue, especially for reservoirs with large drawdown zones, creating a local nuisance or dust storms.

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[1] A project with no more than one day's storage is a widely-used rule-of-thumb definition of a run-of-river project.

2.2.2 Specific sediment yield and catchment land use

The **Specific Sediment Yield** of a catchment refers to the amount of sediment that enters the river or reservoir per unit area of the catchment (i.e. tonnes or m^3 per km^2 of the catchment). Land use practices, including the conversion of forests to agriculture, affect the volumes of sediment inflows. Climate change may lead to an increase in sediment inflows, due to a higher frequency or severity of extreme rainfall events.

A catchment area that is delivering a high specific sediment yield could be managed to reduce that yield, and therefore **Catchment Management**, is a key issue in avoiding storage loss. This might entail catchment protection (i.e. protection from cutting of trees or conversion to agriculture) or catchment reforestation, as well as localised measures such as the prevention of landslides and sediment check dams on tributaries or upstream on the main river.

2.2.3 Reservoir rim erosion

Erosion of the rim or shoreline of the reservoir can be a significant issue, especially where the shoreline is steep and susceptible to landslides. Reservoir-induced instability of slopes results from changes in their mechanical properties because of the infiltration of reservoir water. Rim erosion may occur with drawdown of reservoir levels as saturation leads to bank slumping, or may be due to repeated fluctuations in reservoir levels. Slope failure can result in impulse waves with public safety risks and the possibility that water will overtop the dam. There may be a risk that landslides dam upstream rivers, with catastrophic releases when such a natural dam fails; such events have severe implications for safety and reservoir sediment accumulation. Climate change may increase the probability of slope failure due to a higher frequency or severity of extreme rainfall events.

Measures to mitigate erosion of the reservoir rim include: restrictions on reservoir water level change magnitude or rates, reservoir slope protection works, promotion of the growth of vegetation which tolerates water level changes around the reservoir rim, and restriction on activities around the reservoir rim that cause land disturbance. Full details are provided in Section 4.

2.3 Erosion and sedimentation issues: downstream

Trapping sediment in the reservoir can result in downstream erosion as the water will pick up additional suspended sediment as it passes downstream. However, the actual pattern of erosion also will depend on the volumes of flow passed downstream. Downstream environmental and social impacts do not only result from the loss of land due to erosion, but also from the reduced delivery of sediments to aquatic ecosystems and agriculture.

2.3.1 Sediment-hungry rivers

When a reservoir captures sediment, the sediment load in the river downstream of the reservoir is lower than it was before the dam was constructed. This means that, for an equal volume and turbulence of water, the downstream river will have greater capacity to move bed load and to pick up sediment as suspended load. In so doing, the river will erode the riverbed or banks. The water of the river may be referred to as **sediment-hungry** or **aggressive**, or the river may be said to have **hungry-river syndrome**. The flow may erode the riverbed and banks, producing channel incision (downcutting), coarsen bed material (armouring), and remove spawning gravels used by fish. The mix of riverbed material will affect the pattern of downstream erosion: in sand-gravel mixtures (gravel bed rivers) downstream erosion will be controlled by the coarse surface armour layer; whereas in sand bed rivers the erosion will be more dynamic.

Downstream erosion can give rise to significant social, biological and environmental impacts, including the loss of agricultural land, the lowering of groundwater tables, impacts on biodiversity and fisheries, the undermining of the foundations of infrastructure such as bridges, and reduced availability of gravel and sand for construction.

Impacts may reach as far as coasts, resulting in delta or coastline erosion, and the loss of beaches of value for tourism.

2.3.2 Reduced flows or altered pattern of flows

Downstream issues are not caused only by hungry-river syndrome, as the volume and pattern of flows is also influential. The pattern of erosion and deposition will depend on flow volumes and velocity, and their daily, weekly or seasonal pattern. For example:

- The lower volume of flow in 'dewatered' reaches between a dam and a powerhouse (to which waters are diverted via a tunnel) may be less erosive than the larger pre-project volume of flow;

- Storage projects will moderate the seasonal pattern of flow, and therefore may reduce annual peak flow, which, pre-project, would have eroded the riverbed and banks (though the degradation of riverbeds and banks by sediment-hungry water is likely more dominant); and

- Inter-basin transfers will significantly decrease flow downstream of the dammed river, and increase flow in the receiving river, potentially increasing erosion in the receiving river due to increased flows.

In addition, rapid changes in flow, due to peaking operations or the onset of spilling, can cause erosion.

In downstream reaches with flow that is lower than the pre-project flow, sediment may accumulate at confluences with tributaries, where sediments continue to enter the river. This may have environmental or social implications and may require management.

2.3.3 Reduced sediment delivery to ecosystems and agriculture

The capture of sediment in the reservoir, and the resulting reduction in sediment load downstream, means that aquatic and terrestrial ecosystems in downstream reaches will not receive substrate (for example for spawning) and nutrients (in organic and mineral sediments) that they are dependent on. This may have significant implications for the species composition and abundance of aquatic ecosystems, and for fisheries, including coastal fisheries. In addition, floodplain terrestrial ecosystems may depend on the annual or regular delivery of sediment in flood waters. Many locations that have been developed or are suitable for hydropower projects are precisely the locations that people depend on for floodplain agriculture, because the floodplains are made fertile by the sediments delivered by seasonal floods, as well as by the waters of those floods. Availability of land that is equally fertile may be limited away from the river.

These issues can be considered using the concept of ecosystem services, which consist of provisioning, regulatory, cultural, and supporting ecosystem services. Altering sediment transport in a river system has profound effects on these ecosystem services.

2.4 Erosion from project sites

Movement of sediment from project sites and its deposition elsewhere can be considerable, especially – but not only – during the construction stage.

The temporary diversion of the river during construction, using coffer dams and diversion tunnels, and requiring excavations within the river channel, may increase sediment mobilisation in the river. Surface runoff from exposed earth in all construction areas, quarries and spoil disposal areas, will increase the amount of sediment entering the river, and may result in erosion and stability issues on-site, such as the collapse of roads, embankments, and spoil. There may be erosion from and triggering of landslides by access roads, the construction of transmission towers, and vegetation removal under transmission lines.

Early in the operation stage, ongoing erosion issues may result from a lack of, or poorly implemented, rehabilitation measures on land disturbed during construction activities. Even in the operation stage, there is a requirement to manage surface water and stormwater runoff from project sites to prevent sediments from the site entering the river, and to avoid on-site erosion.

2.5 Damage to civil and electromechanical structures

Maintenance will be required if the sediment contains high levels of hard minerals. Sediment flowing through the turbines will cause abrasion of turbine parts, intake and spillway gates, and valves. Abrasion occurs when the sediments are harder than the metals used to manufacture parts – quartz, feldspar, tourmaline and others. Even silt can cause abrasion if quartz content and pressures (head) are high enough. This is not only an issue in the long-term. For example, in mountainous areas with abrasive sediment, equipment can be damaged in the initial months or years of operation. Damage arising from abrasive wear includes leakages, reduction of efficiency, increased maintenance costs, and prolonged outages for overhaul if no replacement parts are available.

Civil structures can also be damaged, including diversion tunnels, intakes, spillways, and energy dissipaters, as a result of both gradual abrasion and direct damage, especially during extreme events. In some cases, downstream erosion has undermined dam foundations.

2.6 Climate change and sediment management

Climate change strengthens the case for effective sediment management, both to ensure the project itself is resilient to climate change, and to ensure it can contribute to adaptation. Increased hydrological variability (droughts and floods) resulting from climate change will require larger storage volumes to ensure that power generation, water supply, and flood management objectives are reliably met (i.e. the project is resilient to climate change). Larger storage volumes will be required to meet additional demands for water or additional flood management services that become necessary with climate change (i.e. the project contributes to adaptation).

However, increased frequency and intensity of flood events may also increase sediment load entering the reservoir, and glacier retreat will release sediments that were previously fixed in glaciers. More intense rainfall, as well as droughts and wildfires resulting in the loss of vegetation cover, can create additional risks from site-based erosion, embankment collapse, and landslides – thereby increasing the challenge of sediment management, and threatening the very part of the project that enables resilience to increased hydrological variability and adaptation, i.e. its storage capability. Coastal erosion, caused by a sediment-hungry river downstream of a dam, may be further exacerbated by sea-level rise. In addition, climate change can exacerbate the anthropogenic causes of increasing sediment loads.

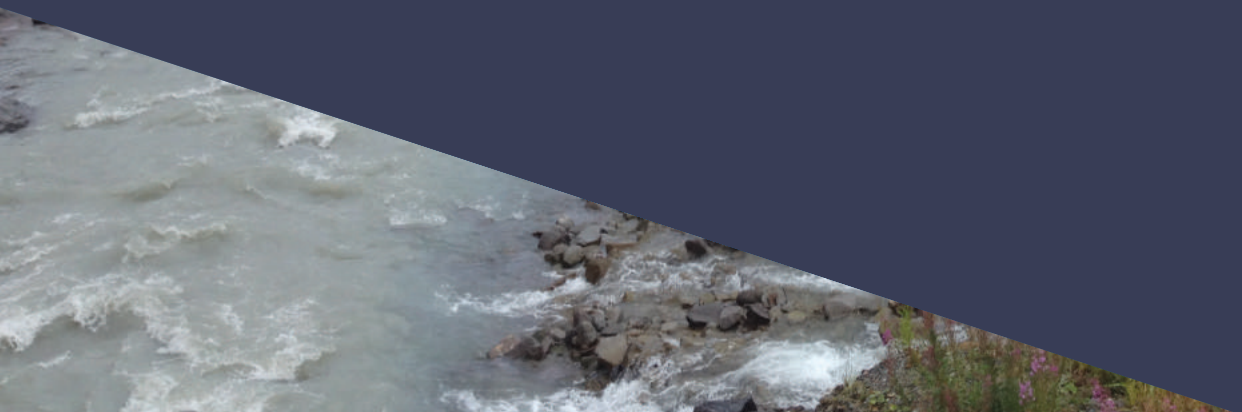
The World Bank Climate Change Knowledge Portal is a useful resource for climate change (https://climateknowledgeportal.worldbank.org). For example, it provides hydrological analysis based on an excerpt of Global Climate Model (GCM) results on temperature and precipitation change, and an assessment of the impact of climate change on hydrologic indicators such as % change of mean annual runoff.

Eroded shoreline near
Keeyask Hydropower Project
operated by Manitoba
Hydro, Canada
Photo credit: Bernt Rydgren

3 Achieving good international industry practice

Achieving good international industry practice

This chapter maps out the methodologies and technologies that are necessary to meet good international industry practice. They are presented in four groups (scoping and siting; assessment and monitoring; design measures; and mitigation measures) according to the HSAP criteria of Assessment and Management. These methodologies and technologies are related to the life cycle of a hydropower project, but they are not confined to any particular stage in the life cycle. Box 3.1 describes how the HSAP topic on erosion and sedimentation relates to the project life cycle.



Erosion control measures near Kaunertal Hydropower Project operated by TIWAG, Austria
Photo credit: Aida Khalil

3.1 Erosion and sedimentation in the project life cycle

3.1.1 Design life vs. life cycle approaches

A design life approach to project development follows a linear timeline and assumes that the project will have served its purpose at the end of its design life. This approach does not sufficiently consider maintenance or decommissioning at the end of the project life, and therefore ignores intergenerational equity: future generations will pay either for the loss of the site's value for water storage, for the project's decommissioning, or for the cost of developing new reservoirs, while earlier generations enjoyed the benefits of the project.

In contrast, **a life cycle approach** encompasses the design, construction, operation, and maintenance of infrastructure to enable its long-term sustainable use, thereby delivering intergenerational equity. Current and future generations can enjoy the benefits of the facility, while spreading the cost of ownership, operations and maintenance over many generations. This life cycle of dams and reservoirs requires operation and maintenance, continued and regular implementation of reservoir sedimentation management, and regular refurbishment of the dam and appurtenant structures.

The distinction between the design life and life cycle approaches can be extended to their ability to accommodate external issues, especially environmental and social issues. Although the design life approach incorporates measures to address such issues at the outset, it does not allow for measures to respond to changes or new issues over the project's design life. In contrast, the life cycle approach allows for measures to be varied or new measures taken to address the changing or emerging environmental and social issues.

3.1.2 New projects

For a newly-developed project, there is a logical sequence of scoping issues and risks during the early stage of the project's development. During preparation, this is followed by further detailed assessment, then the planning of measures to address the issues, and during construction and operation, by the implementation of the measures, monitoring of their effectiveness, and the identification and management of further issues.

Figure 3.1 depicts this sequence in further detail in relation to the project stages. In summary, a developer of a new project should take the following steps:

During the **Early Stage**:

- Avoidance of sites in which it is not feasible to maintain the project in perpetuity and selection of sites with the greatest potential for maximum longevity;
- Identification of erosion and sedimentation risks, and related environmental and social risks; and
- Project siting to avoid and minimise issues.

During the **Preparation** stage:

- Further scoping and detailed assessment of erosion and sedimentation issues relevant to project implementation and operation (both for project longevity, and environmental and social issues); and
- Planning of design, maintenance, and additional mitigation measures for project implementation and operation.

During the **Implementation** stage:

- Construction to the required designs, and mitigation of construction stage impacts; and
- Monitoring.

During the **Operation** stage:

- Operation and maintenance of facilities to manage erosion and sedimentation issues;
- Mitigation of impacts that cannot be avoided; and
- Identification and management of ongoing or emerging issues.

A project in the Preparation and Implementation stages that has not yet considered erosion and sedimentation would still have opportunities to adjust the siting of some components to avoid or minimise erosion and sedimentation issues, and to re-design or plan the mitigation of impacts. They should refer to the steps in Figure 3.1 (and the corresponding methodologies and technologies in Section 4) for the Early Stage and (if already in implementation) Preparation stage.

Please note that *compensation* for the environmental and social impacts of erosion and sedimentation issues is not addressed in this guide. If it is impossible to mitigate erosion or sedimentation impacts on an environmental or social receptor, compensation may be provided as a last resort, following the 'mitigation hierarchy'. For example, loss of land to erosion can be compensated with cash or replacement land, and loss of biological diversity in downstream ecosystems with biodiversity offsets. These measures are discussed in the HGIIP on other topics including environmental and social issues management, project-affected communities and livelihoods, and biodiversity.

Box 3.1 HSAP or HESG assessments and the project life cycle

The HSAP topic on erosion and sedimentation is based on definitions of basic good practice in relation to criteria of Assessment, Management, Conformance and Compliance, and Outcomes. Related guidelines provide further detail on these standards of good international industry practice.

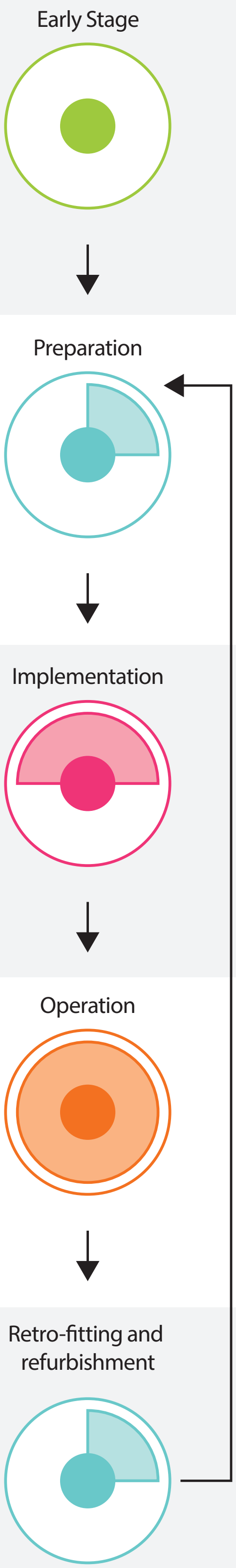
HSAP follows a life cycle approach in principle, for all HSAP topics, including erosion and sedimentation. For example, this is reflected in the Operation stage requirements for topic O-16 Erosion and Sedimentation: *ongoing or emerging issues have been identified* (first part of Assessment), and *measures are in place to manage identified erosion and sedimentation issues* (Management).

In an HSAP or HESG assessment, a project's performance would be evaluated against carefully defined scoring statements. But the structuring of the HSAP and HESG by stage does not mean that actions taken during preceding stages are not considered, or that actions concerning subsequent stages are not assessed. The scoring statements are formulated to enable any stage tool to be used without prior use of the previous tool(s). For example, this principle is reflected in the Implementation stage requirements for topic I-16 Erosion and Sedimentation: *issues relevant to project implementation and operation have been identified through an assessment process* (first part of Assessment), and *plans are in place for the operation stage for ongoing erosion and sedimentation issues management* (Management).

The methodologies and technologies in this guide are presented in four groups: scoping and siting; assessment and monitoring; design measures; and mitigation measures. They are not presented by HSAP stage because: first, many methodologies/technologies are applicable at more than one stage in the life cycle, and can be used at any stage including by operating projects; and second, the detailed HSAP criteria (scoring statements) may concern more than one life cycle stage.

Synopsis of HSAP and HESG criteria on the topic of Erosion and Sedimentation:	
Assessment	Preparation and implementation tools: Erosion and sedimentation issues relevant to project implementation and operation have been identified through an assessment process utilising appropriate expertise. Operation tool: Ongoing or emerging erosion and sedimentation issues have been identified. Monitoring: • Implementation tool: Monitoring is being undertaken during the project implementation stage appropriate to the identified issues • Operation tool: If management measures are required then monitoring is being undertaken to assess if management measures are effective.
Management	Plans and processes to address identified erosion and sedimentation issues have been developed (Preparation tool) or are in place (Implementation and Operation tools) for project implementation and operation.
Conformance and Compliance	Processes and objectives in place to manage erosion and sedimentation issues have been and are on track to be met with no significant non-compliances or non-conformances, and erosion and sedimentation related commitments have been or are on track to be met. (Implementation and Operation tools)
Outcomes	Erosion and sedimentation issues, including issues that may impact on the project, are avoided, minimised and mitigated.

Figure 3.1 Requirements to meet good international industry practice through the project life cycle



Siting, Avoidance and Minimisation

- Initial scoping of erosion and sedimentation issues
- Avoidance of sites that will not be renewable; selection of sites with the greatest potential for maximum longevity
- Preliminary identification of sediment management options
- Identification of related environmental and social risks and mitigation options
- Selection of siting to avoid and minimise issues

Assessment, Design, and Planning Mitigation

- Further scoping of erosion and sedimentation issues
- Scoping of related environmental and social impacts and risks
- Detailed assessment of issues, impacts and risks (both for project longevity, and environmental and social issues)
- Project design to avoid and minimise risks
- Identification of maintenance requirements
- Planning of additional mitigation measures

Implementation of Design and Mitigation Measures

- Construction to required designs
- Mitigation of construction site impacts
- Mitigation of impacts during reservoir filling
- Construction site rehabilitation

Operation of Design Measures, Maintenance, and Mitigation Measures

- Operation of facilities to manage erosion and sedimentation issues
- Maintenance of facilities to manage erosion and sedimentation issues
- Mitigation of impacts that cannot be avoided
- Monitoring of the identified issues
- Identification and management of ongoing or emerging issues

Preparation and Implementation of Retro-fitting and Refurbishment

3.1.3 Operating projects, retro-fitting, and refurbishment

An operator of an existing project may not have adopted a life cycle approach to the management of sedimentation during earlier stages, or it may not have considered erosion and sedimentation issues at all. In these cases, the project operator should refer to the steps identified in Figure 3.1 for the Operation stage, but should also consider the applicability of the methodologies and technologies that correspond to the earlier stages.

The planning and implementation of retro-fitting and refurbishment of projects should follow the same steps as a new project in its preparation and implementation stages:

During **Preparation**:

- Scoping of erosion and sedimentation issues, and related environmental and social impacts and risks;
- Detailed assessment of issues, impacts and risks;
- Retro-fit or refurbishment design to avoid and minimise risks;
- Identification of maintenance requirements; and
- Planning of additional mitigation measures for operation.

During **Implementation**:

- Construction to required designs;
- Mitigation of construction site impacts and construction site rehabilitation; and
- Monitoring.

3.2 Assessment

3.2.1 Scoping and siting

Scoping refers to the initial identification of issues, and definition of the scope of further investigation or assessment that should be undertaken.

For a new project, scoping of potential erosion and sedimentation issues must be carried out at an early stage, in order to inform the siting of the project and the main project components. Even for an existing project, an assessment of emerging issues should begin with a scoping exercise to determine which data, methods, issues, or areas should be focused on during the assessment.

While it may be possible to conduct some initial surveys at this stage, scoping and the siting of the project are likely to be predominantly based on existing secondary information, or use data from geographically-similar river basins. Available sources of secondary data should be identified and included, with greater emphasis on relatively recent secondary data.[2]

The potential issues to be included in scoping should cover the issues set out in Chapter 2, and should include:

- Catchment sediment yields, and trends in the catchment area that will affect yields in the long-term;
- Reservoir sedimentation;
- Slope stability and soil erosivity in the area around the reservoir, and in the construction site and locations of ancillary structures;
- Downstream impacts; and
- Climate change and how it may affect sediment transport.

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[2] 'Secondary information' or 'secondary data' refers to information or data that has been previously gathered by other parties, i.e. it is not primary data gathered by the developer or operator.

The scoping of issues for a river that has existing dams and reservoirs should include the influence on the existing reservoirs or cascade on sediment transport.

It will be necessary to obtain suitable expertise. Professionals working in this area might include, for example, hydraulic and geotechnical engineers and fluvial geomorphologists.

The Methodologies and Technologies chapter therefore details the following areas:

- Section 4.1.1 – Obtaining expertise
- Section 4.1.2 – Early stage scoping of issues for further investigation
- Section 4.1.3 – Options assessment: comparing alternative sites

3.2.2 Assessment and monitoring

Assessment of the issues should be based on field data through surveys, and should establish an understanding of the existing sedimentation regime and dynamics of the river. In addition, there may be a need for surveys to identify and categorise areas according to land stability or sensitivity to erosion. With these surveys, sediment management strategies can be tailored to site-specific conditions and limitations.

Primary data should be collected for:

- Hydrological data, preferably as a series of daily flows, which can be summarised as mean annual flow and mean monthly flows to indicate seasonality;
- Instream sediments (concentrations and loads of suspended and bedload sediment) using equipment and materials that follow recognised standards relevant to the sediment types and amounts;
- Predictions of the effects of climate change on hydrological flows and sediments;
- Existing and planned reservoirs upstream and downstream of the project site, and their implications for sediment issues;
- Catchment condition (e.g. area, slopes, vegetation cover, soil types) including upstream reservoirs, to determine present and likely future sediment yields into the reservoir;
- River channel geomorphological conditions in the project construction area and as far downstream as will experience significant flow changes as a result of the future project; and
- Slope stability and erosion risk from locations in the vicinity of project activities, where land disturbance is planned.

This data should be used in the prediction of outcomes, for example in the rate and locations (pattern) of reservoir sediment accumulation, or the location of downstream erosion risk. This should be combined with assessment of the efficacy of proposed management measures for these outcomes. This may take place through a stand-alone study or studies on specific issues or may be included in the Environmental Impact Assessment (EIA). The EIA should also predict environmental and social impacts arising from the predicted erosion and sedimentation issues.

Once the key issues have been identified, it will be necessary to identify indicators for monitoring their status, defining a baseline, and determining the frequency and locations of monitoring. It is particularly important to monitor issues that affect project sustainability (e.g. reservoir sedimentation), not only environmental and social issues. In addition, there should be a means of identifying and responding to erosion and sedimentation issues that are not included in the monitoring, through a regular management programme review, which may form part of an Environmental Management System.

The Methodologies and Technologies chapter therefore details the following areas:

- Section 4.1.1 – Obtaining expertise
- Section 4.2.1 – Sediment sampling design and survey methodologies
- Section 4.2.2 – Sediment rating curves
- Section 4.2.3 – Particle size distribution
- Section 4.2.4 – Estimating sediment yield
- Section 4.2.5 – Bathymetric surveys
- Section 4.2.6 – Predicting reservoir sediment accumulation
- Section 4.2.7 – Assessment and monitoring of catchment condition
- Section 4.2.8 – Assessment and monitoring of slope stability
- Section 4.2.9 – Comparing alternative management options
- Section 4.2.10 – Defining indicators, baseline, and monitoring programmes

3.3 Management

The aim should be to avoid, minimise and mitigate issues through the use of management structures that are physically built into the design of the project, here referred to as design measures. However, it is often not possible to adequately manage sediment using design measures alone, and mitigation measures are required to further minimise issues and mitigate impacts. In practice, design measures will require operating to ensure that they effectively address the issues for which they are intended.

Strategies that combine design measures, their operation, and mitigation measures should be planned. The techniques that are most suitable will change over time as the reservoir fills with sediment, and more than one technique may also be applied at a given reservoir, either sequentially or concurrently. The applicability of management techniques will depend on the capacity of the reservoir compared to the mean annual sediment inflow, as discussed further in Section 4.1.2 below.

A range of design and mitigation measures are applicable for reservoir sediment accumulation. As shown in Figure 3.2, reservoir sediment accumulation can be managed by: 1) reducing sediment inflow from upstream (using measures carried out in the catchment e.g. slope and bank protection, reforestation, contour ploughing in agriculture); 2) transport or routing of sediments (e.g. by-pass channels, sluicing, flushing, turbidity current venting); 3) removing or redistributing the deposits (using measures carried out in the reservoir, e.g. dredging, dry excavation, and hydrosuction); or 4) implementing adaptive strategies.

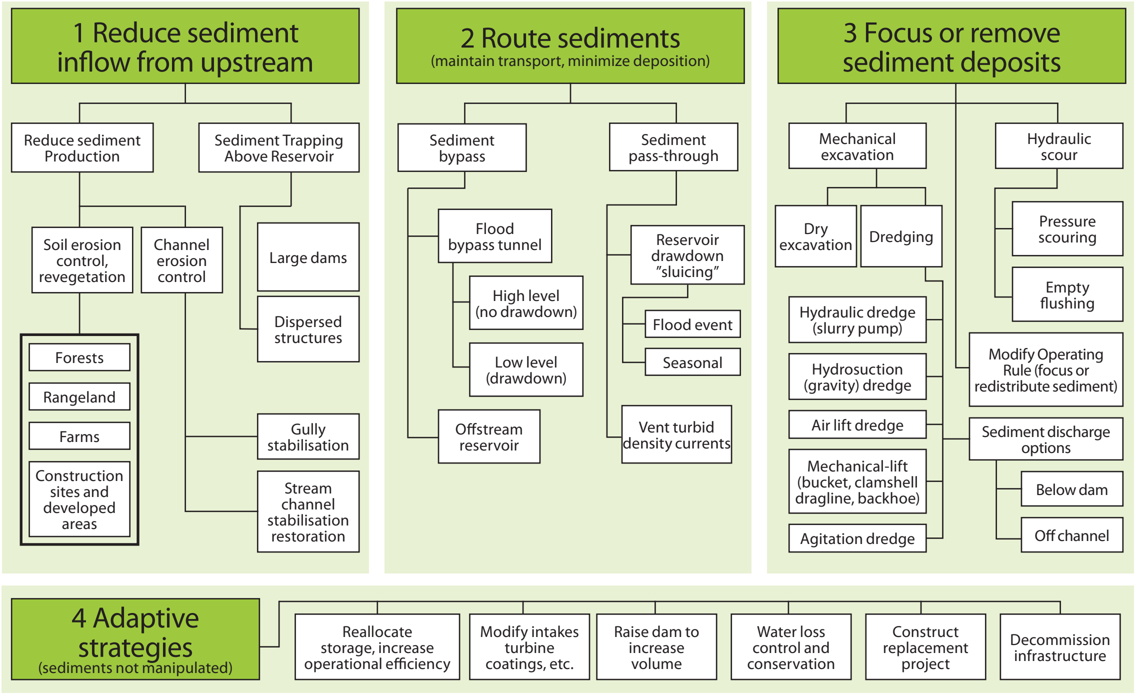

Figure 3.2 Sediment management strategies

Source: Morris, G. (2015). Management Alternatives to Combat Reservoir Sedimentation. In: International Workshop on Sediment Bypass Tunnels. Zurich: ETH Zurich.

3.3.1 Design measures

The removal of sediment from a reservoir is not a simple task, and mitigation of reservoir rim and downstream issues is also costly; therefore, avoidance and minimisation through design is preferable, and globally there is considerable knowledge and experience regarding potential design measures. For example, a low-level outlet to be used to pass sediment downstream could avoid reservoir sedimentation and concurrently minimise downstream erosion.

These measures must be specified in the feasibility study, and included in the detailed designs conducted by an EPC (Engineering, Procurement, and Construction) contractor or the owner's engineer. There is thus an important interface between the assessment of erosion and sedimentation issues, EIA studies, and engineering design. It is also important to specify how any measures that are built into designs should be operated to meet their objectives, and to identify whether any additional mitigation of residual impacts is necessary.

The Methodologies and Technologies chapter details:

- Section 4.3.1 – Sediment by-pass: flood by-pass tunnels and channels
- Section 4.3.2 – Sediment by-pass: offstream reservoirs
- Section 4.3.3 – Sediment pass-through: sluicing
- Section 4.3.4 – Sediment pass-through: density current venting;
- Section 4.3.5 – Sediment removal: flushing
- Section 4.3.6 – Sediment management at RoR headworks
- Section 4.3.7 – Drainage design for construction sites and roads
- Section 4.3.8 – Design of instream diversion during project construction

3.3.2 Mitigation measures

Depending on the context of the project, it may not be possible to avoid some erosion and sedimentation issues through design measures. Moreover, in older projects, it may not be feasible to retro-fit design measures. Even when design measures are effective, there may be significant residual impacts, or impacts associated with operations, that must be managed. This means that additional measures are required.

Measures to reduce sediment inflow from upstream (catchment management) may include the prevention of sediment production or the trapping of sediment above the reservoir. There are various physical measures that can be used to strengthen zones that are susceptible to erosion (around the reservoir rim or downstream), as well as measures to limit on-site erosion, which can affect receiving watercourses. Measures to remove sediment from reservoirs involve some form of mechanical excavation. In addition, operating rules can be used to try to re-distribute sediment within the reservoir.

The Methodologies and Technologies chapter therefore details the following areas:

- Section 4.4.1 – Watershed or catchment management
- Section 4.4.2 – Removing accumulated reservoir sediments through
  - Dredging
  - Redistributing sediment within the reservoir
  - Dry excavation
  - Raising reservoir levels
  - Adaptive strategies
- Section 4.4.3 – Reservoir rim and riverbank protection through
  - Operating rules to avoid and minimise reservoir rim and downstream erosion
  - Protection works
  - Buffer zones
- Section 4.4.4 – Mitigation of downstream erosion and sedimentation
- Section 4.4.5 – On-site erosion management
- Section 4.4.6 – Post-construction site rehabilitation

3.3.3 Adaptive strategies

Adaptive strategies that do not involve sediment itself can be used to mitigate the impact of sediment accumulation on reservoir storage. They should only be considered as a last resort for existing projects that have few opportunities to manage sediment sustainably, and should not be used in new projects that should be designed for longevity and intergenerational long-term use. However, they can be used as complementary measures to the sediment management options that are available to an operating project. They include:

- Progressively raising the minimum operating level (MOL), and moving closer to RoR operation;
- Modifying infrastructure affected by sedimentation, e.g. raising intakes, or refurbishing electromechanical equipment with protective coating;
- Reallocating volumes of storage, i.e. between storage for power generation, and a volume used for flood control; and
- Raising the dam to increase storage volume.

3.4 Environmental and social management

While this How-to Guide concerns erosion and sedimentation, it is also important to link the assessment and management of such issues to procedures and plans used for environmental and social management. Methodologies for environmental and social impact assessment (ESIA), environmental management plans (EMPs), environmental and social management and monitoring plans (ESMMPs), and environmental management systems (EMS), will be addressed in a forthcoming How-to Guide, but the key linkages are considered below.

3.4.1 Erosion and sedimentation in the ESIA

The project ESIA should summarise the findings of scoping and detailed evaluation of potential erosion and sediment impacts. Liaison between the engineering consultants and the ESIA and related studies is key in sharing data and ensuring that a good technical understanding of the project's effects on erosion and sedimentation has been integrated into the identification and assessment of significance of environmental and social impacts. It is advisable to include a separate section, with accompanying annexes, on erosion and sedimentation in the ESIA report.

3.4.2 Environmental management plans for erosion and sedimentation

The measures required to avoid, minimise and mitigate environmental and social impacts, resulting from the ESIA, are set out in EMPs or ESMMPs. The measures to be taken to manage erosion and sedimentation issues should be incorporated into these plans. Each contractual component of the project should have a separate plan that can be attached to contracts: for example, the EPC contractor would have a construction-stage plan. In many cases, detailed sub-plans will be established, some of which relate directly to erosion and sedimentation, for example: an EPC Contractor's Construction Stage EMP; Spoil Management Plans; a Site Erosion Management Plan; a Reservoir Management Plan; and a Catchment Management Plan.

3.4.3 Erosion and sedimentation in environmental management systems

Environmental management systems cconsist of a documented combination of operational procedures, practices, plans, and related supporting documents (including legal agreements) that are managed in a systematic way.[3] EMS may in some cases be integrated into or linked to quality management systems and risk management systems.

The company's environmental or sustainability policy must include commitments relating to erosion and sediment, and the EMS should systematically include operational procedures, practices, and plans for both the management of erosion and sedimentation issues and their monitoring. The EMS might also include documentation of regulatory requirements, adaptive management, responsibilities, and procedures for review.

Including erosion and sedimentation issues in EMS or other management systems will prompt a systematic review of the effectiveness of management measures, as well as a regular assessment of their sufficiency or necessary adjustments in monitoring. Reviews of effectiveness may be included in progress reports on a quarterly, biannual or annual basis.

3.4.4 Safeguards on erosion and sedimentation measures

Some measures taken to prevent reservoir sedimentation, or other measures taken to manage erosion and sedimentation issues may have additional environmental or social impacts that must be managed. The ESIA, EMPs, and EMS should also encompass these issues.

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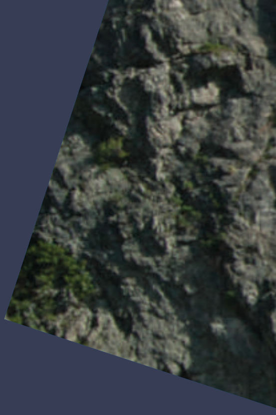
[3] IFC, 2012, Performance Standard 1 – Assessment and Management of Environmental and Social Risks and Impacts

As an example, use of a low-level release valve to remove sediment-laden water or flushing of a desilting chamber can result in significant downstream impacts. This would require planning of sediment-laden discharges, with timing of releases to avoid periods of high sensitivity. These issues are presented in Box 4.3 in Section 4.3.5 concerning flushing and sluicing. A further example is the need for land acquisition to construct bank protection.

4

Methodologies and technologiess



Methodologies and technologies

This chapter catalogues methodologies and technologies for scoping and siting, assessment and monitoring, design measures, and mitigation measures. Each section describes the methodology or technology with diagrams as necessary, and provides sources of further information. Several further case studies can be found on IHA’s Sediment Management Hub: www.hydropower.org/sediment-management

Protection from erosion on cliff near Romanche-Gavet Hydropower Project operated by EDF, France
Photo credit: Bernt Rydgren

4.1 Scoping and siting

4.1.1 Obtaining expertise

Analysis of sedimentation issues, from basic determination of sediment yield to detailed modelling and comparison of proposed measures, is complex and requires the use of suitably-qualified and experienced experts. It will be essential to obtain professional expertise in sedimentation, initially at an early stage to scope erosion and sedimentation issues in or out of further investigations, and subsequently during more in-depth investigations. Qualified and experienced experts with expertise in sediment sampling design, data collection, data analysis and interpretation should be used to prepare any baseline studies.

Professionals working in this area might include hydraulic engineers and fluvial geomorphologists. Hydraulic engineering is a specialised area of civil engineering focussed on the flow and conveyance of fluids and sediments including the design and effects of hydraulic structures (e.g. bridges, canals, levees). Fluvial geomorphology is focussed on the response of the landscape to water movement. Geotechnical engineers may be required for land stability assessment.

Most engineering firms employ hydraulic engineers. For highly specialised studies, for example for physical modelling, it may be necessary to engage specialist expertise at a commercial laboratory offering services in physical hydraulic model studies, or from an academic institution or institute.

Professional institutions, membership organisations, and national dam associations may provide a means of identifying experts. Examples of professional institutions include the Institution of Civil Engineers (ICE) in the UK, the American Society of Civil Engineers in the USA, the Chartered Institution of Water and Environmental Management (CIWEM) in the UK, and others. IHA is an example of a membership organisation, whereas the Canadian Dam Association and the national chapters of ICOLD are examples of national dam associations.

Training and education on sedimentation can be obtained through academic institutions, and initiatives such as those listed in Table 4.1. Regional and national initiatives, including the International Centre for Integrated Mountain Development (ICIMOD) and its Himaldoc database of studies, can provide detailed specialist expertise on the sedimentation issues in a specific geographic context. In addition, professional networks may encompass suitable experts, for instance the range of networks listed in Table 4.1.

Table 4.1 Examples of relevant training institutes and professional networks

Training Institutes	
IHE Delft Institute for Water Education (formerly known as UNESCO-IHE)	https://www.un-ihe.org/
International Centre for Hydropower (ICH)	http://www.ich.no/
International Research and Training Centre on Erosion and Sedimentation (IRTCES)	http://isi.irtces.org/isi/index.htm
UNESCO International Sediment Initiative (ISI)	http://isi.irtces.org/isi/index.htm
ICIMOD	http://www.icimod.org/
Professional Networks	
WaterNet (Southern Africa)	http://www.waternetonline.org/
Nile Basin Capacity Building Network (NBCBN)	https://www.nbcbn.net/home
Collaborative Knowledge Network Indonesia (CKNet-INA)	http://www.cknet-ina.org/
Arab Integrated Water Resources Management Network (AWARENET, Arab region)	https://awarenet.info/
Latin American Water Education and Training Network (LAWETNET)	https://lawetnet.org/
International Association for Hydro-Environment Engineering and Research (IAHR)	https://www.iahr.org/
China Institute of Water Resources and Hydropower Research	http://www.iwhr.com/zgskywwnew/index.htm

4.1.2 Early stage scoping of issues for further investigation

During the very initial stages of project development, or, for older projects, during the initial stages of considering sedimentation issues, an initial scoping of the erosion and sedimentation will be necessary. In some cases, it may be determined that sedimentation issues will not require further investigation after this stage. An initial scoping, carried out by a suitably-qualified and experienced expert, could be conducted through:

- Analysis of secondary information on sediments in the river or nearby similar rivers, conducted over a relatively limited number of days, without any site assessment;

- A site assessment to gather basic observations and samples, combined with analysis of the available secondary information.

In either case, all available sources of secondary data should be identified and included. More emphasis should be given to relatively recent secondary data. The scoping should check whether there have been any changes in the project context since the secondary data was collected (e.g. an upstream dam). With a site visit, the sedimentation expert(s) can verify secondary data with field-based observations and measurements, and can take local knowledge into account.

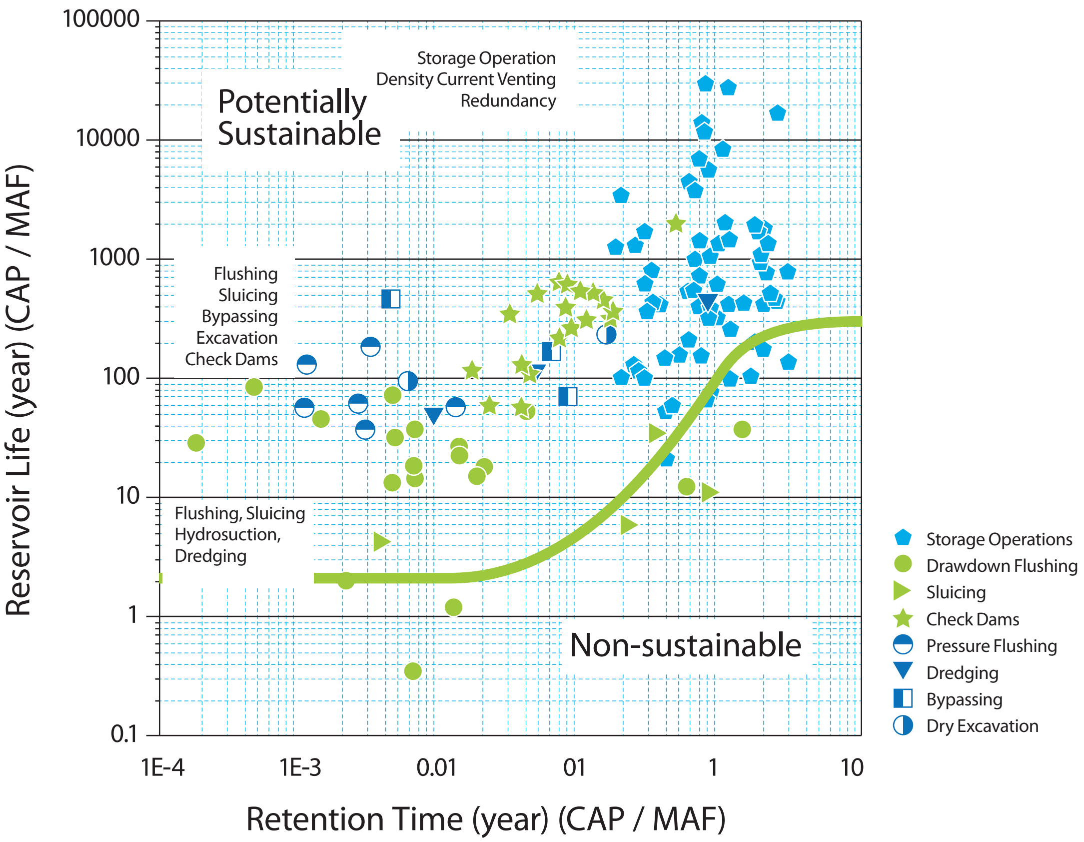
With relatively basic information, sediment management options can also be considered at an early stage. For example, if the catchment area is less than 100 km^2 and soils are fine-grained, there is good potential for effective watershed management. The Reservoir Conservation Model (RESCON) 2 is a tool for the preliminary assessment of sediment management options.[4] It considers the suitability of the options in relation to the capacity of the reservoir as compared to the mean annual sediment inflow, and the mean annual runoff (see Figure 4.1 below), and also considers sustainability and hydrological uncertainties associated with climate change.

Even at an early stage, the implications of climate change for long-term changes in flow, and therefore the implications for erosion and sedimentation, should be considered. Significant changes in flow could arise from more intense weather events, creating additional risks relating to erosion, sediment movement, bank collapse, landslides and mudslides.

Figure 4.1 Preliminary Assessment of Reservoir Sedimentation Management Options

'CAP' refers to the reservoir gross storage capacity expressed in m^3*, 'MAS' is the mean annual sediment inflow expressed in* m^3/a*, and 'MAF' is the mean annual runoff also expressed in* m^3/a*.*

Based on: Annandale, G. (2013). Quenching the Thirst – Sustainable Water Supply and Climate Change. *Charleston: CreateSpace Independent Publishing Platform.*



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[4] Download the tool from https://www.hydropower.org/sediment-management/resources/tool-reservoir-conservation-model-rescon-2-beta

4.1.3 Options assessment: comparing alternative sites

Considering erosion and sedimentation issues at an early stage allows the project developer to compare alternative options. These may be options for hydropower projects in entirely different locations, or options for the precise siting of the project in a particular location. The sedimentation issues in alternative catchments within a river basin could be compared. This may be carried out by key decision-makers such as the Ministry of Energy as part of strategic planning or master planning, or by their stakeholders such as international financing institutions.

Note that siting a new project downstream of an existing storage reservoir can have significant benefits. Although upstream storage may reduce sediment inflows at the new project site, it will be necessary to consider sediment management through the cascade to maximise the longevity of the entire cascade.

In a recent example, slope stability (specifically, the slope stability at the project site, the potential scale of disturbance associated with the project, and the potential impact of the project on slope stability during operations) was factored into a cumulative impact assessment of the Kuri-Gongri river basin in Bhutan, which compared four alternative scenarios of twenty project options. A further recent example is the strategic environmental assessment of the Myanmar hydropower sector conducted by IFC in 2019. This study zoned sub-basins on the basis of geomorphology, including potential sediment production, and delta and coastline stability.

4.2 Assessment and monitoring

4.2.1 Sediment sampling design and survey methodologies

The most important parameter to measure is suspended sediment. Measuring bed load is very difficult, and measurements of suspended sediment alone can be used to determine reservoir sedimentation rates. The number, locations, and timing of sampling must be designed in order to ensure that the samples are representative of the variation in suspended sediment longitudinally along the river, through the river profile, and over time.

A sample collected at the surface or at a fixed point will not be representative. Only the fine particles in the river will be evenly suspended from the surface of the water to the river bed. Sand settles more rapidly than finer sediment, and there can be strong gradients in concentration. This requires that suspended sediment samples are taken at a number of depths through the water column at any particular sampling location, i.e. the sampling is 'depth-integrated' or 'depth-integrating' methodologies are used. Suspended sediment also varies with distance from the riverbank, with higher concentrations in fast-moving water in the centre, so multiple depth-integrated samples are required across the width of the river. The use of water quality samples, which are usually collected as grab samples with bottles close to the water surface, generally results in severe underestimates of sediment yield.

In addition, sediment transport is highly variable over time, and short-term datasets can seriously underestimate long-term sediment load. Rather than the collection of a large number of samples, the key to obtaining representative data is the collection of samples over a large range of flows. For example, it is not uncommon for a large flood to transport more sediment than several years of normal flow. Therefore, special emphasis should be given to sampling infrequent high-discharge events that are responsible for transporting the largest portion of the sediment load. This can be achieved by sampling the larger flood events in any given year and taking samples over several years to increase the chances of sampling large floods.

Box 4.1 provides further guidance on sampling design, including the number of points, locations, and timing.

'Isokinetic' depth-integrated samplers capture water at the same rate as the surrounding flow. They are lowered at an even rate through verticals across the width of the river to obtain a depth-integrated sample, to obtain discharge-weighted suspended sediment concentrations. Point samplers can also be used at fixed intervals

Box 4.1 Sampling design

During the preparation stage, sampling data should be collected over a long period. Because of the role that floods play in sediment transport, variation of sediment data will be high: a record length of four years is expected to have a potential error of 50%, and a 12-month record (one year) has a potential error of 100%. Ideally, data should be collected over several years, up to a decade, to obtain a true picture of sediment transport.

The number and timing of sampling trips should be designed to obtain the most representative data, taking into account any factors that could influence sediment transport. Some examples include: all seasonal conditions of the region; sampling to capture very different flow conditions including during the low flow season, the onset of the high flow season (noting that most sediment transport occurs at this time), and the high flow season; and increasing sampling frequency during low-frequency, high-magnitude events such as intense rainfall during the monsoon period.

There should be a meaningful geographic spread of sampling sites, including river reaches that will experience the most change upon project development or are most sensitive to impacts. Instream sediment sampling data should be collected from a minimum of four sampling locations: upstream and immediately downstream of the future reservoir, and upstream and downstream of the next major tributary downstream of the reservoir (and of the power station tailrace if located some distance away). If possible, locations upstream and downstream of other major tributaries and development activities should also be sampled. Ideally, significant variations in sediment loads from the different upstream sub-catchments should be established to inform catchment management interventions that will reduce sediment load reaching the future reservoir.

through each vertical (preferably in addition to the depth-averaged sampling). Measurements of turbidity, which is an optical characteristic, can be used as a proxy for suspended sediment, but turbidity needs to be calibrated against actual suspended sediment. However, turbidity sampling, although relatively convenient, is not particularly accurate. Advanced equipment such as laser diffraction instruments (LISST sensors) now use laser technology to concurrently measure sediment concentration and particle size distribution, and provide more accurate results than turbidity meters. Figure 4.2 depicts several depth-integrated samplers and an LISST sensor.

For accurate sampling of sediments during high flows, additional sampling can be undertaken with pump samplers, which pump water into a sample bottle as the river or turbidity rises. Frequent measurements, as frequent as hourly, may be required to obtain an accurate picture of sediment flow through the rising and falling phases of a flood. Daily sampling may be adequate in a monsoon season over two or more months. This level of accuracy is necessary if it is envisaged that pass-through or by-pass measures will be used for passing sediment during high flows. Because pump sampling is done at a fixed point, the results must be calibrated against depth-integrated sampling.

Measuring bed load is extremely costly and challenging during flood conditions, and it is therefore normally estimated using equations, or more recently measured using geophones. The standard measurement device is a Helley-Smith device. Bed load is a small proportion of total load, meaning errors will not have great effect on total load estimates; however, it is difficult or impossible to remove from the reservoir and is therefore a chief determinant of long-term reservoir storage sustainability, as well as downstream impacts arising from hungry-river syndrome.

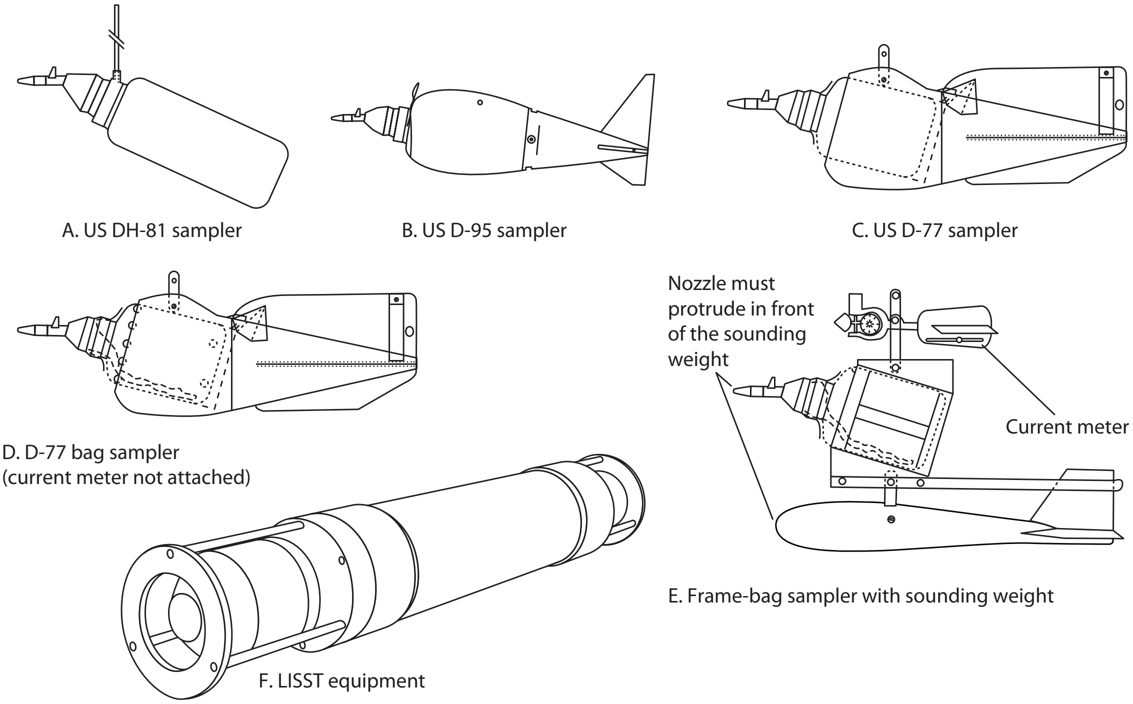
If it is not possible to gather data, a rule of thumb is that bed load is 5 to 10% of the volume of suspended sediment, or 15% for some mountain rivers and even 25% for sand bed rivers. The estimation of bed load requires knowledge of the gradation of parent bed material, and to develop an equation linking bed load and suspended sediment, it would be necessary to sample the coarse material on the bed, i.e. that which is not picked up during floods and therefore included in suspended sediment sampling. This can be achieved with sieve analysis of volumetric samples (the only available option for sand bed rivers) or with non-intrusive sampling methods such as line-by-number or grid sampling (easily applied in gravel bed rivers characterised by sand-gravel mixtures).

Further Information:

- Federal Interagency Sedimentation Project: water.usgs.gov/fisp/
- US Geological Survey: water.usgs.gov/osw/techniques/sediment.html
- Carvalho, N., Filizola Júnior, N., Santos, P. and Lima, J. (2014). *Sedimentometric Practices Guide* (updated in 2017). Brasília: ANEEL.
- Guy, H. (1969). Laboratory Theory and Methods for Sediment Analysis. *Techniques of Water-Resources Investigations of the United States Geological Survey*, 5(C1). Washington, DC: U.S. Government Printing Office.
- Nolan, K., Gray, J. and Glysson, G. (2005). Introduction to Suspended-Sediment Sampling. *USGS Scientific Investigations Report 2005-5077*. Reston: U.S. Geological Survey.
- Edwards, T. and Glysson, G. (1998). Field Methods for Measurement of Fluvial Sediment. *Techniques of Water-Resources Investigations of the United States Geological Survey*, 3(C2). Washington, DC: U.S. Government Printing Office.

Figure 4.2 Iso-kinetic depth-integrating samples

(A–E illustrations courtesy of Federal Interagency Sedimentation Project, Waterways Experiment Station; F. from https://www.sequoiasi.com)



A. US DH-81 sampler

B. US D-95 sampler

C. US D-77 sampler

D. D-77 bag sampler (current meter not attached)

E. Frame-bag sampler with sounding weight

F. LISST equipment

4.2.2 Sediment rating curves

A sediment rating equation or sediment rating curve correlates discharge with sediment concentration, based on field observations. Figure 4.3 shows a hypothetical example of a rating curve. A rating equation may be as simple as:

> SSC (suspended sediment concentration in milligrams per litre) = aQb

where Q is discharge and *a* and *b* are coefficient values particular to the site. There may be different equations for different flow ranges, reflecting conditions in different seasons.

Further Information:

For further information on how to construct sediment rating curves, refer to:

- Glysson, G. (1987). Sediment Transport Curves. *USGS Open-file Report 87–218*. Reston: U.S. Geological Survey.

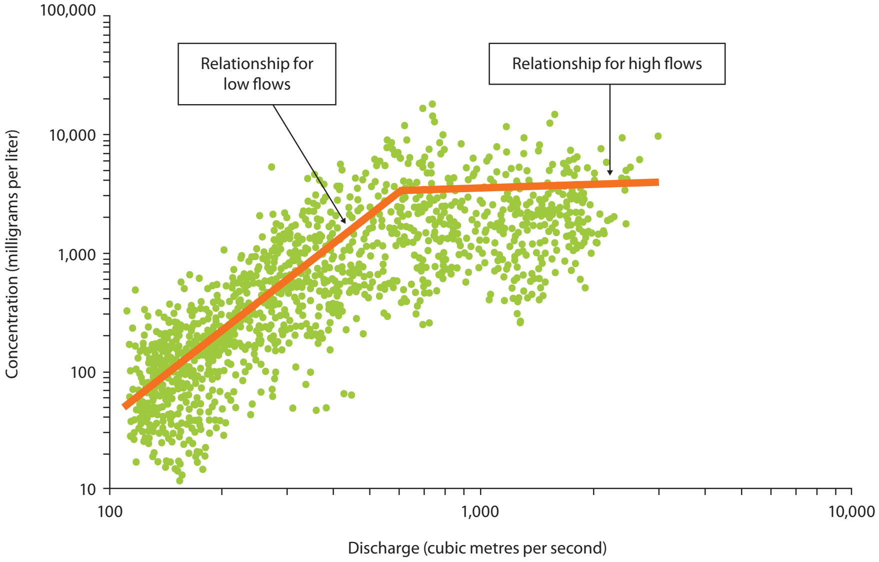
4.2.3 Particle size distribution

The results of sediment sampling are used to show a particle size distribution. This is a profile of the volume or mass of sediment (or % volume or mass) plotted against the particle diameter. Particle size analysis is important for understanding fluvial geomorphic processes, the potential for scouring and erosion, and for determination of potential wear on turbines and other equipment.

- Sieve analysis is used to determine the particle size distribution of bed material, bed load, and the sand fraction of suspended load, while hydrometer tests are used for finer suspended load.
- For existing reservoirs, it is important to determine the in situ bulk density and grain size distribution of sediment deposits, for the planning of dredging or flushing. Depending on the location of deposits along the reservoir and the type of deposits, the sampling and laboratory analysis method might differ. Generally, grab samples are suitable for deltaic deposits, but core drilling will be required for deposits of fine silt and clay material closer to the dam.

Figure 4.3 A sediment rating curve, showing two rating relationships

Source: Morris, G. (2016). Chapter 6 Sediment Monitoring. In: Extending the Life of Reservoirs: Sustainable Sediment Management for Dams and Run-of-River Hydropower. *Washington, DC: World Bank.*



4.2.4 Estimating sediment yield

Estimating sediment yield is not an exact science and is difficult when relevant field data is lacking. The best way to estimate sediment yield is to make use of field data, either concurrent measurements of sediment concentration and water flow data over long periods, or (for existing projects) reservoir resurvey data (see Section 4.2.6). Reservoir resurvey data from other existing reservoirs in the catchment or similar catchment can also be used to estimate average annual yield for a new reservoir.

With concurrent measurements of water discharge (flow in m^3/s) and sediment concentrations in the flowing water (in kg per m^3 of flow[5]), average annual sediment yield can be calculated. Reliable sediment yield estimates use multiple methods for estimating sediment concentrations and require careful evaluation of the results; no one method used in isolation should be relied on. Long periods of data are necessary, with records of only two to four years associated with potential errors of 75–100%.

When data is not available, empirical methods can be used to estimate average annual sediment yield. These include:

- Sediment yield maps which show specific sediment yield and can be used to estimate yields on the basis of the catchment area;
- Empirical methods based on geologic features, climate, anthropogenic influences, population density, level of development, and topography (which should only be used only for large catchments, with caution); and
- Geomorphological approaches, which entail dividing a catchment into geomorphologically-similar regions and proceeding from there to estimate sediment yield.

An example of an empirical method is set out in Syvitski and Milliman (2007). This was developed from a comprehensive database of sediment load measurements and delivers more reliable results than other methods based on weaker databases or fewer parameters.

Computer simulation and GIS-based analysis tools can be used to simulate surface erosion (sediment generation) and transport along the hydrographic network (sediment delivery). Some are semi-empirical, as they are based on empirical approaches such as USLE equation but also use time series of data, for example of rainfall events, and are calibrated using field data. Different scenarios such as land use change can be fed into the analysis, thus providing a more complex and physically-based approach than purely empirical approaches. An example is Soil and Water Assessment Tool (SWAT) software.

The implications of long-term temporal changes to flows and to extreme weather events, potentially induced by climate change impacts, should be considered in the assessment of erosion and sedimentation. Significant changes in flow arising from more intense weather events can create additional risks relating to erosion, sediment movement, bank collapse, landslides and mudslides. These can, in turn, have public safety implications.

Further information:

- Annandale, G. (2016). Chapter 4 Sediment Yield. In: *Extending the Life of Reservoirs: Sustainable Sediment Management for Dams and Run-of-River Hydropower*. Washington, DC: World Bank.
- Syvitski, J. and Milliman, J. (2007). Geology, Geography, and Human Battle for Dominance over the Delivery of Fluvial Sediment to the Coastal Ocean. *Journal of Geology*, 115(1), pp. 1–19.

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[5] Using m^3 per m^3 flow is not recommended as the density of deposited sediment varies, reducing the accuracy of estimates.

4.2.5 Bathymetric surveys

Bathymetric surveys are conducted pre-project to establish a baseline, and during operations, to observe sediment accumulation and calculate sediment yield. In operating projects, the best estimates of historical average long-term sediment yield are obtained from bathymetric surveys. This would entail (i) bathymetric surveys, repeated at intervals, (ii) identification of the trap efficiency of the reservoir, and the sediment bulk density, and (iii) calculation of sediment yield.

Bathymetric surveys are conducted using some form of remote sensing (echosounders, sidescan radar, etc) to map the below-water topography (i.e. bathymetry) of the reservoir. Comparison of this bathymetric map with earlier bathymetric maps, or a pre-project topographic map, enables the volume of sediment deposited in the reservoir over the intervening period to be calculated. It is best to perform repeated bathymetric surveys using a consistent methodology, with ideally the first survey performed soon after impoundment, to obtain an accurate measurement of the sedimentation rate. Surveys should be performed at five to ten year intervals until a consistent pattern of volume loss is established; subsequently, they may be scheduled to coincide with an expected fixed % loss in volume (e.g. 5%) or after extreme flood events.

The **trap efficiency (TE)** of a reservoir expresses the extent to which a reservoir traps sediment. For example, a reservoir with 90% TE is one that traps 90% of sediment inflow, and enables 10% to be discharged downstream. Empirical methods are used to estimate TE of suspended load (TE of bed load is 100% in most cases). Brune (1953) and Churchill (1948) are perhaps the most widely used: a Brune curve (1953) estimates TE of suspended load on the basis of reservoir volume and flow (i.e. the **capacity-inflow ratio**); and a Churchill curve (1948) uses reservoir volume, reservoir length and flow. Generally, the Churchill method is more appropriate for regularly sluiced reservoirs as it also considers the flow velocity in the reservoir.

Sediment bulk density refers to the mass of the sediment per unit volume (kg per m^3) and depends on the particle size distribution and the degree of compaction. To estimate sediment bulk density, representative sampling across the reservoir should be conducted as coarser sediments will tend to settle nearer the reservoir tail, and samples are oven dried to determine the dry weight. Note that deeper sediments that were deposited longer ago will be more compacted, requiring sampling of cores to account for the range of compaction. Models and calibration can be used to estimate bulk density based on shallower cores, collected using portable equipment such as a 'vibracore'.

The **sediment yield** of the catchment in tonnes per annum can then be calculated as: the additional sediment volume added since the earlier bathymetric survey, divided by TE, multiplied by sediment bulk density, divided by the number of years between the surveys. In addition, **specific sediment yield** (t/km^2/yr) can be calculated using the area of the catchment.

Note that for a future estimate of sediment yield, it would be necessary to also consider future trends in the catchment condition as well as the effects of climate change (for example on increased rainfall, resulting in higher sediment yield).

Further information:

- Brune, G. (1953). Trap Efficiency of Reservoirs. *Transactions of the American Geophysical* Union, 34(3), pp. 407–18.
- Churchill, M. (1948). Analysis and Use of Reservoir Sedimentation Data by L.C. Gottschalk. In: *Federal Interagency Sedimentation Conference*. Denver: U.S. Geological Survey, pp. 139–40.

4.2.6 Predicting reservoir sediment accumulation

The pattern and distribution of sediment deposition in the reservoir should be predicted, and used to plan options for the management and maintenance of the reservoir's live storage over the long-term. The common assumption that sediment accumulates first in the dead storage is incorrect, and patterns of sediment accumulation tend to be complex in practice. Modern dam designs must account for the impact of the actual shape of the deposited sediment on reductions in active storage. Broadly, sediments can be expected to accumulate in different parts of the reservoir, depending on the relationship between reservoir capacity and depth, water discharge, and sediment type.

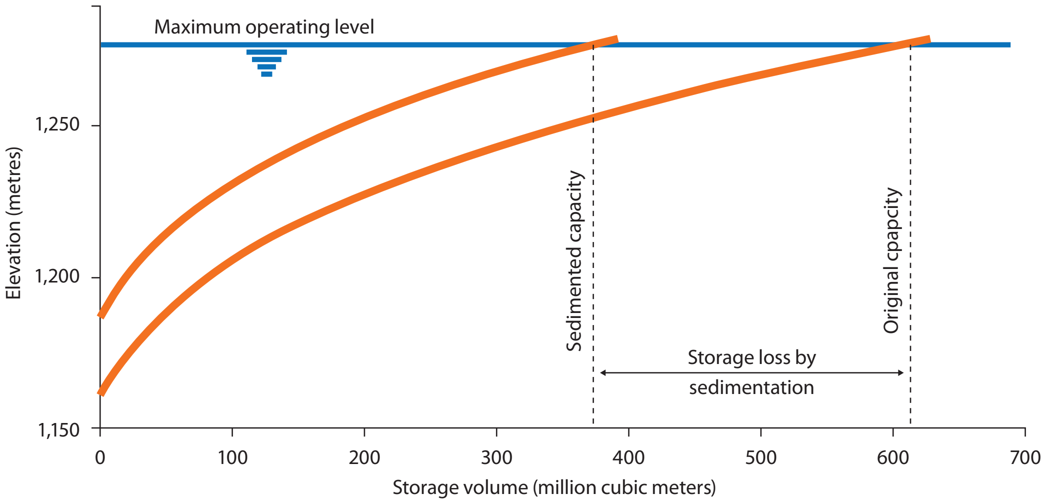
Numerical models and physical models are used to predict the behaviour of sediment throughout the river, including predicting reservoir sediment accumulation. Box 4.2 below provides further information on numerical and physical modelling. Computer simulations are necessary during feasibility studies or later, while empirical methods may be sufficient during pre-feasibility. Sedimentation experts will be able to recommend what simulations are to be used, and why, and should use the latest versions. Modellers should visit the site before modelling, at low flows, to inspect sediment and gather an understanding of key parameters on grain sizes and bed material. It is useful to revisit the project's sediment management strategy based on modifications to the assumptions in the pre-construction modelling, in light of the monitoring results. Examples of open-source software available for modelling are:

- HEC-RAS (US Army Corps of Engineers Hydrologic Engineering Center's River Analysis System, for one- and two-dimensional modelling; and
- MIKE 11, (one-dimensional), MIKEHYDRO, and MIKE 21C (a quasi three-dimensional model).[6]

Elevation-storage graphs are used to highlight the relationship between reservoir levels and storage volume, and can be used to show the effect of sedimentation over time on storage loss. They are used to visualise the results of surveys and modelling, and thereby as a tool for planning. For example, Figure 4.4 shows two elevation-storage curves for (i) the original reservoir and (ii) the reservoir following sediment accumulation, indicating a storage loss of over 300 million m^3. Longitudinal profiles of the reservoir bed, as shown in Figure 4.5, can be compiled by cross-sectional or bathymetric surveys, and are useful for visualising the distribution of sediment in a reservoir. Another very useful plot for the visualisation of spatial pattern of sedimentation is a plan-view contour plot (digital elevation model) of measured bathymetrical data.

Figure 4.4 Elevation-storage graphs, showing the original elevation Storage relationship (the curve on the right) and the sedimented relationship (the curve on the left).

Source: Morris, G. (2016). Chapter 6 Sediment Monitoring. In: Extending the Life of Reservoirs: Sustainable Sediment Management for Dams and Run-of-River Hydropower. *Washington, DC: World Ban*



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[6] MIKE software is available on https://www.mikepoweredbydhi.com/

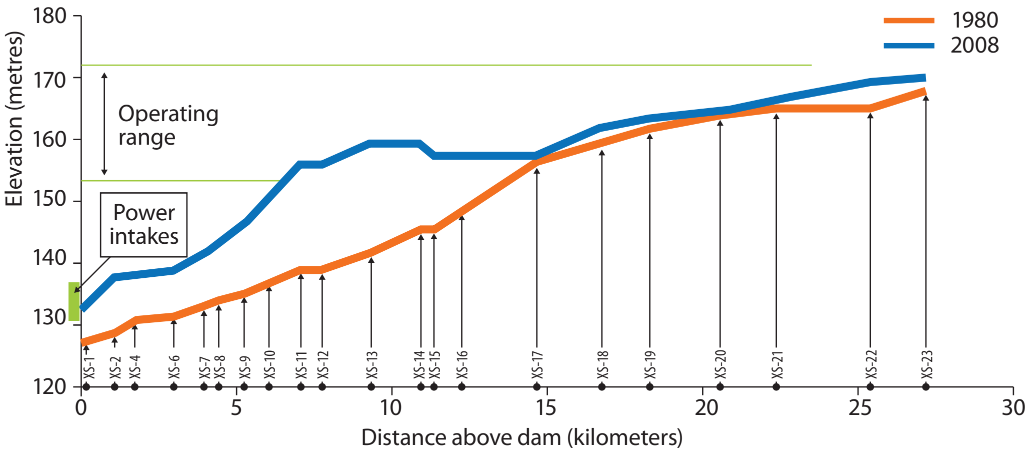


Figure 4.5 Longitudinal profile of the reservoir bed in Péligre Dam, Haiti, showing sediment deposits by 2008

Source: Morris, G. (2016). Chapter 6 Sediment Monitoring. In: Extending the Life of Reservoirs: Sustainable Sediment Management for Dams and Run-of-River Hydropower. Washington, DC: World Bank.

The implications of long-term temporal changes to flows and to extreme weather events, potentially induced by climate change impacts, should be considered in the assessment of erosion and sedimentation. Significant changes in flow arising from more intense weather events can create additional risks relating to erosion, sediment movement, bank collapse, landslides and mudslides. These can, in turn, have public safety implications.

4.2.7 Assessment and monitoring of catchment condition

If it is expected that catchment management measures will be necessary or feasible as measures to reduce sediment yields, it will be necessary to assess the condition of the catchment on a wider scale. This would involve a combination of:

- Remote sensing to identify land uses and forest cover conditions;
- Mapping of land use, forest cover, sub-catchments with most land instability, etc;
- Mapping of key sources of sediment including roads, forest concessions, and settlements, and key processes such as mass movements, debris and mud flows, rockfalls and avalanches;
- Identification of organisations with influence on land use and land management within the catchment, in order to identify potential partners in catchment management; and
- Assessment of potential options for catchment management (see Section 4.4.1 below).

Landsat satellite imagery will be useful in the first steps of identifying land uses and cover. Google Earth now offers access to the whole Landsat archive and functionalities to compute cloud-free mosaic images.

Mapping of key sources of sediment can be combined with GIS modelling of surface erosion and transport along the river network. GIS modelling requires digital elevation models (DEMs) of the catchment, delineation of the hydrographic network, and spatially distributed rainfall and geological data. DEMs, rainfall data and geological data can be obtained from readily available data sources in the public domain, while transport of sediment from the generation sources to the project site is usually based on empirical sediment delivery relationships.

Box 4.2 Numerical and physical modelling

Modelling is the most important aspect of hydraulic design, as millions of dollars in construction and operational expenses can be avoided through project optimisation from modelling.

Numerical modelling

Numerical modelling involves the construction of a computer model to simulate sediment behaviour under different operational scenarios based on sediment transport equations. One-dimensional modelling simulates the reservoir in a linear manner, representing the reservoir as a series of cross-sections. Water and sediment are transported from one cross-section to the next, but no lateral movement from one side of the reservoir to the other can be simulated because conditions are averaged across the entire cross-section.

One-dimensional modelling can provide a good approximation of sediment behaviour in many reservoirs. However, a limitation is that one-dimensional models normally do not simulate the progress of turbid density currents through a reservoir and thus may underestimate the transport of fine sediment into the area of the dam.

Two-dimensional modelling uses a grid to simulate the reservoir's geometry and can simulate the lateral movement of water and sediment across the cross-section, as well as downstream movement. Two-dimensional models are much more computationally intensive than one-dimensional models, resulting in much longer computer run times. Therefore, two-dimensional models have historically been limited to simulating areas of the reservoir where the lateral movement of water and sediment is of particular importance, such as the area near intakes, spillways and the evolution of a delta. They may also be used for short simulation periods, such as individual flood events, as opposed to decades-long time series. However, increasing computer capacity is expanding the range of uses for multidimensional models.

Physical modelling

Physical modelling involves preparation of a physical scale model. Sediment is simulated in the model using either natural sediment of smaller diameter (for the coarse fraction) or a less dense material such as plastic beads (for the finer material). They can be used to model sediment transport conditions at intakes and spillways, including the development of scour downstream of the dam by the spillway discharge. These questions involve complex secondary flow patterns and turbulence, which are not easily addressed by current numerical models. The release of floating debris is another design consideration evaluated by physical modelling. Physical modelling is normally performed for dams which have significant discharges to aid in spillway design and optimise the configuration and placement of the intake and sediment sluicing features, such as low-level outlets or deep crest gates.

The physical model allows the designer to directly observe flow and sediment transport patterns, and to rapidly make geometric changes in the configuration of project structures and immediately observe their impact on sediment transport patterns. It is an unparalleled tool for allowing both design and management personnel to visualize the system, and for the foreseeable future physical modelling is expected to remain the tool of choice for simulating complex flow fields around dam and intake structures and for analyzing spillway discharge. Contracts for physical modelling must specify how long the model should be maintained before it is dismantled.

Sequence of modelling studies

The normal sequence in modelling is to start from the most general model and proceed with increasing detail and complexity as the design is refined. Following this sequence, modelling normally starts with a one-dimensional numerical simulation to analyse the overall rate and pattern of sedimentation, the grain size that will be transported to the area of the intake or outlet works, and how these factors will change over time. This step is sometimes followed by two-dimensional numerical modelling and physical modelling. If both two-dimensional and physical modelling are to be performed, the logical sequence is to perform the two-dimensional numerical modelling first, as this will be used as the basis for determining the design (or design alternatives) to be investigated by physical modelling. To gain time, the one-dimensional and two-dimensional models can be developed simultaneously, but the one-dimensional numerical modelling results will normally be used to establish the sediment transport input for the two-dimensional model of the area closer to the dam. Because of scaling issues, physical models will generally provide a qualitative impression of the spatial distribution of deposited sediment. Results from numerical and physical modelling should be jointly interpreted for decision-making purposes and design refinement.

4.2.8 Assessment and monitoring of slope stability

Slope instability around the reservoir can present risks for safety as well as loss of reservoir storage volume. Developers and operators conduct surveys of soils and geologic conditions around the margins of existing or planned reservoirs to identify erosion- and landslide-prone area. During the early stages, such surveys may enable the project siting to avoid the risks of slope instability, or at any stage, to focus stabilisation works on targeted areas.

Studies can include:

- Reconnaissance, geotechnical, geomorphological, and engineering geology studies to map signs of existing instability;
- Categorisation of zones in the immediate reservoir area into high, medium and low risk;
- Assessment of land mass movement, slope strength, mechanical properties and groundwater pressures, along with slope stability modelling; and
- Monitoring of land mass movement, and hydraulic pressures and deformations, and use of this data to update slope stability models.

Further information:

- ICOLD. (2002). *Reservoir Landslides: Investigation and Management – Bulletin 124*. Paris: ICOLD.

4.2.9 Comparing alternative management options

Because a range of options may be available for the management of the identified sedimentation issues, it will be necessary for the developer or operator to compare them (and combinations of them) according to their effectiveness and economic feasibility. Standard tools for comparing the strengths, weaknesses, practicality, costs, environmental impacts, etc can be used to compare the options.

A specific tool available for the evaluation of options, which combines economic and engineering considerations, is the RESCON 2. This provides a toolkit that can be used for decision-making at the policy level, using dam and reservoir data that is readily available. It offers a mathematical model that uses readily-available data to determine technical feasibility and perform economic optimisation. The output is a comparison and prioritisation of options at a pre-feasibility level. It can be used for operational or proposed projects as it allows initial construction costs for proposed projects to be included in NPV calculations. It also allows a preliminary assessment of sediment management as a climate change adaptation measure.

Further information:

- Efthymiou N., Palt S., Annandale G. and Karki, P. (2017). *Reservoir Conservation Model, RESCON 2 Beta: Economic and Engineering Evaluation of Alternative Sediment Management Strategies*. Washington, DC: World Bank.

4.2.10 Defining indicators, baseline, and monitoring programmes

To understand the effectiveness of any design or mitigation measures following their implementation, it is necessary to identify the indicators that will be used, establish the baseline of the indicators, and define the geographic scope and frequency of monitoring. Erosion and sediment monitoring objectives should be clearly expressed, linked to risks and impacts, and defined separately for the construction and operation stages.

A wide range of erosion and sedimentation-related data will be available from the initial assessments, ranging across the breadth of parameters discussed above: sediment load and suspended sediment concentrations; river channel geomorphology; riparian zone assessments (riverbanks and reservoir rim); reservoir bathymetric surveys; land stability assessments; and satellite imagery. It is important to establish the baseline dataset for the defined indicators using this available data and present the baseline in accordance with any legal, permitting or corporate requirements.

A pre-project baseline report, which may be part of the ESIA, should explain the pre-project status, trends and issues relating to sediment transport, influences on sedimentation (surrounding land uses, locations of settlements, industrial and agricultural activities), river geomorphological processes (including major tributaries, points of land disturbance or sediment stockpiling), and river channel condition and integrity. Where relevant, data should be compared with the relevant environmental standards and interpreted in light of influential factors such as flow, water level, season, activities, and vegetation cover.

A key reason for developers to document a baseline is to compile evidence that can be used to assess any claims that the project has resulted in a specific impact, or to attribute an erosion impact to its cause. For example, gravel extraction could cause the failure of a downstream bridge, but a local community may assume it is caused by trapping of sediment in the reservoir.

The basis for the locations, timing, parameters and methodologies adopted for monitoring should be clearly defined and explained.

4.3 Design measures

4.3.1 Sediment bypass: flood bypass tunnels and channels

A flood bypass tunnel or channel is one of two options for sediment by-pass, the other being off-stream reservoirs as discussed in Section 4.3.2. By-pass tunnels or channels divert sediment-laden water during flood events around an on-stream reservoir, as in the scheme set out in Figure 4.6.

Bypass tunnels or channels are not frequently used, but they can be used to retrofit sediment management facilities on schemes that were not constructed with outlets for flushing sediment. Bypass tunnels or channels use an upstream weir or dam at the upper end of the reservoir to divert sediment-laden flows, principally during floods, through the tunnel or channel. In some cases, when the reservoir length prohibits a long, costly tunnel, a tunnel diverts water with suspended sediment from nearer the dam. The tunnel or channel requires lining with abrasion-resistant material. Because the sediment-laden flows are diverted downstream as they inflow, and as they would without the project (i.e. they minimise the interruption of sediment transport continuity caused by the reservoir), they can have lower environmental impacts than flushing or sluicing.

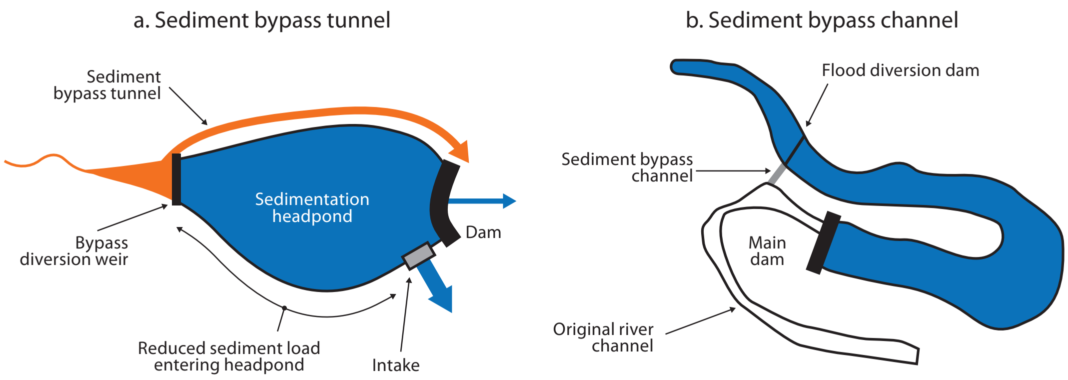


Figure 4.6 Design measures for the bypass of sediment-laden floods

Source: Morris, G. (2016). Chapter 7 Sediment Management Techniques. In: Extending the Life of Reservoirs: Sustainable Sediment Management for Dams and Run-of-River Hydropower. *Washington, DC: World Bank.*

Further information:

Examples of projects with by-pass tunnels are described in:

- Auel, C. and Boes, R. (2011). Sediment bypass tunnel design – review and outlook. In: A. Schleiss and R. Boes. ed., *Dams and Reservoirs under Changing Challenges, 1st ed*. London: Taylor & Francis Group.
- Auel, C., Kobayashi, S., Takemon, Y. and Sumi, T. (2017). Effects of sediment bypass tunnels on grain size distribution and benthic habitats in regulated rivers. *International Journal River Basin Management*, 14(4), pp. 433–444.
- Boes, R. (2015). Proceedings from the First International Workshop on Sediment Bypass Tunnels. In: *First International Workshop on Sediment Bypass Tunnels*. Zurich: ETH Zurich.

By-pass tunnels can also be used in RoR projects, as in the case of Patrind:

- https://www.hydropower.org/case-studies/pakistan-patrind

4.3.2 Sediment by-pass: offstream reservoirs

Offstream reservoirs divert clean water into a reservoir while excluding sediment-laden flood flow. In this case, the reservoir is outside of the main river channel, and is created either by impounding a tributary or constructing the impoundment on an upland area. Large sediment-laden floods pass by the intake and are not diverted into storage. Offstream reservoirs are used for daily regulation in RoR projects and are often part of pumped storage schemes. Note that an offstream reservoir will retain sediment from the small catchment above it, requiring strict catchment management. Figure 4.7 depicts a schematic of an offstream reservoir.

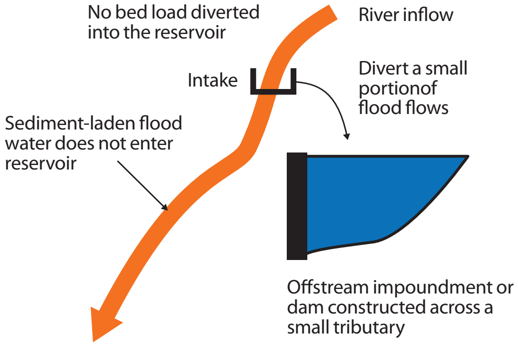


Figure 4.7 Off-stream reservoir to avoid capturing sediment-laden floods

Source: Morris, G. (2016). Chapter 7 Sediment Management Techniques. In: Extending the Life of Reservoirs: Sustainable Sediment Management for Dams and Run-of-River Hydropower. *Washington, DC: World Bank.*

Further information:

- Morris, G. (2016). Chapter 7 Sediment Management Techniques. In: *Extending the Life of Reservoirs: Sustainable Sediment Management for Dams and Run-of-River Hydropower.* Washington, DC: World Bank.

Case studies:

- https://www.hydropower.org/case-studies/chile-la-confluencia
- https://www.hydropower.org/case-studies/bolivia-san-jos%C3%A9

4.3.3 Sediment pass-through: sluicing

Sediment pass-through structures include sluice gates or low-level outlets that are opened for the first part of the rainy season to release sediment-laden flows and accumulated sediments. Sluicing refers to the drawing down of the reservoir level during periods of high discharge, thereby increasing flow velocity while reducing residence time and sediment trapping. Sluicing is usually performed with partial water level drawdown to allow continuation of energy generation even with reduced gross head.

"Aggressive drawdown" creates a riverine flow along the impounded reach and can be used to scour and release a portion of the previously deposited sediment. This approach can be used during a monsoon for example, and can be timed to coincide with floods through real-time reporting gauges. Drawdown is begun before an anticipated high flood event until the reservoir is fully drawn down during the passing of the flood; then the outlet gates are closed before the end of the flood to ensure that the reservoir entirely refills.

Note that flushing or aggressive sluicing can have significant environmental impacts because they are used to release previously deposited sediment. The advantage of sluicing is that the incoming suspended sediment is routed downstream of the reservoir as it would be without the project (minimising the interruption of sediment transport continuity), therefore minimising environmental and social impacts.

Further information:

- Morris, G. and Fan, J. (1998). *Reservoir Sedimentation Handbook*. New York: McGraw-Hill Book Co.
- Case study showing the difference between drawdown sluicing and pressure flushing: https://www.hydropower.org/case-studies/indonesia-bakaru

A good example of sluicing for RoR projects:

- https://www.hydropower.org/case-studies/nepal-kali-gandaki

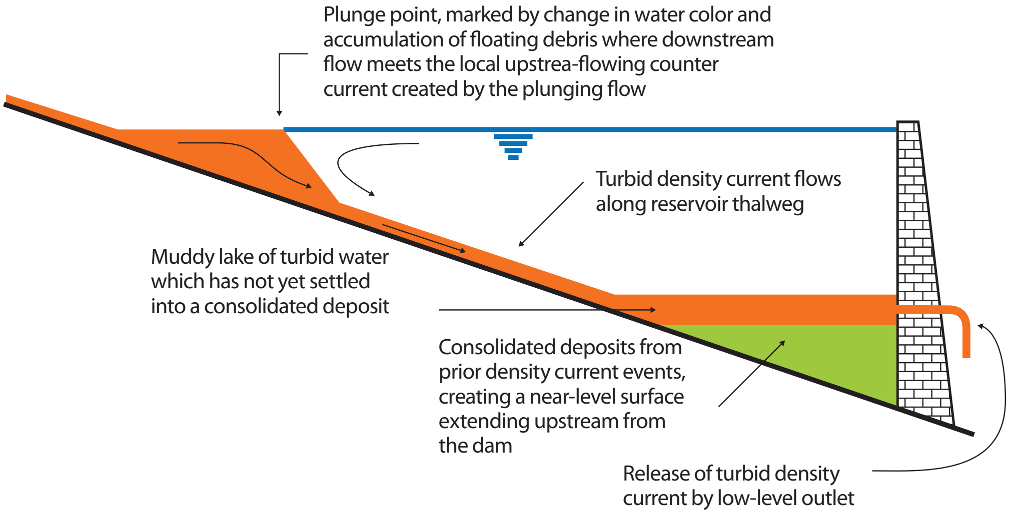
4.3.4 Sediment pass-through: density current venting

A density current or turbidity current is an in-flowing current of high sediment-density water that may travel along the reservoir bed, without mixing with cleaner reservoir water, and that may reach the dam. It may flow beneath the clear water because sediment-laden water is denser than clear water. Density-current venting refers to the use of a low-level outlet in the dam to pass the density current during high floods or whenever the current is expected to reach the dam. Figure 4.8 depicts the basic principle of density-current venting.

Efficient density-current venting requires good monitoring to predict when the current reaches the dam and therefore maximise sediment pass-through. Structures used for density-current venting include a high-pressure low-level gate, multi-level intakes that are installed for the purposes of managing the water quality of downstream releases, and (less frequently) a turbidity siphon which draws turbid water from a low level for discharge through a higher-level outlet. During the early years of

Figure 4.8 Density-current venting

Source: Morris, G. (2016). Chapter 7 Sediment Management Techniques. In: Extending the Life of Reservoirs: Sustainable Sediment Management for Dams and Run-of-River Hydropower. *Washington, DC: World Bank.*



operation, low-level intakes to the power station may be used to pass density currents.[7] In later years of operation, it may not be possible to pass turbid flows at all because coarser sediments that have accumulated in the reservoir will be passed, with greater impact on equipment.

Note that there are approaches (which do not include sediment pass-through) to altering the path of turbidity currents, which prevent turbid currents from depositing sediments near the intake. This can be done with physical barriers (dams), water jets or air bubbling facilities placed on the bed of the reservoir, or geotextile sheets. (Schleiss, A., 2008, Reservoir Sedimentation and Sustainable Development. Presentation to a workshop in Bern).

Further information:

Case studies of density-current venting:

- https://www.hydropower.org/case-studies/chinese-taipei-tsengwenzengwen
- https://www.hydropower.org/case-studies/chinese-taipei-shihmen

4.3.5 Sediment removal: flushing

Flushing or 'empty flushing' entails opening a low-level outlet to completely empty the reservoir, thereby enabling the river to scour sediment deposits. Figure 4.9 shows the stages of empty flushing.

Flushing will not remove all sediment that has built up around a flushing channel within the reservoir and therefore will not effectively pass all sediment. Without large flood events, the reservoir may eventually fill with coarse material that cannot be flushed by normal flows.

Pressure flushing refers to flushing by opening a submerged low-level outlet to release sediment while the reservoir level is high, producing a localised scour cone immediately above the pressure flushing outlet. This technique can be used to keep the immediate vicinity of an intake free of sediment.

Sequential flushing refers to the sequential flushing of two or more reservoirs: water is released from an upper reservoir to scour sediment from a lower reservoir, and sediment released from the upper reservoir(s) passes through the downstream reservoirs with minimal redeposition.

Flushing can have significant environmental and social impacts, as it releases high sediment loads with limited water volumes. Box 4.3 outlines some of the key environmental and social impacts of flushing and sluicing. To minimise the adverse environmental and social impacts of flushing, it can be carried out regularly to frequently flush small amounts of sediment, timed to avoid sensitive periods (for example the spawning season of migratory fish), or diluted by releases from other reservoirs. The concept of 'environmentally-friendly flushing' refers to the release of water from outlets positioned at different levels: the higher outlets release clearer water and the lower outlets release heavily sediment-laden water. This dilutes downstream concentrations, for example at the initiation of drawdown when the sediment concentrations peak.

Flushing may have positive or negative implications for the release of greenhouse gases. In some cases, flushing can result in the release of trapped methane, or the removal of organic sediment, which may aerobically decompose downstream rather than anaerobically thereby creating methane in the reservoir.

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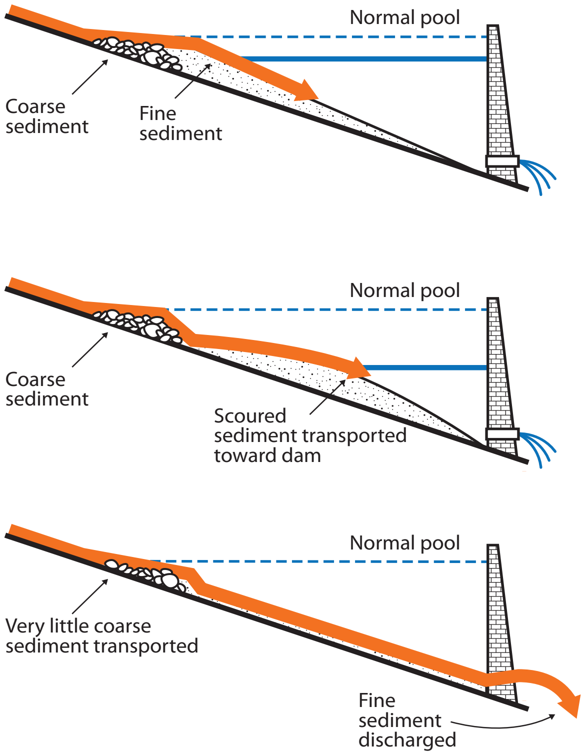
[7] However, this may only be considered after careful consideration of the sediment concentration and quartz content of the fine sediments and its potential for abrasion. Even fine sediment can cause abrasion if concentrations are high and the sediment is hard.



The reservoir is drawn down at the initiation of the flushing event, and sediment from upstream is scoured, reworked, and moved progressively closer to the dam as the reservoir level drops.

When the level drops to such an extent that high flow velocity is sustained along the entire length of the reservoir, the reworked sediments exit the low-level outlet as a thick muddy flow, creating a high spike in downstream suspended sediment concentration.

Sediment concentration then drops quickly as the easily eroded sediment is removed from the flushing channel and the rate of scour stabilises.

Figure 4.9 Flushing

Source: Morris, G. (2016). Chapter 7 Sediment Management Techniques. In: Extending the Life of Reservoirs: Sustainable Sediment Management for Dams and Run-of-River Hydropower. *Washington, DC: World Bank.*

Box 4.3 Environmental impacts of flushing and sluicing

Flushing and sluicing release water with high sediment load, and potentially sediments and water with adverse chemical properties due to their long retention in the reservoir. The release of sediment-laden water can have a cumulative downstream impact, combined with the project's water quality impacts and alteration of downstream hydrological patterns. Impacts may be particularly severe when the sediment-laden water meets a coastal delta or a downstream reservoir, resulting in the sudden deposition of sediment in these areas. A careful balance between the need for flushing to prolong the reservoir lifetime and flushing to restore sediment downstream and maintain downstream morphological features is necessary.

Physical and chemical impacts:	Biological impacts:	Social impacts:
• Release of waters with low dissolved oxygen, lower temperatures, and higher heavy metal concentrations; • Release of waters with strong odour, and H^2S degassing in relatively new reservoirs; • Reduction in visibility and light penetration; • River morphological impacts such as infilling of pools and clogging of river gravels with fine sediment; • Large releases of accumulated solid wastes; • Release of trapped methane, a greenhouse gas.	• Stress on aquatic biota and fish kills; • Direct smothering of benthic flora and fauna; • Destruction of spawning sites and nursery habitats.	• Sedimentation of water treatment plants; • Sedimentation of irrigation canals, as well as flood control and navigational channels; • Impacts on recreational amenity; • Reduction in fisheries productivity; • Safety of river users during flushing.

Further information:

For more detailed reviews of flushing, refer to:

- White, R. (2001). *Evacuation of Sediments from Reservoirs*. London: Thomas Telford Ltd.

For eco-friendly flushing:

- Peteuil, C., Fruchart, F., Abadie, F., Reynaud, S., Camenen, B. and Guertault, L. (2013). *Sustainable management of sediment fluxes in reservoir by eco-friendly flushing: the case study of the Genissiat dam on the upper Rhone River (France)*. In: 12th International Symposium on River Sedimentation. Kyoto: ISRS.

Case studies:

- https://www.hydropower.org/case-studies/costa-rica-angostura
- https://www.hydropower.org/case-studies/japan-dashidaira

4.3.6 Sediment management at run-of-river headworks

Intakes of RoR projects often include design measures such as sediment traps, de-silting chambers, and sluicing outlets. The principles of sediment management set out in this guide apply equally to RoR projects.

Further information:

For a full discussion of the design of RoR projects for sediment management, refer to:

- Morris, G. (2016). Chapter 8 Sediment Management at Run-of-River Headworks. In: *Extending the Life of Reservoirs: Sustainable Sediment Management for Dams and Run-of-River Hydropower.* Washington, DC: World Bank.

4.3.7 Drainage design for construction sites and roads

Hydropower project construction sites are large and complex, requiring large-scale earth movements and excavations, and the construction of roads and other facilities that channel surface water flows. Soil erosion and land instability can result from the exposure of soil surfaces, while the mobilisation and transport of sediment may result from the unmanaged flow of surface water, with further erosion or sedimentation downstream. Even during operations, runoff from project sites may be significant, requiring suitable drainage. These issues can be avoided and minimised at the design stage through adequate siting and design of construction-stage and operation-stage facilities, and the design of drainage systems to direct surface waters and manage infiltration. Measures relating to the further minimisation or mitigation of site erosion during construction and operations are set out in Section 4.4.10.

During feasibility studies, land and slope stability should be assessed through geotechnical evaluation. This will inform the siting of project facilities during both the construction and operation stages and identify any zones where slope stabilisation works are required. For example, the alignment of an access road may be re-routed to avoid raising the risk of landslides in an unstable area, or the transmission line routed to avoid the risk of damage from landslides.

The siting of spoil areas and quarries in relation to land instability is important. Spoil disposal sites and quarries should not be located in areas where they contribute to land instability, for example by creating more infiltration of water into unstable land masses, or by displacing the pre-existing surface water drainage route. Sediment runoff from spoil and quarries can be minimised with careful siting, and drainage facilities, including ditches, bunds, culverts and drainage ponds, can be built into their design.

The drainage of facilities, including during the construction stage, should be planned at the outset for all areas according to engineering standards and designs established for drainage. These might include channels and ditches, lined ponds and channels to capture and direct waters from discharge points, lining of steep channels, slope protection, and ‘soft infrastructure’ such as ponds and wetlands.

Roads should be designed to meet national and international standards, with identified surface materials, limited gradients to reduce runoff-induced erosion, adequate road drainage (side drainage and culverts), and slope protection by rip-rap and gabions. Vehicle crossing points on streams or rivers should be designed to minimise the creation of erosion and sediment runoff through location, gradients of approach, surface sealing, and drainage. Smaller crossings should consist of free-spanning structures (e.g. single span bridges).

Further information:

Some general guidelines may be useful for specific mitigation measures:

- IFC. (2007). *Environmental, Health, and Safety (EHS) Guidelines: General EHS Guidelines, Section 4 Construction and Decommissioning*. Washington, DC: IFC.
- IFC. (2018). *Good Practice Note: Managing Contractors' Environmental and Social Performance*. Washington, DC: IFC.

Many national agencies provide freely available guidance on drainage design, for example:

- Austroads. (2013). *Guide to Road Design Part 5: Drainage – General and Hydrology Considerations*. Sydney: Austroads.

4.3.8 Design of instream diversion during construction

The diversion of the river during project construction is a key source of sediment from hydropower construction sites. How to minimise sediment plumes from river diversion, the construction of coffer dams, and the removal of coffer dams should be considered during design. Options for minimisation are:

- Minimisation of the volume of earth movements required for coffer dam construction and river diversion;
- Timing of the creation of coffer dams and initial river diversion to coincide with low flows and to avoid periods that are critical to biota, for example for migration and spawning;
- Timing of coffer dam removal to coincide with low flows and to avoid sensitive times for biota;
- Isolation of instream works using techniques such as berming and sheet piling.

4.4 Mitigation measures

4.4.1 Watershed or catchment management

Watershed and catchment management is frequently practised by hydropower projects and may be a regulatory requirement in some jurisdictions. It encompasses a range of possible measures, including restrictions on deforestation, reforestation, landslip prevention, limiting land disturbance, and check dams. Watershed management is a significant area of activity, and there is a considerable body of experience on policy approaches and practical measures for catchment management. Three aspects of watershed management are outlined below:

- The structural and non-structural measures used in watershed and catchment management;
- Strategy and planning for watershed management; and
- Integrated and participatory approaches to watershed management.

Structural and non-structural measures

The practical measures used in watershed and catchment management can be grouped into structural and non-structural measures. Non-structural, or vegetative, measures control or prevent erosion at its source, whereas structural measures trap eroded sediment upstream of the reservoir. Structural measures intercept the movement of water, reduce flow velocity, and trap sediment. They are usually more expensive than non-structural methods and require maintenance. Some examples include:

- Check dams and detention basins to collect sediment in specific catchments or sub-catchments;
- Farm ponds to collect sediment runoff from exposed agricultural land; and
- Drainage around roads, trails, and cattle paths to avoid gully formation.

The design of check dams usually follows conventional dam design. Alternative designs, such as a line of steel piles across the river to capture the largest debris, are used less frequently.

Note that if check dams, detention basins, and farm ponds are not properly constructed and maintained, they may eventually be breached and release the stored sediment. This is a particular risk downstream of sites that generate high erosion such as construction sites and mining operations.

Non-structural or vegetative measures comprise:

- Protection of tree cover, for example through the control of logging, and clear-felling;
- Re-afforestation of degraded or exposed areas;
- Protection or re-establishment of vegetation along riparian corridors;
- Agroforestry in farmed areas;
- Terracing of farmland and cultivation along contour lines to avoid rill and gulley erosion; and
- Retention of crop residues and zero tillage agriculture.

Strategy and planning

The catchments of most hydropower projects are vast. Therefore, if a hydropower developer or operator plans to invest in catchment management, it will need to strategically plan its approach. In disturbed watersheds, most erosion comes from a small percentage of the land surface, so the developer or operator should seek to identify the areas that have the highest sediment yield and focus practical measures in these locations. It is also important to understand that the benefits of catchment management may only be felt in the long-term.

The benefits in terms of the effectiveness of alternate watershed management measures should be quantified, and compared with costs to identify the most economically-optimal option. Options for catchment management can also be compared with the alternatives of sediment bypass, pass-though and removal, for example using RESCON 2 for the comparative analysis of alternatives. However, catchment management and sediment management are not mutually-exclusive alternatives and the optimal solution could be a combination.

Integrated and participatory watershed management

Any catchment management programmes should be conducted with the aim of benefitting the participating land users. This principle can be extended to the concept of paying land users for catchment services, even to the extent of (proposed) schemes to link payments to the sediment load of in-flows.

In many cases, a project's watershed management is likely to have wider aims of providing benefits or community development. Watersheds provide local communities and downstream populations with provisioning, regulating, cultural, and supporting ecosystem services, such as potable water, industrial water, dilution of industrial discharges, and flood attenuation. Integrated watershed management, or participatory watershed management, extends watershed management from a narrow activity pursued and targeted by a developer or operator into an aim in itself. Therefore, the question is not 'how can the catchment be managed in specific areas to limit sediment inflows to the project?', but rather 'how can the project contribute to sustainable management and development of the watershed upstream and downstream of the project?'. Integrated watershed management involves a range of stakeholders and extends to Participatory Watershed Governance (PWG), which is intended to empower stakeholders to define and undertake joint actions in a watershed. In addition, watershed management can have significant additional biodiversity conservation benefits; therefore, the objectives of sediment management across a watershed may be closely aligned with objectives of biodiversity conservation.

It is however important for a hydropower developer or operator involved in a broad watershed management programme to have clarity on the objectives of each specific activity, and avoid presenting activities that are mainly or solely for the project's benefit as community benefits or benefits for biodiversity conservation. While some activities may concern support to watershed management for community benefits, others will specifically relate to biodiversity (for example, the re-establishment of stands of an endangered tree species) or watershed management for the project's benefit.

Further information:

For practical measures, indicating how long watershed management has been considered:

- FAO. (1977). *Guidelines for watershed management*. Rome: FAO. http://www.fao.org/3/ad071e/ad071e00.htm
- US Federal Interagency Stream Restoration Working Group. (1998). *Stream Channel Restoration Guidelines*. Washington, DC: NRCS.

Gully control guidelines:

- Valentin, C., Poesen, J. and Li, Y. (2005). Gully Erosion: Impacts, Factors and Control. *CATENA*, 63(2–3), pp. 132–53.
- Desta, L. and B. Adugna. (2012). *A Field Guide on Gully Prevention and Control*. Entebbe: NBI.

Watershed Management:

- Darghouth S., Ward C., Gambarelli G., Styger E. and Roux, J. (2008). Watershed Management Approaches, Policies, and Operations: Lessons for Scaling Up. *World Bank Water Sector Board Discussion Paper series*, Paper No. 11. Washington DC: World Bank.

Payments for Watershed Services:

- Bennett, G., Carroll, N. and Hamilton, K. (2013). *Charting new waters: state of watershed payments 2012*. Washington, DC: Forest Trends.
- Annex 6 – Water Pricing, in Efthymiou N., Palt S., Annandale G. and Karki, P. (2017). *Reservoir Conservation Model, RESCON 2 Beta: Economic and Engineering Evaluation of Alternative Sediment Management Strategies*. Washington, DC: World Bank.

Case studies:

- https://www.hydropower.org/case-studies/costa-rica-angostura
- https://www.hydropower.org/case-studies/chinese-taipei-shihmen

4.4.2 Removing accumulated reservoir sediments

The impact of reservoir sediment accumulation can be mitigated by dredging, redistributing sediment within the reservoir, dry excavations, raising operating levels, or taking adaptive actions.

Dredging

Dredging refers to any system used to remove sediment from beneath the water without requiring reservoir emptying. It is inherently costly, considering the high energy costs of pumping, the high abrasion of pipelines and the cost by unit of volume dredged, which can be higher than the cost of creating new storage (assuming sites are available). The cost depends on the size of the reservoir, and localised dredging in a small reservoir may be cost-effective. Dredging large reservoirs for storage recovery is rarely economical but is sometimes the only solution.

The main components of a dredging operation are: a rotating cutterhead to cut and suspend sediment (if necessary, for compacted deposits); a suction line; a main pump; and a discharge pipeline. Sediments are dredged by a cutting tool up to a predefined gravel size and pumped downstream of the reservoir, or transported elsewhere for disposal. Depending on the volumes to be pumped downstream, a discharge weir may be necessary. In long discharge pipelines covering undulating topography, booster stations may be required between the dredge and pipeline outlet.

If the sediments are to be transported elsewhere, land for their disposal is necessary. Depending on the chemical composition of the deposits, it may be feasible to use them in agriculture or as construction materials. These opportunities should be investigated to reduce the area and cost of disposal facilities, and to avoid social and environmental risks at disposal sites.

Hydrosuction or siphon dredging is a specific technology that does not use a pump, but takes advantage of the height differential between the reservoir level and the foot of the dam downstream to siphon the dredged material downstream. The technical feasibility of hydrosuction depends on the available head and length of the discharge pipeline. Provided that the necessary head is available, it is an attractive option for small reservoirs of limited length. It can also be used to keep the vicinity of intakes free of deposits.

Redistributing sediment within the reservoir

Additional technologies are available in situations where sediments are dredged but then pumped across the reservoir to be deposited in front of the power intake. The dredged sediments are then passed downstream gradually with operations. This provides for a more gradual disposal of sediments downstream, which may have environmental advantages in terms of restoring sediment transport downstream, and stabilising the downstream channel. Water injection dredging is a further new technology, which remobilises deposits using water jets and pushes them towards a low-level outlet structure.

Dry excavation

Dry excavation requires the reservoir level to be lowered or the reservoir to be emptied, allowing access for earth-moving machinery. This measure presents environmental issues associated with the need for a deposit area and the impacts of transport by trucks. There may be opportunities to use the deposits for landscaping, injection of sediment in the downstream river, or beach replenishment. For large projects, dry excavation is more costly than dredging because of lost revenue from the interruption in operations, and it is often not feasible to lower reservoir levels to reach deeper fine deposits below the bottom outlet.

Raising reservoir levels

Raising the MOL of the reservoir progressively through the project life cycle will result in the redistribution of sediment because, as the delta of sediment builds in the upper part of the reservoir, inflows, especially at times when the reservoir is near MOL, scour the delta and push sediment towards the dam. Raising MOL can delay or slow the downstream movement of the delta.

Further information:

For a basic primer on dredging technologies:

- Turner, T. (1996). *Fundamentals of Hydraulic Dredging*. New York: ASCE Press.
- Bates, A., Land, J. and Bray, R. (1996). *Dredging: A Handbook for Engineers*. Oxford: Elsevier Butterworth Heinemann.

Examples of re-use of sediment in geotextile tubes and bricks:

- https://www.royalihc.com/en/news/royal-ihc-and-netics-enter-partnership
- https://www.netics.nl

Case study of hydrosuction:

- https://www.hydropower.org/case-studies/guatemala-el-canad%C3%A1

4.4.3 Reservoir rim and riverbank protection

Erosion of the reservoir rim and riverbanks can be avoided and minimised through operating rules, or mitigated using physical protection works. Many projects use buffer zones around the reservoir and riverbanks to minimise risk. Details of how to assess land stability and avoid areas of mass movement are outlined under Section 4.2.8 above. Monitoring of hydraulic pressures, deformations and land mass movement, particularly in high-risk zones, can be used to prompt these operating rules and protection works, and used to update slope failure models.

Operating rules to avoid and minimise reservoir rim and downstream erosion

Operating rules concerning reservoir levels, and limitations on the rate of filling and drawdown can be used to reduce shoreline erosion, limit wet-dry cycles on potentially unstable slopes, and maintain slope stability around the reservoir. Such rules may include: ramp-down rules; constraints on the length of time the reservoir is held at particular operating levels; freeboards and reservoir lowering to capture incoming floods; and maintenance of stabilising shoreline vegetation. Moreover, slope failure model predictions can be used to identify the zones that require protection and appropriate operating rules. Exactly the same principles apply to the downstream riverbanks: operating rules can be used to manage levels of the downstream river and thereby minimise erosion.

Protection works

Works to improve the stability of slopes, or for slope and riverbank protection include:

- Modification of slope geometry to reduce loads acting on large land masses;
- Drainage and protection of unstable land masses from water infiltration, with surface and subsurface (tunnels or shafts) drainage;
- Slope reinforcement through grouting and anchoring;
- Retaining structures;
- Rip-rap, gabions, and shotcrete to protect shorelines and slopes;
- Planting stabilising vegetation and the promotion of vegetation growth that is tolerable of water level changes; and
- Planting and restoration of vegetation to capture wind-blown sediment eroded from the drawdown area.

Buffer zones

Most hydropower projects manage activities in a buffer zone around the reservoir in order to reduce the consequences of erosion and slope failure, and may acquire the land in the buffer zone. In some jurisdictions, a buffer zone may be a legal requirement. Though it would also be useful in minimising risks, fewer projects manage activities in a buffer zone around the downstream river. Buffer zones can be used as exclusion zones (requiring compensation for physical and economic displacement) to reduce community exposure to erosion and slope instability risks, restrict the community's shoreline activities or govern land use in the buffer zone. Buffer zones are also useful when there is uncertainty around the water levels that will be reached due to uncertainties in topography or the extent of a backwater effect. The exact area of the buffer zone will depend on topography and is normally determined by a vertical and horizontal distance (for example, a minimum 3 m vertical buffer zone with maximum 20 m horizontal width).

4.4.4 Mitigation of downstream erosion and sedimentation

Downstream erosion due to sediment-hungry rivers may be mitigated through the bypass and pass-through measures set out in Sections 4.3.1 to 4.3.4 as this will contribute to restoring sediment balance on a catchment scale. However, localised downstream erosion impacts will occur due to the alteration of sediment dynamics, or significantly lower or more variable flows arising from diversion or operations. These impacts will require specific mitigation measures.

Measures can be considered either as measures to restore the process of sedimentation dynamics or the form of sedimentation. These mitigation measures include:

- Mechanically adding sediment to the downstream river for redistribution by flows (a measure to restore the process), as seen on the heavily modified Rhine River in Europe in order to protect downstream infrastructure;

- Using re-regulation reservoirs or basins to dampen fluctuations in flow (especially rapid daily fluctuations of peaking plants) that can cause shoreline erosion (but note the basin may also present a sediment accumulation challenge);

- Physically-modifying sections of the downstream river channel to optimise flows and re-establish a functional relationship between the revised hydraulic regime, the river channel, and the floodplain; this might include dredging of deposited sediments and structures to train the river, such as bed vanes, spur dikes, groynes, and weirs (where possible, the least intrusive green infrastructure should be used);

- Removing the sediment accumulating at confluences with tributaries if regulated flows are no longer sufficient to remove it; and

- Building artificial riffles for fish spawning and nursery habitat (a measure to restore form).

Further information:

- Kondolf, G. (1997). Hungry Water: Effects of Dams and Gravel Mining on River Channels. *Environmental Management*, 21(4), pp. 533–551.

- Wohl E. and Rathburn, S. (2003). Mitigation of Sedimentation Hazards Downstream from Reservoirs. *International Journal of Sediment Research*, 18(2), pp. 97–106.

4.4.5 On-site erosion management

Section 4.3.7 discussed drainage design for sites and roads. Measures for the further minimisation or mitigation of site erosion during construction and operations are set out here, and consist of prevention measures, measures for the management of surface waters and the trapping of sediment.

Prevention measures:

- Scheduling of land disturbance to avoid heavy rainfall periods (i.e. during the dry season) to the extent practical;

- Modifying or suspending activities during extreme rainfall and high winds to the extent practical;

- Covers and shelter in areas that may contribute significant sediment runoff such as topsoil storage areas, aggregate storage, and batching plants;

- Slope stabilisation works where needed, and the creation of exclusion zones and signage to warn employees and the public of safety risks;

- Contouring and minimising length and steepness of slopes;

- Prohibition of the dumping of excavated materials in watercourses;

- Mulching to stabilise exposed areas;

- Re-vegetating and rehabilitating disturbed areas promptly (throughout the project life cycle, as well as during post-construction site rehabilitation (described in the Section 4.4.6));

- Lining steep channels and slopes with shotcrete or matting;

- Identifying and treating eroding areas promptly, with measures to avoid future incidents; and

- Treating landslips quickly to stabilise and repair them.

Management of surface waters:

- Providing adequate drainage to minimise and control infiltration;

- Maintenance of drainage to specified standards;

- Contouring and drainage during land disturbance; and

- Segregating or diverting clean water runoff to prevent it mixing with water containing a high sediment content.

Trapping of sediment:

- Reducing or preventing off-site sediment transport through use of settlement ponds, silt fences, and water treatment;
- Settling and sedimentation ponds employed during disturbance works; and
- Compaction of spoil areas, construction of bunding and drainage around spoil areas.

4.4.6 Post-construction site rehabilitation

Post-construction rehabilitation of heavily modified construction sites must be conducted to avoid ongoing erosion issues. Good site rehabilitation is based on a landscape design for the operating project, which can also minimise visual impacts and maximise visual amenity.

Practical measures for site rehabilitation include:

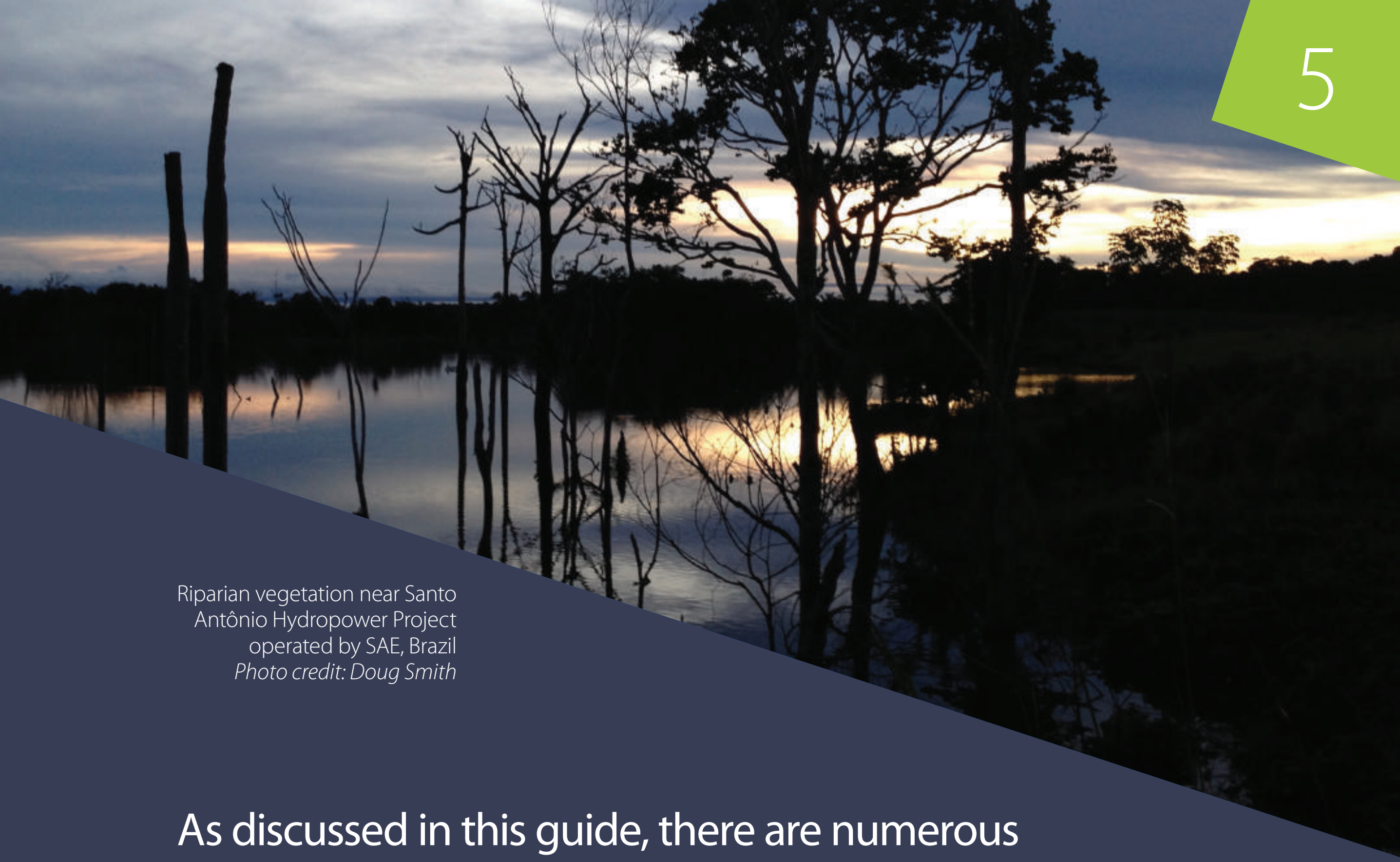
- The storage of topsoil removed during the early stages of construction and its re-use as the topsoil for rehabilitation. This ensures that local soils containing a seedbank of flora of local provenance are used in rehabilitation, and avoids the environmental impacts of removing topsoil from elsewhere and its transport over long distances;
- Planting or seeding with herbaceous species to establish an initial ground cover – some experimentation can be undertaken to determine the species that are most effective at rapidly establishing cover;
- Tree planting;
- Establishment of wetlands and ponds in wetter or low-lying areas (possibly combined with channels that receive effluents from setting ponds and wastewater treatment plants); and
- The use of native species of flora in all of the above.

5

Conclusions

Conclusions

This How-to Guide has provided an overview of the current knowledge on erosion and sedimentation in hydropower projects to support and guide key decision-makers in the sector towards more sustainable resource management. By recognising erosion and sedimentation caused by the project and manage occurrences responsibly, developers and operators can enhance project performance, and increase the operating efficiency and lifetime of their hydropower assets. The approach of this guide was to map out the necessary steps or deliverables that the developer or operator must take or prepare to meet good international industry practice at each stage of the project life cycle.



Riparian vegetation near Santo Antônio Hydropower Project operated by SAE, Brazil
Photo credit: Doug Smith

As discussed in this guide, there are numerous methodologies and technologies to address erosion and sedimentation issues, and it is essential that developers and operators consider these approaches early on in the project life cycle. Clean energy, water supply, flood management, drought control and renewable storage capacity are some of the key benefits hydropower projects can bring to society. By managing erosion and sedimentation issues responsibly, developers and operators encourage the long-term sustainability of project benefits and maximise their contribution to a low-carbon energy system. With the urgency of managing these erosion and sedimentation issues increasing with climate change, effective erosion and sedimentation management is vital to both maximise asset performance and lifetime, and increase project resilience.

Annex 1

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Annex 2

Project examples

From assessments using the Hydropower Sustainability Assessment Protocol

Project	Examples of Assessment and Monitoring	Examples of Design and Mitigation Measures
Blanda, 150 MW, Operation stage, Iceland	Reservoir bathymetric survey using echo sounders, planned every five to ten years. Long-term suspended sediment sampling downstream from 1965 to 2011, enabling establishment of sediment rating curves for the periods before and after the project. Aerial photography and site visits of the downstream river reach and the river mouth.	The ability to eventually flush sediment from the reservoir is maintained through annual tests of the bottom outlet.
Chaglla, 456 MW, Implementation stage, Peru	Sediment modelling, considering alternatives for managing sediments in the reservoir, comparing design options of flushing through a bottom valve, flushing through spillways, or a combination of a bottom valve and spillways.	Design measures: the dissipation pond below spillway; a drainage chamber built into the slope adjacent to the powerhouse to drain and stabilise the slope; a turbine coating designed to withstand abrasive sediments that will allow the turbines to last 30 years according to the manufacturer; and design of the channel downstream of the powerhouse using numerical modelling. An annual flushing procedure designed to flush sediment from the reservoir to allow it to continue to operate after 25–30 years. A major programme for the rehabilitation and stabilisation of degraded areas. EMS procedures for erosion prevention, specifically: the control of earthworks (cut and fill) and the use of containment structures to prevent erosion; the control of quarrying and excavations; and the control of underground excavations.
Hvammur, 82 MW, Preparation stage, Iceland	Depth-integrated sampling carried out up until 1968, augmented by sediment-source and transportation-mechanism studies, for the entire Þjórsá river basin. Catchment approach to assessment, studying cumulative effects along the entire river. Assessment of risks related to wind-blown sand and wind erosion from seasonally exposed riverbeds.	

Project	Examples of Assessment and Monitoring	Examples of Design and Mitigation Measures
Jirau, 3750 MW, Implementation stage, Brazil	Hydro-sedimentological monitoring programme, using GPS technology, taking measurements at six stations (five upstream of the dam and one downstream). 23 control sections for bathymetry are monitored to be able to evaluate changes to the riverbed over the medium to long-term. A digital terrain model and high-resolution satellite imagery used to evaluate erosivity and identify potential critical areas for detailed monitoring. A mathematical model and a physical scale model for sediment transport, reservoir sedimentation, water quality, and the passage of fish eggs, larvae and juveniles downstream.	PACUERA, a regulatory requirement for large dam projects in Brazil: a land use planning exercise with zoning of both the future reservoir and a protection zone defined for the surrounding areas.
Jostedal, 288 MW, Operation stage, Norway		Part of the license requirement is that Statkraft addresses problems related to sediment transport in the Jostedøla river, irrespective of whether the problem is directly related to the operations of the plant. Plan to remove 80,000 m^3 of sediments from the downstream river channel to avoid flooding.
Kabeli-A , 37.6 MW, Preparation stage, Nepal	Suspended sediment sampling at the project's hydrological gauging station for several seasons, using a cableway with sliding carriage and an "Uppsala" sampler that is designed for high-mountain rivers.	A desander, which will be operated with near-continuous flushing approach, and during the monsoon season the gates will be opened in the dam, allowing the flushing-out of sediments from the intake pond. A Catchment Area Treatment Plan, focusing on landslide prevention and management of road construction.
Keeyask, 695 MW, Preparation stage, Canada	Assessment of transport and deposition of mineral and organic suspended solids, undertaken using GIS tools and numerical models, based on wind and post-project flow conditions. A GIS-based wave model was used to predict reservoir shoreline recession rate in mineral soils. Two-dimensional modelling was undertaken using Mike 21 software. A one-dimensional HEC-6 model was used to assess sedimentological changes.	An Instream Construction Sediment Management Plan to minimise the impact of in-stream sediment from construction activities.

Project	Examples of Assessment and Monitoring	Examples of Design and Mitigation Measures
Kaunerthal Expansion, 1015 MW, Preparation stage, Austria	Sediment transport studies included 2-D modelling ,1-D numerical modelling of bedload transport, and a physical model of one of the diversion weirs. Alpine processes such as mass movements and slope stability, debris and mud flows, rockfalls and avalanches are considered systematically for each area of the project. Options assessment for the selection of the location of the upper stage reservoir: one of the sites did not have favourable slope stability conditions. Research initiative on fluvial sediment transport including bedload transport in gravel bed rivers using impact plate geophones.	Operating rules for sediment flushing gates during flood flows, to ensure sediment from these intake catchments does not reach the main reservoir. A Sediment Management Concept, establishing the monitoring and potential dredging locations. A centralised monitoring station linked to an array of electronic metering capabilities for land mass movement of the slopes surrounding the reservoir, allowing TIWAG to anticipate landslide, rock fall and erosion processes that may affect the reservoir.
Kárahnjúkar, 690 MW, Operation stage, Iceland	Wind erosion in the drawdown area: monitoring based on GPS-fixed photographed plots, every 200 metres along the shoreline in July every year; ground sensors and permanent cameras to assist in timely identification of sand movement. Coastline erosion: modelling predicted a combined effect of 280 metres in the first 100 years. A comprehensive baseline was established and monitoring was put in place, utilising bathymetric surveys and aerial photographs.	Sediment traps to capture wind-driven sediment on the eastern shore of the reservoir. Various revegetation programmes improve the resilience of the highland area to windblown sediments and reduce the risk of negative impacts from dust storms. Maximum runoff used in the flushing process, maintained over a minimum of four hours to rinse the sediment out and propel it downstream sufficiently to avoid accumulation immediately downstream. The Community and Environment Manager maintains a stakeholder list to be able to inform all concerned when flushing is to take place.
Romanche-Gavet, 94 MW, Implementation stage, France	Numerical models were used to represent the topography and hydraulics of the river and to consider various development scenarios.	A sediment management regime managed to be as close to the natural regime as possible, facilitated by the ability to open the dam to allow sediment transport during floods.
	Research investigated sediment transport in each of the project phases, the impact of high flows on erosion and sedimentation during construction, the design of the geometry of the water intake, analysis of the particle sizes that are likely to pass though the turbines, the new reservoir sedimentation equilibrium, reservoir flushing requirements, and the impact of decommissioning old plants (to be replaced) on erosion and sedimentation.	

Project	Examples of Assessment and Monitoring	Examples of Design and Mitigation Measures
Santo Antônio, 3568 MW, Implementation stage, Brazil	Modelling of the risk of erosion focused on the increased erosive capacity of the river following sediment deposition: one-dimensional modelling of sediment flow to 350 km downstream; two-dimensional modelling of the river immediately up and down stream of the project. Range of monitoring: 16 gauging stations which take readings twice a day; Acoustic Doppler monitoring to measure the river's discharge of liquid and solid at 9–12 vertical points across five transects to gain an integrated sample; point sampling to obtain the particle size of the bed material and suspended sediments at five points, four times a year; bathymetric surveys; and monitoring of riverbank erosion using radar, which provides better coverage of riverbanks as it can operate through rain and clouds.	Rip-rap has been installed at key erosion points along the riverbank.
Devoll (Banjë and Moglicë), 256 MW, Implementation stage, Albania	Sediment load is continuously monitored with advanced acoustic monitoring techniques (Acoustic Doppler Current Profiler, ADCP), and with turbidity meters and manual bottle sampling including the major tributaries. A numerical model of sediment balance has been established. Bathymetric surveys of the reservoirs, planned every year for the first years, and then every five to ten years. Assessment of the risk of landslides in 32 areas around both reservoirs, categorising risks for the dam and other areas into very low, low, medium and high categories. Monitoring ground movement in the areas of low and medium risk following impoundment (there are no areas of high risk), and on an ongoing basis in populated areas. Historical InSAR (Synthetic Aperture Radar interferometry, using satellite imagery) analysis, covering 2007 to 2010, to produce surface deformation maps, mapping slower and faster moving masses in reservoir areas. Photo-monitoring of slope and shoreline stability of the Banjë reservoir by boat, at least quarterly.	Buffer zone: at minimum, a 3 m vertical (maximum 20 m horizontal) zone in privately-owned land, with additional vertical buffers for steeper slopes and additional vertical buffers where houses are present. Erosion around replacement roads addressed by the inclusion of measures in road design, i.e. bank protection, roadside drainage, and culverts. Afforestation of 18.5 ha within the reservoir buffer zone, plus an afforestation programme, a legal requirement to compensate for the removal of forested areas within the reservoir, designed for erosion control. 'SediCon' dredges, immediately upstream of the intake: a high capacity hydrosuction dredging system, which will transfer sediment by gravity through a 1200 mm diameter pipe installed under the dam.

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The International Hydropower Association (IHA) is a non-profit organisation that works with a vibrant network of members and partners active in more than 100 countries.

Our mission is to **advance sustainable hydropower by building and sharing knowledge** on its role in renewable energy systems, responsible freshwater management and climate chance solutions.