Handbook for Assessing and Managing Reservoir Sedimentation

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February 2019

DRIP
Dam Rehabilitation & Improvement Project

Central Water Commission
Ministry of Water Resources
River Development & Ganga Rejuvenation
Government of India

Front Cover Photograph: Maneri Bhali – Stage I, Uttarakhand.

सत्यमेव जयते

Government of India
Central Water Commission
Central Dam Safety Organisation

Handbook for Assessing and Managing Reservoir Sedimentation

February 2019

Dam Safety Rehabilitation Directorate
3rd Floor, CWC New Library Building
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New Delhi - 110066

Government of India
Central Water Commission
Central Dam Safety Organisation

Disclaimer

A major part of this handbook is based on past and on-going efforts and practices, guidelines, manuals and other publications. All synthesized and adapted materials have properly been cited and acknowledged. However, correctness and validity of synthesized data and information have not been evaluated carefully in this version. Therefore, the authors are not responsible and liable for their inappropriateness and impacts.

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MESSAGE

The lifespan of any dam can be as long as it is safe and operable. In general, if a dam and its appurtenant structures are properly operated and maintained and the ageing processes can be controlled, the condition of a dam and the benefits can be preserved. Proper operation and management of a dam means that there must be a responsible agency, who takes care of a project along with requisite resources, in the absence of which the safety of any infrastructure project will deteriorate rapidly and it can become unsafe in a very short time compared to its designed life.

An appropriate reservoir operation and management system as per defined protocols considering sediment related problems is essential for controlling the ageing processes that may diminish the safety and shorten the reservoir life. The reservoir operation considering sediment management can be considered as one of the key factors in achieving the sustainable benefits from dams and reservoirs. It is one of the key elements to extend the service life as much as possible.

Reservoir sedimentation is a crucial issue faced by the reservoirs across the globe which are bound to suffer a loss of storage potential due to sedimentation, in due course of time. The reservoirs designed and operated to fill with sediment in a controlled manner, while harnessing the benefits from remaining storage over a finite period of time. The ramification of sedimentation is always left to the future. This 'future' has already arrived for many existing reservoirs and most others will eventually experience a similar upshot. The reservoir sedimenta-tion is becoming a potential threat to social, environmental and economic efficacy as well as safety of the dam and reservoir itself. This Handbook intends to provide a help to all the dam professionals in India, who will find it very useful to develop dam specific manual/tailor-made guidelines for assessing and managing sediment-induced problems in dams and reservoirs.

As every dam is unique, it would require specific manual/guidelines for effective operation and handling of sediment-related problems. The current *Handbook for Assessing and Managing Reservoir Sedimentation* is expected to fulfil the need of development of dam specific document and will prove an important milestone in moving towards the direction of integrated dam and reservoir management.

(S Masood Husain)
Chairman
Central Water Commission

New Delhi
February 2019

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FOREWORD

Presently, India has 5254 large dams in operation and 447 large dams under construction having gross storage of more than 300 billion cubic meter. Approximately 80% of these existing dams are more than 25 years old. Their health and safety are of paramount importance for sustainable use of these existing valuable assets, besides providing protection to the people and property in the downstream areas. The existing operation and maintenance practices for majority of these dams need to be improved considering sediment management in order to ensure reservoir life and safety.

For a healthy dam safety management system, various important components of it needs to be in place. Based on experience of Central Water Commission, it is felt that it is high time for India to put required legislation on Dam Safety in place to address the dam safety sector in a comprehensive and holistic way. It will make mandatory for all stakeholders to perform required activities in the very interest of these assets. There are additional issues beyond usual maintenance, which have to be considered with time and shall be addressed scientifically.

Sediment management guidelines is essential for a dam for ensuring its life considering safe and sustainable functioning with desired benefits. The present *Handbook on Assessing and Managing Reservoir Sedimentation* is treated as the important knowledge base that will be helpful to prepare tailored guidelines for specific dam and reservoir. It describes all the elements systematically and comprehensively essential for assessment and management of sediment-induced problems of the dam and reservoir regularly as well as sometimes need based. This handbook has been framed based on global prevailing practices, individual experiences of the experts, as well as experience derived during the ongoing DRIP.

Central Water Commission is striving to put best practices for dam safety management based on sound judgement and worldwide experiences. The documents need continuous revision based on continuous change in technological advancement in rehabilitation materials, surveillance and monitoring systems, comprehensive inspection and risk assessment, etc. All dam owners can use this document for developing and revising sediment assessment and management guidelines for their dams.

I convey my sincere compliment to all the officials and staff who have contributed directly and indirectly in the development of this handbook under the DRIP project, and extend heartily gratitude for sparing valuable time and resources. Central Water Commission also acknowledges the special support extended by World Bank in accomplishing these objectives and especially thank Mr. Jun Matsmuto, past Task Team Leader, DRIP as well as Dr. C Rajgopal Singh, present Task Team Leader, DRIP and their team for extending excellent support all the time.

(N K Mathur)
Member (Design & Research)
Central Water Commission

New Delhi
February 2019

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PREFACE

Central Water Commission (CWC) is Apex Organization of India in the field of Water Resources. To promote safety of the dams right through the planning, design, construction, operation and maintenance of dams, CWC implemented several initiatives including the development of handbooks, guidelines and manuals to be used by dam authorities and professionals. As a part of the institutional strengthening component of DRIP, the project being implemented with the financial support of the World Bank, development of dam safety and rehabilitation related guidelines and manuals has been taken up by CWC. This Handbook for Assessing and Managing Reservoir Sedimentation is one of the series.

It is obvious that any intervention in a natural system induces adverse impacts as well. Nevertheless, the negative impacts of dams and reservoirs can also be attributed to poor planning, mismanagement, inefficient operation and improper consideration (or negligence) of impact mitigation options and conditions. Sediment-induced problems in regulated rivers with water infrastructures (like dams and barrages) are usually associated with alterations in flow regimes, interruption of sediment supply, unrestrained and random operations as well as poor maintenance and management. Furthermore, due to aging of reservoirs and absence of integrated approach for their management, the problem of storage loss has become more critical all over the world. Growing population, land-use changes and encroachments near such water infrastructures without proper management are leading to adverse social, environmental, and economic impacts and even calamity. With further ageing of dams and reservoirs, it is expected that almost half of live storage capacity could be exhausted in most of the reservoirs in the world by the middle of this century, and within 200 to 300 years most of them could be filled up. Particularly in the country like India with large number of dams and reservoirs (more than 5000 large dams), such propensity appears to create large water distress and safety concerns. The importance of dams and reservoirs, their positive and negative impacts shall objectively be weighed vis-a-vis multi-sectorial benefits and any nation's specific priorities and demands.

Proper consideration, assessment and management of sediment-induced problems are an integral and challenging part for a shift towards the concept of safe and sustainable use of reservoirs. Particularly, for existing reservoirs, comprehensive plan and actions with regard to assessment and management of sediment-induced problems are desirable given the fact that these problems are associated with life and safety of not only infrastructures but also inhabitants.

It is difficult to capture all in-depth technical aspects, associated with sediment-induced problems, in one handbook. Nevertheless, the contents of this handbook have been synthesized and adapted from large amount of past and on-going efforts, experiences and researches. The synthesized materials may provide an overview of relevant themes and topics including brief theoretical and technical methodologies, state-of-the-art knowledge, technology, practices, case studies and applications. The handbook also includes a sorted list of references as a knowledge database. This handbook may be of use for a thorough study of existing and potential sediment-related problems in any specific dam/reservoir, and thus for preparing tailored guidelines to manage the specific problem(s).

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Guidelines Review Committee

Chairman	Gulshan Raj	Chief Engineer, Dam Safety Organization, Central Water Commission, New Delhi
Member Secretary	Pramod Narayan	Director, Dam Safety Rehabilitation Directorate and Project Director DRIP, Central Water Commission, New Delhi

Committee Members

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Team Involved in Preparing this Guideline

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ABBREVIATIONS

Acronyms used in this publication are as follows:	
BIS	Bureau of Indian Standards
CDSO	Central Dam Safety Organisation
CWC	Central Water Commission
DDMA	District Disaster Management Authority
DRIP	Dam Rehabilitation and Improvement Project
DSRP	Dam Safety Review Panel
DTM	Digital Terrain Model
GPS	Global Positioning System (uses GPRS for data transmission like browsing the web)
HPP	Hydro Power Project
IAEA	International Atomic Energy Association
ICOLD	International Commission on Large Dams
IRTECS	International Research & Training Center on Erosion & Sedimentation
LIDAR	Light Detection and Ranging
NOAA	National Oceanic and Atmospheric Administration
ROR	Run-of-the-River
SDSO	State Dam Safety Organisation
TANGEDCO	Tamil Nadu Generation and Distribution Corporation Limited
UNEP	United Nations Environment Programme
USGS	United State Geological Survey
USBR	United States Bureau of Reclamation
WMO	World Meteorological Organization
WB	World Bank

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EXECUTIVE SUMMARY: GUIDELINES IN A NUTSHELL

Summarizing all explored and synthesized materials, associated with assessment and management of sediment-induced problems in reservoirs, as a guidance to dam authorities and engineers

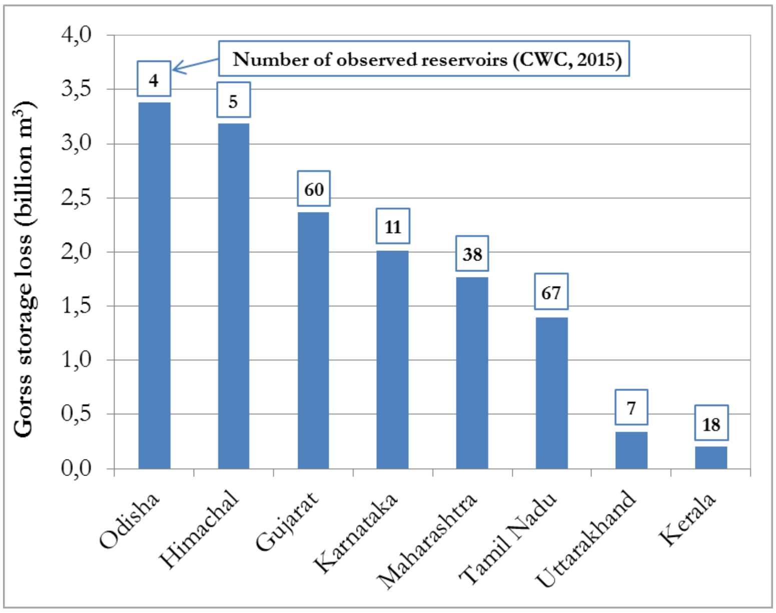
Reservoir Sedimentation
One of the Major Problems for Dam Safety and Water Security

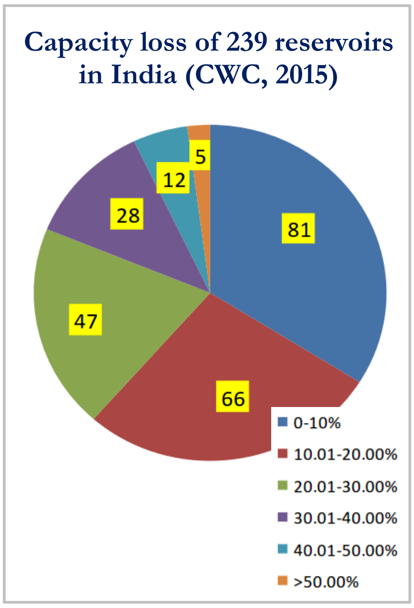
- ✓ **Water & Energy Demand**
- ✓ **Flood Management & Risk**
- ✓ **Safety Concerns**

- ✓ **~50% Reservoir Storage Loss by 2050**
- ✓ **100% in 200 to 300 Years**
  (Global Figure by ICOLD)

Chapter 1, 2

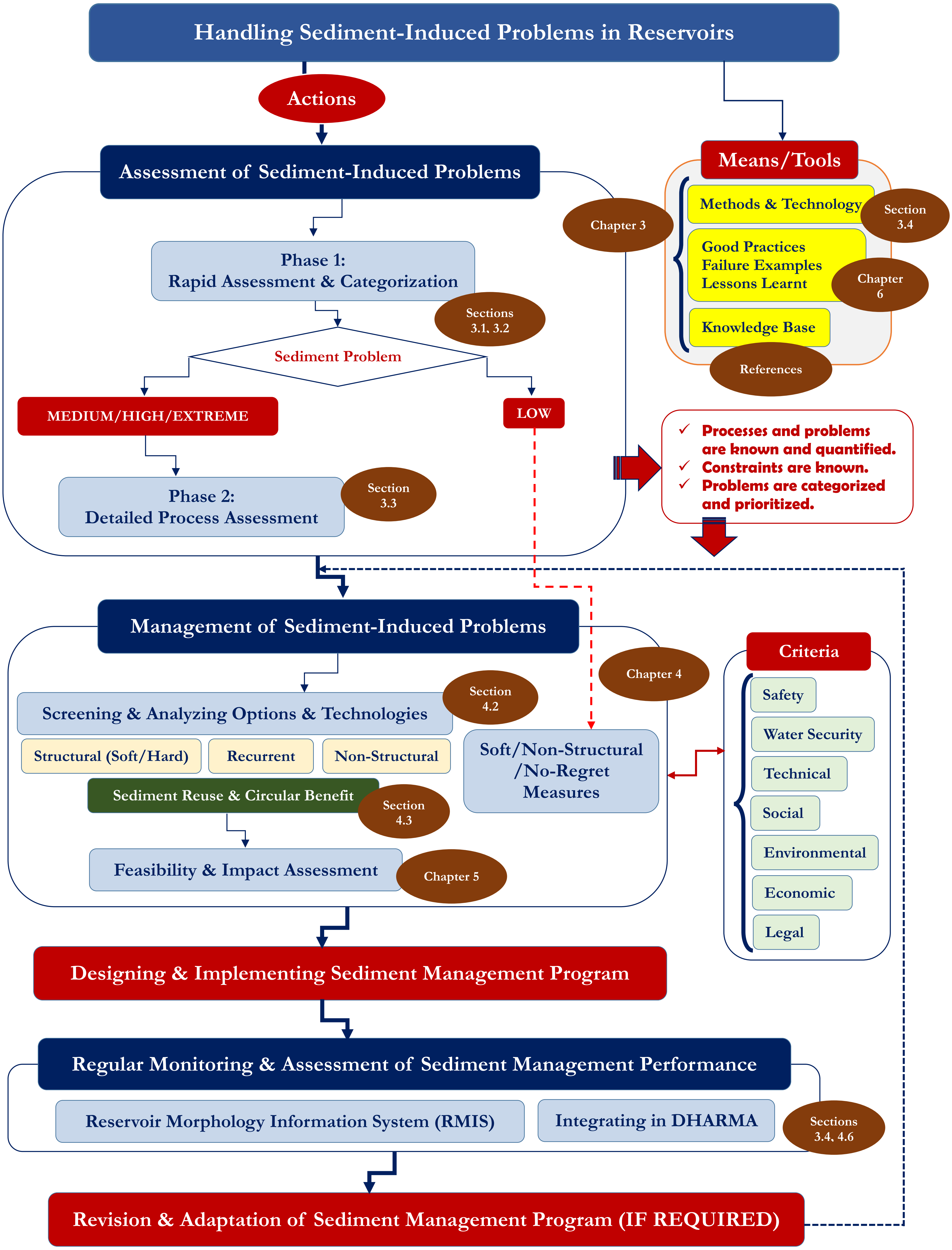
Large Dams in India (NRLD, 2018)
5262 (completed), **437** (under construction)
2329 (commissioned before **1980**)





Endangering the safety of dams, water security and livelihood, particularly in a country like India with rapid economic as well as population growth

The main objective of this handbook is to synthesize procedures, methods, technology and practices that are helpful to assess sediment-related concerns, and subsequently to manage them considering feasibility and impacts of selected measures.



Assessing Sediment-Induced Problems

"What cannot be measured, cannot be managed"

Phase 1. Rapid Assessment & Prioritization

Phase 1a. System Understanding & Problem Analysis

What?

- Field reconnaissance, collection of available data and information about not only reservoir and dam under consideration, but also about the catchment (like surface erosion, other mode of erosion, Catchment Area Treatment plan) and all connected upstream and downstream infrastructures and settlements
- Review and analyses of all collected data and information
- Review of past experiences and sediment handling activities

Why?

- To understand reservoir system and related processes (hydrological, morphological, land-use)
- To understand all surrounding objects, sources of the problem and associated visible impacts
- For first rapid assessment of the scale of problems (storage loss, structural damages)

How?

Chapter 3
Sections 3.1, 3.4

- Field reconnaissance
- Review of past studies
- Review and analysis of available data and information
- Rapid assessment using simple approaches in case of data scarcity (images, global datasets and information if available)
- Quick measurements and laboratory testing

Phase 1b. Constraints, Categorization & Prioritization

What?

- Number of dams with sediment-induced problems and their severity
- Define the category of sediment-induced problem and risk, namely ***LOW***, ***MEDIUM***, ***HIGH*** and ***EXTREME***
- Dam owner's priorities
- Other stakeholders' and user' interests and requirements
- Presence and functional condition of facilities and apparatus for sediment management (e.g. under sluices, scour vents, bypass)
- Exploring physical, operational, economic, environmental, legal and other constraints and limitation
- Technical and economic viability

Why?

- To assess and consider the constraint and limitations
- To categorize the sediment-induced problems and risk and make decision whether it needs detailed process assessment as well as what shall be the level of handling it
- To prioritize in case of larger number of dams with sediment-induced problems

How?

Chapter 3
Section 3.2

- Analyzing results and outcomes of Phase 1a
- Problem and data analysis (collected in Phase 1a)
- Rapid assessments based on information of Phase 1a and some additional observation if need be (like sediment and bathymetry measurements)
- Pre-feasibility check (economic)
- Discussions with Stakeholders and users
- Generating report on rapid handling of sediment-induced problems (as proposed in Appendix E)

Phase 2. Detailed Process Assessment

What?

- Detailed studies of hydrological and hydraulic processes for the 'MEDIUM', 'HIGH' and 'EXTREME' categories of the problem
- Bathymetry measurement to capture morphological feature and analysis of deposition pattern of the reservoir
- Sediment measurement and analysis (sediment characteristics, gradation and spatial distribution, core sampling and distribution, sediment type like uniform, graded, fine/coarse, cohesive/non-cohesive, mud)
- Sediment source and yield, catchment erosion, bed and suspended sediment transport rates (design estimation and observations)
- Temporal variability of sediment transport (e.g. episodic during floods and monsoon period when transport is noticeable or regular throughout the year)

Why?

- To understand and quantify reservoir inflow pattern and seasonal variation
- To quantify the sedimentation volume (storage loss), sedimentation rate, dominant transport phenomena, e.g. turbid flow, density flow, debris flow, mudflow, delta migration, bed forms and sandbar migration, seasonal sediment transport variability
- To identify morphological feature of the reservoir bed (e.g. erosion-deposition patterns, delta formation and migration, deep channel alignment)
- To compare the current catchment and reservoir conditions with initial and earlier observed conditions and quantify the changes
- To create a Baseline (reference) case and process-based (numerical) models for simulating hydraulic and morphological behavior of the reservoir and develop a reference case (to be used further for impact assessment)
- To assess the suitability and relevance of using numerical models by verifying them against observations (in case of lack of observation, simulations are carried out, in which a unverified reference scenario can be compared with synthetic scenarios and scenarios with sediment management measures, but the results need to be judged by specialists)

Chapter 3
Sections 3.3, 3.4

How?

- Review and rigorous analysis of available data, documents and information
- Measurements and observation
- Analyzing hydrological characteristics, seasonal variation of flow using data
- Analyzing of sediment transport variations and morphological conditions (using data and modeling)
- Using simple calculations and/or simplified modelling
- Using complex modelling (like two-dimensional morphological modelling of the reservoir)

Managing Sediment-Induced Problems

"When you can't solve the problem, manage it."

Screening & Analyzing Options & Techniques

What?

- Reviewing and screening sediment management methods and techniques: structural, non-structural, recurrent, adaptive
- Assessing technical possibilities of specific dam and reservoir (presence of sediment management facilities and apparatuses and past experiences)
- Assessing possibilities for sediment disposal and beneficial reuse
- Assessing possibilities and regulations for altering operation rules and storage reallocation

Why?

- To select appropriate sediment management methods and techniques (it can be a combination of different methods and techniques)
- To select few options and alternatives for feasibility and impact assessments

How?

Chapter 4

- Reviewing best practices and experiences (success and failures)
- Assessing the data and information on sediment yield, trap efficiency, inflow-outflow, morphological features
- Using simple methods for pre-feasibility selection based on past experiences
- Maybe some measurements and computations are necessary in case of data scarcity
- Consultations with stakeholders on their concerns and requirements
- Making use of studies, analyses and findings (on location, features, size, limitations, constraints, available facilities, resources, underlying phenomena, capacity), carried out under the section "Assessing Sediment-Induced Problems")

Feasibility Assessment

What?

- Technical feasibility and merits of selected sediment management options
- Economic loss, values and benefits (short- and long-term)
- Social, environmental and ecological aspects

Why?

- To identify what kind of sediment management measures are feasible considering long-term effectiveness, benefits and sustainability

Chapter 5
Section 5.1

How?

- Technical and economic assessment based on basic analysis and professional judgment
- For pre-feasibility, using some tools like RESCON and other empirical approaches that are based on past experiences
- Identify social, economic and environmental advantages as well as benefits like restoring original capacity to augment the drinking as well as other competing water demands, downstream sediment supply, supply of fertile sediments, sediments appropriate for aquatic life, beneficial reuse etc.
- Some modelling exercises and multi-criteria analysis if the system is complex.

Impact & Risk Assessment

What?

- Upstream impacts, e.g. extent and risk of retrogressive erosion, bank erosion, slope failure, channel shifting, aquatic life, wildlife
- Downstream impacts, e.g. other reservoirs, infrastructures, agriculture, aquaculture, aquatic life, habitats
- Cumulative impacts, if the reservoirs are in a cascade system
- Risk and sediment hazards due to release of large amount of sediments (example of Pillur reservoir flushing), water pollution due to contaminated sediment (example of Kallarkutty reservoir flushing) and eutrophication
- Existing legislation, regulations and practices related to impact and risk assessment

Why?

- To assess short- and long-term impacts of sediment management measures as the criteria for safety and sustainability
- To minimize unforeseen adverse effects, risk and hazards due to sediment management interventions

Chapter 5
Section 5.2

How?

- Rapid assessments using simplified methods and other experiences in conjunction with specialist judgment
- Impact studies using different methods and tools like modelling (hydraulic, morphological, economic), multi-criteria analysis
- Measurements and observation

Regular Monitoring & Assessment of Sediment Management Performance

What?

- Development of Reservoir Morphology Information System (RMIS), which may be a simple database system or a more sophisticated and automatized system (dash-board, interactive database management, processing and visualization, coupled with operational forecasting) to be integrated in Dam Health and Rehabilitation Monitoring System (DHARMA), being developed in DRIP India
- Primitive project data sheet and data gap summary sheet
- Inflows and outflows, historical and real-time water levels, discharge (rating curve), periodically discharge and velocity measurements
- Regular measurement of sediment concentration (particularly during rising, peak and falling flow periods at upstream of the reservoir, and during sluicing, flushing and replenishment at the downstream reach), bedload transport estimation
- Basic monitoring and analysis of sediment inflows (bedload and suspended load) if there are several inflow tributaries
- Bathymetry (regularly, based on reservoir size and category based on severity of the problems), at least some characteristic cross-sections if reservoir is very large
- Application of various advanced and remotely controlled techniques, particularly for the topography and bathymetry measurement of larger reservoirs (using various equipment, remote-sensing, satellite imagery, UAV, USV (Unmanned Aeri-al/Surface Vehicles) with mounted laser device or simpler devices like Fishfinder
- Surveillance, CCTV camera (monitoring of meso-scale morphological evolution in downstream, e.g. sandbar formation and other phenomena, bedload transport in hilly areas)

Why?

- To assess the performance of sediment management measures
- To adapt the sediment management approach if necessary
- To have precise data and information (precise measurement is very useful for model verifications, calibration, prediction, assessment of impacts as well as for operational use including forecasting)
- To minimize hazards, their impacts and fatalities
- Regular collection and management of data, information and observations are an integral part of sediment management and very useful for many purposes.
- A monitoring system is in itself a very important non-structural measure, necessary for effective and sustainable reservoir management

Chapter 3
Section 3.4

Chapter 4
Section 4.6

How?

- Reviewing and adapting available techniques - conventional and advanced
- Reviewing and adapting best practices and experiences
- Testing the effectiveness, appropriateness and viability (it can be done in small area like physical laboratory and/or some appropriate dam sites)

Methods, Knowledge & Technology

"Technology is a useful servant but a dangerous master"

Sediment Management: Methods & Techniques

Sediment Management Techniques

Chapter 4 & 6
Sections 4.2, 4.4, 4.5

Structural

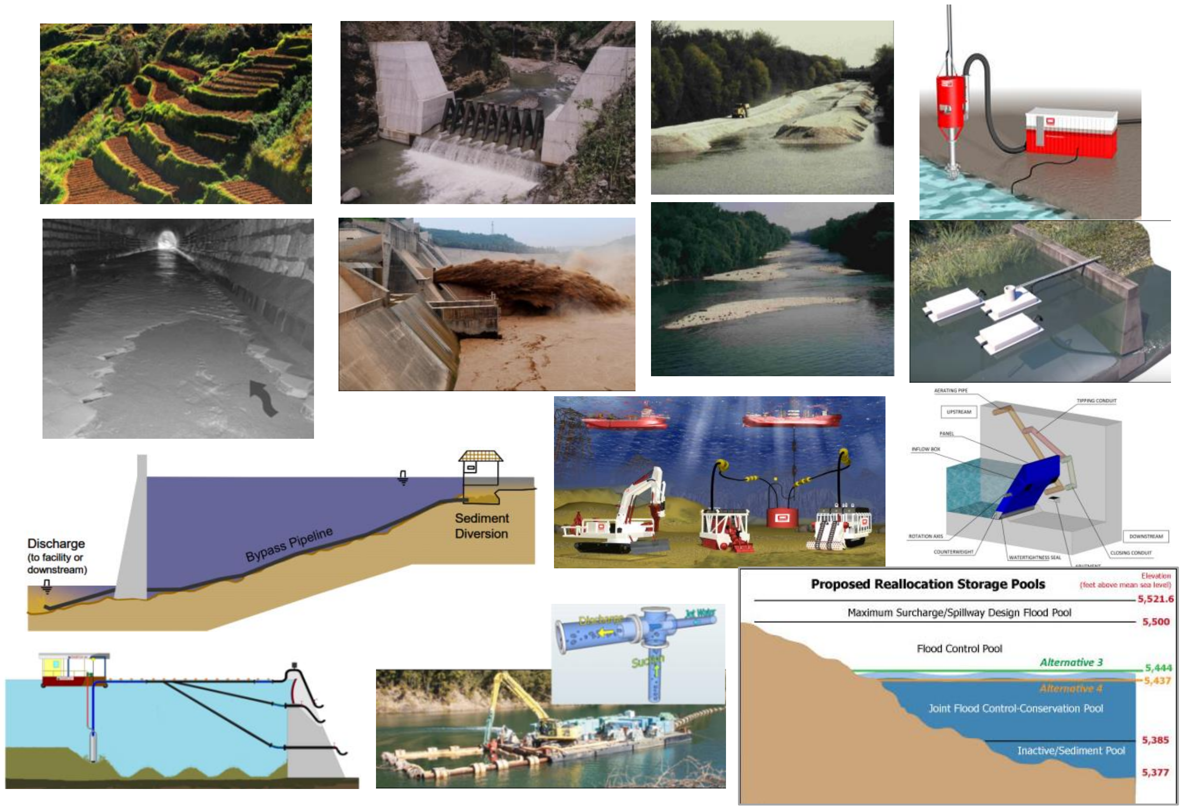
- o Erosion control structures
- o Check dam/sabo dam
- o Sediment traps and retention basin
- o Sediment diversion tunnel and channel
- o Guiding/training structures (open levee, vanes, baffles, weirs, dikes etc.)
- o Off channel reservoir
- o Dam heightening

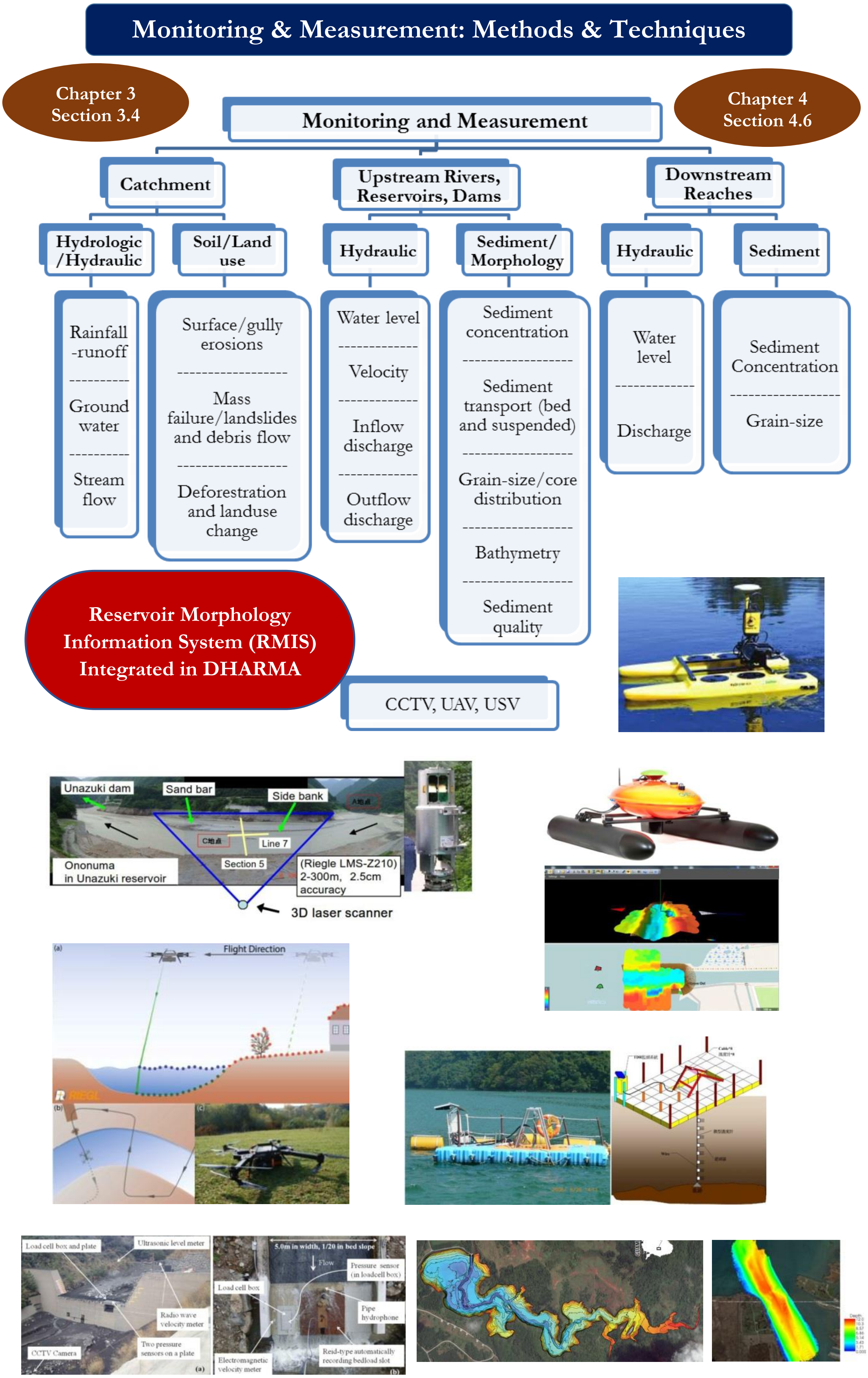
Recurrent

- o Sluicing
- o Flushing
- o Density current venting
- o Sediment replenishment /relocation
- o Hydraulic dredging/syphoning/slurry transport
- o Dry excavation/ trucking/landfill

Non-structural

- o Catchment/land use management
- o Erosion control (afforestation, vegetation, contour farming)
- o Optimization of reservoir operation rule/strategy
- o Storage relocation
- o Sediment modelling
- o Monitoring (real-time periodic)
- o Reservoir Morphology Information System (RMIS)
- o Storage reallocation

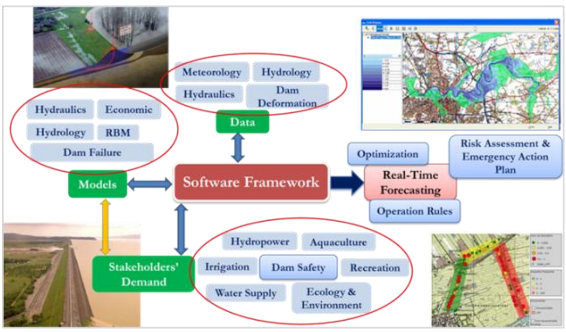



Monitoring & Measurement: Methods & Techniques
Chapter 3 Section 3.4
Monitoring and Measurement
Chapter 4 Section 4.6
Catchment
Upstream Rivers, Reservoirs, Dams
Downstream Reaches
Hydrologic /Hydraulic
Soil/Land use
Hydraulic
Sediment/ Morphology
Hydraulic
Sediment
Rainfall -runoff
Ground water
Stream flow
Surface/gully erosions
Mass failure/landslides and debris flow
Deforestation and landuse change
Water level
Velocity
Inflow discharge
Outflow discharge
Sediment concentration
Sediment transport (bed and suspended)
Grain-size/core distribution
Bathymetry
Sediment quality
Water level
Discharge
Sediment Concentration
Grain-size
Reservoir Morphology Information System (RMIS) Integrated in DHARMA
CCTV, UAV, USV
Unazuki dam
Sand bar
Side bank
Line 7
Section 5
Ononuma in Unazuki reservoir
(Riegle LMS-Z210) 2-300m, 2.5cm accuracy
3D laser scanner
Flight Direction
Load cell box and plate
Ultrasonic level meter
Radio wave velocity meter
Two pressure sensors on a plate
CCTV Camera
5.0m in width, 1/20 in bed slope
Flow
Pressure sensor (in loadcell box)
Load cell box
Pipe hydrophone
Electromagnetic velocity meter
Reid-type automatically recording bedload slot

Reservoir Morphology Information System (RMIS)

Data and Information Needs		
1.	Original design data and information	Most Important
2.	Topographic and bathymetry surveys	Most Important
3.	Area-capacity analysis	Most Important
4.	Satellite imagery/photography	Most Important
5.	Sediment samples/characteristics (cores and surface samples)	Most Important
6.	Sediment quality (physical and chemical)	
7.	Project information (pools, authorized purposes, water control)	
8.	Incidental evidences/observations	
9.	Measured discharge, water levels, water surface and sediment load	
10.	Sediment rating curves	
11.	Flow and sediment rating curves	
12.	Flow and sediment gauge station/ locations, other information	
13.	Past morphological studies	
14.	Morphological modelling	
15.	Volume depletion at different pools	
16.	Sediment management activities (e.g., dredging, flushing, sluicing, etc.)	
17.	Funding over time, sources	
18.	Flow and sediment monitoring system	
19.	Environmental factors driving data collection	
20.	Operational impacts, e.g., stage-frequency shifts, reallocation of pools/ storage	

Chapter 4
Section 4.6



Database Table	Description
Location	Coordinates of each reservoir
Description	Descriptions of the all field in all tables
RMIS01	Details of the location, top of dam and spillway crest elevations, dates of operation, drainage area, and climate of reservoir drainage
RMIS02	The pool elevations, surface area, and capacities of the pools by purpose of operation
RMIS03	The elapsed time since the previous survey for each survey on each reservoir
RMIS04	Details of the survey method and scope for each survey date on each reservoir
RMIS05	Precipitation and water inflow for each survey period for each reservoir
RMIS06	Aerated, submerged, and total sediment deposits, sample number, and average dry weight estimates for each survey date
RMIS07	Definition of reservoir pool layers denoted by elevation for areal sediment distribution
RMIS08	The percentage of sediment deposits occurring in each depth layer for each survey
RMIS09	The percentage of the sediment deposits occurring by distance segment and reach for each reservoir and for each survey date
RMIS10	Water inflow and maximum and minimum reservoir elevations by water year
RMIS11	the storage capacity by elevation stage for each reservoir (may have multiple dates)
RMIS12	Footnote explanations and other remarks
RMIS13	Agencies collecting and reporting data

Mathematical Modelling

Reservoir Modelling

Chapter 3
Sections 3.4

One-Dimensional

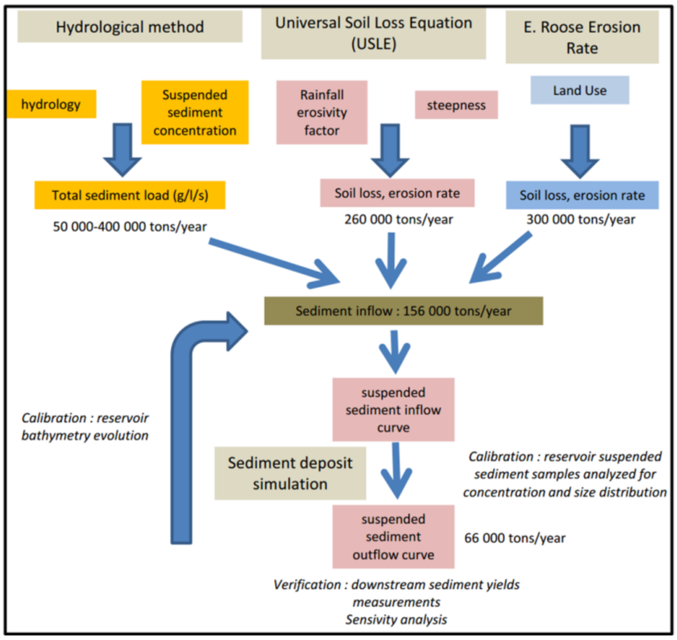
- Far-field modelling including upstream and downstream river reaches
- Assessing long-term morphological impacts
- Quantifying erosion and sedimentation rates and patterns
- Scenario analysis and quantification of impacts on width and reach averaged morphology, i.e. changes in longitudinal direction
- Simulating dredging effects
- Deriving boundary conditions for near-field model simulation (for 2D/3D model reaches)

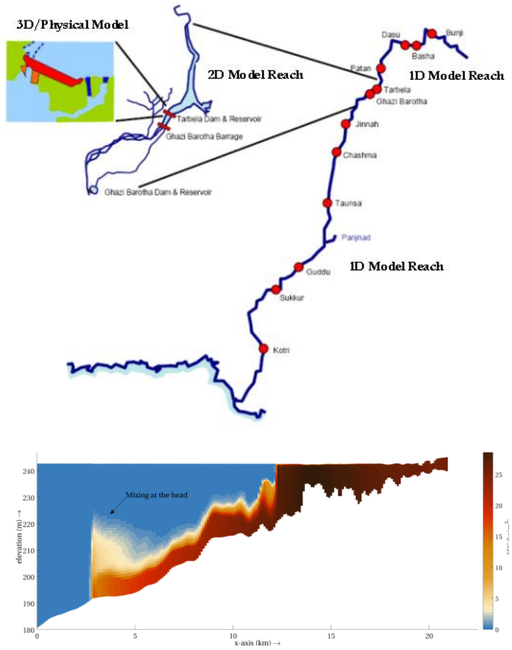
Two-Dimensional

- Simulating depth-averaged hydraulic and morphodynamic behaviour of rivers and reservoirs on time scales of days to years
- Computing the complex interactions between currents, sediment transport and bed topography
- Sluicing, flushing and dredging operations, and their impacts (incised channel formation, sediment concentration, flow and bed level changes etc.)
- Key three-dimensional effects are included through a parameterization, e.g. effect of the secondary flow and transverse bed slope on sediment transport in bends
- Downstream morpholgical development (e.g. effect of sediment replenishment)
- Simulating density current (simplified or vertical 2D modelling)
- Optimizing physical experiments and scenarios

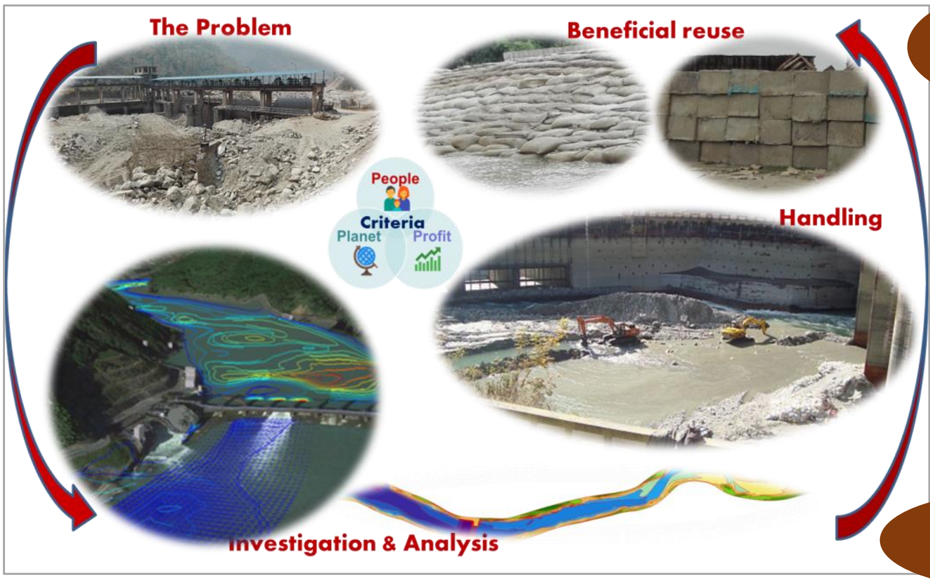
Three-Dimensional

- Computing complex flow around strucutres
- Design optimization of spillway, intakes, sluices
- Supplementary to physical modelling, particulary related to hydrodynamics
- Simulating densitiy current
- Simulating sluicing and flushing operations (based on complexity)





Sediment Disposal & Reuse: Methods, Techniques & Practices

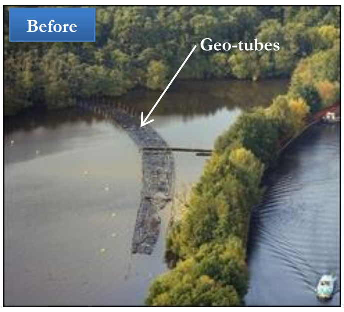


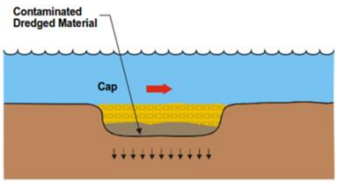
Chapter 4
Section 4.3

Appendix F

Sediment - Natural Resource

- Top Soil Enhancement and Agricultural Use
- Land Reclamation, Improvement & Filling
- Construction & Protection Materials
- Capping
- Fill for Abandoned Mines/Quarries
- Beach Nourishment and Shore Protection
- Habitat Creation and Restoration
- River Management (Sand Plugs for Channel Closure)





Advantages & Limitations of Dredged Material (DM) Reuse Options

Reuse Options	Advantages/Capabilities	Disadvantages/Limitations
Beach Nourishment	○ Helps to prevent localized flooding and control coastal erosion ○ Facilitates and supports local tourism by maintaining a wider beach area ○ Provides a 'soft' engineering approach instead of or in conjunction with traditional 'hard' engineering solutions such as construction of sea walls and groynes.	○ Detailed engineering analysis required to accurately assess the local wave climate and beach erosion rates. ○ If dissimilar material (texture, colour etc.) is used from the in-situ natural beach material then the aesthetics of the beach may be negatively impacted.
Land Creation/ Reclamation or Land Improvement	○ Reclaimed land can provide an economic incentive for dredging stakeholders where benefits to tourism, ports and industry may be realized. ○ Potential profits to be made from reclaimed/improved land may be substantial ○ It may be less expensive to place the DM in a reclamation area than transport to a disposal site ○ The creation of reclaimed land may be more environmentally acceptable than disposal at sea.	○ Final land use of the reclaimed land may be restricted depending on the type of DM used. ○ Reclamation may not be possible where water depths are excessive. ○ Consolidation and drainage is slow, and the final strength achieved may be low. ○ Potential land ownership issues must be resolved ○ May require extensive environmental impact analysis
Landfill Cover	○ Potentially improves the aesthetics of the area upon completion of landfill cover ○ Creation of potential amenity and/or recreation area for local community. ○ Potential environmental benefits through the regeneration of plant life ○ Potential increase in surrounding land values	○ Contamination levels must be at a level suitable for the materials intended use. ○ Dewatering is typically required, desalination of DM may be required to stimulate plant growth
Offshore Berm Creation	○ Established international technology (e.g. applied in Taiwan, USA, and Japan). ○ Recovery site and application may be close reducing DM transport costs. ○ Can provide an environmentally acceptable "soft-engineering"	○ For berms designed to be stable they may yet be prone to erode with the erosion rate dependent on the local wave climate. ○ May not be suitable for locations where conflict with fisheries, ports, outfalls etc. may arise. ○ Optimum placement area must

Reuse Options	Advantages/Capabilities	Disadvantages/Limitations
	solution to coastal protection. o May be created by simple discharge of DM from hoppers	be located and be sufficiently shallow to mitigate wave effects.
Coastal Protection Works (Including Geotubes)	o Versatile technology and relatively simple to implement o May provide an environmentally beneficial and economically viable alternative for elements of traditional rubble mound structures o Use of geotubes can retain and isolate some forms of contaminants	o Risk of tearing / distortion of geotubes with potential to lead to instability and undermining of coastal structure o Generally available in specific sizes which may not necessarily suit a particular application. Custom sizing may be expensive. o Hydraulic equipment is required for geotubes
Wetland Habitat Creation/ Enhancement	o Environmental benefit with preservation of endangered ecosystems/habitats o Restoration of wetland area can alleviate problems associated with flooding, erosion and reduced fish populations.	o Substantial physical, chemical and biological testing is required to determine feasibility o Assigning an economic value of beneficially using DM for wetland restoration is difficult and often subjective
Sediment Cell Maintenance	o Contributes to maintaining the natural sediment regime of an estuarine system which may be affected by dredging activities. o Relatively easy to implement with environmental benefits. o Subtidal and intertidal habitats can be enhanced for benthic macro-fauna.	o Extensive DM characterization and monitoring of the local ecosystem must be undertaken to ensure no negative impacts. o Likely to require advanced computer modelling and specialist involvement at the design stage.
Fill for Abandoned Mines/Quarries	o May be suitable for contaminated DM without a requirement for pre-treatment o May contribute to providing a solution to minimizing the potential environmental threat posed by abandoned mines/ quarries. o May be combined with other 'waste' products such as coal ash to provide a beneficial end use.	o Depending on the specific site; it may be seen as an alternate disposal route for DM as opposed to a beneficial use.
Concrete Manufacture	o May provide an alternative to quarry sourced aggregate in concrete manufacture, potentially reducing construction costs o Dredged sediment is suitable for use in several types of concrete such as light weight and self-	o The quantity of aggregate that can be replaced is dependent on the characteristics of the DM. o Results for the fined grained component of DM only based to date on results of research work.

Reuse Options	Advantages/Capabilities	Disadvantages/Limitations
	consolidating concrete. ○ May potentially provide a beneficial use for contaminated DM without requiring expensive pre-treatment.	
Road Sub-base Construction	○ Offers a range of potential uses in road construction ○ Contaminated DM may be used in the road sub-base construction. ○ May contribute to providing a sustainable alternative to quarry sourced natural sand/aggregate.	○ Fine grained DM requires the addition of a stabiliser, such as lime or cement, to obtain the required mechanical characteristics for the sub-base layer. ○ Use of fine grained DM as a substitute still at experimental stage with pilot road construction in France an example of application
Landfill Liner	○ Can provide a less complex and less expensive alternative to bentonite-enriched soil (BES) or compacted clay liners (CCL). ○ Placing, testing and evaluating the DM will be similar to traditional liner materials, thus existing machinery and testing apparatus are appropriate for DM	○ Possible stabilisation and grading of DM may be required depending on physical characteristics. ○ Ideally only suitable for DM sourced from consolidated clay ○ To date reliance on research pilot-type schemes
Manufactured Topsoil	○ May provide a potential income stream for ports/harbours that produce significant quantities of maintenance DM on a regular basis. ○ Significant research has been undertaken with several projects completed in the U.S. and the U.K. ○ May contribute to reduced organic municipal waste disposal costs as it is used with DM in the manufacture of topsoil ○ Both hydraulic and mechanical dredging can be used	○ Relies on a market demand for the product near to the point of source ○ Stringent requirements apply to the characteristics of the DM ○ A reliable and consistent supply of suitable organic material is required
Production of Bricks/ Ceramics	○ Contaminated DM may be used with contaminants becoming neutralized in the manufacturing process. ○ Selling the DM as a raw material for the brick/ceramic manufacturing industry may provide an income stream.	○ Consistency of the DM characteristics required for successful brick manufacture. ○ To date only small to medium scale pilot schemes have been undertaken in France and Germany.

Sediment Management Measures & Associated Positive & Negative Impacts

Chapter 3 & 5
Sections 3.4, 5.2

Measures	Impacts (positive and negative)		
	Social/Safety	Environmental	Economic
Catchment treatment	○ Improved catchment condition ○ Better land use ○ Reduced sediment inflow ○ Employment	○ Better environment (forestation, land-use)	○ Moderate cost ○ Implicit gains (depending on size and problems)
Catchment/ river erosion control structures	○ Interventions in landscape and basin system ○ Safety and sustainability concerns ○ Reduced sediment inflow ○ Employment	○ Environmental concerns due to structural intervention	○ Noticeable cost ○ Implicit gains (depending on size and problems)
Dam height raising	○ Upstream inundation ○ Dam stability problem ○ Downstream impacts ○ Some gains (employment, water availability, flood control)	○ Upstream and downstream hydraulic and morphologic changes and impacts	○ Higher cost ○ Some storage gain (water use, energy, flood control)
Fusegates	○ Similar but less concerns comparing to dam height raising	○ Less concerns comparing to dam height raising	○ Higher cost ○ Some gains (storage and controlled flow release)
Additional storage reservoir	○ Land-use ○ Landscape intervention ○ Flood control	○ Land use changes ○ Basin intervention ○ Flow diversion	○ Higher cost (land, diversion/pumping facilities) ○ Some gains (storage, energy, flood safety)
Storage reallocation	○ Changes in flow release frequency and water use ○ Safety and risk	○ Changes in flow frequency and quantity (downstream impacts)	○ Lower cost ○ Some gains (water, energy), implicit loss (e.g. flooding pool)
Sluicing/ venting	○ Flow and sediment supply to downstream (water and silt for agriculture and aquaculture) ○ Sometimes safety concern	○ Quasi-natural flow and sediment supply ○ Morphological and environmental impacts (positive, but sometimes negative)	○ Low cost ○ Water loss (energy, water supply)
Flushing	○ Retrogressive erosion ○ Bank erosion ○ Increase in turbidity ○ Water and silt for agriculture and aquaculture ○ Storage gain ○ Safety concern (downstream sediment hazards)	○ Downstream impacts (high concentrated flow, contaminated sediment)	○ Low cost ○ Water loss (energy, water supply)
Bypass tunnel/ channels	○ Structural intervention ○ Safety concern ○ Storage gain	○ Flow and sediment balance ○ Landscape intervention	○ High cost ○ Storage gain and other indirect benefits
Sediment	○ Storage gain	○ Less environmental	○ Higher cost

Measures	Impacts (positive and negative)		
	Social/Safety	Environmental	Economic
replenish-ment	○ Employment** ○ Noise and pollution (if trucking) ○ Downstream sediment supply	impact (can be controlled)	○ Low storage gain ○ Indirect benefits
Hydro-suction removal	○ Storage gain ○ Employment ○ Less safety concerns	○ Less environmental impact (can be controlled)	○ Moderate cost ○ Low (no) energy cost ○ Low storage gain
Hydraulic dredging	○ Storage gain ○ Employment ○ Noise and other pollution, ○ Less safety concerns	○ Pollution ○ Upstream and downstream impacts (can be controlled)	○ Higher cost ○ Some gains (storage, safety)
Dry dredging and trucking	○ Storage gain ○ Employment ○ Noise and air pollution ○ Safety concerns (during trucking)	○ Air pollution (trucking) ○ Disposal sediment	○ Higher cost (removal, trucking , disposal) ○ Storage gain ○ Reuse possibilities
Non-structural measures	○ Less encroachment ○ Employment ○ Resource ○ Knowledge and capacity development	○ Control of environmental impacts	○ Lower cost ○ Implicit and long-term benefits

Methods & Tools for Assessing Impacts of Sediment Management

Measures	Resulting Impacts to Quantify	Methods & Tools
Catchment treatment	Reduction of erosion rate, morphological changes in channel(s) and reservoir due to sediment inflow reduction, cost and benefit	Catchment erosion calculation and/or modelling, river and reservoir erosion-sedimentation calculation and/or modelling, economic analysis (calculation/modelling), review of other experiences, data analysis
Catchment/ river erosion control structures	Reduction of erosion rate, effectiveness of control structures, morphological changes in channel(s) and reservoir due to sediment inflow reduction, cost and benefit	-ditto-
Dam height raising	Backwater, hydraulic load, reduction in downstream flow, modified flow release and dam break analysis, cost and benefit	Hydrodynamic and morphological computations, economic analysis, review of other experiences, data analysis, economic analysis (calculation/modelling)
Fusegates	-ditto-	-ditto-
Additional storage reservoir	Hydraulic and morphological changes in the river and reservoir due to water diversion, effectiveness of additional storage, cost-benefit analysis	Hydraulic and morphological calculations and computation, economic analysis, review of other experiences, data analysis
Storage allocation (for multipurpose reservoir)	Changes in reservoir operation, flood risk (e.g. due to reducing the flood control pool), downstream flow and morphology, reservoir morphology	Calculations/computations of reservoir operation and optimization, river and reservoir hydraulics, downstream flow and morphology, flood inflow and risk
Sluicing/ venting	Effectiveness of sluicing/ venting, sediment transport and morphology of the reservoir and downstream reach	Morphological calculation/ computation of the upstream reach, reservoir and downstream reach, economic analysis
Flushing	Effectiveness, quantity and quality of deposits, sediment transport and morphology of the reservoir including upstream and downstream changes, cost and benefit	Analysis of quantity and quality of deposits, review of other experiences, modelling of flushing operations including upstream and downstream sediment transport and morphology, calculation/computation and analysis of retrogressive and bank erosion, economic analysis (calculation/modelling)
Sediment replenishment	-ditto-	-ditto-
Hydro-suction removal	-ditto-	-ditto-
Hydraulic dredging	-ditto-	-ditto-
Dry dredging and trucking	-ditto-	-ditto-
Bypass tunnel/ channels	Effectiveness, flow and sediment transport in the tunnel/channel, sediment transport and morphology of the reservoir, upstream and downstream reaches, abrasion, maintenance, cost and benefit	Calculation/computation of the flow and sediment transport at the upstream river, bypass, reservoir and downstream reach, abrasion calculation, economic analysis (calculation/modelling)

Lesson Learnt

"Failure is success if we learn from it"

Chapter 6

- A problem, which has been accumulated since decades, is not possible to be assessed and managed simply and quickly.
- Sediment-induced problems in reservoirs are generally very complex and ambiguous, and there is no "Elixir" to resolve them in a straightforward and easier ways.
- Sediment management measures and interventions can cause serious disaster as well. Consequently, it is very important to carry out thorough investigation considering all possible threats and impacts. This is in particular valid when the problem has been accumulated for a long period.
- Such complex problems can only be managed by putting proper efforts, capacity and resources in a justifiable manner. For example, the flushing operation at Genissiat reservoir (in France) in 2012 required mobilization of 400 people for about 10 days, and it did cost around 8 million Euros.
- There are experiences, practices, examples (successes and failures), knowledge and technology that are very useful to consider, although it is not always possible to adapt them easily and straightforwardly.
- There are also knowledge gaps and lack of adequate experiences, which imply that there are needs for further exploration, experimentations and research in a regular basis as well as "Learning by doing".
- Building capacity, developing professional human resources and specialized institutions are some of the key prerequisites to handle the problems related to sediments. Assessment and management of sediment-induced concerns in rivers and reservoirs are associated with multiple disciplines that require widespread specialization and knowledge integration.

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Chapter 1. INTRODUCTION

Dams and reservoirs are important infrastructures, particularly for the countries like India with strong seasonal variation in flow pattern as well as rapid growth of economy and population leading to increasing water and energy demand. It is obvious that any intervention to a natural system induces adverse impacts as well. Nevertheless, the negative (social and environmental) impacts of dams and reservoirs can also be attributed to their mismanagement and improper consideration (or negligence) of mitigation options and conditions. The importance of dams and reservoirs, their positive and negative impacts shall objectively be weighed considering multi-sectorial benefits, demands and criteria. This was probably not easy to quantify during last century, but presently rapid development of innovative tools and technologies enables us to incorporate all available knowledge, concepts and approaches to address multi-sectorial aspects in an integrated manner.

Present situation around the world with increasing water and energy demand on one hand, while catchment degradation and sediment-induced problems in reservoirs on the other hand leads to the fact that there is a need for a major shift towards the concept of integrated and optimized dam and reservoir management considering collective benefits, safety and water security. Another important fact is that nowadays construction of new dams and reservoirs has become more difficult due to increasing social and environmental constraints and compliances. Consequently, dam safety and rehabilitation efforts have become indispensable in many countries with large number of dams.

Reservoir sedimentation is one of the major issues to be earnestly considered in dam improvement and rehabilitation efforts.

Figure 1-1. Sediment deposition in Lake Mill reservoir *(Photo Courtesy of Tom Roorda)*

1.1 Sediment-Induced Problems in Reservoirs

The global net amount of reservoir storage has been decreased in recent years because the sediment management was not a standard practice in the past. As per the finding of International Commission of High Dams (ICOLD), 50% of the storage would be lost globally by 2050 and 100% within 200 to 300 years due to sedimentation. Such situation would be endangering water security and livelihood.

Sediment-induced problems induce a number of adverse impacts not only within reservoirs, but also in both upstream and downstream areas of river systems with dams. Some of the adverse effects, induced by sedimentation and erosion processes in river system with reservoirs, are outlined as follows:

- Reduction of storage volume in reservoirs due to sediment deposits
- Flood level increase in upstream of the reservoir (higher than estimated during design) due to changed river slope

- For flood control dams and reservoirs, reduction of storage implies altered regulation and operational strategies leading to less effectiveness of flow/flood management, and thus more risk
- Erosion and shifting of river banks and bed incision in downstream areas
- Coastline erosion due to the lack of sediment supply from rivers
- Adverse effects on agricultural activities in downstream areas due to lack of fertile silt and nutrient supply
- Impact on aquaculture like fisheries, aquatic plants etc. at downstream areas
- Possible alteration in static and dynamic loads on structures due to large deposition in front of dam/spillway
- Erosion of turbines and its accessories
- Malfunctioning and clogging of hydro-mechanical equipment, such as flow control gates, sluice outlets and vents
- Abrasion and cavitation of concrete structures like spillways, roller buckets, cut-off wall, sediment bypass tunnels and channels etc.
- Deterioration of aquatic environments, ecology, water and sediment quality leading to eutrophication, contamination of sediments in the reservoir (this is usually the case due to industrial effluents, reaching the reservoir)
- Concerns related to random sediment removal activities (like uncontrolled and irregular flushing) with large turbidity may have an effect on water quality and aquatic environment as well as may cause other sediment hazards in downstream area.

An example of changes in natural sediment balance due to dams and their operation is depicted in Figure 1-2.

The sediment-induced concerns worldwide can be attributed to some of the following factors:

- Deforestation and land use changes
- Selection of location and design approach without considering river morphology and sediment transport
- Underestimation and ignorance of sediment and morphology-related issues and their impacts
- Lack of proper knowledge and technology for application of integrated

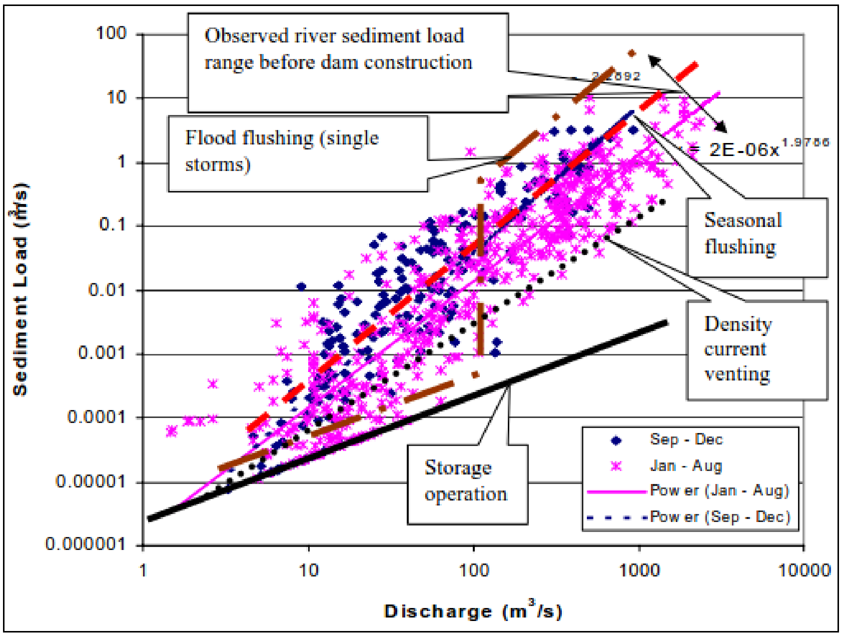

Figure 1-2 Change in sediment load – discharge relationship due to dams and their operations *(ICOLD, 2007)*

and optimized operation and management strategies

- Ageing of dams and reservoirs
- Lack of regular maintenance as well as absence of proper regulation and tailor-made guidelines on sediment management in regulated rivers and reservoirs

Notwithstanding all the impacts, adversities and controversies, structural interventions in natural system like rivers are inevitable to create alternatives in order to fulfill societal demand for water and energy resources as well as for water-induced disaster management. Such development projects are not always against environment and livelihood, but rather they can bring benefits in case of proper selection, planning, execution, maintenance and management. Consequently, these issues are supposed to be addressed in an integrated manner and with special care right from the beginning, i.e. during selection of the location and design, as well as during operation and rehabilitation to minimize adverse social, environmental and economic impacts. This requires a whole set of studies and investigation making use of available knowledge, novel tools and technologies, their proper implementation and regular development.

1.2 Scope and Objectives

This handbook synthesize the state-of-the-art approaches and technologies to assess and manage reservoir sedimentation problems for different types of dams and reservoirs.

Main objective of the guidelines is to synthesize procedures, methods, technology and practices that are helpful first to assess sediment-induced concerns and subsequently to manage them considering feasibility and impacts of selected measures. The guidelines are focused on existing reservoirs considering Indian context of dam rehabilitation. Although the sediment-induced problems are rather common and valid for reservoirs in other countries as well. The handbook also applicable to planned reservoir as it includes additional sections, dedicated to them where necessary.

The handbook can be used for following purposes (but not limited to):

1) Assessment of sediment-induced problems in existing reservoir, which includes:
    - Understanding the system behaviour and properly identifying the problems
    - Finding out constraints and priorities
    - Reviewing and selecting appropriate methods and technology for the assessment and quantification of the problems
    - Conducting detailed process assessment related to the problems
2) Management of sediment-induced problems in existing reservoirs, which includes:
    - Screening and selecting sediment management options and measures
    - Conducting pre-feasibility and feasibility assessment of sediment management measures
    - Assessing impacts of sediment management measures and interventions
    - Formulating and following the conditions for mitigating or minimizing impacts
    - Reviewing and selecting methods and tools for feasibility and impact assessment
    - Reviewing existing practices, methods, technology as well as legislation and regulation on treatment and beneficial reuse of dredged material around the world

3) Establishing Reservoir Morphology Information System (RMIS): Database (online/offline), reports, monitoring and measurement systems
4) Learning from past problems, failures and best practices
5) Preparing tailor-made (project specific) guidelines for a particular reservoir

This handbook complement the existing BIS guidelines, namely IS 12182 -1987 (reaffirmed 2002) and IS 6518 – 1992 (reaffirmed 2002), with some additional information based on present potentials and development.

1.3 Stakeholders

The major stakeholders associated with sediment management are almost all sectors, such as hydropower industries and authorities, flood control, water supply and irrigation authorities, beneficiary farmers, consumers, recreational and tourism industries, research institutions and so on. Besides, it is necessary to maintain river environment and livelihood in downstream areas, which includes not only flow release, but also release of sediment as well as aquatic life and species. Consequently, it is always a challenging task to manage the water demand and optimize reservoir operation strategies and approaches taking into account interest of all involved stakeholders as well as fulfill the requirements to minimize adverse social and environmental impacts.

1.4 Publication and Contact Information

A draft version of this document is available on the CWC website (*www.cwc.gov.in*) and the Dam Rehabilitation and Improvement Project (DRIP) website (*www.damsafety.in*) for general discussion, review and inputs. The handbook will undergo continuous improvements with updated version, particularly during the project period.

For any further information contact:

The Director

Dam Safety Rehabilitation Directorate

Central Dam Safety Organization

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1.5 Acknowledgments

In preparing this handbook, the works of others in India and elsewhere have been drawn from liberally.

Grateful appreciation is extended to the following organizations whose publications and websites provided valuable information:

Central Water Commissions (CWC)

International Commission on Large Dams (ICOLD)

United State Bureau of Reclamation (USBR)

World Meteorological Organization (WMO)

European Sediment Network (SedNet)

United States Army Corps of Engineers (USACE)

World Bank (WB)

In addition, contributions upon request by the institutions like DELTARES (The Netherlands), J-Power (Japan), Kyoto University (Japan) as well as many other websites and freely downloadable materials are of great help in preparing this handbook.

Chapter 2. Reservoir Sedimentation in India

According to recently published National Registration of Large Dam (NRLD, 2018), there are 5262 large dams (completed) and 437 dams are under construction. It should be noted that 2329 dams were commissioned before 1980. Consequently, loss of storage capacity in these dams has become one of the major concerns for dam safety and water security. Assessing and managing reservoir sedimentation problems have become very important in India due to rapidly growing economy as well as population (thus increasing water and energy demand).

For the sake of comparison, it is to be noted that the reservoir sedimentation studies of only 243 dams in India, published by CWC (2015), have revealed that about 26 billion m^3 of gross storage volume has already been lost, which is more than total storage capacity (about 23 billion m^3) of all large dams (2730) in Japan.

Figure 2-1. Deposition up to crest level, seen in an empty Hagari Bommanahalli reservoir in Karnataka, India

2.1 National Records and Regulation of Dams in India

Records and compilation of the dams in India are available and documented as National Registration of Large Dams (NRLD, 2018). The definition of "large dams" corresponds to the specification defined by the International Commission on Large Dams (ICOLD). As per available records in NRLD (CWC, 2018), there are 5701 large dams in India among which 5264 are completed dams and 437 are under construction. The NRLD, published on the website of CWC (2018), includes data about number of large dams in all states and one union territory of India.

Besides, as per NRLD, 69 large dams (10 are under construction) have been categorized as "Dam of National Importance". These dams are equal or higher than 100 m or having gross storage capacity of 1000 Mm^3 or more.

As mentioned in the document, each large dam in NRLD has been given a unique Project Identification Code (PIC). The PIC consists of ten-digit-alpha-numeric code (XX11XX1111). First set of two-digit alpha code represents the State in which dam is situated; second set of two-digit numeric code represents the concerned Dam Safety Organization (DSO) if it exists, or the department/agency, which is operating and maintaining the large dam, third set of two-digit alpha code indicates the category of dam under the pertinent project; and fourth digit numeric code indicates the Serial number of the dam. The following categorization of large dams is adopted for the PIC indication: VH- Very High (Height ≥ 100 m); HH- High Height (100 > Height ≥ 30 m); MH- Medium Height (30 >Height ≥ 15 m); LH- Low Height (15 >Height ≥ 10 m).

2.2 Indian Standard Code, Guidelines and Compendium on Reservoir Sedimentation

The Indian Standard Code, guidelines and a draft policy are available that are briefly described as follows:

I. Indian Standard CODE OF PRACTICE FOR CONTROL OF SEDIMENT IN RESERVOIRS (IS 6518, published in 1992 by Bureau of Indian Standards and reaffirmed in 2002).

Scope of the document: (i) This standard covers the various engineering measures for the control of sediment in reservoirs; (ii) It does not cover the agronomical and forestry measures in detail for the control of watershed erosion and the situation arising out of landslides, avulsion, etc. in the reservoir.

II. Indian Standard GUIDELINES FOR DETERMINATION OF EFFECTS OF SEDIMENTATION IN PLANNING AND PERFORMANCE OF RESERVOIRS (IS 12182, published in 1987 by Bureau of Indian Standards and reaffirmed in 2002.

Scope of the document: This standard lays down guidelines for determining the various effects of sedimentation on the performance of reservoir projects in order to make suitable allowances in the design of such projects at the time of initial planning.

III. Compendium and Draft Policy on Sediment Management

Ministry of Water Resources, River Development and Ganga Rejuvenation has published a draft policy on sediment management for Indian rivers and reservoirs (MoWR,RD & GR, 2017). In order to develop an appropriate policy, a one-day conference on "Sediment Management in Indian Rivers" (MoWR,RD & GR, March, 2017b) was organized with the objective to comprehensively discuss the issues related to sedimentation of Indian rivers and reservoirs with all the stakeholders. Furthermore, Watershed and Reservoir Sedimentation Directorate at Central Water Commission has published a Compendium on Silting of Reservoirs in India (2015). The compendium provides collection of sedimentation data for 243 reservoirs in India. The document contains a number of useful information like storage loss, sedimentation rates, sediment characteristics and grain-size distribution, vertical distribution of deposits and other useful information and analyses.

2.3 Reservoir Sediment Management in India

In a country like India, dams and reservoirs play an important role for the development of water resources and energy sectors. Since majority of dams in India had been constructed 3-4 decades ago (and some of them are even older, built during British regime), it is obvious that many of them are suffering from siltation problems.

Against the background of such issues in Indian reservoirs, the then Ministry of Agriculture and Irrigation had set up a Reservoir Sedimentation Committee in 1978 with an aim to conduct in-depth investigation and analyses to assist the Government to develop the policies that can ensure adequate sediment management strategies for longer life and benefits of the existing reservoirs. Followings are some of the recommendations provided by the committee (CWC, 2015):

- The sediment observation stations in the major streams and important tributaries should be equipped with latest equipment and manned by qualified and well-trained staff.
- Capacity surveys on regular intervals of once in 5 years for all major reservoirs should be carried out by the project authorities.
- Cultivation in the foreshore is to be prohibited as per existing instructions of Govt. of India to reduce entry of silt into reservoirs. In any case, ploughing should not be allowed. However, broadcasting can be permitted to limited extent wherever possible.

- There should be a databank of sediment inflow, outflow and sedimentation of reservoirs at States and Central level with easy accessibility.

In order to accomplish these recommendations, Watershed & Reservoir Sedimentation Directorate of CWC was declared as a nodal agency, where all state and project authorities are supposed to regularly submit all collected data, information and reports. The Directorate is supposed to compile all the data and information and publish them on a regular basis.

Central Water Commission have incorporated sediment management and planning practices in the Indian Standard Code on "Guidelines for Determination of Effects of Sedimentation in Planning and Performance of Reservoirs" (IS: 212182, published in 1987 and reaffirmed in 2002) to make this national practice. Some basic features of these practices as included in IS: 12182 (1987) are as follows (CWC, 2015):

- The sedimentation rate is to be decided on the basis of observations of river sediment flow and reservoir surveys.
- Methodologies for trap efficiency and sediment distribution have been specified.
- The live storage is to be so planned that the benefits do not reduce for a period of 50 years (Full Service Time) for irrigation or 25 years for hydropower on account of sedimentation.
- The feasible service time for irrigation projects shall not be less than 100 years after start of operation. For hydropower projects the feasible service time should not be less than 70 years.
- For simulation, if sedimentation is not serious, the simulation studies for conditions expected at the end of the full service period may be made. If the problem is serious, studies are to be done by more realistic method. It should be sufficient to consider sediment trapped in every 10 years block, and to use the expected sediment elevation area capacity curve at the end of each 10-year block for simulation of that block.

It is to be noted that the IS codes related to sediment management practices and guidelines have to be updated based on new knowledge, development and best practices.

2.3.1 Sedimentation Data and Observation in Selected Reservoirs

The sedimentation surveys of reservoirs in India dates back to as early as 1870, but the systematic surveys started only in 1958 when the Central Board of Irrigation and Power undertook a coordinated scheme of reservoir sedimentation and entrusted this task to several research stations in the country. Under this scheme, 28 major reservoirs have been surveyed (CWC, 2015). Furthermore, the State Government and CWC carried out survey of a number of reservoirs in the country.

Survey data and information

The survey details, data and brief analyses for 243 reservoirs throughout the country have been published by Watershed and Reservoir Sedimentation Directorate of CWC (CWC, 2015). The publication contains following useful data, observation and information:

- Region wise classification of the reservoirs based on sedimentation zone, namely (i) Himalayan region (14 reservoirs), (ii) Indo-Gangetic plains (15 reservoirs), (iii) East flowing rivers up to Godavari (5 reservoirs), (iv) Decan Peninsular east flowing rivers including Godavari and south Indian rivers (115 reservoirs), (v) West flowing rivers up to Narmada (53 reservoirs), (vi) Narmada and Tapi (10 reservoirs), and (vii) West flowing rivers beyond Tapi and south Indian rivers (31 reservoirs).

- Average rate of sedimentation, storage loss and other information of each reservoir
- Original and latest observed trap efficiency for some selected reservoirs
- The list of reservoirs which have served for more than 50 years
- List of reservoirs which have lost more than 25% of their gross storage
- Vertical distribution of sediment deposits (volumes) for 21 selected reservoirs
- Spatial variability in grain-size distribution for 32 selected reservoirs
- Sediment volume distribution curves for 28 selected reservoirs

Key Findings

Based on collected data (by CWC, 2015), observation and analyses, some key findings are summarized as follows:

- Most of the reservoir data reveals that the actual rate of sedimentation is larger than design value (reaching more than 5 times for 23 reservoirs).
- 239 reservoirs out of 243 have lost their storage capacity with an average annual rate of 0.42% (gross storage loss). Based on the sedimentation rate of 86 reservoirs, the average annual rate of dead and live storage losses is 0.494% and 0.04% respectively.
- Figure 2-2 shows loss of storage volume in some selected reservoirs in eight States of India with large number of reservoirs, which has revealed that the reservoirs in Odisha have largest volume loss, apparently due to the presence of large reservoirs in this State.
- Figure 2-3 shows the level of storage loss for 239 reservoirs, which has revealed that more than 40% of the surveyed reservoirs have lost more than 20% of the storage.

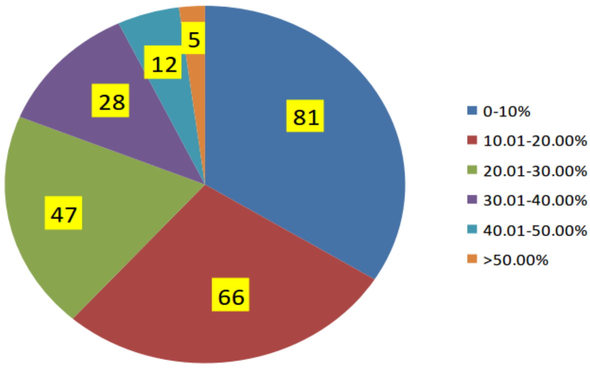

Figure 2-3. Categorization of storage loss of 243 reservoirs *(CWC, 2015)*

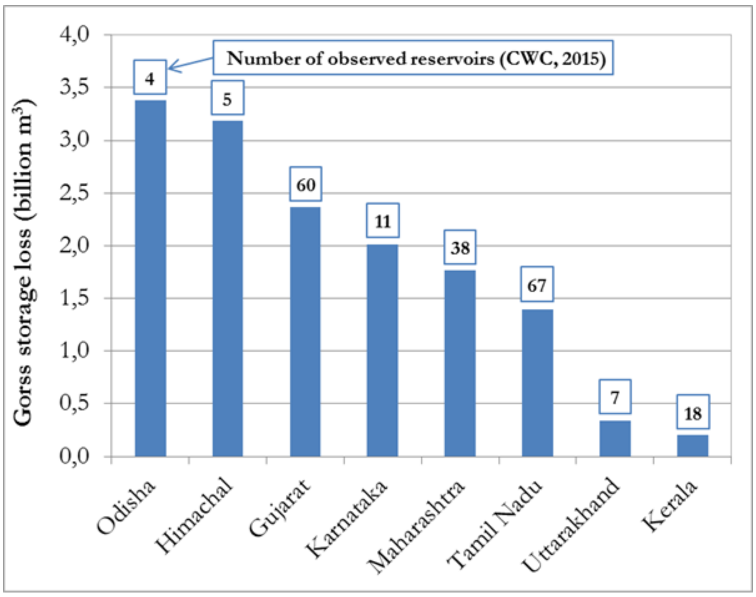

Figure 2-2. Reservoir gross storage in some States of India *(based on data of CWC, 2015)*

- Based on analysis of the data from 21 reservoirs, distribution of sediment deposit volume over reservoir depth has been quantified. Figure 2-4 shows the vertical distribution of the sediment deposits averaged over 21 reservoirs. As it can be inferred from the result, for every 10% segment of the depth, the highest amount (about 16% of total volume) is found to be deposited in top 10% (i.e. near the water surface) of the reservoir, while lowest amount (about 4.5% of total volume) is deposited in the bottom 10% of the reservoir. Rest of the deposited volumes appears to have been deposited almost equally over the reservoir depth. From the result, it can be inferred that more than 60% of sediment deposits have been taken place at upper half of the reservoir depth.
- Out of 243 surveyed reservoirs, 34 reservoirs with an average age of 21 years show more than 1% of annual gross storage loss, whereas 126 reservoirs with an average age of 42 years show 0.1% to 0.5% annual gross storage loss.
- The average sediment density is found to be varying between 780 and 1555 kg/m^3 with an average value of 1191 kg/m^3 (based on samples of 21 reservoirs). As reported, the density appears to be predominantly affected by the clay content in the samples and also that the density gradually increases with the distance from the dam. Furthermore, the collected data shows that factors such as reservoir operation, side tributaries flowing into the main reservoirs etc. also influence the density. The lower densities have been observed in the vicinity of dam under submerged conditions, while the higher densities are observed in the upstream portions of the submerged area as well as in the exposed areas as a result of periodic drawdown of the reservoir.
- Spatial variation of grain-size distribution based on samples from 32 reservoirs shows usual feature of refinement towards the dam containing clay and silt near the dam, while coarser fraction in upstream reach.
- The trend of sedimentation rates usually observed in the reservoirs is similar in surveyed reservoirs as well, which shows the higher sedimentation rates during the initial period of their operation and thereafter it reduces significantly.
- Some selected reservoirs (28) have been classified based on sediment volume distribution using some conventional methods.
- Seven sedimentation zones within India

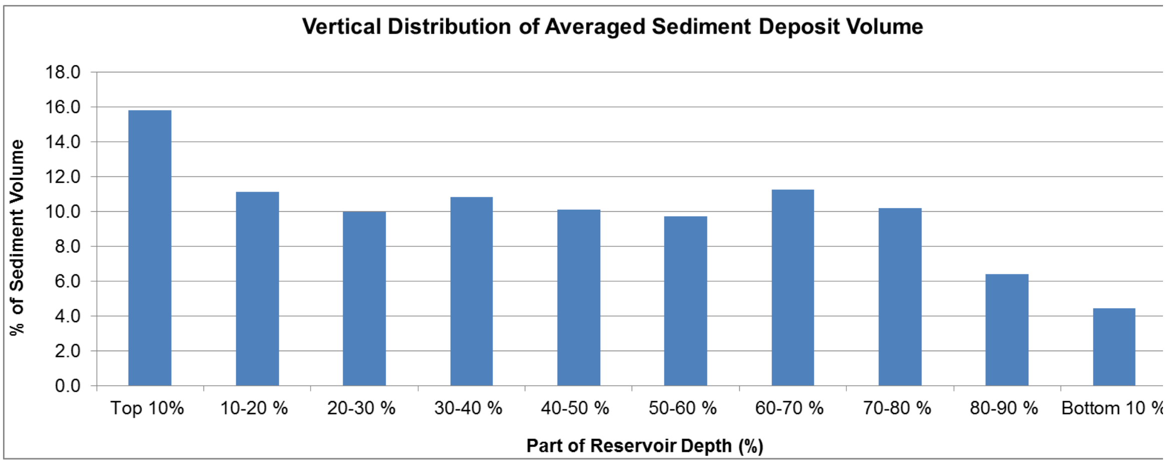

Figure 2-4. Distribution of sediment deposits (in %) over the depth of reservoirs (averaged over 21 reservoirs)

have been classified, and sedimentation rates in the reservoirs, which are located at each sedimentation zone, have been analyzed. The analysis has revealed that the sedimentation rate is highest (with median value of 2.1 mm/year) in the reservoirs that are located in West flowing rivers beyond Tapi and South Indian rivers. It is to be noted that the sedimentation rates of reservoirs, located at the Himalayan sedimentation zone are second highest (with median value of 1.53 mm/year).

Remarks

Following are some remarks on the compendium:

- The compendium has very valuable data, some basic analysis and information about 243 reservoirs. In addition to these, many other reservoirs in India have been suffering from sedimentation and thus need attention in individual basis.
- Most of the reservoir surveys are old. The most recent one was carried out in 2014 (only one reservoir). As it has been recommended in the compendium as well, the reservoirs shall be surveyed every 5 years, it is required to carry out new surveys to assess the magnitude of the issues.
- It should be noted that a number of survey is based on remote sensing technique, i.e. analysis of satellite images, which does not consider the deposition below the MDDL. Such inaccuracy shall be considered more carefully for medium and small reservoirs in particular given the fact that the resolution of (freely available) satellite images is usually coarse. The method is applicable when the reservoir is large and thus difficult to carry out detailed bathymetric survey (although there is new measurement technology like interferometric multi-beam eco-sounding that is capable of scanning the reservoir bed with larger swath width as presented in Appendix A.
- There could be newer survey and measurements of the reservoirs, which have not been included in the compendium. Therefore, it would be desirable to update the compendium with additional data and information.
- Please note that the outcomes about the sedimentation rates for each classified sedimentation zones are based on the surveyed reservoirs only and, in effect, may not reflect the overall erosion rate and/or transport capacity of the catchments and rivers that are located in these sedimentation zones. Therefore, these generalized results shall be considered and used with care. It would be useful to analyze this further using supplementary data and information.
- It has been mentioned in the compendium that the sedimentation rates, observed in surveyed reservoirs, are not alarming. This is true in terms of general analysis; however, the problem can be crucial for certain reservoirs. Moreover, considering the necessity and efforts on reservoir sustainability and rehabilitation, we have to take reservoir sedimentation issues more seriously and start to deal with them. This compendium itself is a good example of the effort made, which shall be tailored to each reservoir in all States of India.
- All the data, presented in the compendium shall be a part of reservoir database system (e.g. Reservoir Morphology Information System as described in Chapter 4. (Section 4.2.4).

2.3.2 Addressing Reservoir Sedimentation under DRIP

The primary goal of the Central Dam Safety Organization (CDSO) of the Central Water Commission (CWC) in general, and the DRIP project in particular is to encourage and facilitate dam safety practices. This is to ensure operation of dams in India to their maximum possible capacities and intended purposes. This would also help to reduce the risk to human lives and properties as the consequences of both structural and operational dam incidents and failures.

Within scope of the DRIP, the reservoir sedimentation issues, particularly sediment removal operations, were not considered as a major activity, and were supposed to be addressed only in exceptional circumstances when the regained reservoir volume would have a high economic value. There were concerns from some State Electricity Boards and Public Water Department to explore sediment removal possibilities for some reservoirs, which are not only losing the storage capacity, but also under the threat of malfunctioning of apparatus and structures due to significant siltation including consolidation of the deposited silt and clay as well as large debris flow.

In first phase of the project, based on the request from the States, four reservoirs have been selected for reservoir sedimentation studies and feasibility of sediment removal, namely Kundah Palam, Pillur and Papanasam reservoirs in Tamil Nadu and Maneri Bhali Stage I in Uttarakhand. The differences in feature, scale and magnitude of the problems in these reservoirs demonstrate their complexity and uniqueness, indicating need for distinctive and tailor-made approach to address the problems.

The complexities associated with silt removal approach are not only technical, but also other nuances like the cascade scheme of dams and reservoirs as well as the fact that some of the reservoirs are located in the neighbourhood of the preserved forest and eco-sensitive zone. Apart from electricity generation, some reservoirs also serve for water supply, irrigation as well as recreational purposes. This implies that the upstream and downstream effects are of the major concerns, and thus the environmental, ecological and social compliances are supposed to be ensured while preparing sediment management plan.

A brief analysis based on available data from 35 reservoirs in one of the DRIP States, namely Tamil Nadu with gross storage loss of more than 15% (with maximum loss of 63%) reveals that the average storage loss is about 30%. This implies that about 1.2 billion m^3 of reservoir volume has already been lost (this is valid for selected 35 reservoirs for which not all data are up-to-date). In addition, analysis of reservoir sedimentation, based on CWC data for some states (also other than DRIP dams), has revealed significant storage loss (as depicted above in Figure 2-2). This is a serious concern, particularly for the States, suffering from water scarcity during dry period. The situation may be even worse if consider current situation (as some of the data are already few years old) is considered with information from other reservoirs.

The examples of sediment management plan, which has been prepared for above mentioned DRIP reservoirs, can be found in Section 6.3 of 0Some works have been published in national and international conference proceedings as well (Giri et al., 2016, 2017).

2.3.3 Sediment Management in Indian Reservoirs: Good Practices and Problems

Some real-world examples of sedimentation issues in some selected reservoirs in India including plans and execution of sediment management can be found in a number of publication, presented in the reference list ('India-Related Publications'). Some good practices as well as problems associated with sediment removal in Indian reservoirs are presented in Section 0 of Chapter 6. Such examples are useful to consider while investigating, screening and designing sediment management options and plan for other reservoirs.

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Chapter 3. Assessing Reservoir Sedimentation

In order to manage the sediment-induced problems in existing reservoir (or cascade of reservoirs) in an effective manner, it is of foremost importance to assess them comprehensively. It is possible to address and solve the problem only if its magnitude is known. The assessment of sediment-induced problems includes two main phases as follows:

- *Phase 1*: This phase includes system understanding and problem analysis (*Phase 1a*) as well as problem categorization, prioritization and constraints (*Phase1b*). Some of the activities to be carried out in this phase are field reconnaissance, data inventory, rapid analysis and assessment of the relevant processes and problems as well as weighing up the constraints. This phase is important to understand the nature, magnitude and severities of the problems. Based on outcomes of this phase, the sediment-induced problems can be categorized and prioritized to make decisions on whether they need detailed assessment (Phase 2) as well as what shall be the level of sediment management measures.
- *Phase 2*: Detailed process assessment and quantification, which includes detailed investigation and in-depth analysis and assessment of the sediment-induced problems using measurement and monitoring, simple to sophisticated methods, models and tools. This shall be carried out for prioritized reservoirs, which require urgent sediment management interventions, particularly recurrent and structural measures.

This chapter includes brief descriptions of these two phases as well as available knowledge base, approaches, tools and technologies that are useful to carry out all relevant studies and analyses.

3.1 System Understanding and Problem Analysis (Phase 1a)

The assessment begins with the system understanding, problem analysis, screening and quantifying the magnitude and severity of the sediment-induced problems. Understanding the system enables us to define the scale and source of the problems and all underlying processes. Figure 3-1 gives an impression about some relevant processes and problems in a reservoir.

It should be emphasized that a reservoir must be considered as a complex system that depends upon several aspects, such as:

- Scale of the influence, e.g. river reach, catchment, basin, inter-basin or even transboundary
- Purposes, e.g. single or multi-purpose that may include various stakeholders with different goals and interests, such as hydropower, irrigation, water supply, flood management, recreation etc.
- Associated impacts (social, environmental, economic), cumulative impacts and cascade effects

As a first step, field reconnaissance including collection, review and analysis of available information and data shall be carried out. In general, the magnitude of the problem could be known for the reservoirs, where there is already a system in place for monitoring and measurements (e.g. inflow, outflow, sediment transport and reservoir bathymetry etc.).

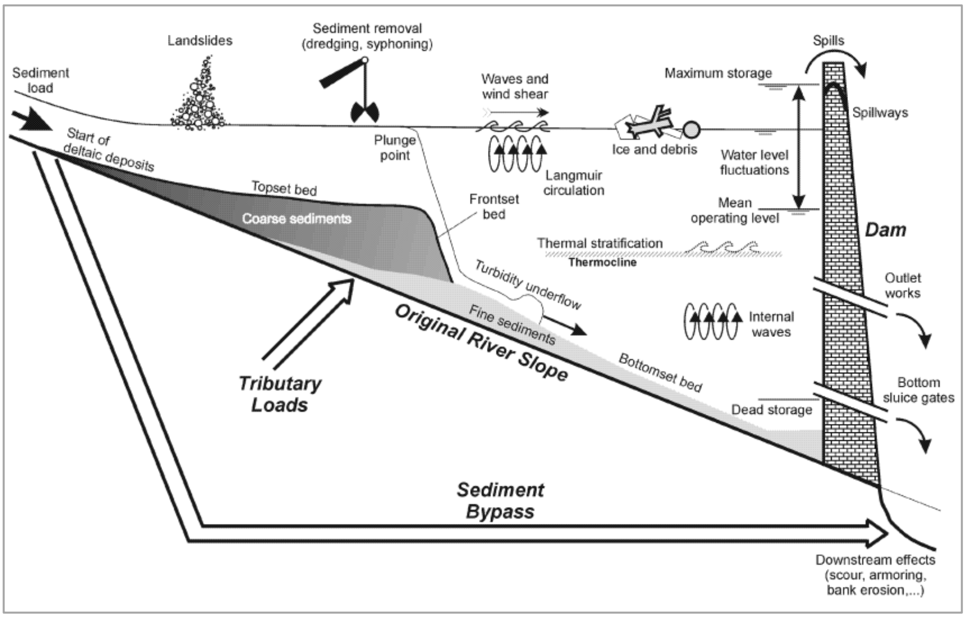

Figure 3-1. Schematic sketch of typical physical processes in a reservoir

(USBR, 2006)

Based on understanding of the magnitude and severity of the problem and its analysis, the reservoirs shall be prioritized for implementing the measures related to sediment management. This is particularly valid when there is a large number of reservoirs with sedimentation problems like in India.

3.1.1 Purpose

The main purpose of Phase 1 is to identify and (roughly) quantify the severity of the sediment related problems and possible future impacts. This will help to categorize the sediment-induced problems and thereby decide about to what level of details the assessment of sediment-induced problems shall be carried out. Followings are what are possible to get (but not limited to) from system understanding, field reconnaissance as well as review and analysis of collected data and information:

- Overall behavior of the system, such as source of flow and sediment, their feature and variability (spatial, temporal, seasonal), present system behavior and history of the changes in behavior
- Quantity, age, type, severity and possible impacts of the sedimentation problems to define the category and priorities
- Quantity of deposition, which is also useful to quantify the catchment erosion, transport and sedimentation rates
- Past investigation and experiences of addressing the problems and sediment management efforts such as sluicing, flushing, dredging, catchment area treatment and others
- Relation between reservoir inflow, outflow, operation rule, reservoir level and storage loss
- Morphological feature of the reservoir, spatial deposition patterns and distribution of sediment characteristics within the reservoir and affected reach
- Interests and priorities of stakeholders, e.g. hydropower, irrigation, water supply, flood control, recreation/ tourism authorities etc. and if there is conflict of interest or not and also how it has been managed
- Data and information that are necessary to prepare Reservoir Sediment Data

Summary Sheet as shown in Appendix C.

- Summary of data gap, reasoning (what is available and what is not and why), proposition and recommendations

3.1.2 Field Reconnaissance and Data Inventory

Field reconnaissance including collection and analysis of data and information (historical and present) is necessary for understanding the system behavior as well as quantification of the sediment-induced problems. For most of the reservoirs in India, regular monitoring and measurements including proper database management and information system may not be in place. Therefore, proper field investigations and collection of data and information from all possible sources are necessary to carry out.

It is to be emphasized that this phase is important to categorize the level of the sediment-induced problem. Consequently, the sedimentation study, which includes bathymetry measurement of not older than 5 years, shall be desirable. This implies that if the data is not available, the meaurement shall be carried out and the sedimentation study shall be updated.

Relevant Data and Information

Following data and information are useful:

- Sediment-induced problem statements, such as storage loss, malfunctioning of apparatuses, damage of structural components etc. including the 'age' of the problem
- Reservoir condition, dam/spillway feature, such as availability of sediment removal facilities like low level outlets, under-sluices, dredgers or pumps, desiltation chambers (settling basins) etc.
- Information on past activities on sediment management in reservoir and the catchment (notes, reports, images, videos etc.), reservoir operation data including regularity (periodicity) of flow release and sluicing during high flows
- Catchment condition (land cover, land use, agricultural practices, deforestation or afforestation etc.), conditions of upstream and downstream river reaches and tributaries and their impacts
- Upstream and downstream infrastructures, recreations, communities and habitants, environmentally reserved areas (like forest and wildlife area), aquaculture and other relevant information
- Historical and current data and information related to catchment hydrology like rainfall-runoff, river hydraulics like water levels, discharges (reservoir inflow and outflow), reservoir bathymetry, sediment characteristics, sediment quantity and quality, water quality and ecology
- Availability of monitoring and measurement facilities with the reservoir authority, particularly related to flow, sediment and bathymetry measurements
- Quick collection of data for first analysis when data is scarce, such as water levels, reservoir depth in some easily accessible locations (using portable eco-sounder), sediment sample in some easily accessible location, photographs with geo-referenced location (almost every camera has GPS, otherwise a portable GPS device can be used).
- LANDSAT images that are freely available (and shall be purchased if necessary) and can be used when data is scarce.
- Data and information about stakeholders (hydropower, flood control, irrigation, water supply, tourism authorities) and decision-makers (central government authorities, State government authorities, private owners or others)

3.1.3 Review and Analysis

Followings are some of the steps for review and analysis of collected data and information:

- Synthesize and review available and collected hydrological, hydraulic, sediment and morphological data, historical photographs, design drawings, reservoir operation strategies, check their reliability and correctness
- Carry out reanalysis of all available data, information, reports, strategies etc.
- Review methodology of sediment analysis, used for planning and design, e.g. the level of details, estimation of sediment yield, bed and suspended sediment loads, impact of landslides, debris flows (depending on the region and relevant phenomena), trap efficiency, sedimentation and reservoir life (for example, how the estimations were made? Were they made based on historical data and/or using empirical formulations and/or using more sophisticated tools and methods (e.g. numerical modelling)? Were extreme events associated with inflow and sediment transport considered or not?)
- Check available IS codes and guidelines relevant for the problems
- Quantify and demonstrate magnitude and severity of the sediment-induced concern, level of impact and risks, e.g. percentage of sedimentation (storage loss), damages and malfunctioning of structures and apparatuses
- Carry out planform and bathymetry analysis, such as morphologic feature of the reservoir, changes over the time (if data is available), planform variation (water spread area change), and sedimentation pattern over the depth, spatial deposition pattern along the reservoir and other specific information based on the reservoir
- Analyze sediment transport features and magnitudes as possible, such as dominant mode of transport (bedload like bed form and sediment delta migration, suspended load, turbidity current transport, high episodic transport (e.g., in North hilly part of India with high sediment transport during flash flood), not very extreme and slower transport rate and mostly from slope erosion and supply from agricultural lands (like in Peninsula region in South India)
- Analyze sediment characteristics and its variation (spatial and temporal), gradation, cohesive and/or non-cohesive, contamination, consolidation, reuse possibilities like for mining industries, construction material, agricultural nutrient and fisheries
- Quantify and analyze land-use change within reservoir catchment(s)
- Quantify and analyze upstream and downstream conditions and effects
- Analysis of changes in the reservoir area including upstream and downstream reaches and the catchment(s) based on Google Earth and freely available satellite images
- Assess uncertainties and inaccuracies such as: (i) input data uncertainty or gaps, which may include inflow hydrograph, reservoir sediment volume, grain-sizes and spatial distribution, sediment contamination and consolidation, reservoir sediment erosion volume, (ii) uncertainty in predictions (or no studies during design), which may include sedimentation rate, trap efficiency, sediment concentrations, channel incision and morphological patterns, estimated life time and impacts and other relevant aspects
- If data and information are not available and it is not possible to carry out aforementioned analyses, present the problems and reasons as well as possibilities for carrying out studies and measurements.

3.2 Constraint, Categorization and Prioritization (Phase 1b)

3.2.1 Constraint

Most of the dams and reservoir have their distinctive combination of constraints. This is particularly the case for multipurpose reservoirs with conflicting interests and requirements of different stakeholders. This aspect is important to address already in preliminary assessment phase (described in the section above) prior to development and implementation of sediment management measures. Besides, other general constraints shall be identified and considered for developing a sustainable reservoir sediment management program. These constrains can be categorized as follows (partly from Collins et al., *internet source*):

- *Physical constraints*: (i) Dam height, (ii) storage volume, (iii) reservoir length and width, (iv) hydrology, (v) geology, (vi) deposition pattern, (vii) spatial sediment distribution, (vii) sediment grain size
- *Operational constraints*: (i) Allocation of use (for multipurpose reservoirs), (ii) carryover storage
- *Economic constraints*: (i) Loss of benefit (short-term), (ii) reduction of benefit, (iii) cost of decommissioning under no alternative
- *Environmental constraints*: (i) Downstream impacts (infrastructures, water quality, reversal of channel degradation, other reservoirs in the cascade system, aquaculture, recreation spots), (ii) upstream impacts (aquaculture, reversal of channel aggradation, retrogressive erosion), (iii) preserved forest and wildlife, (iv) contaminated sediment
- *Legal constraints*: (i) Laws and regulations on sediment removal, disposal and reuse, (ii) regulation for reservoir operation, particularly for the reservoirs in trans-boundary rivers, (iii) regulation for water release, (iv) regulation for intervening preserved forest and protected areas
- There may be other specific constraints as well based on regional and local particulars.

3.2.2 Categorization

After quantifying and analyzing the sediment-induced problems, their magnitude, severities as well as associated risk for each reservoir, they can be categorized. This is necessary to make decision on whether it needs to be considered for Phase 2 activity, i.e. detailed process assessment. Secondly, the sediment management approach and measures shall be based on the category of the problem and risk.

Indicator

At this stage, it is proposed to categorize the sediment-induced problem based on a simple indicator, namely observed percentage of annual storage loss (ASL) of the reservoir.

ASL = Total storage loss in %/Total years of operation

It should be noted that total years of operation shall be considered until the date of storage loss measurement.

It is proposed to categorize the problem and risk as presented in :

Table 3-1. Categorization of sediment-induced problems

	Category
$ASL \leq 0.2\%$	LOW
$0.2\% < ASL \leq 0.5\%$	MEDIUM
$0.5\% < ASL \leq 2.0\%$	HIGH
$ASL > 2.0\%$	EXTREME

Important Remarks

- The indicators are proposed as a preliminary recommendation and subjected to change based on specific conditions of a particular reservoir.
- In addition to *ASL*, the age of the dam shall also be considered. For example, if the dam is older than 50 years, even a lower value of ASL can be considered with higher risk level.
- Recommendation on handling of sediment-induced problems based on proposed indicator shall not be taken straightforwardly as an obligation, since it will depend on technical and economic possibilities of dam authorities and their priorities.
- This is valid for the problem that is only related to storage loss. In case of other sediment-induced problems, such as structural damages, degradation of water and sediment quality and ecology, the problem shall be categorized based on analysis of specific problem regardless of the proposed indicator (although most of the problems are related to sedimentation and storage loss).
- The proposition is based on the context of India.

3.2.3 Prioritization

- When there is a large number of reservoirs with sediment-induced problems (like in DRIP project, having more than 250 dams in seven States of India), it is usually necessary to prioritize them based on severity of the problem, quick analysis of available sediment management options.
- The greater the problems and the associated risk and impacts (like economic, environmental and social), the greater should be the level of assessing and managing them.
- All these aspects can be evaluated during relatively short period based on review and analysis of available information and data as described in the section above.
- However, if data and information are scarce, this may take more time and efforts. In case of more complexity, there are methods to prioritize, for example, based on multi-criteria and decision analysis. However, in most cases in India, the problems and impacts are relatively clear for the dam authorities and other relevant institutions.
- It should however be emphasized that regardless of certain priorities that have been given to certain reservoirs with significant sediment problem, each and every reservoir shall have regular monitoring, investigation and sediment management plan and countermeasures. Most importantly, the bathymetry measurement is desirable, particularly if there is no measurement during last 5 years. There are number of non-structural measures that shall be considered for each reservoir (described in next chapter).

It is suggested to develop a tool, which will help to support the decision making process for the prioritization of the reservoirs for sediment management (particularly for the follow up dam safety project in India).

3.3 Detailed Process Assessment (Phase 2)

For the prioritized reservoirs, before exploring the sediment management options and alternatives as well as assessing their feasibility and impacts, it is important to carry out detailed assessment of all relevant processes associated with a particular reservoir under consideration (or group of reservoirs if it is a cascade system). Essentially, this is continuation of the activities that are carried out as described in section 3.1.

The detailed assessment of relevant processes from basin to reach scale includes (but not limited to) following aspects and activities:

- Thorough investigations and analyses of relevant sources and processes associated with hydrology, hydraulics, sediment transport, morphology, water quality, ecology and relevant problems
- The detailed analysis shall be based on available information on past events, historical observation and data (hindcasting) as well as previous review and analysis that are carried out in Phase 1 (as mentioned in section 3.1).
- Detailed exploration and analysis shall be carried out by making use of various methods, tools and techniques, from simpler to sophisticated such as empirical and analytical methods, process-based modelling, physical experiments as well as specialists' judgment. This is particularly the case when there is lack of data and information.
- Quantification and analysis of existing situation using measurement and monitoring techniques; this is particularly the case when there is no monitoring, information and database system in place, and thus lack of historical and contemporary records and information.
- Measurements and monitoring shall be carried out based on nature, magnitude and severity of the problems that are quantified based on the activities of Phase 1 (as mentioned in section 3.1). The most important measurements are bathymetry, flow and sediment characteristics of the reservoir as well as part of the upstream and downstream reach (to be selected based on the reservoir site, the problem and available resources).

The necessary processes and parameters that have to be measured as well as some methods and tools to assess them are summarized in Table 3-2. In addition, the processes are briefly described in sections below.

In addition, it is recommended to make use of relevant manuals, guidelines, information systems, which were developed during Hydrology Project and can be downloaded via *http://hydrology-project.gov.in/GuidesandManuals_SurfaceWater.html*

Table 3-2. Processes & Parameters to be Measured, Methods & Tools

<table>
<tr><th colspan="2">Processes & Parameters to be Measured</th><th colspan="2">Methods, Tools & Techniques</th></tr>
<tr><td rowspan="2">Hydrological/Hydraulic</td><td rowspan="2">o Rainfall, snowfall, ground-water at catchment
o Water levels at upstream reach, reservoir and downstream reach
o Velocity at upstream inflow points (where inflow discharge is measured)
o Discharge at inflow point during different flow period
o Spillage from spillways, all intakes, under-sluices, evaporation and seepages</td><td>Direct</td><td>o WMO guidelines (2008a, b) provides detailed methods and tools
o Most commonly used equipment are current meters, ADCP (Acoustic Doppler Current Profiler) for velocity and discharge, while pressure transducers and Automatic Ultrasonic Limnimeter for water level measurements</td></tr>
<tr><td>Indirect</td><td>o Rating curve (based on observed water levels and discharges)
o Meteorological/Hydrological/hydraulic modeling
o WMO guidelines (2008a, b) provides detailed methods for indirect measurement
o Hydrology Project guidelines</td></tr>
</table>

Processes & Parameters to be Measured		Methods, Tools & Techniques	
Surface, slope and bank erosion	○ Soil loss ○ Bank and slope erosion (shallow and deep landslides upstream areas and at the reservoir)	Direct	○ Reconnaissance methods (cheap and simple), i.e. measurement of changes in soil surface levels ○ Volumetric methods, i.e. measurement of the rills, gullies, etc. (lengths and cross sections) ○ Bank shift analysis (based on ground measurement and Satellite images)
		Indirect	○ Measurement of deposition at check dams, sediment traps, reservoirs, sediment retention basin (this is better way if the source is predominantly surface erosion) ○ Catchment erosion modeling (using (Revised Universal Soil Loss Equation (RUSLE)) ○ Remote sensing and image analysis
Suspended sediment transport	○ Concentration and grain-size analysis of sample of the water-sediment mixture ○ Computation of sediment discharge ○ Suspended sediment rating curve based on flow discharge and sediment concentration relation (derived from the measurement data)	Direct	○ Direct sampling, pumping (e.g. equipment using bottles or bags, Delft bottle) ○ Turbidity meter (portable or fixed) ○ Computation of sediment discharge ○ Laboratory test for concentration analysis of sample: ▪ Filtration method ▪ Evaporation method ▪ Settling tube method
		Indirect	○ Optical (backscattering) – good for particle size range of 200 to 400 μm and concentration range up to 100 g/liter ○ Optical (transmission) – based on absorption or scatter of a portion of light by the particles and the concentration is determined by using empirical calibration information ○ Nuclear measurer (portable or fixed) based on the attenuation or backscatter of radiation by the particles (the concentration range is 0.5 -12 g/liter) ○ Acoustic sampling – based on backscatter of a portion of the sound by the particles ○ Laser diffraction (e. g., Sequoia LISST-SL) ○ Pressure differential (the concentration range is dependent on the sensitivity of the transducer and temperature gradient, turbulence affect the measurement) ○ Digital imaging – based on numerical algorithm to determine number and size of the particles from the images ○ Time Domain Reflectometry (TDR) ○ Use Hydrology Project guidelines ○ See Appendix A

Processes & Parameters to be Measured			Methods, Tools & Techniques
Bedload Transport	○ Bedload sediment traps like check dams, sediment retention basin ○ Samplers or portable devices is fixed on the bed from 2 minutes to 2 hours depending upon the filling up of 30% to 50% of its capacity ○ Calculation of Grain-size analysis, temperature hydraulic parameters and computation on entrainment discharge and bed load through existing bedload transport formulae ○ Bedform (dunes, delta) tracking or Trench filling	Direct	○ Acoustic Monitoring Techniques (e.g. Acoustic Doppler, Dual Frequency Acoustic, Geophones, Hydrophones) ○ Weight sensor – scour plates (good for monitoring bedform migration in flumes, scour at bridge) ○ Pressure difference type sampler (e.g. Helley Smith sampler, Toutle River sampler) ○ Portable bedload traps ○ Permanent bedload traps (conveyor belt slot system, the vortex tube system, the weighing pit sampler system, the Birkbeck-type automatic monitoring slot sampler) ○ Nuclear Gauges ○ Tracer Method ○ Use Hydrology Project guidelines ○ See Appendix A
		Indirect	○ Tranport formulae, such as Ackers & White (1973), Einstein (1950), Laursen & Copeland (1958, 1989) Meyer-Peter and Muller (1948), Van Rijn (1984, 2007), Wilcock-Crowe (2003), Yang (1973, 1984), Engelund-Hansen (196, for total load) and others. ○ Temporal variation of measured bedlevels based on high-resolution bathymetric survey using echo-sounders, in which sediment delta and bedforms like dunes are captured (measuring the volume of migrated portion) ○ Measurement of trench filling and migration and their volume (measuring the volume of migrated and filled portion) ○ Use Hydrology Project guidelines ○ See Appendix A
Total sediment load	Total sediment transport into the reservoir	Direct	○ Topography and bathymetric survey of the reservoir, determination of deposited volume, trap efficiency and period to quantify total sediment transport rate
		Indirect	○ Sampling bed and suspended sediment, concentration analysis, grain-size analysis, temperature measurement, hydraulic parameters and computation of total discharge using total sediment transport formulae, such as Engelund-Hansen, modified Einstein's method, simplified Colby's method (1964), Van Rijn

Processes & Parameters to be Measured			Methods, Tools & Techniques
Sediment characteristic and sources	Suspended sediment grain-size analysis		○ Settling tube method (approx. limit of grain diameter 0.001-1.0 mm and concentration 300 to 10000 ppm) ○ Pipetting (approx. limit of grain diameter 0.001-0.0625 mm and concentration 3000 to 10000 ppm) ○ Densimeter/Hydrometer (approx. limit of grain diameter 0.001-0.0625 mm and concentration 60000 to 160000 ppm) ○ Visual accumulation tube (approx. limit of grain diameter 0.0625-2.0 mm and concentration 125 to 25000 ppm) ○ Dual frequency acoustic - The tower tank experiment ○ Laser diffraction particle size analysis (particle size range 0.02-2000 µm/0.01-3500 µm) ○ Photon correlation spectroscopy (particle size range : 1nm to 5 µm) ○ Laser diffraction (a non-intrusive technique, in which distribution of scattered intensity is analysed by using an algorithm to yield the particle size distribution) ○ Use Hydrology Project guidelines
	Bed sample grain-size		○ Sieving (wet sieving, air-jet sieving) ○ Densimeter ○ Pippeting ○ Visual accumulation tube ○ Settling tube method ○ Image/Photo analysis (e.g. BASEGRAIN – an object detection tool for grain-size analysis of photographs of fluvial gravel bed surface) ○ Use Hydrology Project guidelines
	Reservoir bed strata		○ Sub-bottom profilers ○ Side scan sonar ○ Core sampler (gravity, vibracorers) ○ Check guidelines (Morris and Fan, 2010,UNEP/MAP, 2006; EPA 2001; Carvalho et al., 2000 and others)
	Bulk density of deposited sediment		○ Calculation method is described in Appendix B
	Sediment source		○ Collection of sediment and soil samples in reservoir as well as catchment, river reach and tributaries, determine their lithological/mineralogical features and comparing them to find the source (X-Ray Diffraction laboratory analyses on the mineral content in the sediment samples)
River and reservoir morphology	○ Bed topography ○ Spatial feature of reservoir bed ○ Longitudinal profiles (sediment delta, bedforms) ○ Deep channels		○ Total station, 3D laser scanner for dry areas ○ Fishfinder ○ Echo-sounders (interferometric multi-beam, other multi-beam, single-beam, leadline) ○ LIDAR, Radar and image technology ○ Laser devices and profilers, mounted on UAV and USV

Processes & Parameters to be Measured		Methods, Tools & Techniques
	○ Bed level at critical areas (near intakes)	○ See Table 3-4 ○ See Appendix A
Water & sediment quality	○ Physical (color, temperature, turbidity, odour and taste), chemical (pH, B.O.D. etc.) as well as bacteriological properties of water in the reservoir ○ Specific sediment quality measurement in case of reuse	○ Various sensors, buoy (for periodic and real-time measurement) ○ See guidelines (WMO, 2008a,b), Hydrology Project guidelines (*http://hydrology-project.gov.in/GuidesandManuals_SurfaceWater.html*) and internet sources ○ See Appendix F for reuse of dredged material and their quality

3.3.1 Hydrological and Hydraulic Processes

First, it is important to assess hydrological and hydraulic processes within all the catchments and river system that are related to the reservoir (or cascade of reservoirs). In effect, hydrological and hydraulic observation and studies must be available for existing dams and reservoirs, since it is usually necessary for the design and rehabilitation. Besides, a number of literatures are available that describe approaches, methodologies and tools for assessing hydrological and hydraulic processes (review the materials, given in the reference list). Therefore, detailed description of these processes are beyond the scope of this handbook. The most important outcome of this analysis is the reservoir inflow and outflow as well as their seasonal variation including design and extreme conditions. These data and information can be correlated with sediment transport and reservoir morphology.

The relevant aspects and the methodology on how to assess the hydrological and hydraulic characteristics of catchment and rivers are briefly outlined as follows:

- Hydrological processes of catchments, such as rainfall and surface runoff, are useful to calculate reservoir inflow and erosion processes (this is particularly important in case there is no proper data and observation on water levels, velocity and discharges at reservoir inflow, upstream and downstream reaches of the river)
- Usually there are weather stations at the catchment to measure the precipitation, from which runoff can be computed using different methods and models (see reference list of numerical modelling and case studies).
- If the weather stations are not installed or not sufficient, the global meteorological data can be useful. They are generated using satellite data as well as simulated using global models like Numerical Weather Prediction (NWP) models. These model results are usually very coarse resolution, and there are efforts to downscale such results to a certain region. Based on the weather prediction (like precipitation), computed by NWP models, runoff can further be computed using simple analytical approach and/or sophisticated hydrological models. There are several literatures and guidelines on hydrological analysis.
- Computation of runoff can directly provide reservoir inflow (if the discharge points of all the catchments are located at the reservoir mouth(s)).
- River channel hydraulics and processes are important as well, particularly when flow and bed sediment transport through the river channel system are significant. In this case, it is useful to have hydraulic data (discharge and water levels at the upstream and downstream reaches of the reservoir) and the models

for more precise prediction of reservoir inflow and outflow. For example, the hydraulic model of the river reaches flowing into the reservoir and/or only the model of the reservoir extent to replicate the flow propagation from the inflow point to the dam location are useful. This is in particular necessary for long reservoirs with limited observation data.

- Observation data (e.g. water levels, discharge, and velocity) must be good enough for the assessment phase (there are usually discharge and water level measurement stations at the inflow location and/or near the dam). However, for the sediment management feasibility study and impact assessment, the models are useful and available measured data can be used to verify the model performance before using them for feasibility and impact assessment.
- It should be noted that the hydrological processes differ based on the region, such as flashfloods during monsoon in the north part of the India, return monsoon and storm in the south part of India and so on.
- It is necessary to understand the complexity and uncertainties in predicting hydrological and hydraulic processes, particularly when using global data, numerical models and analytical solution for data scarce regions. Therefore, involvement of specialist and their judgment is necessary for better interpretation and evaluation of the outcomes.

3.3.2 Erosion, Transport and Sedimentation: Sources and Processes

Sediment sources and transport processes may be different depending on the hydrological phenomena and catchment characteristics. This may differ depending on the region (Himalayan, mountainous, hilly or lowland region), such as glacial erosion, erosion of agricultural landscape, slope erosion, gully erosion, landslides (transport of landslide material), mudflow, debris flow, river bank erosion.

Catchment Erosion

Since inflow to the reservoir depends on catchment run-off, the erosion from the catchment contributes to sediment load to the reservoir through rivers and streams in form of suspended load, wash load and bedload transports. There are various types of erosion such as (Pandit et al., 2009):

- *Glacial erosion*: This is mainly predominant in mountainous region. In these regions, the predominant source of sediment in rivers and reservoirs is due to glacial erosion. The erosion and transport of sediment mass (the debris) usually takes place during flashfloods due to heavy rainfall or snowmelt as well as due to Glacial Lake Outburst Flood (GLOF).
- *Sheet erosion*: Erosion of soil particles by the impact of raindrops and their transportation down the slope by runoff in the form of a sheet instead of well-defined channels or rills is known as sheet erosion. This process is responsible for the removal of top soil from cultivated fields as well as non-cultivated lands.
- *Rill erosion*: This is soil erosion process in localized small washes in well-defined channels with dimensions of few centimeters and depth not exceeding 15 to 25 cm. The intensity of downward moving water further leads to gully formation, therefore it is called gully erosion as well.
- *Landslide erosion*: This can be natural slope failure or due to human interventions like construction of roads, deforestation in hilly areas. Landslide erosion material as well as Landslide Dam Outburst Flood (LDOF) cause large sediment (and debris) transport in the rivers.

- *Wind erosion*: The wind erosion takes place when soil surface is exposed to natural forces of wind. The catchment area with completely denuded and devoid surface is prone to wind erosion. This mostly occurs in trans-Himalayan zone of India.

Some examples are depicted in Figure **3-2** and Figure **3-3**.

Figure 3-2. Gully erosion on the slope upstream of Kundah Palam reservoir in Tamil Nadu (India)

Figure 3-3. Shallow landslides at Hidrotuango reservoir in Colombia *(Internet source)*

It is rather difficult to have precise estimation of the sediment yield contributed by catchment erosion, since it depends on variety of factors such as climate, lithology, geology, topography, catchment area, land use, triggered soil erosion, landslides, forest fires etc. Additionally, transport to a reservoir further depends on river discharge, temperature and the trap efficiency of upstream reservoirs (if there are other reservoirs in the same basin).

It is usually estimated and expressed in terms of sediment mass (kg or ton) per unit catchment area per unit time. It is usually not suggested to express it in terms of volume, since the bulk density of sediment may vary, making it difficult to provide consistent estimates of the volume of sediment discharging in a river (Annandale et al., 2016).

The soil erosion problem is prevalent over about more than half of the territory in India (Narayan and Babu, 1983). Soil erosion induced areas in India can be categorized as the Himalayan/Lower Himalayan region and other regions. The Himalayan and lower Himalayan regions are greatly affected by soil erosion due to intensive deforestation, large-scale road construction causing slope instabilities and heavy landslides, mining and cultivation on steep slopes. The report of Pandit et al. (2009) provides good overview of catchment erosion in North region of India. Additionally, the regions of high erosion include the rivers Yamuna, Chambal, Mahi and other west flowing rivers in western Indian States having significant slope and gully erosion as well as southern rivers like the Cauvery and the Godavari river systems (Kothyari, 1996). The most severe problem in the catchment of these rivers is associated with sheet and rill erosion. The lateritic soils are found to lose about 4000 t/km^2 of valuable topsoil annually due to erosion in Peninsular India (Ram Babu et al., 1978).

It must be noted that temporal measurement of reservoir bathymetry provides quantification of sedimentation rate, which corresponds to erosion rate of the catchment contributing to the reservoir (if there are multiple reservoirs, then they shall be taken into account as well). Therefore, regular measurement of reservoir bathymetry and the changes in storage is one of the most reliable ways to estimate the surface erosion rate at the catchment. This information can subsequently be used to verify proposed relationships (or modelling outcomes) for estimation of catchment erosion.

The estimation of catchment erosion can be made in more detailed and accurate way for a specific catchment by using remote sensing (e.g. Jasrotia and Singh, 2006; Kothyari and Jain, 1997) and modelling techniques (Shrestha et al., 2013; Singh, 2009). Besides, some other studies, listed in the reference ('Publications Related to Numerical Modelling'), provide some examples, which include prediction of catchment sediment yield by using numerical models.

Sediment Transport in Rivers

The undisturbed river systems have more or less balanced sediment transport and morphodynamic processes. Any kind of interventions in a natural river system may significantly alter this balance due to the quiescent water body in front of the structure with resulting backwater effect as well as hindrances in downstream flow, sediment transport, and in turn, the morphology of the upstream and downstream river reaches. These impacts are important to assess during the planning of a new project as well as during sediment management interventions for existing reservoirs. In general, the transport processes in reservoirs are distinguishable consisting of the components like inflow, entrainment, deposition, convection and the outflow, creating a continuity and momentum balance.

In general, the eroded material from the catchment enters into the reservoir through the river system. However, the source and the transport mode can be different. In some cases with specific catchment characteristic (like in mountainous regions), the transport of riverbed and bank material may be significantly higher than the slope erosion at the catchment. Moreover, in some rivers, particularly in lowland and delta areas with high erodibility, bank erosion contributes significantly to river sedimentation and morphological processes (such as Brahmaputra in Assam and Bangladesh).

The type and mode of sediment transport in rivers can basically be characterized based on several mechanism and factors. Some of the ways to characterize the type of sediment transport can be outlined as follows:

- Based on transport mechanism: (i) Bedload (rolling, sliding, jumping), and (ii) suspended load (picked up by upward flows and turbulence)
- Based on origin: (i) Bed-material load (local, coarse), and (ii) wash load (from upstream, fine particles)
- Based on limiting factors: (i) Capacity-limited transport, and (ii) supply-limited transport (not necessarily wash load: the transport of coarse sediment can also be supply-limited in accelerating flow over a non-alluvial bed)
- Based on adaptation to changing flow conditions: (i) Equilibrium transport (immediate adaptation), and (ii) non-equilibrium transport (retarded adaptation)

Sediment Transport in Indian Rivers

Most of the rivers and streams in India are ungagged for measurement of sediment loads. Moreover, it is rather difficult to have direct measurement of suspended and bedload transport, particularly during high flow period. Nevertheless, some governmental agencies are involved in measurements of sediment load in rivers and reservoirs in India (CS&WC, 1991; Shangle, 1991).

Subramanian (1996) published a paper summarizing information on sediment transport in Indian rivers. Although this is relatively old publication, the information could be useful given that no new records appear to be available. The record gives an impression about contribution of Indian rivers for sediment supply to the coast at a global scale. Besides, it also reveals the significant spatial and temporal variability of riverine sediment transport, including their geometric and mineralogical characteristics, in the Indian sub-continent. The major rivers appear to deliver more than a billion tonnes of sediment annually to the Indian

Ocean, although there are large contrasts in the specific sediment yield ($t/km^2/year$). The Himalayan rivers are characterized by high water flow, high relief, large catchment areas, and greater instability, involving landslides and earthquakes. Their geology is dominated by unconsolidated rocks of younger formations. In contrast the peninsular rivers are characterized by relatively low flow, smaller drainage areas and an older and more stable geology. There are also differences between the Himalayan and peninsular rivers in terms of climatic conditions, the degree of urbanization and in the use of water resources, which eventually affect the magnitude and nature of sediment transport (Subramanian, 1996). Such regional characteristics are well reflected on sedimentation problems in reservoirs, which are rather distinctive, based on the region, e.g. Himalayan (in North) and peninsular (in South) regions.

Transport during Extreme Events

The river carries large amount of sediment and debris during the extreme events like debris flow, mudflow, Landslide Dam Outburst Flow (LDOF), Glacier Lakes Outburst Flow (GLOF). Such transport can severely damage dams and reservoirs. A number of studies are available related to these phenomena.

3.3.3 Morphological Processes

Understanding of morphological behaviour based on river engineering and other aspects is very useful for proper site selection as well as during planning and design phases.

River Morphology

Assessing changes in morphological feature along the river reach, influenced by a reservoir (or a group of reservoirs) is useful to understand and quantify the sedimentation processes in the reservoir. This could be useful for large reservoir with larger water level variation, and thus the changes in upstream areas during MDDL can be assessed by analyzing the changes in morphological pattern. Moreover, it is very important to assess the morphological changes at upstream and downstream reaches due to the sediment management measures. This is important for impact assessment (see Chapter 5.).

Reservoir Morphology

The morphological pattern of a reservoir may be different depending on the size of the reservoir, location (hill or flat areas), transport mode (bedload or suspended load dominant), type (fine or coarse) etc.

In most of the larger reservoirs, the upstream part of the reservoir contains coarse sediment with less fine grain fraction, forming an advancing sediment delta, while the downstream deeper part contains fine sediments (usually silt and clay), forming a more uniform bottom-set bed. Figure 3-4 shows a basic schematized representation of deposition in reservoirs, in which the deposition zone is longitudinally divided in to three parts, namely top-set, fore-set and bottom-set. There are different longitudinal morphological patterns as shown in Figure 3-5 as follows (Wang and Wu, internet source):

(i) Delta feature: These are sediment deposition in upstream area, which usually contains coarser fraction.

(ii) Wedge-shaped feature: These are deposits with thick part near the dam and thinner at upstream area. Such morphological feature is usually caused by fine sediment transport by turbidity current. This is also found in small reservoirs, in which fine sediment transport is large as well as in large reservoirs that are operated at low water level during flood events (this causes sediment transport and deposition near the dam area). A real-world example of this type of morphological development pattern is shown in Figure 3-6.

(iii) Tapering feature: Such morphological pattern takes place when sediment deposits become thinner towards the dam. This is usually evident in long reservoirs, which are normally held at high water level leading to progressive deposition of fine particles with thinner layer towards the dam.

(iv) Uniform feature: Uniform morphological pattern is rare in the reservoirs and usually occurs in narrow reservoirs with frequent water level fluctuations and low fine sediment transport.

(v) Combined feature: This may be the case in most reservoirs.

A general rule for deposition patterns, proposed by IRTCES (1985), is (i) Delta pattern if V/W > 0.3, and (ii) Wedge-shaped pattern if V/W < 0.3, in which V is storage capacity (m^3) and W = amount of water during a flood season (m^3). The validity of these rules have not been checked in this document.

The morphological patterns of the reservoir may be more complex depending upon the planform and other aspects. For example, a reservoir planform with bend configuration generally has deposition in inner bend and erosion in outer bend (Figure 3-7 gives an impression about this). Small reservoirs may have different morphological patterns owing to specific hydraulic and sediment transport conditions and characteristics (e.g. Giri et al., 2016). Morphological features of small reservoirs (used for Run-of-the-River hydropower plants) in hilly region are very different. In many cases, the reservoir is filled up to the dam crest, like in case of Maneri Bhali Stage I HPP (Giri and Pillai, 2016). In such areas, flash floods induce significant transport of debris, boulders and fine sediment. This leads to ambiguous patterns of deposition and sediment gradation as depicted in Figure 3-8.

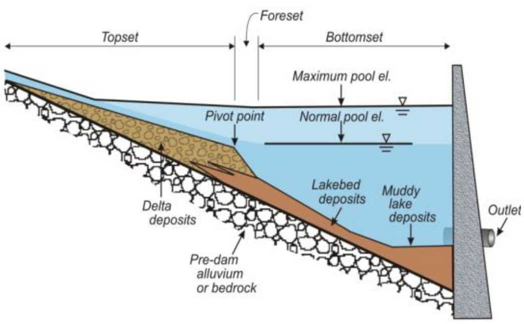

Figure 3-4. Basic longitudinal feature of reservoir bottom and its division *(Morris and Fan, 1997)*

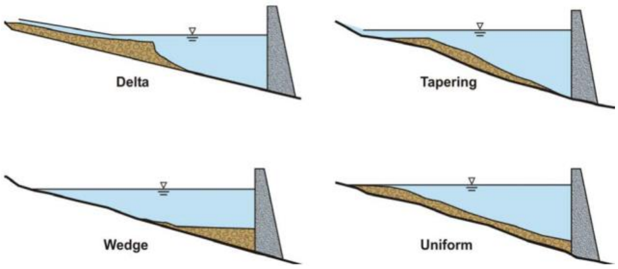

Figure 3-5. Schematic sketches of basic longitudinal morphological patterns in a reservoir *(Morris and Fan, 1997)*

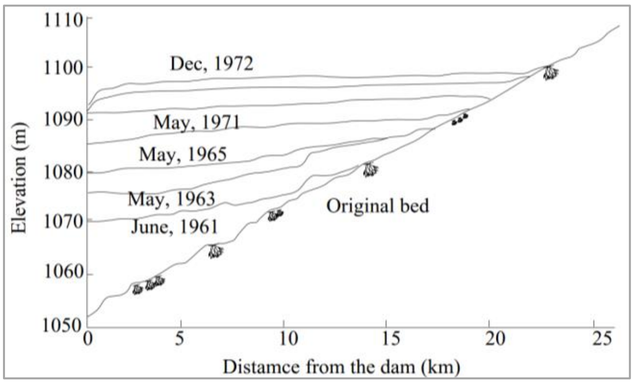

Figure 3-6. Development of wedge-shaped morphological patterns in Bajiazui reservoir on Puhe River, China *(IRTCES, 1985)*

Figure 3-7. Large deposition along the inner bend of Middle Marsyangdi hydropower reservoir in Nepal

Figure 3-8. Sediment deposition at Maneri Bhali I after the flood. Upper picture shows deposition of fine sediment over coarse sediment layer, while lower picture shows deposition of coarse sediment and boulders near the dam area reaching up to the spillway crest

Despite the fact that usually sedimentation occurs in the reservoirs, there are conditions when erosion can take place within the reservoirs as well, e.g. due to water level fluctuation and reservoir operation, after removal of sediment from the near dam area etc. Erosion within reservoir area can be as follows (X. Yang, 2003):

(i) Retrogressive erosion: This is erosion process, which develops towards upstream from the pivotal point of the delta during water level lowering. This can also be caused by deepening of reservoir bed in the vicinity of dam area, e.g. due to dredging.

(ii) Progressive erosion: Such erosion is caused by the gradient in sediment transport capacity, i.e. when sediment transport capacity at the reservoir is greater than inflow sediment transport.

(iii) Erosion in the fluctuating backwater areas: During lower reservoir level, part of water spread area becomes river channel, so erosion may take place during drawdown as well as during filling of the reservoir. During drawdown, the progressive erosion of deposited sediment may occur, while during filling of the reservoir (usually in flood season) erosion may occur in the areas between water level fluctuations.

3.4 Methods and Techniques

Several methods, approaches and techniques can be employed for assessment and relatively precise estimation of all relevant phenomena and processes that are explicitly or implicitly associated with reservoir sedimentation problem in a catchment (or basin) scale (mentioned in section above). Some of them are as follows:

- Measurement and monitoring
- Multispectral satellite imagery
- Empirical and analytical methods
- Physical Modelling
- Computational Modelling

Table 3-3 provides some basic comparison between the methods and techniques based on their advantages and disadvantages. These methods and techniques are described briefly hereafter.

3.4.1 Measurement and Monitoring Techniques

Monitoring programs and measurements are integral part of the water and sediment assessment and management in rivers and reservoirs. Presently a number of innovative methods, technologies and equipment are available. Besides, there is rapid growth in available knowledge and tools on post-processing and analyses of real-time measurement and monitoring data, remote sensing techniques and freely available satellite data and images. The major challenge is a proper processing, application, analyses and interpretation of these data and information, which requires human resources with sound technical background on the issues and relevant disciplines.

Regular measurements, monitoring and analysis of data are one of the best approaches as non-structural or recurrent measures for sustainable operation of dams and reservoirs, since they help to understand the system behavior, quantify all related phenomena and problems, and sometimes even forecast them.

Measurement and monitoring data are important to carry out hydrologic, hydraulic and morphological investigations in all stages including planning, design, feasibility, impact and risk assessment as well as during operation that enables to optimize and adapt the strategies and management practices.

The diagram, depicted in Figure 3-12, gives a basic idea about general monitoring and measurement quantities and the locations. Sediment monitoring concepts are presented in other literatures and guidelines as well (Morris, 2015, Morris and Fan, 2010 etc.). All such techniques and tools shall be in complement with Reservoir Morphology Information System (RMIS as described in Section 4.6).

Flow Quantity and Quality Measurement

Hydrologic and hydraulic measurements are very important, since they are explicitly associated with erosion and sedimentation processes. Availability of flow data enables to estimate, assess, and analyze erosion-sedimentation processes in the reservoirs by using simple morphological calculation and/or more sophisticated modelling (for example, sediment transport, morphological changes etc.), which is particularly of importance in case of insufficient sediment data. Secondly, precise flow information is very important to estimate and predict sediment transport and morphological processes. Therefore, flow measurements must be considered as an integral part of assessment and management of sediment-induced problems as well.

Table 3-3. Merits and Shortcomings of Methods and Techniques for Process Assessment

Methods	Advantages	Disadvantages
Analytical/ Empirical	○ Simple, unambiguous and quick (good for rapid assessment) ○ Appropriate for first approximation and basic insight ○ In some cases, better than measurement (e.g. quantification of bed-load transport) ○ Inexpensive	○ Inaccuracies and errors ○ Sufficient experience and verifications are required ○ Specialists' judgment is required
Numerical Modelling	○ Physics-based approach ○ Provides insight into the physics of the problems ○ Good for scenario analyses and impact studies (relative to a reference case) ○ More accurate in many cases ○ Accessible and widely used ○ The cost is getting lower due to fast advancement in modeling techniques and computer capabilities ○ Freely available modeling software	○ Difficult to handle complex models ○ Time consuming, if the model is complex and large (spatial and temporal scale) ○ Good knowledge, expertise and experience are prerequisite ○ Uncertainties in outcomes (depending on input data quality) ○ Calibration and verification are required ○ Complexity in interpretation of the outcomes

Methods	Advantages	Disadvantages
	o Good in combination with field observation and laboratory experiments	o Specialists' judgment is required
Physical modelling	o For complex and local phenomena (e.g. near flow and sediment transport near the intake/flushing gates, stilling basin, vortex formation, local scour) o Appropriate for quantifying complex hydrodynamic near structures o Good in combination with numerical modelling	o Expensive o Labour intensive and time consuming o Inaccurate and unreliable for sediment modeling due to scale effect, particularly for fine sediment
Field Measurement	o Unambiguous and accurate in most cases o Only option in some cases (e.g. for the measurement of bathymetry) o New techniques and tools are becoming accessible and cheaper o Regular measurement and monitoring is inevitable option and useful for other methods techniques as well (for their calibration and verification)	o Labour intensive and requiring human resources o Requiring proper knowledge for data processing, quality assessment and analysis o Relatively expensive
Remote Sensing/ Satellite Images	o Emerging technology with future prospects o Appropriate for rapid assessment and reconnaissance purpose o Accurate enough for dry areas Getting accurate due to emerging advanced processing techniques o Getting accessible and cheaper o	o Requiring proper knowledge and techniques for processing o Availability of images depends on weather condition (except for radar images) o High resolution images and data are still not free and relatively expensive o Good knowledge and specialists' judgment are required o

Furthermore, it is important to measure regularly the quality of water, since many reservoirs have water quality problems due to stagnant flow and industrial and household effluents.

Following hydraulic and water quality measurements can be considered to be important and useful:

(i) Discharge at inflow river sections upstream of the backwater area of the reservoir: For this, measurements of cross-section, flow current and water level (or using more advanced equipment like Acoustic Doppler Current Profiler) at different flow period are carried out to define stage-discharge rating curve.

(ii) Outflow/spillage from the spillways, intakes, under-sluices etc.

(iii) Tailrace discharge of upstream hydropower (valid for cascade system of reservoirs) and any other additional inflows to the reservoir

(iv) Water levels at the reservoir as well as upstream and downstream river reaches (this is useful for modelling purpose as well)

(v) Physical (color, temperature, turbidity, odour and taste), chemical (pH, B.O.D. etc.) as well as bacteriological properties of water in the reservoir

Most of these measurements must be regular (real-time and synchronic) to use them for meaningful analysis. There are several (from simple to advance) measurement devices available nowadays for direct, real-time and intrusive or non-intrusive measurements of these quantities (Figure **3**-**9**, Figure **3**-**10** and Figure **3**-**11**).

WMO (2008a, b) guidelines provide clear descriptions about hydrological and hydraulic measurement techniques and methods.

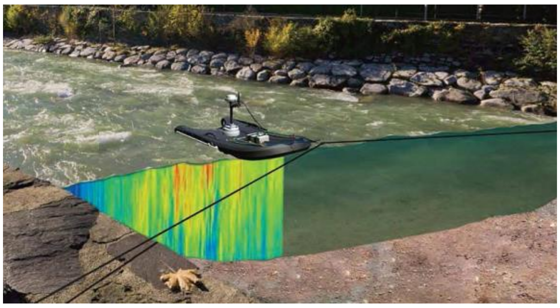

Figure 3-9. Flow measurement (velocity, discharge) using ADCP *(Courtesy: Sontek)*

Figure 3-10. Current meter for flow measurement

Figure 3-11. Buoy for real-time water quality measurement *(Courtesy: Eijkelkamp)*

Sediment Transport and Characteristics

Setting up of sediment monitoring network (transport and characteristics) in river and reservoir systems is one of the requirements to have proper input during planning, design, efficient operation and management. This is also very important for existing reservoirs while carrying out sediment management measures like dredging. Given the complexity of the sediment-induced phenomena, it is not always easy to set up a reliable and useful data acquiring system, particularly related to detect the transport magnitude under high flow period. Consequently, it usually requires a holistic approach taking into account the physics of river and reservoir dynamics and sediment transport phenomena and use of indirect methods. The monitoring is a supplementary part, associated with a variety

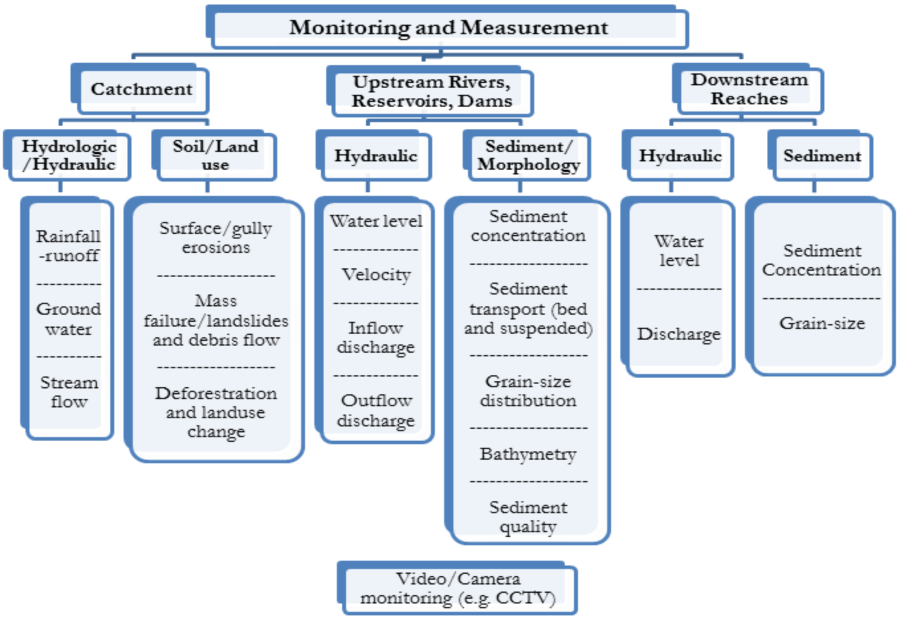

Figure 3-12. Diagram, showing the monitoring and measurement quantity and location

of river and reservoir engineering issues, which can be rather complex and broad based on several aspects from steep rivers (torrents) to inland deltas.

Some processes, descriptions and techniques are briefly described hereafter (and also summarized in Table 3-2, presented above).

Remark: For sediment transport measurements, among others, the design manual (volume 5) of Hydrology Project can be used (available at *http://nhp.mowr.gov.in/docs/HP1/MANUALS/Surface%20Water/5014/SW%20Design%20Manual%20Volume%205%20Sediment.pdf*).

Bedload Transport Measurement and Sampling

- It is important to have an estimation of bedload transport as accurate as possible. However, measurement of bedload transport is a very challenging task even in rivers with low sediment transport. This is more complicated in mountainous rivers given the extreme hydrological changes, large sediment quantities, the variations in sediment gradation as well as the topographic variations. Consequently, direct measurement may not always be reliable and justifiable, particularly when related to bedload transport.
- The bedload samplers usually give quite different results depending on river characteristics. Consequently, a combination of sampling methods should be used and it is important to use the same type of sampler throughout the sampling duration in order to achieve consistent results (IAEA, 2005).
- Proper monitoring and measurement of hydraulic features (discharge, current velocity and water levels) and sediment and bed characteristics in the reservoir and upstream river reach (grain-size distribution, bathymetry and feature of deposited layer) at properly selected locations in conjunction with simple calculation or computational modelling would provide better quantitative outcomes, and hence greater their usefulness (indirect method). Therefore, basic knowledge about the phenomena and physics-based modelling tools shall be integral components of the monitoring processes enabling to carry out proper data interpretation and analyses.
- The essence here is that primarily bed topography and grain-size patterns are measured instead of direct sediment transports. The sediment transports inferred from these data by means of calculation or modelling are more reliable than direct measurement of sediment transport (this is particularly valid for bedload transport).
- There are several approaches to track and measure the bedload transport process depending upon the type and location of the rivers and associated sediment transport phenomenon (e.g. steep or lowland rivers etc.). Here are some of the bedload monitoring techniques:
  - Acoustic Monitoring Techniques
  - Pressure-Difference Type Sampler
  - Portable and Permanent Bedload Traps
  - Nuclear Gauges
  - Tracer Method
- Some selected methods are briefly mentioned in Appendix A. Most of these methods can be found in other guidelines, e.g. IAEA (2005).
- Sampling of the bed sediment for grain-size distribution as well as to quantify vertical strata (particularly in existing reservoir) is also important aspect to consider with care. Only surface sample and its distribution is not enough to characterize the sediment properties, deposited in a reservoir.
- For example, Figure 3-13 shows formation of vertical strata of deposits in one of the reservoirs in hilly area of

Nepal. Similarly, Figure **3**-**14** shows the sediment cores from the reservoirs in Switzerland, showing different feature of the deposited layers.

- Spatial variability of grain size distribution, particularly longitudinal (sometimes transverse at important location, depending on the reservoir, as well) is important as well.
- The desirable way is to take core sample over the whole depth of deposits, since this provides information about the layer thickness and vertical strata, which can be used for various analysis including sediment removal (e.g. dredging) activities. If this is not possible for some reason, it can be done for part of the depth of few meters based on preliminary investigation and analysis of their purposes (e.g. thickness of the sediment layer to be dredged).
- Sub-bottom profilers provide useful information and prediction of presence of non-erodible layer and hard rock outcorps below the silt deposits, layer thickness of soft sediment, layer of non-cohesive sediment over clay layer etc.
- Sub-bottom profiling can be carried out by using echo-sounder in order to determine the profile of sediment layer at some characteristic location. Standard sub-bottom profiler can be used for such measurement.
- Nowadays, side scan sonar or bottom classification sonar are being increasingly used as well (information can be found in the internet).
- Such data and information is also useful for characterization of contamination in deeper layer of sediments.
- In case of unavailability of such equipment (or insufficient financial resources), core sampler can be used to determine the vertical profile of sediment layer. Core samplers typically use weights or piston devices to drive a hollow tube into the sediment surface, where a core of sediment is to be retrieved. Any suitable core sampler can be used based on the sediment type and properties.
- For example, gravity core samplers are typically used in loosely consolidated, soft- to fine-grained sediments and can collect core samples up to 3 meters long (EPA 2001).
- Vibracorers are the most commonly used core samplers because they can retrieve deep core samples in most types of sediment. Box core samplers are designed to collect samples of mud, silt, and other soft sediments. Piston-core samplers can collect samples from shallow streams to ocean floors and large lakes up to 20 meters deep.
- Available guidelines (UNEP/MAP, 2006; Morris and Fan, 2010, Carvalho et al., 2000 and others) are useful to check the details of sampling procedure, which has to be adapted to each specific situation.

Figure 3-13. Sediment deposition strata in the Kulekhani reservoir in Nepal (a coarse layer deposition below in the layer appears to be deposited during 1993 floods) *(Shrestha, 2012)*

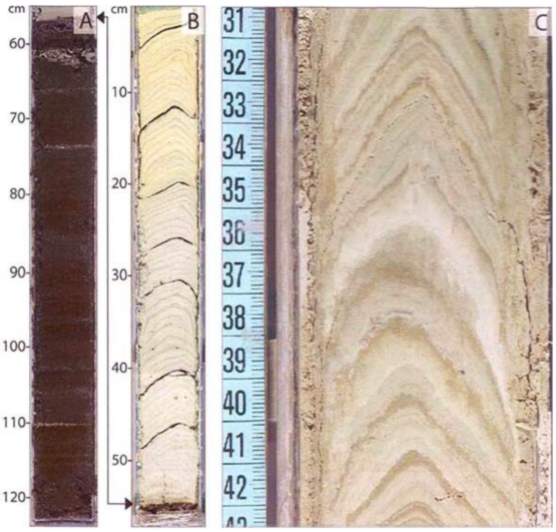

Figure 3-14. Sediment cores from reservoirs in the Aare basin, Switzerland, A, B: Cores from Grimselsee reservoir - Sediment from former natural lakes location, showing diatom-rich gyttja (dark brown, A), overlain by 71 proglacial varves (B) that were deposited after the first inundation of the Griemselsee in 1929; C: Core from Oberaarsee, showing details of proglacial varves. The darker layers represent fine-grained sediments that are deposited during winter in the frozen lake *(Anselmetti et al., 2007)*

Suspended Sediment Measurement

Particularly during high flows, river carries large amount of suspended load, which in case of limited flow release may be settled in the reservoir.

Figure 3-15 shows comparison of water turbidity during high and low flows in a reservoir in Tamil Nadu (India).

Some of the conventional suspended sediment monitoring techniques are as follows:

(1) Direct Measurement using Sampling

(2) Optical Method

(3) Nuclear Method

(4) Acoustic Method

(5) Laser Diffraction Method

(6) Tracer Techniques

There are some new developments and techniques, which are briefly described in Appendix A.

Spatial and temporal resolution and frequency of sampling are also important to extract meaningful application of measured data. Following points must be considered while taking sampling for suspended sediment concentration:

- Measurement location must be at all incoming channels, contributing to the reservoir. Besides, sediment concentration at both upstream and downstream reaches must be carried out. This is useful to evaluate the effectiveness of sediment removal operation (like sluicing, flushing, density current venting) by quantifying sediment balance. Moreover, this is necessary to monitor the environmental impact of such operations at downstream reach.
- Few measurement points over the depth (more than 2) are preferable to consider in order to get more precise vertical distribution profile of sediment concentration. This is particularly necessary at the upstream river reaches of the reservoir, and in the reservoir where turbidity current is dominant.
- Real-time monitoring is preferable as nowadays as a number of advanced techniques are available. Otherwise, the priority must be given to the flow period when there is larger inflow of suspended sediment (usually just before, during and after the monsoon period). Particularly in mountainous region, a river can bring large amount of sediment during flood responsible for storage loss (as shown an example in Appendix A.
- It is conventional to derive a sediment rating curve when data from gaging station is available for large period of time over wider flow range (from high to low flow. The suspended sediment rating curve is the relation between flow discharge and sediment concentration. However, such relationships are not

always reliable to use given the large scatter and hysteresis effects (i.e. for same discharge during rising and falling limb of a flood, the concentration could be different, which cannot be represent by one curve). Therefore, data must be analyzed properly and the outcomes must be used and interpreted with care by doing some sensitivity studies. This is well described in some literatures and guidelines (review the reference list of guidelines).

- It is also useful and effective to measure real-time turbidity to detect density current and manage its release from the reservoir in case such phenomenon occurs in the reservoir.

Section 8.2 of Reservoir Sedimentation Handbook by Morris and Fan (2010) provides description about suspended sediment sampling.

Figure 3-15. Kundah Palam reservoir during monsoon (upper picture) and low flow period (lower picture)

Trench Filling and Dune Tracking

Monitoring the filling of a trench in a river allows estimating the sediment transport rate at that particular location and at that particular time interval. This can be done in complement with a numerical model (at least a 1D model), reproducing the observed filling process. The numerical model is usually able to simulate the evolution of the trench. In general, the part of sediment transport that contributes to trench filling is the bedload component as well as a part of the suspended load, in particular the particles travelling in the lowest layers near the bed that easily fall in the trench. The longest the trench is, the more suspended sediment is trapped. Consequently, in order to include the contribution of all bed material loads (suspended plus bed load, but excluding washload), the trench should be designed as an efficient sediment trap, longer than the distance covered by the sediment travelling in the upper layers near the water surface (Crosato, 2015).

The advantage of this method lies in the fact that trench filling is a relatively long process, if the excavated trench is large. It is the result of the cumulative contribution of all sediment transport rates occurring in the time of trench filling, at both high and low discharges. Trench filling may therefore give an indication of the yearly sediment transport rate, particularly in lowland rivers. Details of this method can be found in the note of A. Crosato (2015).

In recent days, high resolution measurement of river bathymetry can be performed using single- or multi-beam eco-sounder. Such measurement is able to detect the micro-scale bed forms like dunes. So, successive measurements of bathymetry can provide their size and celerity, which can be roughly translated to bedload transport rate. The sediment that contributes to the formation and propagation of dunes is the bedload component and the sediment that is transported in suspension in the lowest layers near the bed. Therefore, the amount of sediment transport, estimated using this method, will not include the bed material load travelling in suspension in the upper layers of the water column.

The method requires the knowledge of the average dune height and celerity. It is based on the integration of the Exner's equation for a bed form of average height, assumed across the entire channel width, and leads to the following relation (Simons et al., 1965):

$$q_s = (1\text{-}p)\ c\ \beta\ h_b + C \qquad (1)$$

where, q_s = volumetric transport rate per unit width excluding pores (m^3/sm); h_b = average bed form height; c = celerity of bed form (m/s); β = coefficient to average the cross-sectional area of the bed form ($0.55 \leq \beta \leq 0.6$); and C = an integration constant to account for the material not associated with the migration of bed forms (with dominant bedload C = 0).

The general application of this method is complicated by the fact that bed form characteristics, such as height, wavelength and celerity, change with the flow condition. This means that the bedload rate can only be computed for specific flow condition (e.g. discharge). In order to have an overview of the yearly bedload transport, the bed form characteristics and evolution process under variable flow condition shall be determined. Besides, there are hysteresis effects, i. e. under the same discharge during rising and falling, the bed form size usually differs. Recently, some noticeable physics-based modelling works have been carried out, which provides insight into these processes and applicable to real-world situation as well (Giri et al., 2015; Nabi, 2012; Giri and Shimizu, 2006; Neumann et al., 2012).

Bulk Density of Sediment

The specific weight or dry bulk density is the dry weight of sediment per unit volume of deposit. Since sediment yield is expressed in terms of mass (e.g. t/yr) and bathymetric surveys only measure the deposit volume, the bulk density is required to convert between sediment load and the reservoir volume displaced by sediment once it has been deposited (Annandale et al., 2016). Accurate bulk density values depend on obtaining representative, undisturbed in situ samples of the sediment.

Some methods and example to determine bulk density of the sediment is given in Appendix B. Besides, Reservoir Sedimentation Handbook (Morris and Fan, 2010) and the technical note (Annandale et al., 2016) among other available literatures provide detailed descriptions of the process and methodology to determine necessary parameters and properties.

Cohesive Sediments

Reservoirs often contain deposits of clays in different form of consolidation, particularly if sediment removal is not carried out regularly.

It is rather challenging to determine transport processes of cohesive material, since it does not depends on grain-size as in case of non-cohesive materials. Erosion and deposition processes of cohesive sediment depend on a number of factors like clay mineralogy, chemical interactions and other site-specific parameters like shear stress. Usually it is possible to determine some of these parameters from laboratory tests. Furthermore, it is important to measure the cohesive sediment content and properties in the reservoir to select proper sediment management measures.

Chapter 4 of USBR Erosion and Sedimentation manual (2006) provides detailed descriptions and methodology about cohesive sediment processes, their measurement and studies (including numerical modelling). In addition, section 9.11 of the Reservoir Sedimentation Handbook (Morris and Fan, 2010) provides good description of characteristics and methodology for predictions of parameters for cohesive sediments.

Bathymetry Measurement

The bathymetry is one of the most important measurement data for reservoirs. This can be very helpful not only to quantify changes in storage capacity, but also understanding morphological patterns and development. Such information can be useful for selection, planning, feasibility as well as assessment of sediment-induced problems and selection of short and long-term sediment management measures.

Purpose and Frequency

The reservoir survey usually includes both terrestrial and underwater parts as relevant to the specific studies. The quantification of new storage capacity, sedimentation level (storage loss) and morphological patterns are the main purposes of the topo-bathymetric survey. Other usefulness of the periodic bathymetry measurement is quantification of inflow sedimentation rate and trap efficiency in combination with outflow transport estimation.

The frequency of surveys in reservoirs depends on several factors, e.g. the reservoir capacity and the tentative amount of sediment deposits. The small reservoirs and those with large sediment inflow shall be more frequently surveyed. On the other hand, the reservoirs with low sediment transport naturally or due to, for example, upstream dams or decrease of the drainage due to erosion control measures etc. can be measured less frequently.

The financial aspect is always one of the major factors. Therefore, the cost-benefit analysis of such measurements shall be made. Usually, regular bathymetry survey is important for reservoir with higher sedimentation rate to address number of issues and to plan and design remedial measures.

The measurement frequency can be decided based on following aspects:

- Information/data about changes in inflow sediment load
- Observation of changes in water spread areas during drawdown period
- Need for reviewing reservoir capacity curve
- If there is large changes due to big floods (expected to bring large sediment inflow into the reservoir)

In the compendium, published by CWC (2015), it has been recommended to carry out the bathymetry measurement every five years.

Survey Techniques

Chapter 9 of USBR's Erosion and Sedimentation manual (2006) and Reservoir Sediment Handbook (Morris and Fan, 2010) provide detailed guidelines on the performance of reservoir survey.

We briefly describe here mostly those techniques, which are often used. Although conventionally simple techniques are still being used, particularly when financial resources are not sufficient. Besides, some new developments in recent years have been briefly presented as well, since the cost of these equipment is decreasing rapidly and becoming accessible and feasible to be used in developing countries as well.

Water depths can be measured using a portable sounder connected to a GPS. The GPS records both the location coordinates and the depth measurement of the sounder. DGPS is often used, which allows for rapid collection of bathymetric data in open areas, so this is suitable for reservoirs as well.

Fish-finder is also a useful low-cost device to measure the bathymetry in easy way. Usually they are used to find fish. Since they record water depth also, it is possible to use them for measuring bathymetry of rivers and reservoirs (Figure 3-16).

Other methods are water depth soundings using single or multi-beam eco-sounders (Figure 3-17), which are rather commonly used these days as it produces fast and high resolution mapping of bathymetry. Such bathymetry measurement provides clear feature of the reservoir bed. A real-world example is depicted in Figure 3-18 showing the bathymetry of one of the reservoirs in Poland, which reflects the basic feature with shallow areas in upstream of the reservoir at all tributaries entering to the reservoir. The bathymetric feature shows that the area near the dam is deeper. Besides, there is a deep channel in the reservoir, which appears to be the old river course. There are some situations when reservoirs with fine sediment deposition appear to fill from the dam towards the backwater and no delta forms at the upstream area.

Figure 3-16. An example of using Fish finders to measure bathymetry

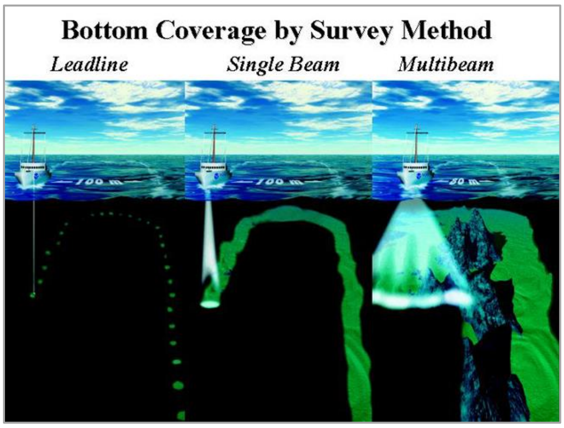

Figure 3-17. Bathymetry using eco-sounders *(Source: NOAA)*

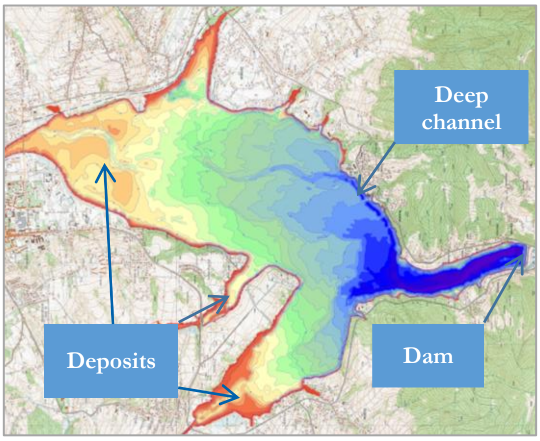

Figure 3-18. Bathymetry at Tresna reservoir in Poland, showing sediment deposits at all tributaries entering to the reservoir (Dark blue to dark orange color variation denotes deep to shallower areas respectively) *(Data courtesy: Krakow Water Boards, personal communication)*

Another recently developed technique is advanced interferometric technique. Interferometric technique uses a more complex technique with tomographic-type

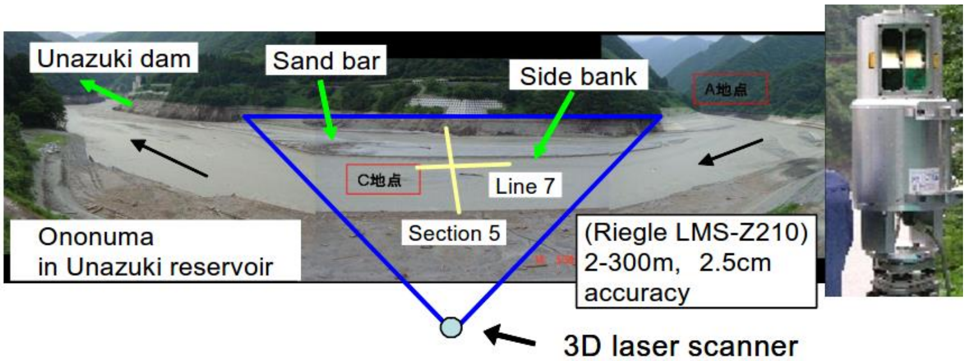

Figure 3-19. Set-up of 3D laser scanning of Unazaki reservoir, Japan *(Sumi, 2006)*

inversion of the data. It can typically measure a swath 12 depths wide and in many case there are experiences of actually measured swaths up to 40 depths in width. This means the work can take much less time for big areas, which is typical for reservoirs. The system is entirely portable, can be set up on a boat, and surveyed a great deal of the area in a short time. An example of this technology with detailed descriptions is presented in Appendix A.

3D laser scanner is another advanced equipment, which may be suitable for topographic scanning of surrounding area (only dry areas). An example of using this technology is depicted in Figure 3-19, showing the set-up made for Unazaki reservoir, Japan. Nowadays, the scanner is used with the help of drones as well (UAV), which can cover larger area to measure the topography.

Other advanced (remote sensing) tools and technologies, such as satellite images, other laser, photo and video equipment, mounted on Unmanned Aerial Vehicle (UAV) and Unmanned Surface Vehicle (USV) are briefly described hereafter (as a separate section).

3.4.2 Satellite, UAV and USV

Multi-Spectral Satellite Imagery

The variation in reservoir surface area can be detected and quantified using remote sensing and satellite imaginary as nowadays such data and images are freely available, and moreover this has potential of rapid growth in future. The most popular methods to detect water mask from multispectral (satellite) imagery are based on the fact that water absorbs radiation at near-infrared wavelengths and beyond. A number of spectral indices (Normalized Difference Water Index) were developed in the last two decades by Gao, 1996; McFeeters, 1996 and later, Xu, 2006. While detection of clear water features appears to be trivial, a number of factors make it more difficult, these are mainly caused by the presence of clouds, snow and ice. Additionally, false positives can be observed in the areas with shadows due to topographic conditions or presence of clouds. Furthermore, water is almost never clear in areal world, resulting in changes of its spectral curve and as a result uniform threshold values that should be used to separate water pixels may no longer work.

One of the recently developed methods (Donchyts, 2016) to determine surface area of the reservoirs is based on number of steps, that enable automated calculation of changing reservoir surface area using both cloud-free and partially cloud-free images. Figure 3-20 briefly shows these steps in an example, while Figure 3-21 gives

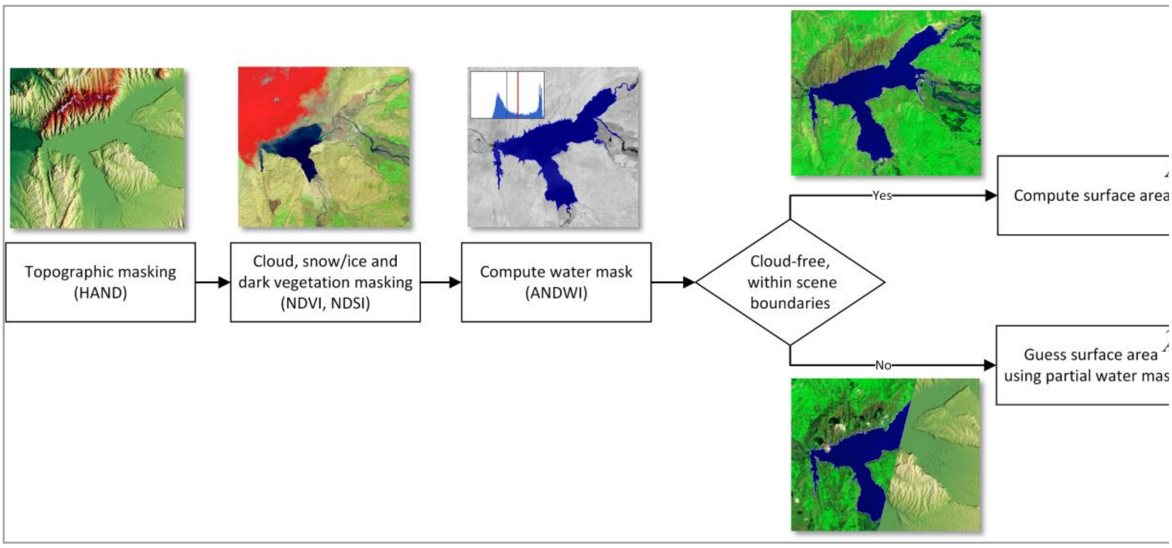

Figure 3-20. Steps during surface water area detection for reservoirs *(Donchyts, 2016)*

example of water mask detection and surface area dynamics observed during a couple of years. Benefits of the method increase for larger reservoirs and/or for the reservoirs, where cloud frequency over surface water is higher. Based on this Landsat processing technique using Google earth engine, an online system, Deltares Aqua Monitor, has been developed (*http://aqua-monitor.appspot.com/*), which enables to quantify changes in water body during selected year on-the-fly. This tool can be used to estimate spatiotemporal extent of the morphological processes, particularly in large rivers and reservoirs (the changes can be assessed only up to the MDDL and dry areas). A couple of examples of spatial changes in reservoir morphology in Tungabhadra dam (India) the Kosi barrage (Nepal) are depicted in Figure **3-22** and Figure **3-23** respectively, demonstrating the capability of the tool for a rapid assessment. However, care should be taken while processing and analyzing the outcomes for the reservoirs with large water level variation considering the fact that they could be different during the periods of comparison. Therefore, the image processing method and analysis should be tailor-made and in complement with water level observation data. Some additional information about Satellite-derived bathymetry is presented in **Appendix A**.

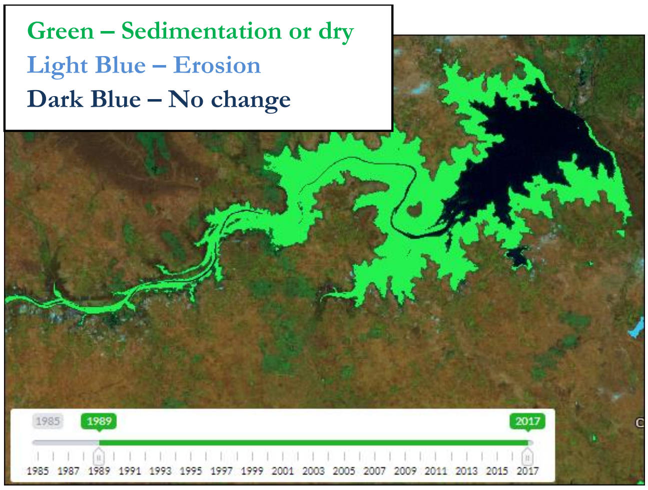

Figure 3-22. Changes in Tungabhadra reservoir between 1989 and 2017, **showing** the dry area *(Deltares Aqua Monitor)*

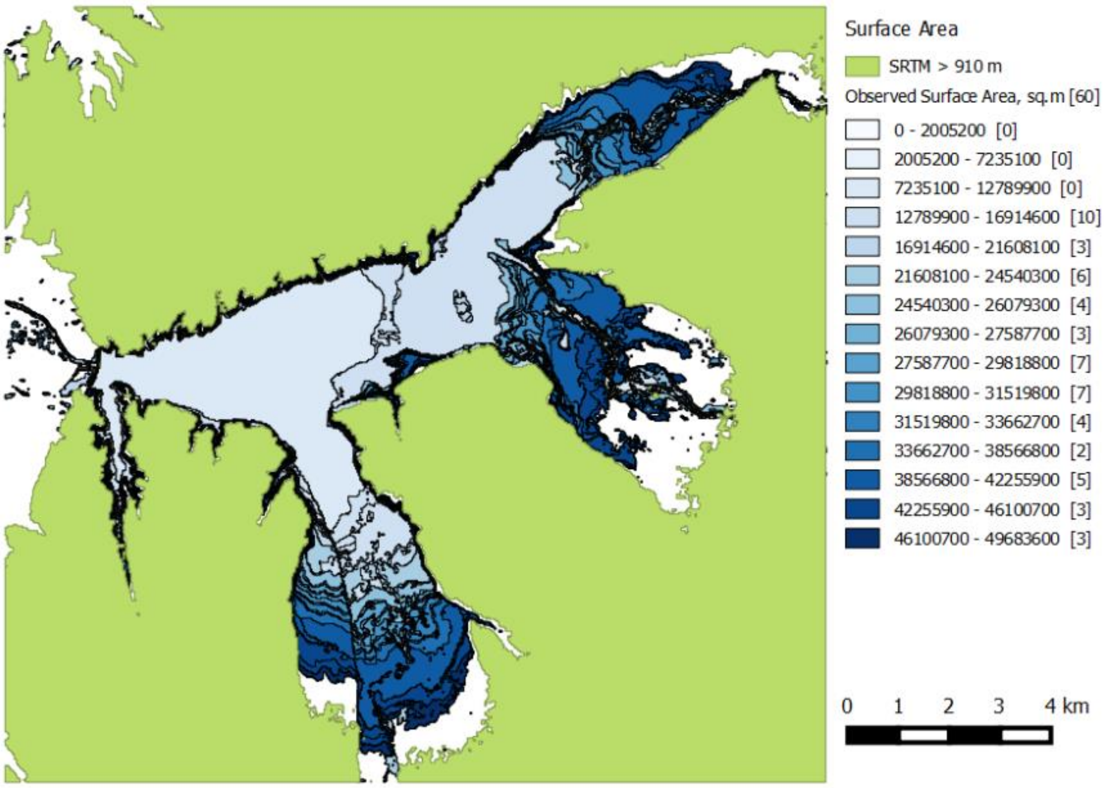

Figure 3-21. Isolines from the detected water mask during 2013-2014 using cloud-free and full-scene images. The numbers in the legend indicate number of images processed for a given surface area range *(Donchyts, 2016)*

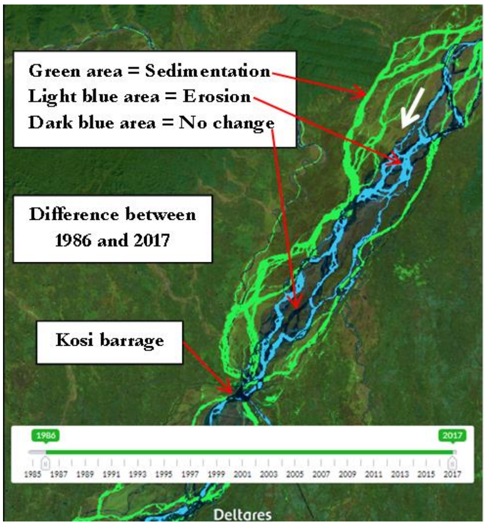

Figure 3-23. Sedimentation and erosion at upstream of the Kosi barrage during selected period *(Deltares Aqua Monitor)*

Other Remote Sensing, UAV and USV Techniques

- There are other remote-sensing and remote-controlled techniques to measure bathymetry apart from high resolution satellite imagery (Mohamed et al., 2016), such as green LIDAR (Kinzel et al, 2012), UAV-borne topo-bathymetric laser profiler as depicted in Figure **3-24** (Mandlburger et al., 2016).
- A review paper by Jawak et al. (2015) provides an overview of the bathymetric mapping technologies using satellite remote sensing with special emphasis on bathymetry derivation models, methods, accuracies, advantages, limitations, and comparisons.
- Another example is a lightweight surface vehicle for shallow water hydrographic surveyss, monitoring and surveillance, so called SONOBOT (Kebkal et al, 2014) as shown in Figure **3-25**. This is an automnomous Unmanned Surface Vehicle (USV) for hydrographic survey with hydrostatic communication.
- Smaller USVs are particularly useful for measuring the depth and bottom configuration of water bodies like lake and reservoir. An autonomous or remotely controlled surface vehicle can be equipped with radio- and underwater acoustic communication and positioning devices for underwater acoustic surveillance and monitoring, as well as with on-board echo-sounder, side-scan sonar and other sensors to collect valuable data in automated mode (Kebkal et al., 2014).
- A similar technique of using simpler device like Fishfinder or other type of portable echo-sounder and other necessary devices and data logger and transfer system, mounted on surface drones, is used for bathymetry survery as shown in Figure **3-26**.

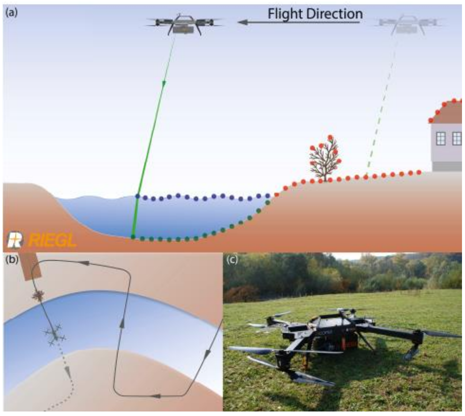

Figure 3-24. (a) Laser range finder mounted on UAV platform, (b) profile oriented data acquisition and (c) BathyCopter *(Mandlburger et al., 2016)*

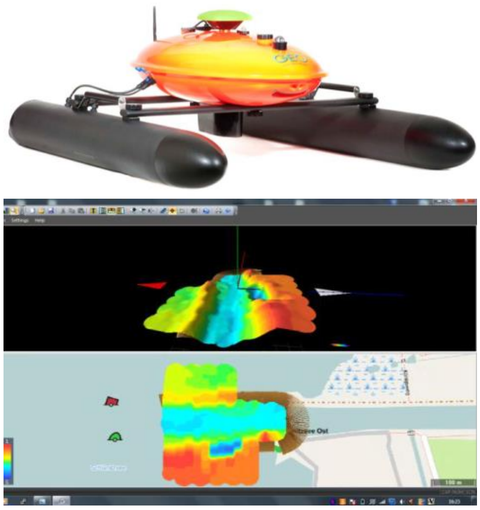

Figure 3-25. The USV Sonobot (above) and 3D plot of the surveyed area estimated as a result of combining echo-sounder data and side-scan data *(Kebkal et al., 2014)*

Figure 3-26. A surface drone, equipped with GPS, portable echo-sounder and other devices to measure bathymetry *(www.cansel.ca)*

Outline of topo-bathymetric measurement techniques including their advantages and limitations are presented in Table 3-4. There are other guidelines to get more ideas and information about monitoring techniques and approach (e.g. WMO guidelines, USBR guidelines, ICOLD guidelines).

3.4.3 Post-Processing and Analysis tools for Topo-Bathymetric Data

A number of tools and software are available for post-processing and analysis of bathymetry including volume calculation. A number of measurement equipment are supplied with their own software for post-processing. Most commonly used software (also in India) are Arc GIS, MATLAB, IMSL, and Autodesk products like AutoCAD, Civil 3D, Hydrographic Information Processing System (CARIS HIPS), Bathy DataBase Suite (*www.caris.com*), R2V, Global Mapper, Surfer etc. Some detailed descriptions about how these software can be used are given in the IHO-IOC GEBCO Cook Book. Therefore, it is suggested to refer to this book, which can be freely downloaded via *www.star.nesdis.noaa.gov/sod/lsa/GEBCO_Cookbook/*.

These are powerful tools, but they are commercial. Some other tools are briefly described hereafter that are free or open source.

Generic Mapping Tools

Generic Mapping Tools (GMT) (Wessel and Smith, 1998) is a collection of open source mathematical and mapping routines for use on gridded data sets, data series, and arbitrarily located data. These tools are used for manipulating geographic and Cartesian data sets (including filtering, trend fitting, gridding, projecting, etc.) and producing PostScript illustrations ranging from simple x–y plots via contour maps to artificially illuminated surfaces and 3D perspective views; the GMT supplements add another 40 more specialized and discipline-specific tools. GMT supports over 30 map projections and transformations and requires support data

The GMT package is available for download from the University of Hawaii website (*http://gmt.soest.hawaii.edu/*).

ParaView

ParaView is an open-source, multi-platform data analysis and visualization application, widely used for variety of pre- and post-processing application. One of the application is for visualizing and processing point cloud data from a variety of sources. ParaView enables users to create a virtual workbench for interactive visualization and processing of point cloud data from a variety of sources including depth cameras, stationary LiDAR scanners, and vehicular or aerial LiDAR. Applications include robotics, 3D mapping, surgical guidance, generation of simulation models and more. Adding the PCL-ParaView plugin provides a wide variety of point cloud processing tools within the Paraview platform.

ParaView features that are useful for this type of analysis include:

- Built-in features for subsampling, cropping, and thresholding data
- Support for time-varying data

- Python programmable filter for custom algorithms
- Streaming and parallel processing
- Advanced visualization techniques such as eye-dome lighting
- Plugin mechanism

Other information, details and downlaod page can be found at *www.paraview.org* .

Table 3-4. Bathymetry & Topography Measurement Techniques, Their Capabilities & Limitations

Measurement Techniques	Advantages/Capabilities	Disadvantages/Limitations
Single-beam echo-sounder	o Produces consistent high resolution bed profile o Simple and inexpensive method o Good for line measurements (cross-sections, longitudinal sections) o For typical reservoirs a frequency around 200 kHz is used which is ideal for water shallower than 100 meters.	o Inappropriate for large scale bathymetric survey work o Some inaccuracies in depth measurements that correspond to well defined locations on the bottom bed o Time consuming for large number of measurement (low acquisition rate) o Service range up to 10 km depending upon the working frequency
Multi-beam echo-sounder (USGS)	o Simple to operate o Better resolution and large area coverage o Better representation of reservoir bathymetry with higher mapping resolution comparing to SBES o Typical frequency is higher than 200 kHz for depth shallower than 100 meters. o Advanced multibeam echosounder with interferometric technology has large swath width and collocated side scan (see Appendix A)	o Measurement of range and beam angle is more complex than simple single beam echosounders, a number of factors contribute to the error in the readings. o Resolution depends on the acoustic frequency, beam widths and algorithm to perform bed detection. o Provides data only along a single path directly beneath the track of a surveying ship. o Acquisition of bathymetric data is limited by the speed of the vessel. o Unsafe to operate in shallow waters
Light Detection And Ranging (LiDAR) Air- and UAV-borne	o The airborne laser system with a laser scanning system, global positioning system and an internal measurement unit o UAV-borne laser system are cheaper than airborne o Very efficient and high	o Water clarity is the primary constraint (very sensitive to suspended material and turbidity). o In less clear waters, the measurement could be successful at the depth of two to three times

Measurement Techniques	Advantages/Capabilities	Disadvantages/Limitations
	speed compared to the traditional acoustic systems. ○ No water depth dependence (as it is an acoustic system) ○ Good coverage also in extreme conditions of temperature, where acoustic systems may produce poor quality data. ○ Suitable for the large reservoirs, and where it is not possible to take boats. ○ Measuring bathymetry up to about 40 m deep clear water ○ Safety is a major advantage.	the visible depth. ○ High initial and operational cost of airborne systems
Airborne electromagnetic system	○ Based on a geophysical survey technique for measuring the electrical conductivity of bedrock or the thickness of a conductive layer ○ High speed of data acquisition as compared to the traditional acoustic systems ○ Good coverage ○ Usable in areas, where it is not possible to take boats. ○ Since low frequencies are used, it is possible for operating over thick ice	○ The initial cost here is high as compared to the acoustic systems. ○ Suitable for reconnaissance purpose only I ○ In the range of 0 - 40 m of depth, the representative difference between the interpreted depths and the charted depths is about 2 m.
Arial photography, video and satellite and radar image analysis	○ Ability to correlate light intensity with depth using advanced processing and algorithm ○ Useful and accurate at definite depth ○ Useful in reconnaissance, planning of bathymetry surveys (e.g. delineate the boundaries of reservoirs, quantify spatial changes in water spread area) ○ Useful for a qualitative description of the reservoir bed, mainly the changes in surface area under same water levels (depending on availability of dry period images) ○ Processing algorithm is advancing due to high perfor-	○ Sensitive to suspended material, turbidity, cloud cover, atmospheric conditions and also reflective properties of the bottom surface ○ Calibration with ground data is needed. ○ Less accurate for larger depth ○ The exact depth of deeper part of the reservoir cannot be measured. ○ Area limitation for video imaging (useful for small reservoirs) ○ Depending on image resolution, quality and varying with processing algorithm ○ Satellite image analysis is not very useful for small reservoirs (unless the resolution is

Measurement Techniques	Advantages/Capabilities	Disadvantages/Limitations
	mance computers and other technological advances ○ Fast and low cost due to freely available images (and decreasing cost) ○ Video imaging has relatively high accuracy	very high).
Lead line and sounding pole	○ Lead lines are ropes or lines with depth markings and lead weights attached at regular intervals (usually sounding manually in depth of less than 50 m) ○ Such mechanic systems are not sensitive to aquatic environment unlike other advanced system. ○ Old but still in use even today. ○ The lead line aids in resolving echo-sounder misinterpretation caused by spurious returns. ○ Lead lines and sounding poles are	○ A labor-intensive and time-consuming process ○ While the initial depth soundings may be accurate, they are limited in number, and thus, coverage between single soundings is lacking.
Fishfinder	○ Cheap, light and easy sounding device ○ Good for shallow depth (but not less than a meter) ○ Less number of personnel ○ Relatively precise measurement, particularly suitable for smaller reservoir ○ Possible to mount on a Unmanned Surface Vehicle (USV)	○ Time consuming for large reservoirs
Side-scanning sonar	○ See every objects under water ○ High resolution and large coverage around the boat (e.g. 180^0 depending on the device) ○ Accurate and better image of the reservoir morphology including underwater side slopes ○ Suitable for searching stationary underwater objects (rocks, debris etc.), sediment feature and hard layer (useful infor-	○ Costly ○ Complex ○ Unsafe in shallow depth

Measurement Techniques	Advantages/Capabilities	Disadvantages/Limitations
	mation for dredging operation)	
Radar Altimetry	o Global coverage o Requires only simple altimetry	o Very low accuracy o Possible over a limited wavelength band o Applicable for coarse bathymetry (not suitable for small and medium reservoirs)

3.4.4 Empirical and Analytical Methods

Catchment Sediment Yield

Estimation of sediment yield from the catchment contributing to a reservoir is rather difficult due to large uncertainties and variability of natural and human-induced factors determining its magnitude. For an existing reservoir, the sedimentation data (bathymetry) can be used as an indication of sediment yield from the catchment.

Some conventional empirical relationships can be used for the first estimation, but more complex approach and detailed analysis should be carried out considering uncertainties as well as extreme and episodic events.

One of the widely used methods for estimation of soil erosion rate is Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1978). There are revised (RUSLE) and the modified (MUSLE) versions of this approach as well (Jones et al., internet source). Usually this formula is coupled with hydrological models to estimate soil loss in catchments (see section 0). The approach is based on erosion plot and rainfall simulator experiments, which is composed of six factors and reads as:

$$A = R\,K\,L\,S\,C\,P \qquad (2)$$

where, A = the soil loss per unit area; R = the rainfall and runoff factors; K = the soil erodibility factor; L = the slope-length factor; S = the slope steepness factor; C = the cover management factor; and P = the support practice factor.

There are a number of other approaches and formulations (one of recent approaches, described in Syvitski and Milliman, 2007, like BQART model). In India, various governmental agencies (ICAR, 1984; CBIP, 1981; CS&WC, 1991) conduct survey for determining soil erosion rates. The Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1978) is generally used for estimation of erosion rates. An iso-erodent map of India has been produced based on the erosion index values (Ram Babu et al., 1978), which shows the potential erodibility of rainfall (Singh et al., 1990). Methods have also been evolved for determination of the off-site deposition of eroded soil and the sediment yield from large catchments (Garde and Kothyari, 1987; Narayana and Ram Babu, 1983; Kothyari et al., 1994). One of the most detailed studies for estimation of sediment yield from large catchments was done by Garde and Kothyari (1987). An analysis of the data from 50 catchments with areas ranging from 43 km^2 to 83880 km^2 produced the following equation for mean annual sediment yield (Kothyari, 1996):

$$S_{am} = C\,P^{0.6}\,F_e^{1.7}\,S^{0.25}\,D_d^{0.1}\,(P_{max}/P)^{0.19} \qquad (3)$$

where, S_{am} = mean annual sediment yield (in cm), C = coefficient depending on the geographical location of catchment, P and P_{max} = average annual and average maximum monthly rainfall respectively (in cm), S = land slope, D_d = drainage density (km/km^2), A = catchment area (km^2), and F_e

= erosion factor, which is determined as follows:

$$Fe = (0.8F_A + 0.6\ F_G + 0.3F_F + 0.1\ F_w)/A \quad (4)$$

where, F_A = the area of arable land in the catchment, F_G = the area occupied by grass and scrub, F_F = forest area, and F_w = the area of waste land.

Based on the data from 154 catchments in India, an iso-erosion rate map was prepared by Garde and Kothyari (1987). The result reveals that mean annual erosion rates in India vary between 350-2500 t/km^2/year.

High erosion rate, as found in the north-eastern region, parts of Punjab, Uttar Pradesh and Bihar as well as in certain areas of Andhra Pradesh can be attributed partly to the higher rainfalls in these regions and partly to the geologic conditions and land use.

Garde and Kothyari (1987) proposed a modified form of relationship to estimate annual erosion rate (S_a) given that only rainfall variable is changeable, which reads as follows:

$$S_a = C\ F_e^{1.7}\ S^{0.25}\ D_d^{0.1}\ (P_{max}/P)\ P_a^m \quad (5)$$

where, P_a = annual rainfall (cm), and m = coefficient, associated with annual rainfall variation.

Sediment Transport Rate

Based on transport mechanism in alluvial rivers, the sediment transport can be divided in to bedload and suspended load. Bedload is the sediment near the river bed, transported by the flow by rolling, sliding and jumping. While suspended load is the sediment, picked up by upward flow and turbulence and transported in the water column. This usually occurs under high flow condition when finer particles are transformed from rolling/sliding/jumping to suspension regime.

If we consider reservoir condition, the suspended sediment load, which is transported during high flow period, would be deposited with time within backwater area, induced by the dam, due to reduction of flow velocity and turbulence. A part of suspended sediment loads may be transported downstream if the flow is released from spillway and/or under sluices. On the other hand, almost all the bedload are deposited in the reservoir. The bedload together with deposited suspended load basically form the morphological patterns of the reservoir bed and their dynamic evolution, such as formation and propagation of sediment delta, wedges, tapering etc.

There are a number of transport formulae to calculate bedload, suspended load and total load transport rates of non-cohesive sediments. Usually a proper selection of the formula in complement with a mathematical model provides better estimation, since measurement of bedload transport involves complexities and inaccuracies. There are mainly two types of formulae, those which are directly proportional to flow velocity like Engelund and Hansen (1967) (EH), and those which include excess shear stress (flow shear stress minus critical shear stress of the particles) like Mayer-Peter and Muller (1948) (MPM). In former case, there is always some transport, while in later case there is transport only when flow shear stress (or shear velocity) is larger than critical shear stress (or shear velocity) of the particles. Selection of each available sediment transport formula should be based on its applicability for particular hydraulic, sediment and morphological conditions.

Following are the formulae among commonly used around the world: (i) Mayer-Peter and Muller (MPM) (1948); (ii) Van Rijn (1984, 1993, 2007); (iii) Engelund and Hansen (1967); (iv) Bijker (1971); (v) Ashida-Michiue (1974); (vi) Kovacs and Parker (1994); (vii) Parker (1990); (viii) Wilcock-Crowe (2003); (ix) Laursen &

Copeland (1958, 1989); (x) Yang (1973, 1984) and others.

Some of these formulae are suitable for fine sediments (e.g., Engelund and Hansen, Van Rijn), some for coarser sediment or more universal (e.g., MPM), some for fractional transport of graded sediment (e.g., Wilcock-Crowe, 2003). Besides, formulae like Engelund and Hansen and MPM consider total load, while Van Rijn formula treats bedload and suspended load separately.

Usually for some river systems, a relationship between flow discharge and average sediment concentration (sediment rating curve) is developed based on direct or indirect measurement of suspended sediment concentration during different flow conditions. However, such relationships must be analyzed and used with care.

Trap Efficiency

When a natural water and sediment flow is disturbed by creating a dam and reservoir, part of the water as well as sediments are trapped in the reservoir. While some part of sediment passes during flow release through the spillway and/or under sluices. The parameter trap efficiency (TP), which is defined as a ratio between amount of sediment deposit in the reservoir and total amount of sediment inflow, is used to assess this. Commonly used empirical curves to estimate the trap efficiency are Churchill curve (1948), a sediment index method mostly used for small reservoirs, Brune curve (1953) (a capacity-inflow method) mostly used for large reservoirs, and Brown's curve (a capacity-watershed method).

Figure 3-27 shows trap efficiency curves of Brune and Churchill, which includes four large Indian reservoirs as well. As it can be seen from the figure, two of them fit to Brune curve and two to Churchill curve.

Some simple formulations for trap efficiency is provided by Leo van Rijn (2013, www.leovanrijn-sediment.com). As it is revealed in this work, the trap efficiency varies significantly for different formulations (in an example, shown in the paper, it is found to be varying from 0.55 to 0.99 for different formulae).

These methods and examples are described in Appendix B.

An EXCEL program (SED-RES, van Rijn, 2013) is available to compute the sedimentation in a reservoir for given

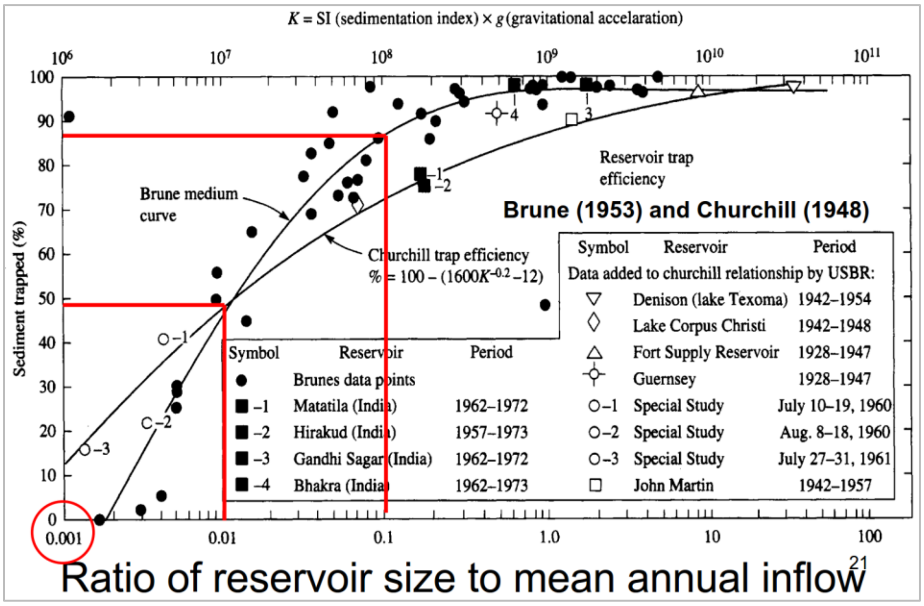

Figure 3-27. Estimation of reservoir trap efficiency using Brune and Churchill curves *(Randle and Bountry, 2015)*

sediment transport and sediment characteristics at the upstream reservoir boundary.

Numerical computation can also be carried out to replicate the trap efficiency, although a number of assumptions and analysis are necessary to make in case there is lack of data, particularly on sediment inflow (review some works from the reference list).

Reservoir Capacity Loss

A study by Froehlich et al. (2017) has revealed distinctive sedimentation rates for the reservoirs that are located on seven classified sedimentation zones (as shown in Figure **3**-**28**). Based on the data of 243 reservoirs, they have proposed empirical formulations for capacity loss in reservoirs on eastward flowing rivers (i.e. rivers at sedimentation zones 1, 2, 3 and 4) and westward flowing rivers (i.e. rivers at sedimentation zones 5, 6 and 7). The general formula reads as follows:

$$\hat{Y} = K A_c^{\alpha} A_r^{\beta} C_0^{\gamma} T^{\varphi} \qquad (6)$$

where $\hat{Y}$ = expected value of reservoir capacity loss (Mm^3), A_c = catchment area (km^2), A_r = surface area of the reservoir at FRL (km^2), C_0 = initial storage capacity of the impoundment (Mm^3), T = time since the initial filling of the reservoir (years), K, a, β, γ and φ = empirical constants, which is proposed to be 0.0067, 0.1, 0.05. 0.8 and 0.9 respectively for the reservoirs on eastward flowing rivers, while 0.03, 0.15, 0.3, 0.5 and 0.65 respectively for the reservoirs on westward flowing rivers.

Furthermore, they have proposed a relationship for reservoir Half-Life calculation, which reads as follows:

$$T_{50\%} = \left[\theta_1 A_c^{-\theta_2} A_r^{-\theta_3} C_0^{(1-\theta_4)}\right]^{\theta_5} \qquad (7)$$

Where θ_1 to θ_5 = empirical constants, which is proposed to be 74.2, 0.15, 0.1, 0.3 and 1.11 respectively for the reservoirs on eastward flowing rivers, while 16.6, 0.15, 0.3, 0.5 and 1.15 respectively for the reservoirs on westward flowing rivers.

All the formulae have been derived based on surveyed data as well as the formulations are generalized, therefore it shall further be verified with new measurement data. In principle, the tailor-made approach shall be followed for each reservoir (or a group of reservoirs on the same basin) for more precise assessment of the sedimentation rate and life of the reservoir.

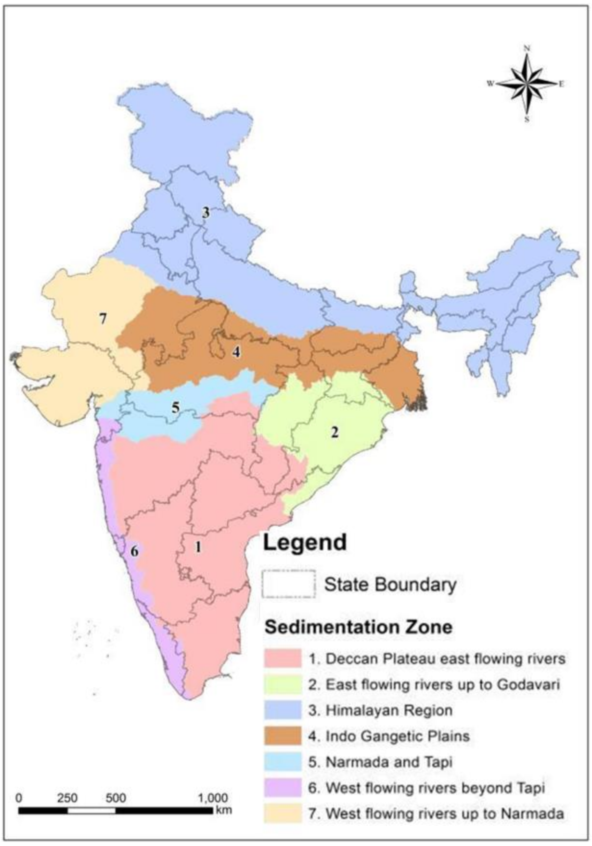

Figure 3-28. Classification of sedimentation zones in India *(*CWC*, 2015)*

Reservoir Morphology

Some useful description about reservoir morphological pattern is briefly described in section 3.3.3. The general morphological shape and patterns and their dynamic behavior like progression of deposited sediment in a reservoir has profound consequences on dam design.

For quick assessment (e.g. during pre-feasibility phase), some conventional empirical methods can be used as briefly described below. It is also possible to consider tailor-made-approach to analyze reservoir morphology based on bathymetry measurement and numerical simulations to assess the morphological patterns in the reservoir, since most of the morphological impacts are governed by shape of the reservoir, water and sediment inflow as well as reservoir operation.

Borland and Miller (1960)

Borland and Miller (1960) have classified types of reservoirs based on analysis of reservoir sedimentation data and the shape of reservoirs. The data indicates a relationship between the reservoir shape and the percentage of sediment deposited at various depths throughout the reservoir. The type of reservoir can be related to the reciprocal value (M) of the slope of the line obtained by plotting reservoir depth as ordinate and reservoir capacity as abscissa on log-log scale. Following four types are identified (Figure 3-29):

a) Lake type (I): M= 3.5-4.5; greater portion of the sediment is deposited in the upper part of the reservoir
b) Flood plain-foot hill type (II): M= 2.5-3.5
c) Hill type (III): M= 1.5-2.5
d) Gorge type (IV): M=1-1.5; greater portion of the sediment is deposited in the deeper part (dead storage zone) of the reservoir.

These types of standard curves were found to be valid for some reservoirs in India as

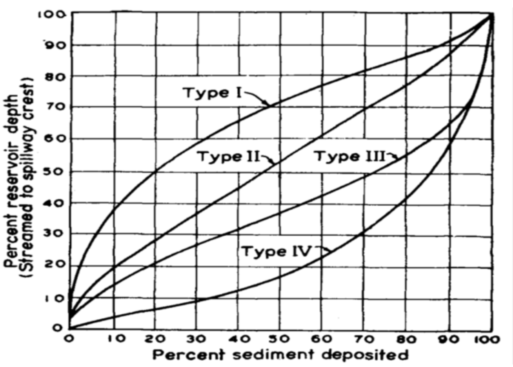

Figure 3-29. Reservoir classification *(Bornald and Miller, 1960)*

well (Murthy, 1977). Also, some examples of quantifying the type for some Indian reservoirs are given in CWC compendium (2015).

Annandale (1987)

Annandale (1987) found that the distribution of deposited sediment for those reservoirs, i.e. tapering or uniform distributions, was related to the rate of change in the width of the reservoir from upstream to downstream. This rate of change is expressed by the following term (Annandale et al., 2016):

$$\frac{dP}{dx} \approx \frac{P}{x} \qquad (8)$$

Figure 3-30 shows how the total sediment volume in a reservoir is distributed as a function of the dimensionless distance along the reservoir, measured from the dam for various values of P/x. The figure indicates that sediment is less uniformly distributed if the reservoir is relatively wide, and that it is more uniformly distributed when the reservoir is narrow. In principle this makes sense. The sediment transport capacity in a narrow reservoir will remain relatively high throughout, thereby transporting sediment further into the reservoir, and vice versa for a relatively wide reservoir. For a wide reservoir, relatively more sediment will deposit in the upstream reaches.

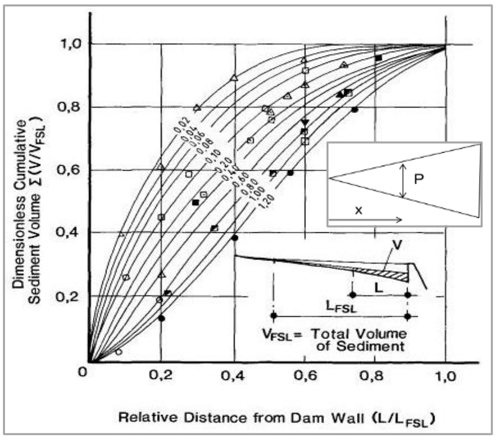

Figure 3-30. Dimensionless cumulative mass curve explaining distribution of deposited sediment in a reservoir as a function of dP/dx *(Annandale, 1987)*

Figure 3-31 using the same nomenclature as Figure 3-30, provides an indication of how much sediment might be deposited upstream of the maximum water surface elevation in a reservoir. It indicates for the reservoirs considered that the amount of sediment deposited upstream of the maximum water surface elevation equals about 4% of the total amount of sediment deposited in the reservoir and that it may be mainly deposited over a distance equaling about 20% of the reservoir length, or so, in an upstream direction (Annandale et al., 2016).

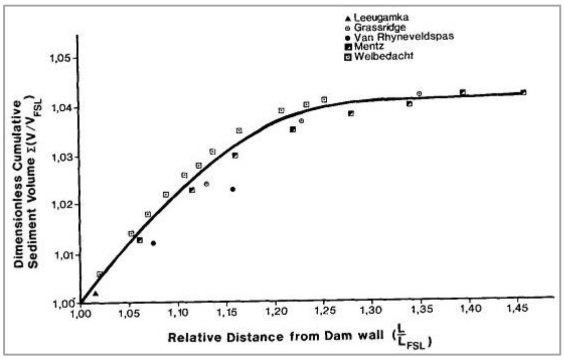

Figure 3-31. Distribution of deposited sediment above full supply level in a reservoir *(Annandale, 1987)*

Van Rijn (2013)

Van Rijn (2013) developed a method for empirically estimating the distribution of deposited sediment in the longitudinal direction of reservoirs. This is accomplished by quantifying the trap efficiency in pre-defined reaches of a reservoir. The trap efficiency is formulated as:

$E_{res} = 1 - \exp(-A_{vr^*}L^*(h-h_o)/h_2)$

where, L= length of reservoir, ho= flow depth at upstream reservoir boundary (x=0 m), h= mean flow depth of reservoir (or section of reservoir as depicted in Figure 3-32), $A_{vr}=\alpha_s(w_s/u^*)(1+2w_s/u^*)$ = deposition parameter, α_s= 0.25= coefficient (in range of 0.2 to 0.3), w_s= settling velocity of sediment, u*=mean bed-shear velocity in reservoir. Comparison of calculation results using this technique was found to reasonably represent actual reservoir surveys (van Rijn 2013).

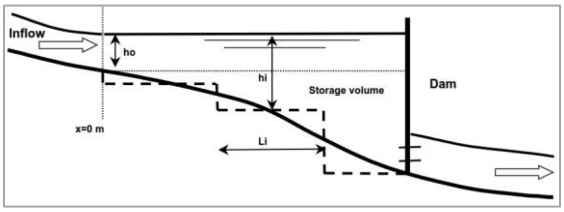

Figure 3-32. Schematization of reservoir into compartments (storage volume is volume below line through bed level at x=0 m) *(van Rijn, 2013)*

Some other relationships and examples can be found in literatures (Annandale, 1987; Morris and Fan, 1998 etc.).

Rapid Morphological Analysis

In general, rivers attain a dynamic (quasi) equilibrium state as long as there are no interventions caused by natural and man-made changes. However, this is usually not the case, since rivers are often subject to human interventions as well as extreme and episodic variations in climate. Such interventions and events often cause temporal or permanent variations in the river system. In effect, river systems adapt to every intervention and after a transition period eventually reach a new (dynamic) equilibrium alignment, characterized by a new longitudinal slopes, mean water depths, sediment size distribution and gradation as well as channel widths. An important aspect of the river response to human interventions is that the morphological changes may affect the river also far from the intervention, for example dams and reservoirs, both in downstream and upstream direction. Therefore, every intervention is felt by a large part of the river system and for this reason interventions must be carefully planned and their consequences analyzed.

There are a number of ways to analyze natural and human-made consequences and impacts on river system regardless of the fact that usually it is not very simple to quantify and replicate them. There are some simple methodologies for quick evaluations of the river response on the short and long term (Crosato, 2015). The evaluations can be carried out without the use of complex and laborious tools and techniques like mathematical modelling and detailed measurements. Such evaluations are particularly useful for preliminary assessments of the river response to the interventions and remedial measures as well as for understanding system behavior and feasibility studies. However, these simplified methods usually provide only approximate results, which need to be verified at a later stage with real-world observation, and if necessary, more sophisticated studies by using multi-dimensional mathematical model. Such basic knowledge is useful, particularly for analyzing phenomena associated with reservoir as an intervention and their impacts as well as remedial measures related to intervention in the reservoir itself.

Some simple conceptual and empirical approaches with a focus on reservoir sedimentation issues are briefly presented. These approaches are useful for estimation of relevant quantity as a first approximation. Basics about sediment transport are necessary for studying and analyzing morphological processes.

Rapid feasibility assessments of the river and reservoir responses after interventions, which also include structural, recurrent or/and non-structural measures, are rather important and desirable. The responses are usually immediate (short-term) after the interventions, and the long-term response, which is described by the new equilibrium configuration. The immediate response gives an insight in to the initial impacts as well as the temporal changes that occur during the transition period until the system attains new dynamic equilibrium state. The new equilibrium configuration describes the final state (theoretically) of the river.

The simple methodologies are mainly focused on the reach scale changes and apply to rivers and reservoirs which respond to human interventions on adapting their longitudinal bed slope rather than their planform. Rivers with low and easily erodible banks respond by adjusting their planforms (widening, narrowing, and forming a braided or meandering configuration) rather than their longitudinal profiles. In particular, the method to assess the new morphodynamic equilibrium does not apply to gravel-bed rivers, in which changes of the grain composition at the river bed take place, such as sediment sorting and armouring (due to erosion of fine and exposure of coarse sediments on the river bed) as well as hiding-exposure effects (reduction of fine sediment transport due to hiding and increase of coarse sediment transport due to exposure). In the extreme cases, the presence of an armoured bed can stop the morphological evolution. A simple methodology is given to assess the longitudinal bed slope for cases in which the river develops permanent riverbed armouring, as it may occur if the discharges are permanently lowered by the construction of a dam upstream (Crosato, 2015).

For further details, the published notes of Crosato (2015) can be reviewed.

3.4.5 Physical Modelling

Physical modeling implies a scale model of the prototype project. Sediment in the prototype is simulated in the model using either natural sediment of smaller diameter, or a less dense material such as plastic beads, ground walnut shells, etc. The main problem is the scale effect while carrying our scale model of phenomena that include not only flow but also sediment.

A number of parameters are important to determine the rate and pattern of sediment transport, for example water depth, velocity, shear stress of water against the bed, and sediment diameter. It is usually impossible to scale all these parameters coherently, therefore the flow and sediment scales have to be distorted, which is rather questionable for their translation and interpretation of the real-world phenomena. Nevertheless, physical experiments are useful to get proper insight and quantification of the complex phenomena, which at the same time can be used to verify and validate the numerical models.

Physical models are commonly used when the problem has complex dimension, i.e. usually complex and localized problems, which involve complex interaction between flow and sediment (e.g. local erosion around structures which is a three dimensional problem with the involvement of turbulence-sediment interaction). Such complex phenomena are almost impossible to replicate correctly by using a numerical model due to lack of proper physical formulation on interaction between flow and sediment motion, particularly when it is related to large-scale simulations.

Due to increasing application of numerical models that are capable of incorporating a number of knowledge and concepts on complex physical processes in parameterized way as well as reduction of computational costs (see section below for details), physical models are used less and less due to their high cost and long duration, particularly for morphological assessment in rivers and reservoirs.

Some examples of physical models of a spillway, arch dam and a sediment bypass are given in Figure **3-33**, Figure 3-34 and Figure 3-35 respectively.

Figure 3-33. Physical model of a spillway at CWPRS (India)

Figure 3-34. A physical model of a double arch dam in Hydro Lab (Nepal)

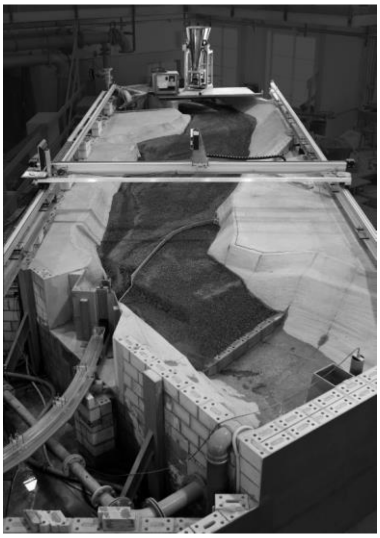

Figure 3-35. Physical model of sediment bypass at ETH-Zurich (Switzerland)

3.4.6 Computational Modelling

Application of numerical models to simulate complex processes, associated with catchment erosion, river and reservoir flow and morphology, have become rather common due to increasing possibility to use high performance computers and inexpensive computational time. Nowadays, there are number of innovative computational models, which incorporate the efficient methodology to deal with optimized reservoir operation, coupled with sediment transport and morphology, which can be used to simulate sediment management measures (for example, Mool et al., 2017). Such physics-based approach is very useful: (i) to get insight into the fundamental processes of complex phenomena like reservoir morphology and sediment management, (ii) to replicate morphological processes and storage loss in the reservoir, (iii) to assess effectiveness and impacts of sediment management measures, (iv) to assess and optimize reservoir operation considering sediment management, (iv) to check hypotheses and simulate synthetic scenarios (for which the data is scarce) and so forth.

Modelling Catchment Yield

It is possible to use process-based hydrological models, coupled with soil erosion modules, to estimate catchment sediment yield, for example Soil and Water Assessment Tool (SWAT), Water Erosion Prediction Project (WEPP), WFLOW etc. are commonly used models. Such model predictions are useful when there is scarcity of data. However, such models are sensitive to a number of parameters and the prediction may vary significantly depending upon the parameter used. Therefore, it is important to have some field data and information to calibrate the models and evaluate their performance to make meaningful and realistic predictions. Some basic ideas about the model approach, parameter used and their sensitivity including expert judgment are necessary for proper interpretation and application of the model results.

A combination of GIS application in view of available remote-sensing data images together with process based modelling is very useful to quantify catchment sediment yield and its variation.

In case of reservoirs, the record of deposited quantity in a reservoir may provide a quantitative idea about sediment yield, which can be used to calibrate the model. Several literatures and references can be found, in which the models have been used to estimate the runoff and sediment yield at catchments and watersheds (e.g. Me et al., 2015; Shrestha et al., 2013 ; Memarian et al., 2013 ; Shrestha et al., 2010 ; Shen et al., 2009; A. Singh, 2009). Flow chart, depicted in Figure 3-36, shows computational procedure of USLE model.

Modelling River and Reservoir Morphology

Computational modelling of rivers and reservoirs has been increasingly applied for last few decades due to rapid development of high performance computational facilities and decreasing computational cost. Besides,

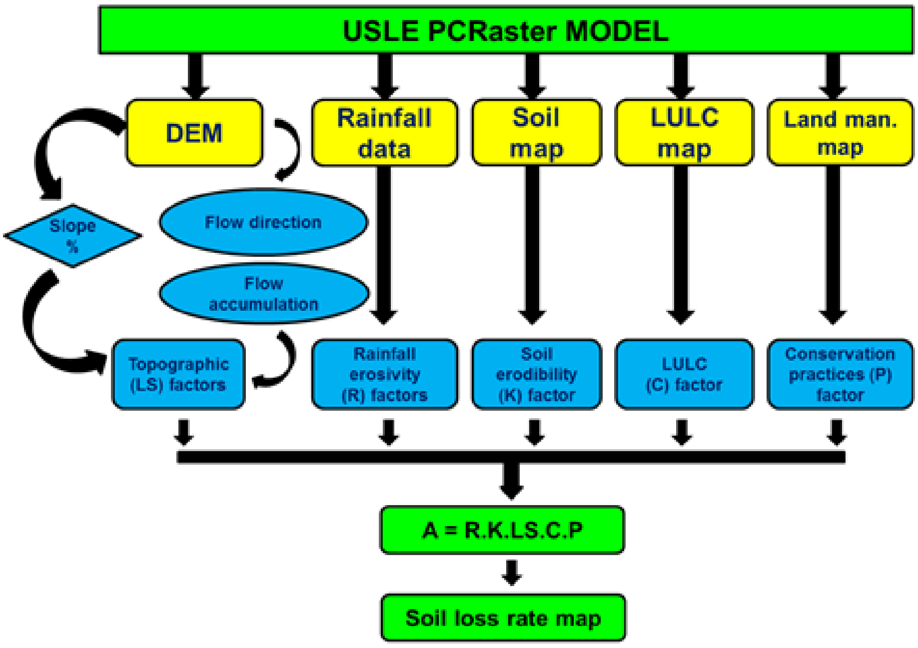

Figure 3-36. Schematic representation of USLE model to compute soil loss rate
(Courtesy: Deltares)

a number of numerical models are open source and available for free, such as Delft3D, NAYS2D, HEC-RAS, GSTARS, SSIIM, OpenFOAM etc. Advanced data collection techniques (remote sensing, LANDSAT, LiDAR, multi-beam eco-sounders etc.) and their easier availability have further expedited the application of computational models as one of the widely used and reliable tools for addressing river and reservoir flow and morphological problems.

Various modelling approaches, depending on the relevant processes, have been presented in a chart (in **Figure 3-37**), and briefly described hereafter.

One-Dimensional Model

One-dimensional (1D) models are widely used to simulate flow and sediment related problems in reservoirs due to their simplicity and cheaper computational efforts. Some of the features and distinctions of 1D models are outlined as follows:

- Usually the model solves one-dimensional St. Venant (shallow water) equation coupled with sediment mass continuity (Exner equation) and sediment transport.
- Different types of sediment and mud transport formulae are used to compute sediment transport rate.
- One-dimensional model simulates the

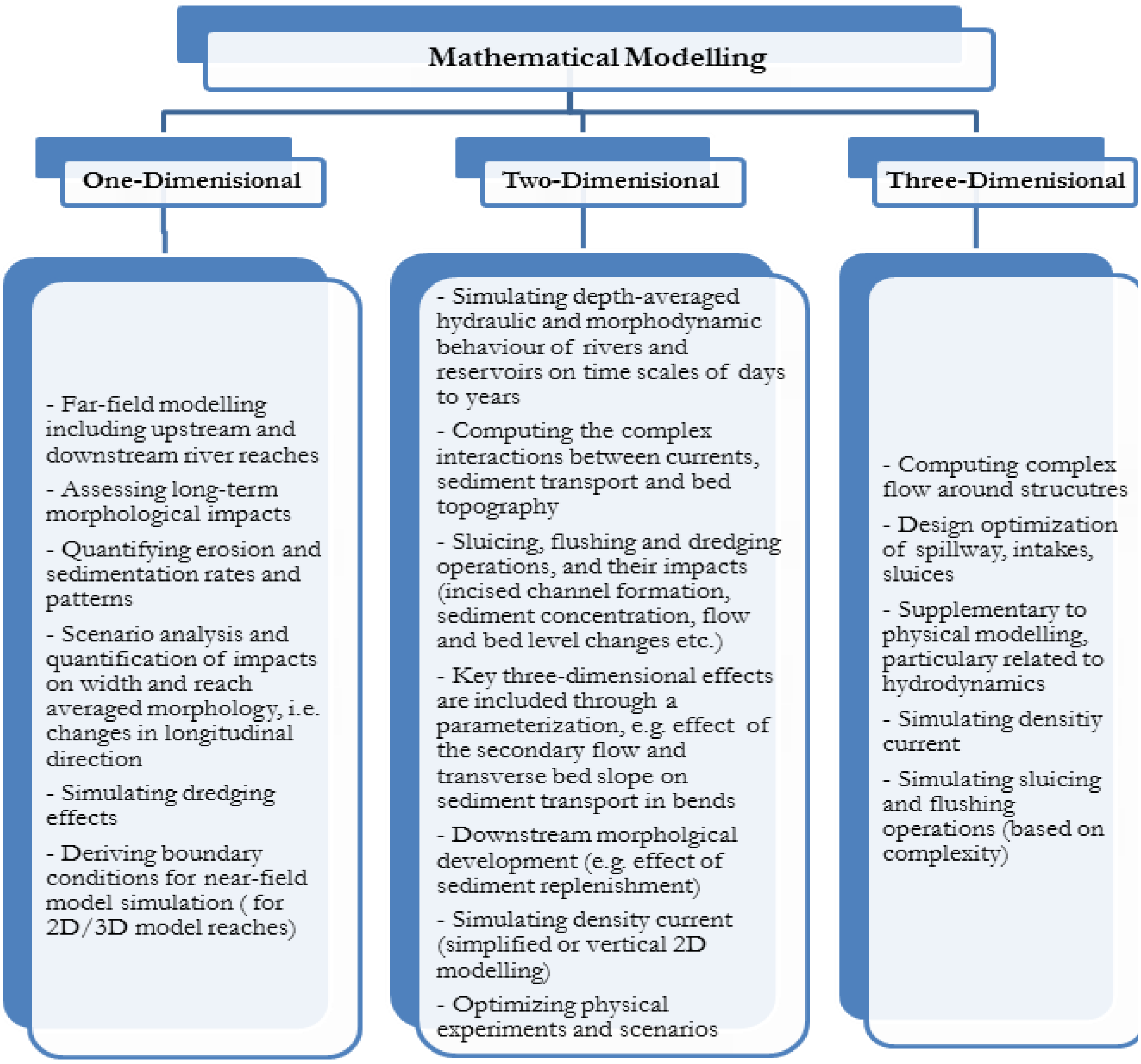

Figure 3-37. Outline of mathematical modelling approaches and relevant concerns

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 as conditions are averaged across the entire cross-section.
- A 1D model represents an obvious simplification to the real system, because sediments tend to be carried downstream with the predominate current along the reservoir. In many cases, a good approximation of sediment behavior in the reservoir can be obtained by using 1D model.
- 1D models are usually used for the evaluation of long-term morphological development as well as to examine how design and operational alternatives influence long-term morphological evolution of the reservoir.
- It is possible to include various sediment transport features in 1D model, e.g. graded sediment transport replicating hiding-exposure and armouring processes, mud transport etc.
- As a limitation, 1D model does not simulate planform morphological pattern, which is important when sedimentation and erosion in the reservoir are mostly governed by planform feature. When the reservoir has complex planform with bends, then a 1D model is not applicable to reproduce erosion and sedimentation pattern in a correct manner. For example, a cross-section in a bend reach usually shows erosion in outer bend and sedimentation in inner bend, which cannot be replicated by a 1D model as it can compute either erosion or sedimentation along the whole cross-section.
- A 1D model is not very suitable to replicate the complex processes like progress of turbidity currents through a reservoir. Although there are some examples of application of 1D models to replicate turbidity current with some improved approach.

A number of publications on 1D reservoir sedimentation modelling are available (Toniolo and Parker, 2003; Rehman et al., 2015; N. N. Rai, 2016).

Two-Dimensional Model

A two-dimensional model is more appropriate for replicating more complex and spatial patterns of erosion and sedimentation in the reservoir, e.g. transverse variation, near the intakes, sluices etc. Some features and distinctions of such a model can be outlined as follows:

- Usually the model solves depth-averaged two-dimensional (2D) St. Venant or Navier-Stokes equations coupled with sediment mass continuity (Exner equation) and sediment transport formulae.
- The models may include advection-diffusion equation for suspended sediment transport as well. However, it is not necessary to use complex approach depending on the situation, since some general transport formula considers suspended part of the total load in a parameterized way. For example, this may not be very relevant if the transport mechanism contributing to the morphological evolution in reservoir reach is predominantly bedload, since the large part of suspended load is flushed out through the spillway and desilting chamber. However, it may be important while replicating the deposition process in the reservoir with predominant suspended sediment.
- A 2D model is a depth-averaged model, which is mostly used to address river and reservoir morphological problems. Physically a depth-averaged model is not able to compute the effects of secondary flow and transverse slope on sediment transport at river bends (i.e. secondary

flow causes transverse sediment transport towards the inner bend, while transverse bed slope causes more transport towards the outer bend). However, these effects can be incorporated in the model in parameterized way (e.g. approach of Koch and Flokstra, 1980). Therefore, a 2D model is capable of simulating the morphological feature at bends as well.

- The 2D model may incorporate various useful aspects, amongst which consideration of floodplains including wet and dry processes, sediment transport over non-erodible layers and functionality for sediment management to assess dredging and dumping strategies etc.
- 2D model can also be used to create initial bathymetry, particularly upstream and downstream part of river reach, in case there is data scarce. The model can be used to replicate and analyze the morphological development of deposited sediment at downstream reach, morphological development of upstream reach, effects of sediment removal from reservoir on upstream reach (e.g. it is possible that erosion may progress upstream when sediment is removed from the reservoir).
- A 2D model can be used for simulating erosion and sedimentation pattern considering reservoir operation. This is possible by coupling the gate operation toolbox (like feedback control tool) with morphological models (Mool et al., 2017).
- A 2D model, coupled with gate operation toolbox, can also be used to replicate the effects of flushing operation, formation of erosion channel during flushing operation etc. (Mool et al., 2017).
- A number of references of 2D modelling studies are available ((Mool et al., 2017; Giri and Pillai, 2016; Giri et al., 2016; ICOLD, 2007, Sloff et al., 2004 etc., see reference section).

Three-Dimensional Model

A three-dimension model is usually used to resolve complex and local problems only, since such a model requires large computational effort, and not always justifiable due to complexity of flow and sediment coupling. Some features and distinctions are as follows:

- Three-dimensional 3D) model is a complex technique, which resolves three-dimensional Navier-Stokes hydrodynamic equation, coupled with sediment continuity and transport.
- Such complex modelling approach is relevant only when vertical acceleration is dominant, and thus very important to consider. This is generally not the case for rivers and reservoirs except for some local complex phenomena such as flow and transport around structures, which includes complex flow and turbulence.
- Particularly, for modelling morphological changes, it is not always relevant to simulate complex flow-field, since there is not much physical formulations, which can be used to replicate the interaction between complex flow, sediment transport and morphology.
- Many key three-dimensional effects can be included through a parameterization, e.g. effect of the secondary flow and transverse bed slope on flow and sediment transport in bends. Sometimes, 2D modelling with such parameterizations is good enough for practical application, since it needs considerably less computational efforts.
- It is difficult to apply 3D models for real-world large-scale modelling purpose. It is usually used for small scale high-resolution modelling to get insight in to the fundamental processes in complement with laboratory experiments.

- A recent example of application of a 3D model to replicate reservoir flushing can be found in Esmaeili et al. (2017).

Modelling Density Current in Reservoirs

An extensive review on turbidity (density) current studies is presented in Lai et al. (2015). Most numerical models adopt the layer-averaged approach that was first introduced by Ellison and Turner (1959). A complete set of layer-averaged governing equations was derived by Parker et al.(1986) for unsteady flows. Layer-averaged models have been reported by Akiyama and Stefan (1985), Fukushima et al.(1985), and Garcia (1993) for steady-state currents, and by Parker et al.(1986), Choi and Garcia (1995), Imran et al. (1998), Choi(1998), Pratson et al. (2001), Toniolo et al.(2007), La Rocca et al. (2008,2012b), and Adduce et al. (2012) for unsteady currents. The model by Toniolo et al. (2007) focused on the prediction of turbidity current movement and reservoir trapping efficiency by taking into consideration several important processes.

Only a few two-dimensional (2D) layer-averaged models have been reported that deal with unsteady, non-conservative turbidity currents. Bradford and Katopodes (1999) studied turbidity under-currents in the deep sea environment. They developed a high-resolution, total variation-diminishing, finite-volume numerical model to capture the current front.

Another category of turbidity current models is the laterally averaged 2D model, which was developed for long and relatively narrow reservoirs (e.g., Karpik and Raithby 1990). The benefit of such models is that the vertical variation of variables is resolved, which can be important for some stratified reservoirs. Laterally averaged models are applicable if water surface level does not vary significantly and there are no lateral inflows or outflows (WellsandGordon1980). The most accurate traditional models, in theory, are those based on the Navier-Stokes equations without invoking lateral or layer (vertical) averaging. Studies have been reported using the Reynolds-averaged 2D equations (e.g., Bournetetal.1999; Oehy and Schleiss2007; Huangetal.2008), the Reynolds-averaged 3D equations (e.g., Paik et al.2009; Perez 2010; Georgoulas et al. 2010), and the large eddy simulation (LES) and direct numerical simulation (DNS) models (e.g., Necker et al., 2002; Patterson et al., 2005; Ooi et al. 2009; Mahdinia et al. 2010; Radhakrishnan et al. 2012). Recently, a new and innovative approach, the Lattice Boltzmann method, was reported by La Rocca et al. (2012a, 2013) to simulate turbidity current flows. A recent comprehensive work on modelling (vertical 2D and 3D) turbidity current and its application to practical case can be found in Commandeur (2015).

General Considerations for Numerical Modelling

- First, it is necessary to identify the problems and parameters, which have to be addressed and quantified. The approach is also based on size and magnitude of the projects. It is always useful to start with more general and simple modelling approach.
- The details and complexity can be added while fine-tuning the study. Besides, the domain of interest can be divided in different reach based on nature and scale of the problem. An example of modelling approach for Tarbela reservoir in Pakistan is depicted in Figure 3-38, which provides an idea about how the modelling approach must be selected. Additionally, a chart depicted above in Figure 3-37 gives an idea about the modelling approaches and problems, which can be addressed as per their magnitude, importance, scale and relevance.
- It must be considered that more complex modelling approach, more computational efforts and time are required. Therefore, usually it is not even possible (and maybe not very

relevant) to carry out complex modelling exercise (e.g. 3D modelling) while addressing problems related to reservoir morphology and sediment transport.

- A 3D modelling is usually carried out for complex hydrodynamic simulation near the structures for the purpose of optimizing design as well as providing supplementary analysis in addition to physical experiments. For example, it may be very time consuming and expensive to carry out experiments for different scenarios. In this case, few limited scenarios can be studied using physical experiments, while modelling can be carry out for replication of more scenarios and analysis. The model can be verified and validated based on available experiments and expert judgment.
- For complex situation, approach must be as generic and simplified as possible given the fact that replicating morphological impacts using numerical model (and also physical model, in effect) is challenging task, which needs appropriate background knowledge on morphological and sediment transport processes.
- One must be aware of the limitations and nuances regarding morphological modelling of rivers and reservoirs. It is usually not possible to be assured that the quantities, estimated by the models are accurate enough. The modelling technique must be used to check the hypotheses, for conducting relative studies and assessment based on different scenarios and assumptions as well as to trigger the discussion, which are necessary for pre-feasibility, feasibility and impact studies.
- Figure 3-39 gives an impression about the dominant processes and relevant

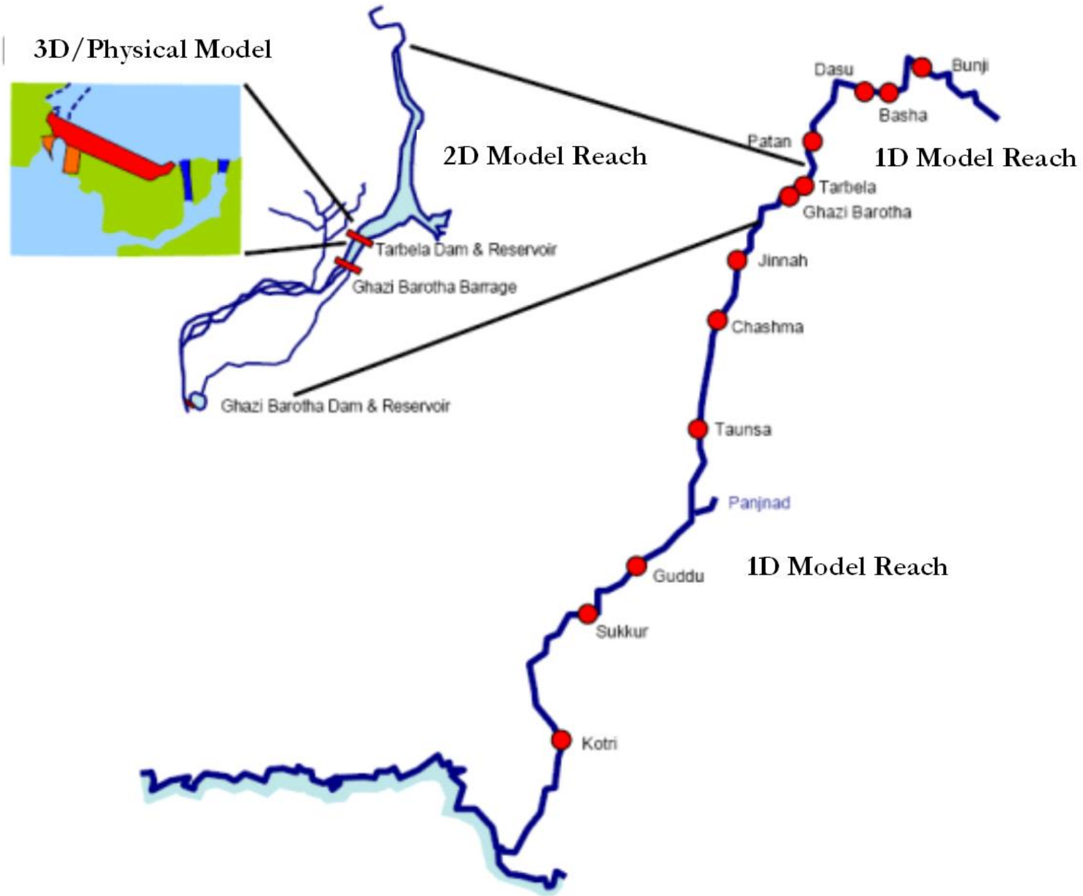

Figure 3-38. An example of modelling approach, used for modelling Tarbela reservoir in Indus River, Pakistan *(Courtesy: E. Mosselman, Deltares)*

models to simulate sediment management measures and their impacts in a cascade system of dams.

- ICOLD Bulletin (2007) and chapter 5 of USBR erosion and sedimentation manual (2006) provide a comprehensive theories, guidelines and case studies on mathematical modelling of sediment transport in reservoirs. In addition, there is a list of references in this guideline (Publications Related to Numerical Modelling), which provides useful examples of numerical modelling of reservoir.

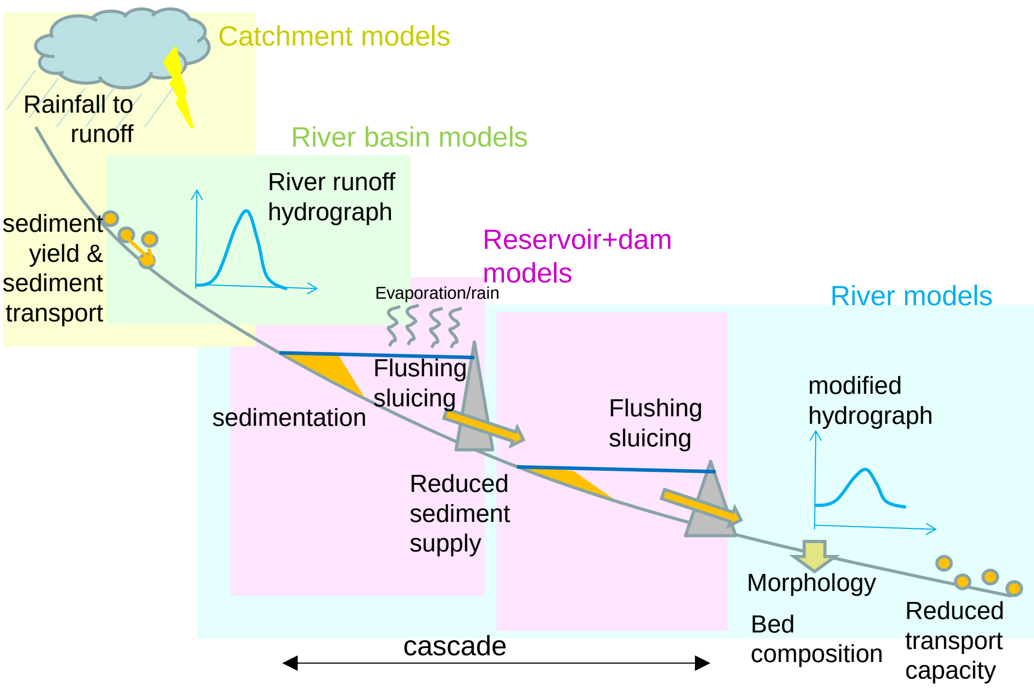

Figure 3-39. Dominant processes, and relevant models to simulate sediment management measures and their impact *(Sloff et al., 2016)*

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Chapter 4. MANAGING RESERVOIR SEDIMENTATION

4.1 General

For existing reservoirs, after having assessed the reservoir sedimentation problems in detail (as described in Chapter 3.), the sediment management measures shall be selected, designed, analyzed and implemented. The basic steps are as follows:

- Screening sediment management options and technologies
- Analyzing suitability based on constraints and limitations
- Conducting detailed feasibility and impact assessment
- Developing short- and long-term sediment management plan
- Developing monitoring and information system as well as adaptation plan (if deem necessary)

The sediment management plan shall be tailor-made for a specific reservoir or for a system of reservoirs in the same cascade and river basin (depending on to what extent they are connected to each other).

Regardless of the fact that fundamentally sediment transport and morphological processes in the reservoirs appear to be typical, there is no generic and straightforward approach and methodology to address the sediment related problems and remedial measures. Therefore, there must be a tailor-made approach (and even separate guidelines) for sediment management of each reservoir or a system of reservoirs (if they are in the same cascade or basin) to deal with these issues. The sediment management approach is based on a number of factors such as (but not limited to):

- Size and alignment of the reservoir
- Location and accessibility
- Available apparatuses and facilities in the reservoir
- Volume and type (quantity and quality) of the deposited material
- Sedimentation rate (fast, medium, slow)
- Upstream and downstream conditions
- Availability of space for silt disposal
- Morphological feature of the reservoir
- Purpose of reservoir (hydropower, irrigation, water supply, flood control or multipurpose) and its importance
- Economic, environmental and social impacts

4.2 Sediment Management Options and Techniques

Most existing sediment management measures and techniques can be grouped in different ways. One approach is to group sediment management measures and technique based on type of measures, such as structural, non-structural and recurrent, as shown in Figure 4-2. Another approach is to group them based on area or reach and methods as follows (Figure 4-1):

I. *Management, control and reduction of erosion and sediment yield at upstream catchment and rivers*: The general practice for these measures is watershed and land use management, construction of erosion control structures and sediment retention basins and traps in catchment and rivers, slope and bank protection works and diversion weirs in upstream rivers to reduce sediment inflow into reservoirs etc.

II. *Routing of sediments towards downstream*: This includes sediment bypass channel and tunnel, sluicing and density current venting.

III. *Sediment removal from the reservoir*: This includes flushing (with partial or full

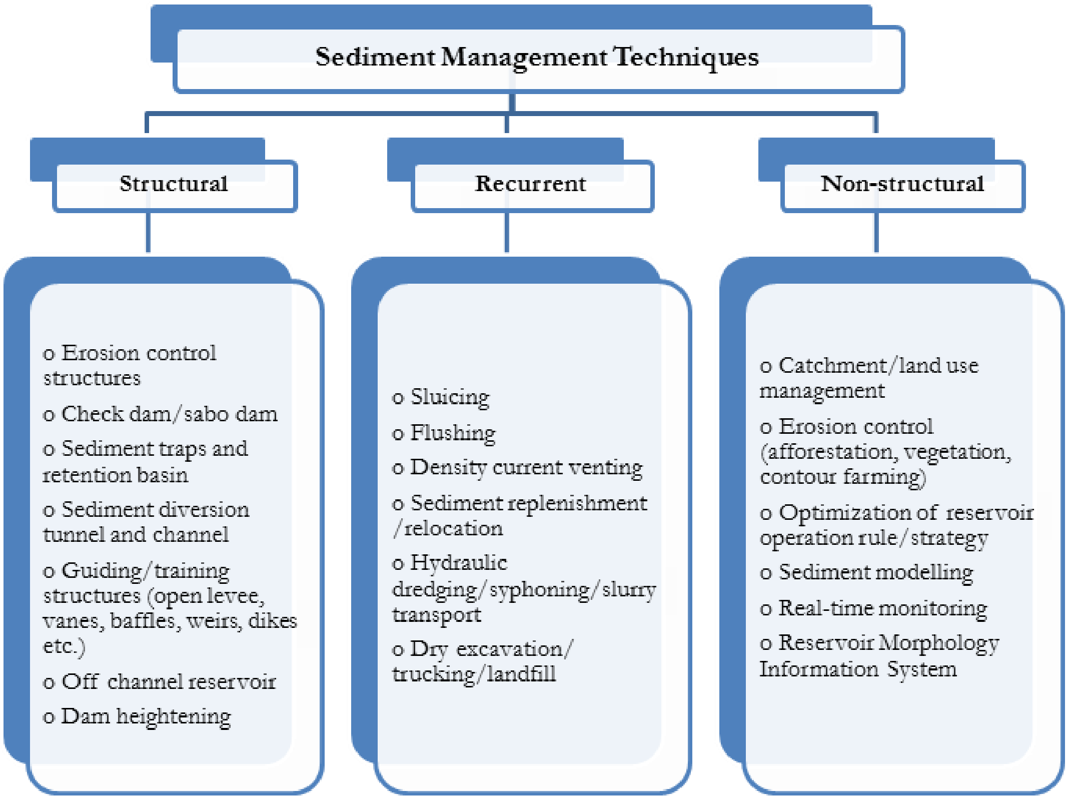

Figure 4-2. Sediment management techniques and measures

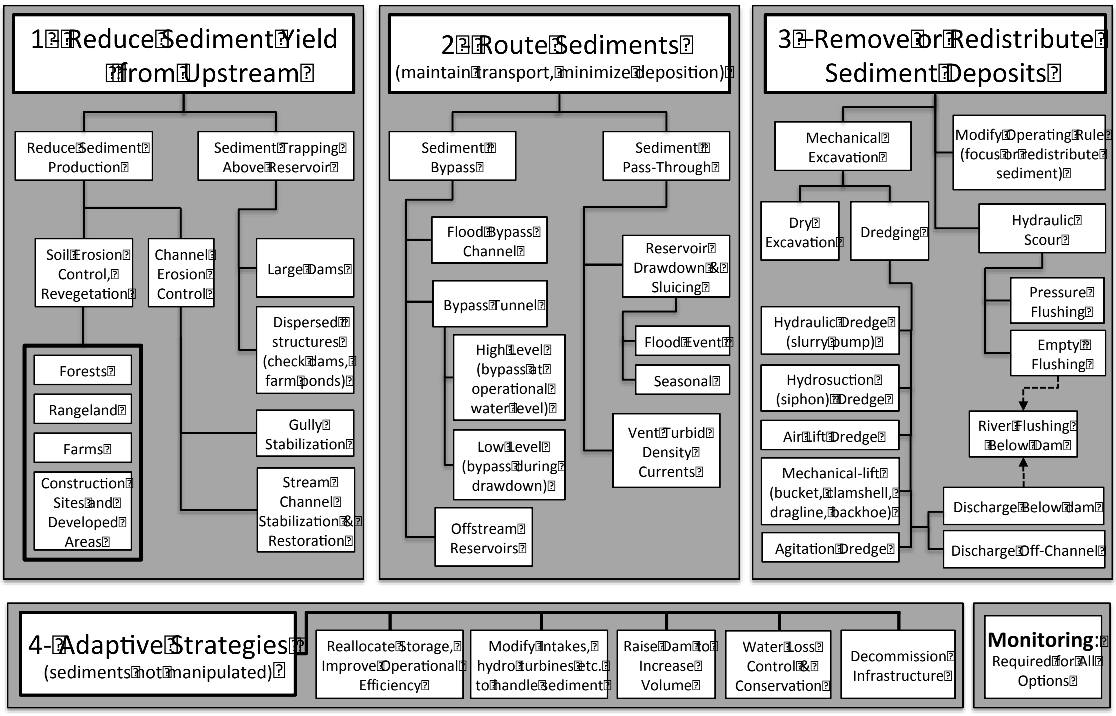

Figure 4-1. General approach of sediment management in reservoirs *(Morris, 2015b)*

drawdown), sediment redistribution inside the reservoir, sediment replenishment (dumping of coarse sediments at downstream that are transported by flood water release), dredging (hydraulic and mechanical), and syphoning.

IV. *Increase of storage capacity*: Depending upon the design condition of the dam foundation, the storage increment can be achieved by raising the dam height. This is only possible if the stability of the dam is assured. However, this solves only one problem

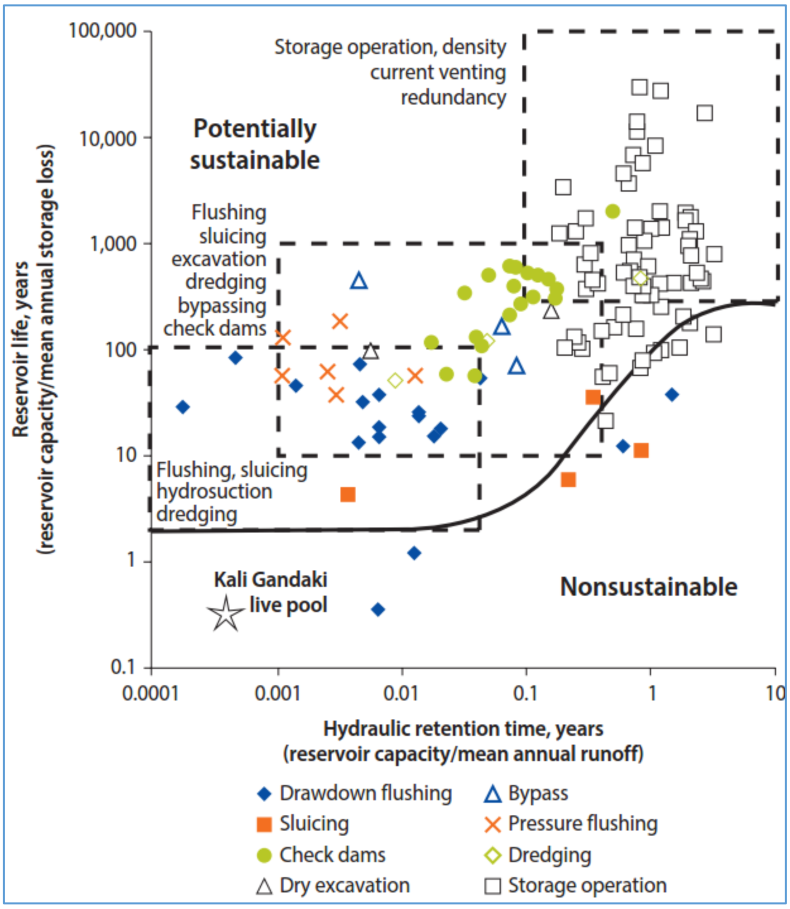

Figure 4-3. Applicability of sediment management techniques based on hydraulic parameter and sediment loading *(Annandale et al., 2017)*

regarding storage of water quantity (although the water loss increases due to evaporation and seepage), and not the sedimentation problem. Moreover, it might create other issues such as resettlement of the populace, higher cost to treat dam safety aspects, impact of dam use etc. (Howard, 2000).

A general methodology for preliminary assessment of the applicability of different sediment management techniques are presented in Figure 4-3. An example of sediment management and monitoring techniques using check dam, diversion weir and bypass tunnel in Miwa reservoir, Japan is depicted in Figure 4-4. Some more examples and practices on reservoir sediment management are presented in Section 4.2 of 4.2.

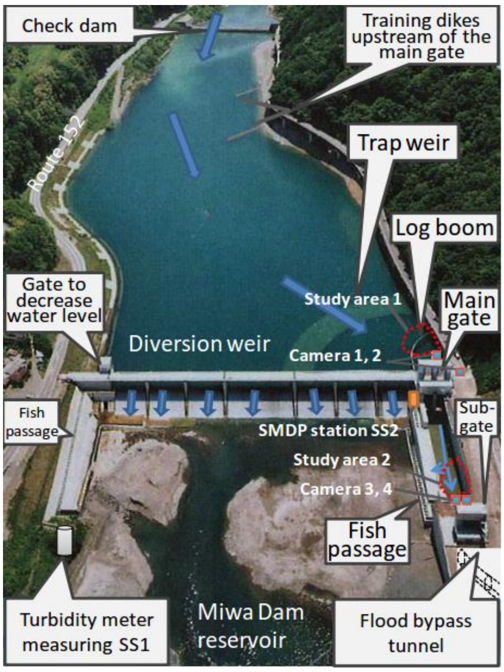

Figure 4-4. Sediment management and monitoring facilities at Miwa dam *(Kantoush et al., 2011)*

4.2.1 Erosion and Sedimentation Control

Erosion is a natural process, but human interventions can increase erosion rates by a factor of 10 or more (Annandale et al., 2016). Worldwide, most of this accelerated erosion is due to agricultural (cropping and animal husbandry), deforestation, forest fire, land and river bed encroachment and so on. All the eroded materials from basin to reach scale are source of sedimentation in rivers and reservoirs. Seeking to reduce the erosion rate to levels similar to the natural or pre-disturbance rate is one of the approaches to reduce the sedimentation in reservoirs.

Erosion control activities include structural as well as non-structural measures such as:

- Reduction of soil surface erosion, typically by promoting the growth of vegetation and afforestation
- Control of river channel erosion, particularly bank erosion
- Management of mass movement including landslides and debris flows

An overview of erosion control techniques has been compiled by Ffolliott et al. (2013).

Such control structures are usually used to control surface/slope/gully erosions at the watersheds as well as retain and/or trap the sediment at the river reach upstream of the reservoir. For the gully erosion control guidelines, publications by Geyik (1986), Valentin et al. (2005) and by Desta and Adugna (2012) are useful. Some of the structural and non-structural measures and techniques are briefly described hereafter.

Check Dams/Sabo Dams

In Japanese, the direct translation of Sabo (sa-bo) is "sand protection" (Chanson), 2001). Generally, this term refers to mountain protection system. Early sabo works were undertaken during the 17th and 18th centuries in Japan. This is basically similar to check dams. Originally, these structures used to be constructed to reduce the large sediment flow, which causes the downstream river aggradation. These days the Sabo or check dams are used to reduce the debris and torrents in hilly areas. These structures may not be economically effective due to their short lifetime and higher cost. Figure 4-5, Figure 4-6, Figure **4-7** and Figure **4-8** show different types of Sabo or check dams, constructed in different countries. There are also small check dams from local material (Brushwood check dams) that are used in India as shown in Figure 4-9.

In a review of 70 check dams installed in a semi-arid watershed in the southwestern USA, Gellis et. al. (1995) found that 47% of the structures had failed and several more were near failing after about 50 years. It was noted that check dams were most effective in reducing sediment yield when used to stabilize conditions to the point that revegetation can occur and the gullying process can be arrested. Furthermore, there are some situations when the accumulated sediments at these check dams can be used by sediment mining industries for producing construction materials. In such situation the economical effectiveness of the construction of such structures could be justified.

Some recent work on design of sediment traps can be found in Pilton and Recking (2015). In addition, different classification of check dams, their parameters and design criteria are presented by Wehrmann et al. (2006), and shown in Figure 4-10.

Figure 4-5. Sabo/check dam from steel pipes *(Sumi and Kantoush, 2010)*

Figure 4-6 Sabo dam in Ecuador *(Source: Internet)*

Figure 4-7. Slit dam in a hilly streams in Portugal, designed for a debris flow Q = 200 m^3/s *(Courtesy: LCW website)*

Figure 4-8. A sabo dam which seized debris at the time of floods of 2003, Ormoc, Leyte in Philippines (Courtesy: International Sabo Network website)

Figure 4-9. Brushwood check dam *(Image: CRD, Kerala)*

Sediment Traps/Retention

Sediments may be trapped naturally in small depressions, behind small obstructions, in channels bends forming natural morphological features like sediment bars. Therefore, the inflow sediment to the reservoir might be much less than the eroded amount from the catchment.

Retention basin is an effective way to trap sediments. Sediment trapping occurs in retention basins of all sizes, ranging from large storage reservoirs to small farm ponds. The combined effect of numerous small dispersed structures can be large. For example, there are at least 2.6 million small farm ponds, which capture runoff from 21% of the total drainage area of the conterminous in USA, representing 25% of total sheet and rill erosion (Renwick et al. 2005). However, if these check dams are not built of erosion-resistant material, and properly constructed and maintained, sediment storage structures will eventually be breached and released stored sediment. Reasons for breaching could be internal erosion (piping), downstream scour, undersized spillway, and active arroyo deepening and widening (Annandale et al., 2016).

Catchment Erosion Control

Several key elements should be considered in developing soil erosion control strategies (Annandale et al., 2016), which may help to develop long-term erosion control activities:

- Maintaining soil for the benefit of the land users and farmers must be a key priority. If farmers see benefit from soil conservation practices, these practices will become self-sustaining rather than dependent on costly subsidies or incentives.
- The effective and sustainable techniques focus on maximizing vegetative cover, including the use of minimum-tillage or no-till agriculture. Besides, terrace farming rather than bare slope cultivation must be practiced (a number of examples of bare slope cultivation without terraces can be found in South India, subjected to large surface erosion and sedimentation in the reservoirs, like in Kundah basin as shown in upper picture of Figure 4-12).
- In disturbed watersheds most of the erosion comes from a small percentage of the land surface. Consequently, it is necessary to identify and focus on areas that have the highest sediment yield and are most amenable to treatment in order to reduce erosion effectively. Forested areas, for example, may contain intensely disturbed areas such as logging roads, which capture and concentrate surface runoff flows and account for a disproportionate amount of the total erosion. Treatment should focus on these erosion hot spots.
- The most common measures are afforestation, vegetation (in catchments and riverbanks), terrace farming as well as operational measures and best management practice. Vegetation measures are based on the natural regenerative properties of vegetation or the management of crop and crop residue (mulch) to protect the soil. Vegetation is generally less expensive than structural measures and is self-renewing once it becomes established, thereby eliminating a long-term maintenance needs. If critical scour thresholds are exceeded, however, vegetation alone will not resist erosion

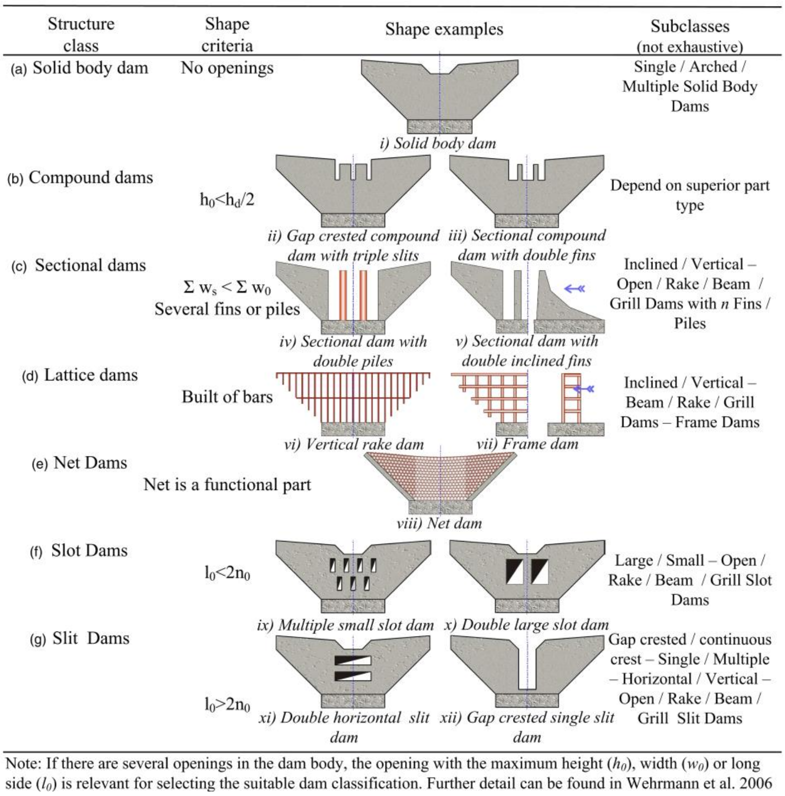

Figure 4-10. Classification of different check dams with definition of shape parameters, main classes and subclasses of structures, shape criteria and examples *(shown in Piton and Recking, 2015)*

by concentrated flows on channel banks for example (Annandale et al., 2016).

- Some other approaches are operational measures, which imply management and scheduling techniques that minimize erosion potential, such as organizing construction activities to minimize the area of exposed soil, or scheduling of timber harvest to avoid periods of high rainfall and erosion hazard. Operational measures seek to minimize erosion rate and the need for either vegetative or structural measures.
- Various bioengineering methods are being developed for controlling the soil erosion. The reasons for their use are non-availability of stones, steels, cement, sand etc. at the site and also, at places, these materials from the prepared structure are theft by the people. Various biological materials like grass tufts, pine needles and various agricultural waste is being used to stabilize the loose soil on slopes or in gullies (Pandit et al., 2009). Some of the techniques are well described in Pandit et al. (2009) including some biological methods.

There are various agricultural institutions and research centres in India that are able to deal with these problems. It may take decades for the benefits of erosion control practices in the watershed to translate into reduced sediment delivery downstream. Therefore, erosion control needs to be addressed as a long-term community-wide activity.

Figure 4-11. Catchment treatment in Kundah catchment *(Image:DRIP)*

Figure 4-12. Cultivation on bare slopes in Tamil Nadu (upper) and an example of terrace farming with vegetation protection (lower) *(Lower picture: Internet source)*

4.2.2 Sediment Routing

There are several techniques for sediment routing that take advantage of the temporal variation in sediment discharge, managing flows during periods of highest sediment yield to minimize sediment trapping in the reservoir. The basic strategy is to impound the clear water and release the sediment-laden flood flows.

Sediment routing approaches include followings (Annandale et al., 2016):

- Diverting clear water into the reservoir while selectively excluding sediment-laden flood flows
- Bypassing sediment-laden flood flows around the reservoir
- Reservoir drawdown to pass sediment-laden floods through the impoundment at a high velocity to minimize deposition, termed as sluicing
- Venting of turbid density currents through a low-level outlet

In all cases, the objective is to release sediment-laden water and impound clear water in a more or less natural way.

Sediment routing techniques require a part of the river inflow and storage volume for transporting sediment around or through the reservoir. Consequently, this may not be feasible in reservoirs, where all the inflow is being captured and stored. However, as reservoir capacity is diminished by sedimentation, sediment routing may become more feasible. This needs a careful study and optimization of reservoir operation.

Some structural and non-structural techniques of sediment routing are briefly described hereafter.

Sediment Bypass Tunnel

Bypass tunnel or channel is constructed to divert the approaching sediment-laden flow, particularly during the flood with high sediment transport. This measure is costly, so presently it is not very popular. Nevertheless, there are some advantages of this approach, e.g. it can be built at any stage, no need to drawdown the reservoir level as well as low impact on downstream environment due to the natural sediment-laden flow during floods. So far, such tunnels have been constructed only in some developed countries like Japan (3 existing and 2 under construction), Switzerland (6 existing) (Kondolf et al., 2014), Taiwan and may be some others.

One challenging issue related to the bypass tunnel is the proper design and well-planned operation considering the abrasion of tunnel surface due to sediments given that the structure is rather expensive. Presently, a number of research activities and studies are being carried out, particularly in Japan and Switzerland, to optimize their operation and effectiveness as well as to investigate the possibility to reduce negative impacts like abrasion.

Some options of bypass system are depicted in **Figure 4-13.** A real-world examples of the sediment bypass system at Miwa reservoir is shown in Figure **4-14**. While Figure 4-15 shows an evidence of abrasion problem in one of the bypass tunnels in Switzerland.

Figure **4-16** gives an impression about sediment management arrangements with check dam and bypass tunnel in Asahi reservoir in Japan, showing the behavior and effectiveness of flushing operation during floods. As it is seen in lower plot of the figure (i.e., B), the sediment discharge increases during lower level of falling stage of flood wave. This is due to the fact that the tunnel entrance becomes submerged during higher level of flood by backwater from the check dam and create orifice flow. Transport capacity of coarse sediment into the tunnel reduces due to low velocity in front of the submerged tunnel entrance. When flow rate diminishes and free flow

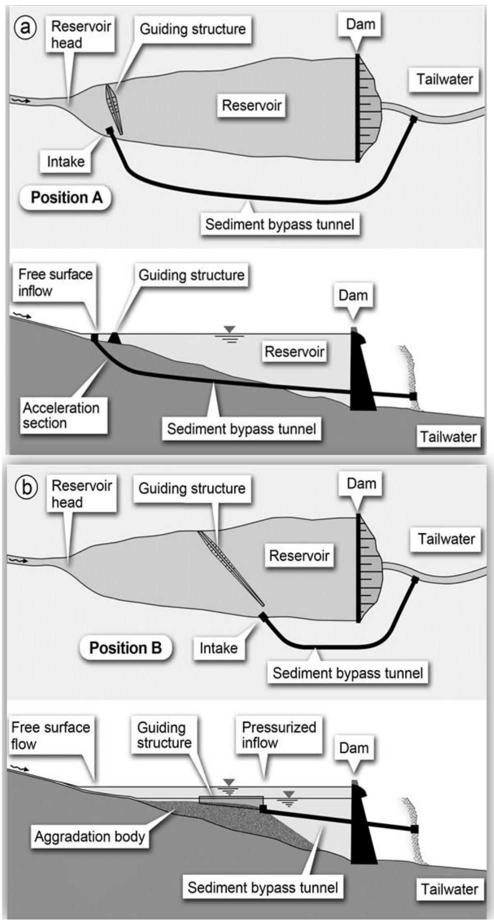

Figure 4-13. Sediment bypass options *(Auel & Boes 2011)*

occurs again at the tunnel entrance during falling stage of the flood, the higher velocity shallow flow again transports coarse material into the tunnel (Morris, 2015b).

Some examples of existing and planned bypass tunnels (in Japan, Switzerland and Taiwan) are presented in Appendix D.

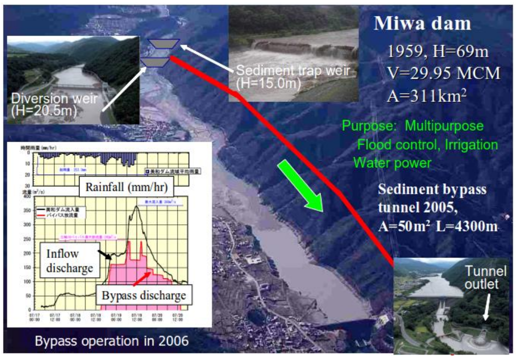

Figure 4-14. A sediment bypass system at Miwa reservoir *(Sumi & Kantoush, 2011)*

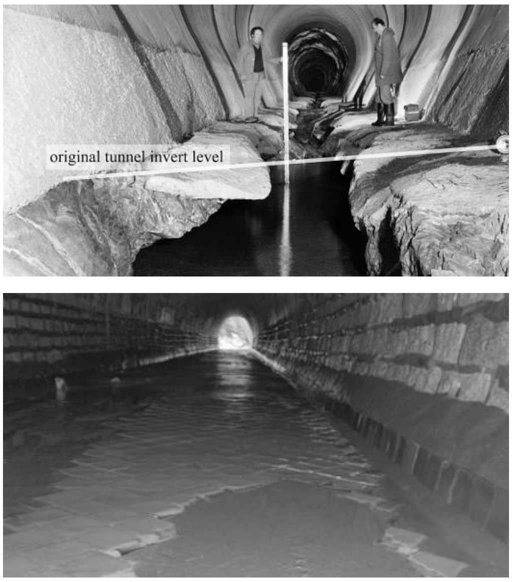

Figure 4-15. Invert abrasion in Palagnedra sediment bypass tunnel (upper image), and Pfaffensprung sediment bypass tunnel in Switzerland *(Auel & Boes, 2011)*

Sediment Sluicing

Sediment sluicing implies sediment release during flood season, when the flow carries large amount of bed material and wash loads. Sediment sluicing related features and experiences can be outlined as follows:

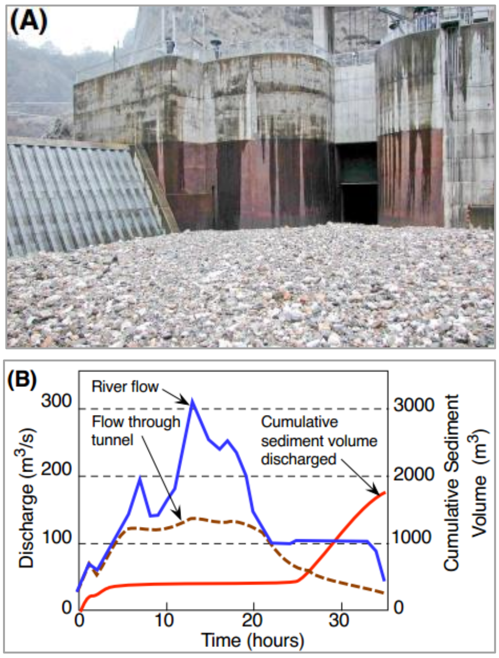

Figure 4-16. (A) Entrance to the bypass tunnel at Asahi reservoir, Japan, with check dam on left. (B) Sediment bypass tunnel behavior showing that bed material sediment is discharged only at lower level of falling stage of flood when the tunnel entrance is not submerged *(Fukuda et al. 2012; Morris, 2015b)*

- Minimize the trapping of incoming sediment in the reservoir during high flow season by designing an appropriate operation strategy
- Sluicing can also mobilize the deposited sediment in some cases (particularly when there is significant drawdown).
- The sluicing has an advantage over the flushing in terms of downstream environment, since the sediment transport in downstream takes place more or less in natural way than in flushing operation.
- For the sluicing the availability of excess discharge during the flood is important.
- The sediment characteristics, shape and morphological feature of the reservoir dictate the effectiveness of the sluicing.
- Sluicing requires sluices with large capacity for a proper release of sediment-laden flows.

- Sluicing with aggressive drawdown, reducing the reservoir level to create river flow along the impounded reach during a flood may lead to scouring of reservoir deposits and their downstream release. Such operation is also performed during the monsoon in some Himalayan run-of-river hydropower dams to preserve peaking capacity.
- Drawdown may also be planned to match the floods based on real-time observation and model forecasting. In this case, a real-time hydrologic and/or hydraulic models are used to predict inflow and optimize gate operation to pass sediment-laden floods through the reservoir.
- A basic schematic sketch of sluicing is depicted in Figure 4-17. While Figure 4-18 shows a real-world case of the sluicing during a flood flow release in the Xiaolangdi Reservoir on the Yellow River.

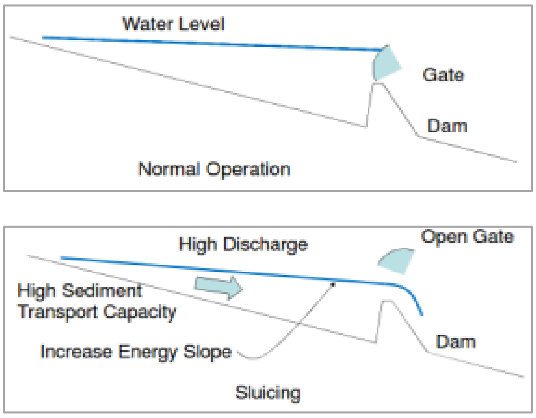

Figure 4-17. Basic schematic sketches of sluicing (Kondolf et al., 2014)

Figure 4-18. Sluicing of sediment-laden flow in the Xiaolangdi Reservoir on the Yellow River during a flood peak adjustment operation in China in 2012 *(Courtesy of Xinhua/Li Bo)*

Sediment Flushing

Unlike the sluicing, the flushing operation with partial or full drawdown of reservoir level can be carried out in any season. The flushing operation is conducted to achieve the reservoir bed erosion and re-suspension of deposited sediment and transporting it to the downstream. Some points related to reservoir flushing can be outlined as follows:

- Drawdown flushing can be categorized in empty flushing or simply flushing and sequential flushing (Annandale et al., 2016). Empty flushing, or simply flushing, entails opening a low-level outlet to completely empty the reservoir, thereby scouring sediment deposits. Sequential flushing occurs when two or more reservoirs in series are flushed simultaneously. Flow is released from an upper reservoir to scour sediment from the lower one, and the operation is planned in a way that sediment released from the upper reservoir(s) passes through the downstream reservoirs with minimal deposition. A more detailed review of flushing is given by White (2001) and Atkinson (1996).
- A generalized sequence of a flushing event is schematically illustrated in Figure 4-19 (A) (Annandale et al., 2016). As the reservoir is drawn down at the initiation of the flushing operation, sediment from upstream is eroded, reworked, and moved progressively closer to the dam as the pool level drops. When the level drops so 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 suspended sediment concentration. The concentration drops quickly as the easily eroded sediment is removed and the flushing channel and rate of erosion stabilizes. This variation in discharged water quality is conceptually outlined in Figure 4-19 (B).

- When a reservoir with consolidated sediments is flushed for the first time, the peak concentrations are typically lower than in a reservoir that is flushed on a regular basis, but the high-concentration flow is sustained for as long as the flushing channel is being actively being eroded.

- In the case of regular flushing, the sediment deposited into the flushing channel each year does not consolidate. It is rapidly mobilized and discharged as soon as free flow exists through the low-level outlet, resulting in extremely high spike in suspended sediment concentration.

- Flushing releases high sediment loads with limited water volumes, frequently producing downstream environmental impacts including low dissolved oxygen, high sediment concentration that interferes with the function of gills and smothers stream benthos, reduction in visibility and light penetration, and channel morphological impacts such as infilling of pools and clogging of river gravels with fine sediment, thereby eliminating spawning sites and habitat.

- Social and economic impacts include the interference with water treatment processes for municipal or other users, sedimentation within irrigation canals if not designed to transport sediment, accumulation in heat exchangers which draw water from the river, reduction of recreational quality, impacts to fisheries of economic importance, accumulation in flood control and navigational channels, and impacts to coastal areas.

- Regardless that the total amount of sediment released may not be different from the natural transport in the absence of the dam, the combination of high sediment concentrations during flushing, changed upstream and downstream flow and morphological conditions due to the dam, and the release of sediment-laden flow that does not fully replicate the natural hydraulic and biological cycles can produce large adverse impacts (Annandale et al., 2016).

- The maximum instantaneous suspended sediment concentration in water flushed from a reservoir with fine sediment accumulation may exceed 100,000 mg/L. In contrast, in small reservoirs with low-crest spillway and large gates (such as a barrage for hydropower or flood control), and which have accumulated predominately coarse sediment, the maximum increase in suspended sediment concentration during flushing may be as small as 5 mg/L when drawdown is controlled and

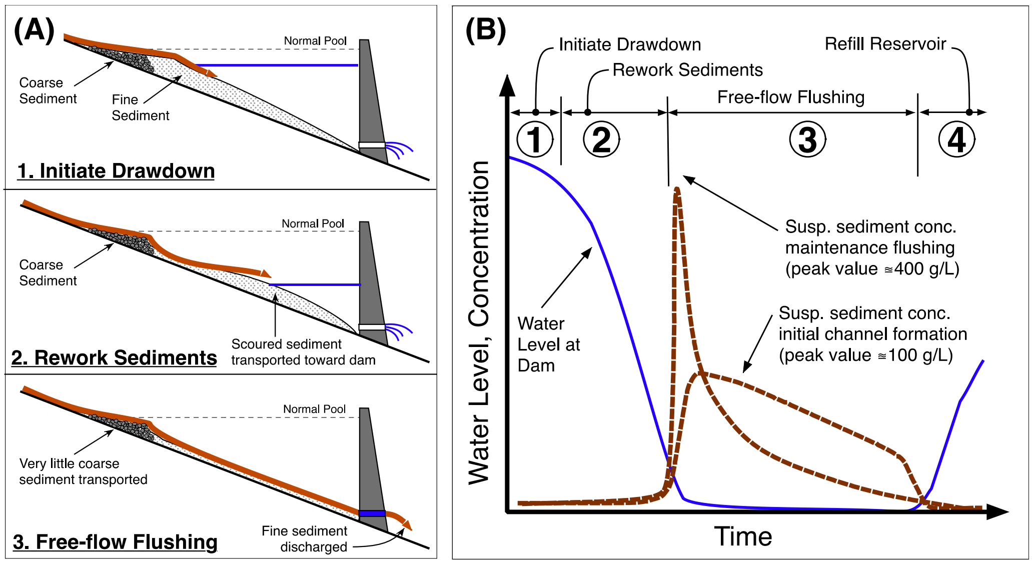

Figure 4-19. Flushing sequence (left, A) and corresponding variation of discharged flow and sediment concentration (right, B) *(Annandale et al., 2016)*

a large dilution flow is available (Espa et.al. 2014).

- Measures to minimize the adverse environmental impacts of reservoir flushing include optimizing the timing of flushing release to avoid environmentally sensitive periods (such as spawning), providing large dilution flows from either natural runoff events or releases from other dams, and flushing more frequently so that each event releases a smaller amount of sediment that can be more readily assimilated by the downstream environment.
- There is also a flushing approach without drawdown of reservoir level, referred to as pressure flushing. In this case, only bottom outlets are opened that leads to the removal of sediment within a short area with a cone-shape scour. Therefore, the removed amount of sediment is very small, and not very effective as free flow flushing. This technique can be used to maintain the immediate vicinity of an intake free of sediment. Figure **4-20** shows an schematic sketch of pressure and drawdown flushing.
- The effectiveness of the flushing operation depends on the several factors, like location and size of flushing gates, size and alignment of reservoirs. Usually, the reservoirs with low-crest spillway and gates are effective to flush (this is usually the case of flood control and irrigation barrages).
- The flushing is usually effective for narrow and small reservoirs, when flow is concentrated within a limited width without sudden expansion near the dam area. On the other hand, in wide reservoirs only a small portion of the original volume may be sustained free of sediment.
- There is a mechanism like formation of flushing channel and side erosion of reservoir deposits during water level lowering. Because of the limited duration and discharge of flushing events, the coarse fraction of inflowing sediment which is delivered to the reservoir by large flood events may continue to accumulate.
- The gate operation, its speed and opening-closing pattern and sequence may also have the effects on flushing efficiency. This is a subject of tailor-made investigations for specific reservoir (so far, not much has been done in this regard).

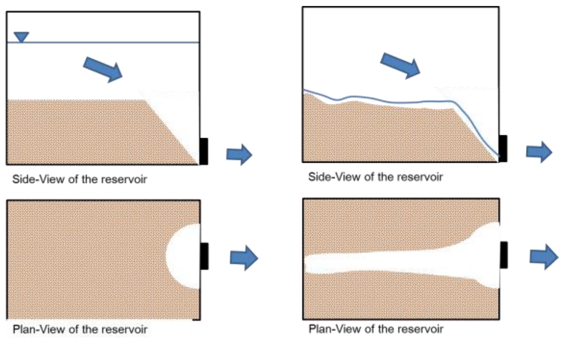

Figure 4-20. Schematic sketch of pressure flushing (left plot) and drawdown flushing (right plot) *(Meshkati et al., 2009)*

A number of references can be found regarding sediment management with flushing. A report on feasibility of flushing sediment from reservoirs (by E. Atkinson, (1996) provides some technical ideas about flushing operation of the reservoirs as well as lists of successful and unsuccessful cases of reservoir flushing).

Density Current Venting

Some specific features and points related to density current venting are as follows:

- The density current forms due to approaching flow with high sediment concentration, which has higher density, and flows along the bottom layer of the reservoir without mixing with upper layer with lower density water (a schematic sketch is depicted in Figure 4-21.

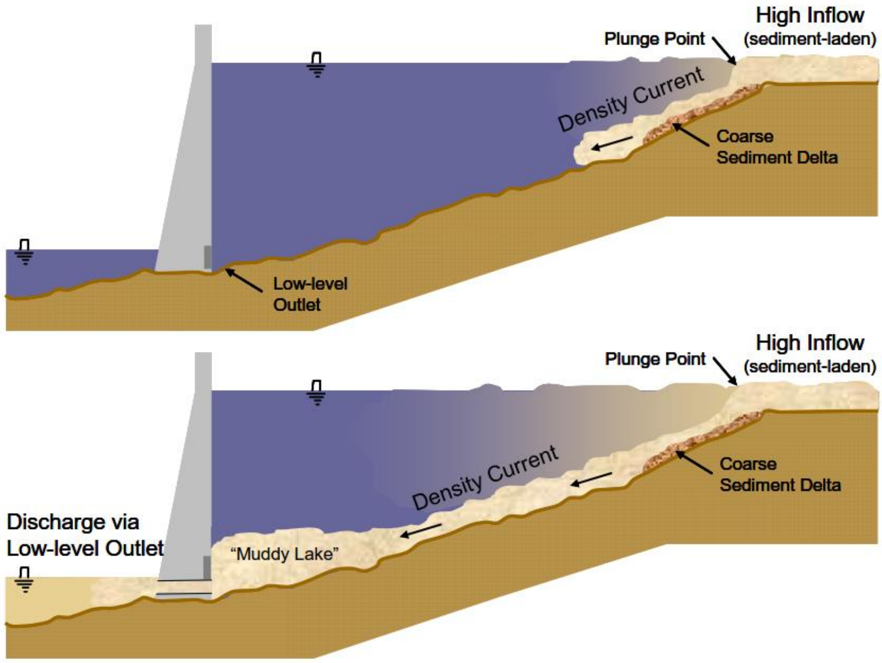

Figure 4-21. Density current venting *(Utah State Water Plan report, 2010)*

- Such density current occurs in many reservoirs, usually in deep reservoirs where there is sudden change in depth when flow enters the reservoir (so called plunge point).
- It is usually possible to allow these sediment-laden density flows to pass through the vents (bottom outlets) if they are detected and the gates of the outlets are operated timely. Therefore, the real-time measurement is important to detect the density flow near the bottom. This is not easy, but there are some advanced measurement techniques to measure real-time sediment concentration over the depth of the reservoir (an example of such monitoring system is depicted in Figure **4-22**).
- This operation does not require the drawdown. This operation is effective in case the incoming density flow has enough velocity and fine particles to form turbid flow and it should reach the dam.

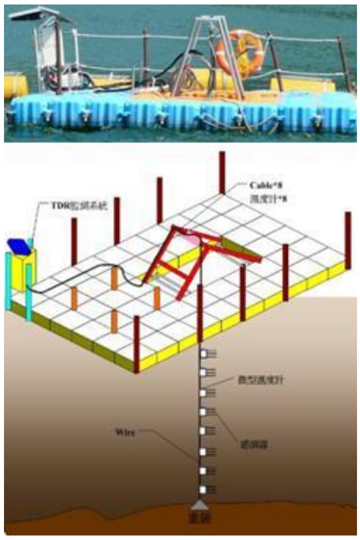

Figure 4-22. Automatic real-time sediment concentration monitoring station featured by floating installation and multi-point measurements at different depths (*www.interpraevent.at/palm-cms/upload_files/Publikationen/Tagungsbeitraege/2010__115.pdf*)

- There are several factors, which the effectiveness of density current venting depend on, such as shape and morphology of the reservoirs, sediment characteristics, approaching flow conditions, size and position of the vents (since the path of the density flow is uncertain). The efficient release of turbidity currents is dependent on successfully predicting the arrival time at the dam and timing of opening and closing the bottom outlets to minimize the settling period. Therefore, it may need real-time observation of sediment concentration and there are already some experiences with this, e.g. in Shihmen reservoir, Taiwan (Figure **4-23**). There are numerical modelling efforts as well to simulate and predict the effectiveness of density current venting process (Commandeur, 2015).

- Some of the experiences show that this operation is successful in some cases and not in others. Since density current venting does not require drawdown of the reservoir or similar operational measures, they can be well suited for sediment release starting from the first years of reservoir operation. Hydropower facilities with low-level power intakes may be well suited to release turbidity currents as long as only fine sediment reaches the dam.

- Figure 4-23 gives a schematic view of the density current venting with five zones that read as (Lai et al., 2015): (i) Zone 1: the initial zone of entering water-sediment mixture, (ii) Zone 2: the transition zone due to the plunge of the heavier incoming mixture, (iii) Zone 3: the two-layer flow zone with the undercurrent attached to the bed and propagating down the slope, (iv) Zone 4: the transition zone from undercurrent to interflow if the reservoir is stratified, and (v) Zone 5: the interflow due to the lift up of the undercurrent from the bed.

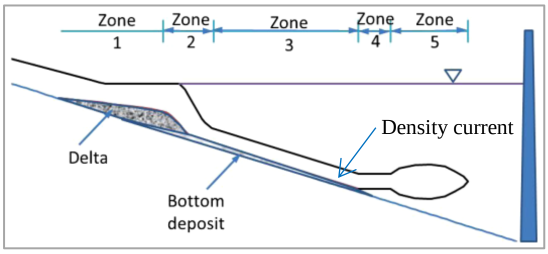

Figure 4-23. Schematic sketch of density current venting with five zones *(Lai et al., 2015)*

- Multi-level or selective-withdrawal outlets are a standard feature at many dams for water quality management and are typically used to selectively withdraw and mix water of different temperatures and depths to meet downstream water quality requirements. This same approach can also be used to release deep turbidity currents in deep reservoirs where it may not be practical to install a high-pressure low-level gate.

- A multi-level outlet or a turbidity siphon may be installed to aspirate turbid water from deeper levels in the reservoir for discharge through a higher-level outlet. Figure 4-24 illustrates turbidity siphon configurations to release deep water through a higher-level (lower-pressure) outlet. A turbidity siphon of the type illustrated in Figure 4-24 (A) is currently under construction at the Zengwen reservoir in southern Taiwan, and the ungated curtain-wall configuration for the release of turbid flood water of the type shown in Figure 4-24 (B) has been installed at the Katagiri dam in Japan (Annandale et al., 2016).

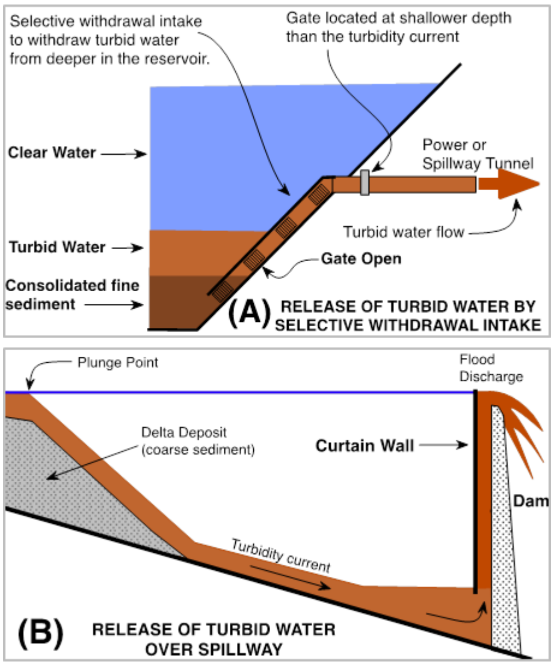

Figure 4-24. Turbidity siphon configurations to release turbid density currents (A) through a higher-level intake, and (B) over a spillway during floods *(Annandale et al., 2016)*

4.2.3 Sediment Removal

Usual technique for sediment removal from beneath the reservoir is dredging. It can be dry excavation and trucking (by depleting the reservoir) or hydraulic dredging. Some of the approaches of sediment removal and disposal as well as techniques are briefly described below.

Sediment Replenishment

Some specific features and examples of sediment replenishment are outlined as follows:

- Sediment replenishment method is one of new measures of sediment management. It is an approach to relocate the deposited sediment to the downstream. Such approach was tested in some reservoirs and still in research phase to achieve more effects and minimize downstream environmental consequences.
- In this method, trapped coarse sediment is periodically excavated (or dredged depending on the site conditions) and then transported and placed temporarily on the channel downstream of the dam, in a manner decided according to the sediment transport capacity of the channel and the environmental conditions (Kantoush and Sumi, 2011).
- The replenishment processes are efficient to restore the bedload transport and the associated habitats by coupling reintroduction with floodplain habitat restoration.
- In some developed countries, it is common practice to remove accumulated coarse sediment by excavation and dredging, and to make effective use of the removed sediment. A couple of examples have been depicted in Figure 4-25 and Figure 4-26.
- There are a number of examples, in which sediment replenishment has been exercised and investigated (Battisacco, 2016).

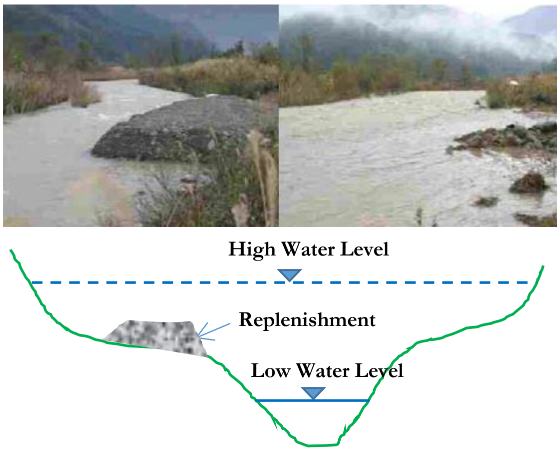

Figure 4-25. Sediment replenishment in downstream of the dam before and after the flood (upper picture) with a schematic sketch *(Sumi et al.,2010)*

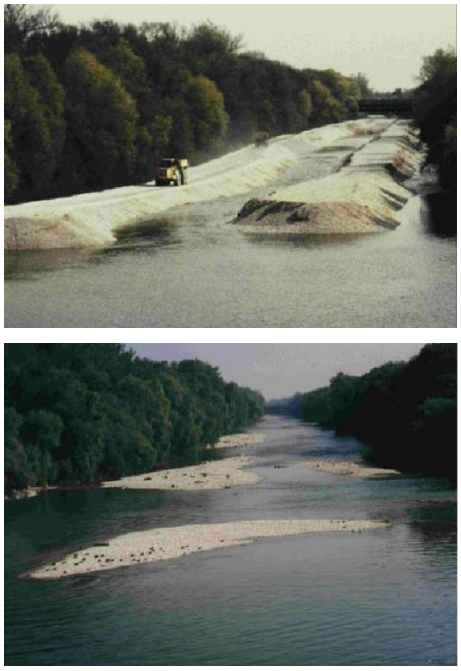

Figure 4-26. Sediment Replenishment in Isar River, Germany: upper picture shows 100 000 m^3 of gravel transported to downstream, while lower picture shows morphology after the flood *(Courtesy: S. Hartman, ALPRESERV project)*

Hydro-Suction Removal

There are two ways to remove the sediment using hydro-suction technique, namely hydro-suction bypass and hydro-suction dredging.

Hydro-suction bypass is similar to other sediment bypass approach (like bypass tunnel), in which a portion (or all) of the inflow sediment-load is captured before it enters the reservoir and transported to the downstream. In case of hydro-suction bypass, a bypass pipe at or near the reservoir bottom is used, and the sediment is removed by making use of the hydraulic head, created by the elevation difference between the reservoir and downstream water levels as well as some gravity is there if the reservoir bed is steep (Figure **4**-**27**). This technique is suitable for small to medium reservoirs with sufficient hydraulic head and finer sediment load.

Hydro-suction dredging is a sediment removal technique, which works as a syphon to remove the sediment from the reservoir to downstream through an outlet or over the dam. The technique makes use of available hydraulic head at the dam to remove the sediment through slurry pipe. Therefore, this does not need pump. Since the maximum energy available for slurry transport is limited by the dam height, operation of a hydro-suction dredger will typically be limited within a few kilometers of the dam. Figure 4-28 shows a schematic example of such system.

There are longstanding experiences of using syphoning system for sediment removal in Chinese reservoirs like in Tianjiavan, Xiahuasha, Youhe, Xihe, Taoshupo, Beichaji among others. In these reservoirs, the removed sediment slurries were used for irrigation. Another example of testing syphon dredging is Wonogiri multipurpose dam in Indonesia (Sumi et al, *internet source*). A report by Utah State Water Plan (2010) gives good overview of these (and other) sediment removal techniques.

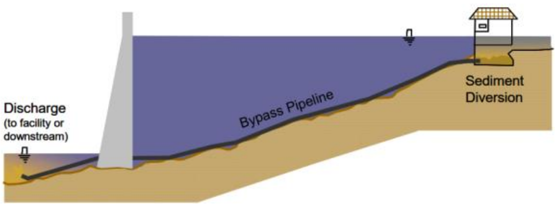

Figure 4-27. Hydro-suction bypass *(Utah State Water Plan report, 2010)*

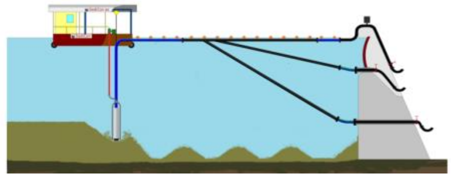

Figure 4-28. A syphon dredging system *(Jacobsen & Gupta, 2016)*

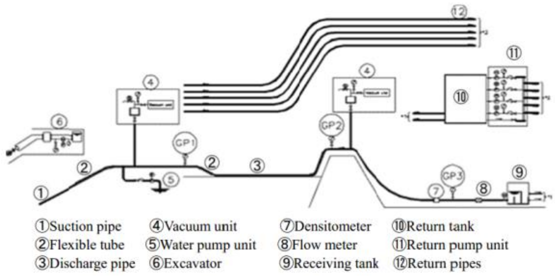

Figure 4-29. Schematic chart of syphon dredging arrangement in Wonogiri reservoir *(Sumi et al., Internet)*

Hydraulic dredging

Having dredging equipment in reservoirs for maintenance purpose is a normal practice. Some of the technologies are outlined here:

- There are equipment, adapted from conventional cutter suction (shown in Figure 4-30), which can be applicable for short- and long-term sediment removal plan from reservoirs.
- There are environmental friendly light pumps, which are suitable for maintenance work as well as for long-term sediment removal from reservoirs (Figure 4-31).
- A new technology, called dredge crawler, has been developed for under-water dredging and mining (as shown in Figure **4**-**32**). This technology could be suitable for maintenance and localized dredging as well as for sediment relocation in the reservoir (like near intakes, near under-sluices and other problematic areas).
- One of the dredging equipment that are used in the reservoirs are a modular dredger (by Damen), which has been used in the Tablachaca dam in Peru. This is easy to transport due to limited

size of the various components of the modular dredger. It is capable to dredge up to the depth of 35 m. (Figure **4-33**).

- There is also a continuous sediment transfer technology, developed by DB Sediment, which can be applied to some of the reservoirs (Figure **4-35**; www.youtube.com/watch?v=IS91ZxkRnjU).
- There are many other dredging technologies that are suitable for reservoir dredging.

Figure 4-30. A cutter-suction dredger suitable for reservoir dredging *(IHC)*

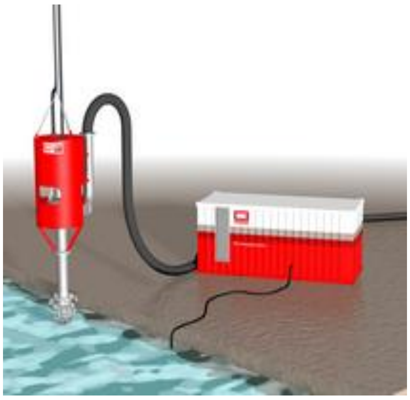

Figure 4-31. Reservoir dredging pump *(IHC)*

Figure 4-32. Dredge crawler technology for under-water dredging *(IHC)*

Figure 4-33. A modular dredger with pump in the Tablachaca dam in Peru *(https://youtu.be/UlqvF0Xq_QM)*

- While using simple installation like suction dredger, the breaching process could be interesting to analyze for removing sediments from reservoirs effectively (see Figure 4-34). Breaching is the occurrence of instabilities on a sandy slope causing a density flow running downwards from the slope. The big advantage is that it uses a relatively simple installation, which consists of a pontoon, a suction tube, a dredge pump and a discharge pipeline. The suction tube is lowered to a certain depth in a sand layer, where a hole is created around the suction mouth. The walls of this hole

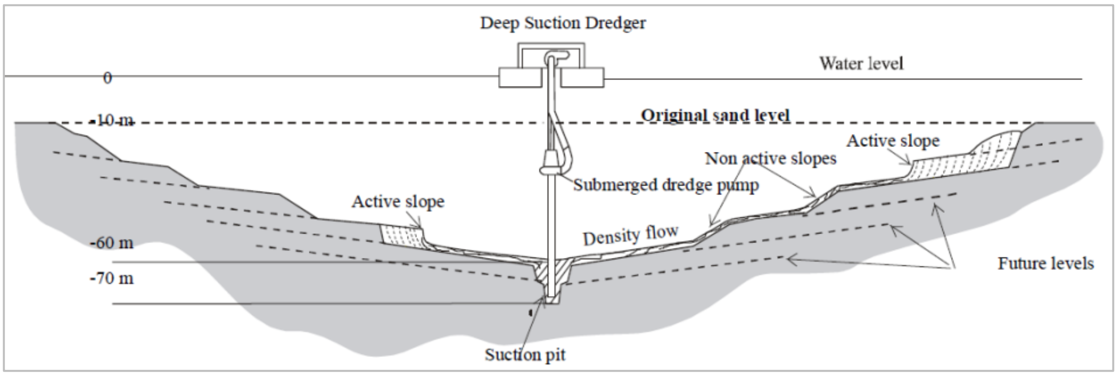

Figure 4-34. The breaching process during suction dredging *(van Rhee, 2003)*

are almost vertical and when time passes, these walls will move away from the suction tube. The sand will flow over a certain slope towards the suction mouth.

The simplicity of the installation makes is possible to use it in places where other suction dredgers, like the cutter suction, are not applicable. The production and the accuracy for this type of dredging is high, which makes the method very effective. It can be used at large depths, which is the case for most reservoirs. However, the method is effective when reservoir bed contains mainly sand (Bronsvoort, 2013).

- *Ejector Pump Dredger System (EPDS)*: This dredging equipment was developed in Japan. The EPDS (Figure 4-36) picks the deposited sediment up by means of the pressure gradient generated by jet water. This technique can be used for fine sediment as well as for gravels with maximum size of approximately 150 mm, and the suction head can be changed based on reservoir bed sediment type (also a suction head with crusher can be used). A case study can be found in Temmuyu et al. (2013).

Figure 4-35. A continuous sediment transfer technology *(DB Sediment)*

Figure 4-36. A EPDS installation in a Japanese reservoir *(Temmuyu et al., 2013)*

- *Water Injection Dredging*: Basic principle of Water Injection Dredging is that water is injected in the top layer of the bottom, where the material from the bottom is stirred up and transported away under the influence gravity (like forced density current). More specifically, the Water Injection Dredger consists of a water jet array, which is lowered to the bottom. The water jet nozzles penetrate the bed and inject large amounts of water to up the bed material. Because the bottom material is now suspended in the water, the density of mixture decreases until it becomes a liquid. This liquid will have a higher density than the ambient water and will start flowing under the influence of gravity towards lower situated areas (see Figure 4-37).

- The following requirements should be taken in account while using Water Injection Dredging:
  - A lower situated deposit site should be available, where the density current can deposit the sediments
  - A channel with a slope of 10:3 or steeper, so that the density current can flow under the influence of gravity
  - The grain sizes should smaller than 0.2 mm for the method to be effective
  - A long straight channel is preferred so that the density current can continue to flow without meeting any obstacles
  - The pump capacity of the Water Injection Dredger may range from 3000 to 12000 m^3/hr.

- The details about this method can be found in the work of K. Bronsvoort (2013).

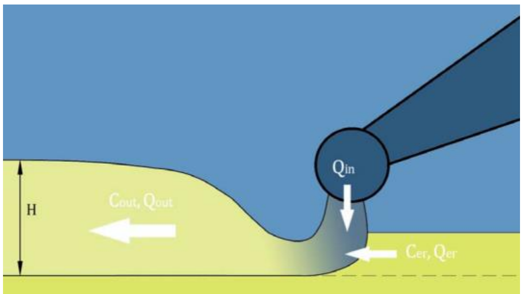

Figure 4-37. Density current created by water injection dredging *(Bronsvoort, 2013)*

Dry Excavation

- Sometimes dry excavation is inevitable for sediment removal due to a number of restrictions for using other techniques.
- Unlike dredging, it requires the reservoir level to be lowered or depleted completely to allow access to deposits by earth moving equipment.
- At some sites with predictable seasonal water level variation, dry excavation can be undertaken on a seasonal basis.
- Dry excavation can easily remove coarse material from upstream shallow (and even dry area during low flows) and the sediment delta, but removal of deep deposits of poorly consolidated fine sediment creates significant difficulties related to a period for dewatering and consolidation.
- Disposal area limitations (like in hydraulic dredging), and particularly trucking is usually more disruptive than a slurry pipeline. For large sediment volumes, dry excavation is more costly than dredging and not viable.
- An example can be found in Giri et al. (2016). A dry excavation plan in combination with hydraulic dredging has been proposed for Kundah Palam reservoir.

Remarks on Sediment Dredging and Disposal Related Aspects

Some remarks related to sediment dredging, disposal and other aspects are outlined here:

- Dredging may remove many years of sediment deposits in a single year. However, this can be economical viable only for small reservoirs with smaller dredging volume and with low sedimentation rate. At the same time, a dredging facility is usually necessary for maintenance work in most of the reservoirs.
- The disposal of dredged material is an important limitation to sustaining long-term reservoir capacity by dredging.
- In some instances, it is permissible to discharge dredged material to the river channel downstream of the dam. Discharge below the dam is advantageous for environment and ecology. However, dredged sediment is released continuously rather than being timed to coincide with natural discharge events.
- At smaller dams (usually run-off-the-river HPP) in mountainous areas with frequent downstream releases, and with most of the dredged material consisting of coarse sediment, discharge below the dam can represent a good alternative if sediment can be temporarily stored in-channel and then eroded and mobilized downstream by natural flood events.
- When downstream sediment discharge is not feasible, dredging is effective only if there is landfill area or space available for dumping close enough for slurry or trucking.
- Dredging is inherently costly, since it requires pumping slurry containing both water and sediment. A slurry pipeline must be designed to transport the largest grain sizes in the material to be dredged, and the high velocity required to sustain sand or coarser material in suspension generates high friction loss, which requires high energy input for pumping, and also increases abrasion.
- Slurry velocity, pumping costs and abrasion damage are lowest when removing uniformly fine-grained

material. Although a variety of novel dredging systems exist, including automated systems, all of them require pumping energy to move the dredged slurry and are subject to abrasion, and even novel systems cannot escape these major cost items.

- Dredging is typically much more costly than creating storage volume by dam construction, particularly in developed countries. However, it may be cost effective and useful due to engaging local work force in developing countries.
- Also, depletion of the reservoir for a long period may economically and socially not be viable and permissible.
- Dredging costs include engineering and permitting, acquisition and management of the dredged material to dump site as well as the cost of dredging itself. Use of electric drives on the dredge can significantly reduce energy costs, especially at hydropower dams, which can self-supply the electricity.
- Setting-up of dredging equipment in the reservoir as a part of long-term sediment management plan may be viable and effective for some reservoirs.
- *Before sediment removal*: Of primary importance are high-resolution contour maps of the bottom configuration for the entire reservoir and for specific sites. Comparing this information with pre-impoundment contours and selected sediment coring to verify thickness in certain locations will enable stakeholders to develop well-defined project goals and work plans to support the bidding process. All interested contractors can receive clear project goals and an accurate view and quantification of the reservoir bottom contour conditions to be reconfigured. This will minimize unknown factors and encourage preparation of the most accurate, cost-effective bids and most mutually acceptable work plan (K-State Research and Extension publication, 2008).
- *During sediment removal*: Excavated sediment can be quantified most accurately with mapped contour changes at each bottom site before and after excavation. During the sediment removal process, bottom configuration information should be available immediately before the dredge moves into a new area and immediately after the new area is completed. Such data allows contractors to more accurately quantify sediment removal continually during the project, a determination that is difficult (if not impossible) to make based only on excavated slurry on land that might still be combined with an undetermined volume of water. Quantifying excavated sediment will improve contractors' sediment removal efficiency and provides contractors and stakeholders an ongoing measure of progress related to the original goals and work plan (K-State Research and Extension publication, 2008).
- A report by TWDB (Plummer et al., 2005) provides a comprehensive overview of comparing dredging versus new reservoirs. Some experiences and practices on sediment removal are included in 0 While section 4.3 contains some information about sediment disposal practices and techniques.

4.2.4 Structural and Non-Structural Adaptive Measures

Adaptive measures are actions to mitigate the impacts of sedimentation, but they do not involve handling the sediment directly. They may be used along with or instead of active sediment management. Adaptive measures can be structural or non-structural. Some of the structural and non-structural adaptive measures are described below (some of them are adapted from Annandale et al., 2016).

Structural Modification

Sediment accumulation will eventually reach critical structures and equipment including spillways, intakes, and hydro-mechanical equipment. These components may be modified to handle the sediment, for example, by raising or otherwise modifying intakes, by providing protective coatings to hydro-mechanical equipment, or other measures.

Raising Dam

Storage of the reservoir can be increased by raising the dam. Depending upon the design condition of the dam foundation, the storage increment can be achieved by raising the dam height. This is only possible if the stability of the dam is assured. However, this solves only one problem regarding storage of water quantity (although the water loss increases due to evaporation and seepage), and not the sedimentation problem. Moreover, it might create other issues such as resettlement of the populace, higher cost to treat dam safety aspects, impact of dam use etc. (Howard, 2000). Some examples are depicted in Figure **4**-**38** and Figure **4**-**39**.

Figure 4-38. Spillway raise in Papanasam forebay in Tamil Nadu, India

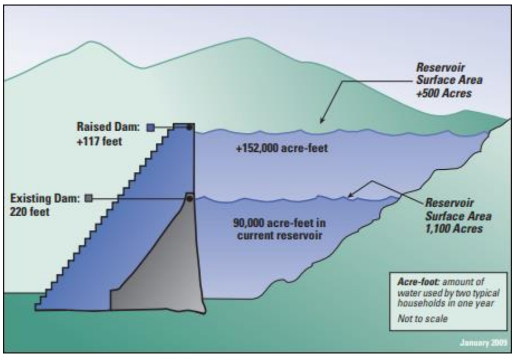

Figure 4-39. Cross-section of San Vicente dam raise (*www.sdcwa.org/ san-vicente-dam-raise)*

Raising Dams using Fusegate Systems

The fusegate systems, developed by the Hydroplus, have been applied in real-world situation in many countries (including in Gujarat, India).

- As it is claimed by the Hydroplus, the fusegate system enables the storage capacity of reservoir dams to be quickly and effectively increased, without deteriorating and, rather even improving the safety of dams during extreme floods.
- The basic idea is to remobilize a significant portion of the unused storage volume between the threshold level (Normal Level) and Highest Water Level (HWL) the installation of fusegates as an economic and environmental-friendly alternative, comparing to dredging or building a new dam.
- There are different types of fusegate systems, namely classic, folding and smart fusegates (Hydroplus).
- A Classic fusegate is a simple system with reliable operation. A sketch is shown in Figure **4**-**40**.
- A folding fusegate is a recoverable system, based on the same triggering principles as the Classic fusegate. The difference is that it is not dragged by the flood; rather it disappears downwards like a valve. It can be set back in place manually by the operator after the flood has passed (as shown in Figure **4**-**41**).
- The Smart fusegate system (Figure **4**-**42**) is also based on a single triggering principle, still independent and without energy contribution, is not dragged by the flood. It tilts around an axis and is repositioned after the passage of the flood. Alone or in conjunction with Classic fusegates, it is an effective system for optimizing the management and safety of structures, lacking energy or operation flexibility.

- Detailed information about design, functionality and real-world application of the fusegate systems can be found in *www.hydroplus.com*.
- Some real-world examples are depicted in Figure **4-43**. They have been used in five Dams in Gujrat, namely Chhaparwadi, Chopadvav (Figure **4-44**), Kakdiamba, Sonmati and Wanakbori. Besides, a case study on fusegate application in Timi N'Outine Dam in Morocco is useful to review (Ghomari and Rey, 2017).
- It is to be noted that while implementing such measures, the safety and stability of the dam as well as downstream impacts due to flood release should be assessed carefully given the suitability, upstream and downstream conditions that may be specific for each dam.

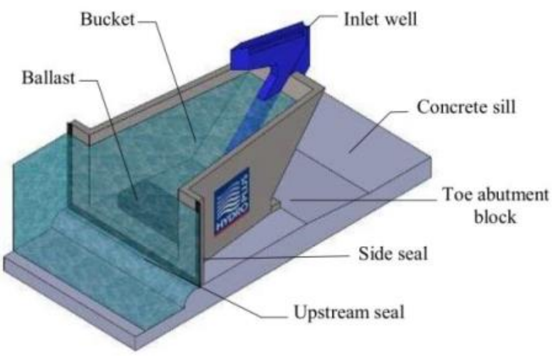

Figure 4-40. A sketch of a Classic fusegate (*www.hydroplus.com*)

Figure 4-41. A Folding fusegate (*www.hydroplus.com*)

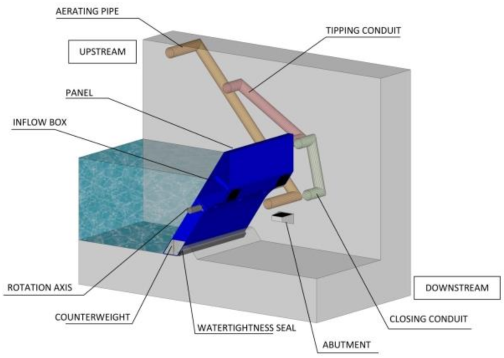

Figure 4-42. A sketch of a Smart fusegate (*www.hydroplus.com*)

Figure 4-43. The Fusegates in Black Rock Dam, US (upper) and Vorotna Dam, Armenia (lower) (*www.hydroplus.com*)

Figure 4-44. The Fusegates in Chopadvav Dam in Gujrat (India) (*www.hydroplus.com*)

Additional Storage Pond

Constructing a new storage pond nearby existing reservoir is also one of the ways to deal with storage problem, if the location allows. This is usually the case for the pump storage system in some countries, particularly in Europe. One example is shown in Figure **4-45**.

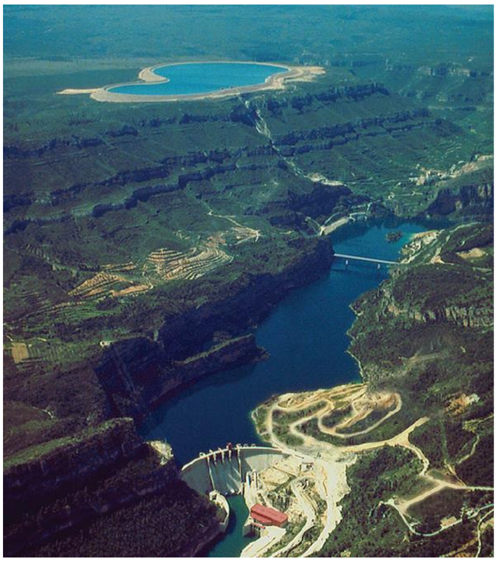

Figure 4-45. La Muela HPP with an additional pump storage pond **(***Wikipedia***)**

Decommissioning

Decommissioning implies the removal of dam and safe passage of flow and sediment, which is economically effective in case the operation cost of the dam and reservoir is more than benefits gained from them. Apart from this, there could be other reasons to consider the dam removal such as (Howard, 2000): (i) Water quality improvement, (ii) flora and fauna improvement, (iii) public safety hazard elimination, and (iv) aesthetical improvement.

However, dam decommissioning must consider the long-term management of sediment. For example, will sediment flowing over the dam eventually endanger the structure? Will the delta continue to grow upstream and threaten upstream communities or land uses? Should the dam be modified or removed to restore environmental conditions along the river? What is the fate of the sediment released by dam removal? These questions are crucial to be addressed during most of the dam removal activities.

Storage Reallocation

Multi-purpose reservoirs may be divided into two or more beneficial pools, defined based on water level. For example, a reservoir may have a high-level normally-empty pool reserved for capturing flood flows, and a lower-level normally-full water conservation pool used for water supply and/or irrigation storage. The lowest pool, dead storage, may be allocated to "sediment storage", although sedimentation will normally affect all pools. However, sedimentation does not affect all pools equally, and in many reservoirs the flood control storage pools have experienced much less sedimentation than the lower pools for water use, especially in areas where sediment inputs are primarily composed of fine material. As a result, sedimentation will impact water use pool much quicker than flood control. Pool limits may be modified to reallocate the storage loss in a more equitable manner among users so that sedimentation affects both pools to the same degree. This pool reallocation is accomplished by adjusting the boundary limit between the two pools, for example, by raising the elevation of the top of the conservation pool at the expense of the flood control pool (Annandale, 2016). An example of relocation alternatives is depicted in Figure **4-46**.

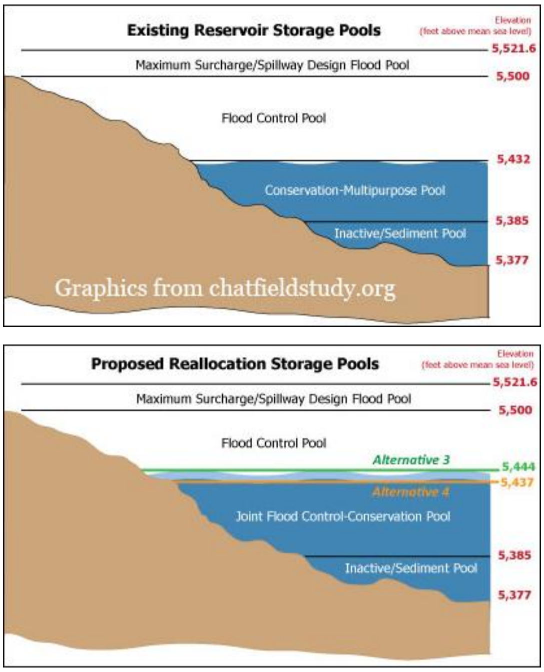

Figure 4-46. Storage reallocation alternatives (lower plot) in Chatfield project *(www.thegreenwayfoundation.org/chatfield-reallocation-project.html)*

Inflow Forecasting, Smart Operation and Optimization

One of the non-structural adaptive approaches is modification or optimization of reservoir operation rule. Some points are outlined as follows:

- If the reservoir is used for a single purpose (like hydropower), it is easier to modify the rule to deal with sediment related problem (like by raising the minimum operating level and/or changing the operation to get better flushing effect if possible).
- It may be more complex when the reservoir is multi-purpose. This needs optimization of utilization of the available storage considering all water users' demand.
- An optimized operation rule can be developed in an effective way in complement with real-time meteorological, hydrological and hydraulic observations as well as forecasting and early warning system.
- Improvements in operational efficiency are typically very economical compared to many types of active sediment management, or the construction of new dams.
- Smart gate operation to vary the morphological pattern in the reservoir and also to have more effective sediment removal when it is possible. This needs explorative studies and investigation.
- Careful manipulation with the water level at reservoir may also help to improve deposition pattern and restrict the migration of sediment delta towards the dam. Reservoir deltas are normally comprised of coarse sediment and every time the reservoir is drawn down the river flows across the top of the delta and scours sediment, moving it downstream and closer to the power intake. To slow the advance of the delta, the reservoir's minimum operating level may be gradually raised, focusing delta deposition into the upper portion of the reservoir. Figure **4-47** compares delta advancement for a constant minimum operational level against an increasing minimum operational level, showing that by gradually increasing the minimum operating level the downstream advance of the delta is retarded (Annandale et al., 2016). However, such changes have to be carefully investigated and monitored.
- Another example is implementation of Flexible Dam Operation (FDO) in a number of dams in Japan, the purpose of which is to improve the downstream river environment (Sumi and Kantoush, *internet source*). This is achieved by utilizing so called "usable capacity" without interrupting prime flood control. The "usable capacity" implies a reserved portion of dam's capacity for the event during rainy and typhoon seasons. The water stored in this capacity is called "usable water". The FDO requires temporary storage of water up to its design level or "usable water level" within flood control storage capacity as depicted in Figure 4-48. This usable storage capacity, which is newly created, is used for usable discharge as follows:

  (i) Discharge to increase the in-stream flow: The purpose is to improve fish habitat and migration, water quality, recreational view of the vicinity and conservation of downstream environment (like restoring wetlands).

  (ii) Flushing discharge: The purpose is to stir up the riverbed and flush out silt and mud, removing problematic algae and enhancing its rejuvenation, improving water odor and environment.

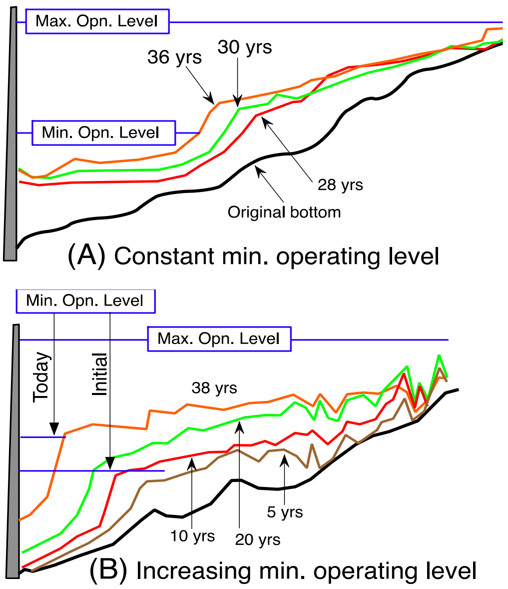

Figure 4-47. Advancement of reservoir delta: (A) with constant minimum operating level and (B) with an increasing minimum operating level. *(Morris 2015a)*

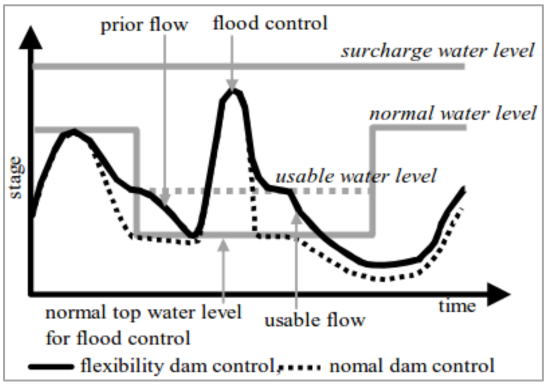

Figure 4-48. Multipurpose dam operation system-the "normal-top-water-for-flood-season" system *(http://ecohyd.dpri.kyoto-u.ac.jp/content/files/sumi-paper/2010/cSS4F-5.pdf)*

Water Loss Control and Conservation

Some ways to control and conserve the water loss are outlined:

- Water supply systems frequently contain multiple opportunities to increase water use efficiency, sustaining productivity while using less water. This may include water use conservation, practicing water reuse, and similar techniques. Water-intensive lo-valve activities may be eliminated. This strategy has considerable opportunity to address water shortages from drought and reservoir sedimentation.
- For irrigation reservoirs, the storage loss and thus reduction in availability of water may be adjusted to some extent by changing the crop pattern and/or the dependability criteria (IS 12182 guidelines, 1988). Many researches and exercises are being carried out to develop crops that require less water per unit mass of production. One more example is a recent publication in "Nature communication" could be interesting to consider and explore (Głowacka et al., 2018). All such innovations shall be considered as a part of integrated and sustainable water use.
- Minimizing the evaporation loss and other leakages from the reservoir
- In some regions, the conjunctive use of surface and ground water may be an effective strategy to reduce the impact of storage loss.

Reservoir Morphology Information System

Establishing a Reservoir Morphology Information System (RMIS) is one of the effective non-structural and very necessary measures for sustainable flow and sediment management. This is described in a separate Section 4.6.

Sediment modelling (physical and numerical) and analyses are also one of the non-structural measures, which shall be a part of RMIS. The description about modelling and analysis has been provided in previous chapter (in Section 3.4).

Advantages and limitations of afore-mentioned sediment management options are briefly outlined in Table 4-1.

In addition, it is recommended to make use of relevant manuals, guidelines, information systems, which were developed during Hydrology Project and can be downloaded via *http://hydrology-project.gov.in/GuidesandManuals_SurfaceWater.html*

Table 4-1. Sediment Management Options: Advantages & Limitations

	Options	Advantages/Functions	Disadvantages/Limitations
Structural/Adaptive	Erosion control structures (catchment treatment, check dams, sediment traps/retention)	o Reducing soil surface erosion, gully erosion o Controlling sediment and debris transport o Providing quantitative idea about upstream transport o Decreasing the slope of steep stream reach locally o Arresting gully erosion process o Trapped sediment can be reused.	o Short life time in high sediment transport region (like in North India) o Relatively higher cost o Effective only if sediment/debris is regularly removed and reused o Suitable for narrow steep streams (check dams, sabo)
	Sediment diversion structures (tunnel, channel, pipes)	o Keeping nearly natural sediment balance o Diverting large amount of bed-load transport o Reservoir operation may not be disturbed o Possibilities to use the tunnel for trucking	o High initial and maintenance cost o Abrasion problem o Low transport capacity of coarse sediment at submerged entrance (during falling stage of flood)
	Guiding/training structures (open levee, baffles, weirs, dikes, bank and slope protection)	o Reducing bank erosion o Protecting slopes, and managing landslides o Guiding flow and sediment o Retaining/trapping part of the sediment	o Limited and temporary effect o Needs careful analysis of the impact of interventions o Costly
	Off-channel reservoir	o Increasing water storage o Flood safety	o Sediment problem remains o Availability of space o Cost o Maintenance
	Dam heightening	o Increasing water storage o Safer option using Fusegate system (see Section 4.2.4)	o Sediment problem remains o May not be sustainable approach o Safety concern (due to additional load on dam) o Expensive
Recurrent	Sluicing	o Maintaining downstream river environment and quasi-natural sediment transport o No spillage (usually inflow is equal to outflow) o Minimizing trapping of incoming sediment during monsoon (releasing sediment is important particularly during first high flow of the monsoon) o Mobilizing partly deposited sediment o Low cost o Usually a requirement for the reservoir with high sediment laden flow during high flows	o Excess discharge is necessary o Effectiveness depends on predominant transport mode (suspended or bedload), reservoir and spillway feature o Requires large spillage for effectiveness

	Options	Advantages/Functions	Disadvantages/Limitations
	Flushing	○ Mobilize and remove part of deposited sediment ○ Effective for barrages with low-crest spillway ○ Effective for narrow and not very long reservoirs ○ Relatively lower cost	○ Flushing facilities are necessary (low-crest spillway with large gates, bottom outlets, scour vents) ○ Disturbed the power generation and other functionality, therefore it could be expensive ○ Water loss, particularly during drawdown flushing ○ Affecting downstream aquatic environment (necessary to maintain the turbidity) ○ Risk of downstream sediment hazard, particularly when amount of deposited sediment is large due to rare flushing operation (or no flushing for a long period of time) ○ Gate operation, its speed, opening-closing pattern and sequence may also have effects on flushing efficiency ○ Requiring proper study and planning
	Density current venting	○ Release near-bed highly concentrated flow, so large amount with less spillage ○ No drawdown is needed	○ Only for the reservoir where the phenomenon occurs (usually for deep reservoirs with sudden change in depth at the entrance, called plunge point) ○ Timely detection is necessary to operate the bottom outlet duly, therefore real-time observation of near-bed concentration is needed ○ Reaching density current up to the dam depends on reservoir shape and size ○ Requiring regular study and analysis
	Sediment replenishment	○ Controlled removal of sediment ○ Less environmental impact at downstream ○ Favourable for downstream morphology and aquatic environment	○ Transport and dumping of sediment downstream is required ○ Not very large volume ○ Effective for bedload transport (coarser sediment) ○ Requiring regular study and analysis

Options		Advantages/Functions	Disadvantages/Limitations
	Hydraulic dredging, hydro-suction by-pass, syphoning using slurry pipe transport	o Effective and environmental friendly for some reservoirs o Maintaining reservoir bed at critical areas like near intakes, outlets o Controlled removal with less environmental impacts o Possibility of sediment reuse o Syphoning is cheaper and environmental friendly o Sometimes possible to avoid disturbance (comparing to dry dredging)	o Initial cost o For hydro-suction by syphoning, head is necessary o Could disturb power generation and other functionality
	Mechanical dredging (usually dry), trucking	o Sometimes dry excavation is inevitable for sediment removal due to limitations for other option o Usually necessary for maintenance o Sometimes possible to avoid disturbance (e.g. usually larger deposition occurs at upstream reach that can be made dry without lowering the water level below minimum drawdown level) o Suitable on a seasonal basis with predictable seasonal water level variation o Effective for small reservoirs with low sedimentation rate o Could be cost effective in developing countries like India	o Costly and not effective if the volume is large o Dumping area is necessary o Difficult for consolidated deposition layer o Time consuming o Transportation may not be easy in remote areas o Environmental impact during transportation o Difficult in reserved forest and wildlife areas o Having permissions and approvals is problematic, particularly in India
Non-Structural/Adaptive	Catchment/land-use management, afforestation, vegetation, contour farming	o Erosion control o Efficient water use o Improving environment o Efficient farming o Low cost	o Social concerns (changing the way of using water and land, possible resettlement of populace)
Non-Structural/Adaptive	Optimization of reservoir operation strategy, storage allocation, crop management	o Efficient and optimal use of water o Increasing safety o Proper distribution of sedimentation problem among all storage allocation (for multipurpose reservoirs), i.e. the impact is distributed as well o Adaptive measure with low impact and cost	o Decreasing amount of water for some allocation o Requiring study and analysis of effectiveness and impacts o Requiring regular monitoring and adaptation plan
Non-Structural/Adaptive	Real-time/regular monitoring and forecasting, Reservoir Morphology Information System (RMIS)	o Improving knowledge about the system and problems o Optimizing the water use and minimizing the problems o Inevitable non-structural measure for effective and long-term sediment management o Useful (and necessary) for all above-mentioned sediment management options	o Requiring regular financial and skilled human resources o Requiring knowledge improvement and capacity development programs

4.3 Sediment Disposal and Beneficial Use

Sediment mining and its beneficial use (reuse) is a normal practice in India and around the world. Table 4-2 gives an impression about reuse of dredged materials in some selected developed countries. Similarly, Table F-1 (**Appendix F**) provides an impression about some existing national strategy and practices on dredged material management in some EU countries and USA. However, the removal and disposal of the reservoir deposits are specific problem due to various reasons.

4.3.1 Regulation in India

Major sources of sand mining in India are: (i) riverbed and floodplain, (ii) lakes and reservoirs, (iii) agricultural fields, (iv) coastal and marine areas, (v) palaeo-channels. Regulation for handling dredged material is complex as it is at the borderline of water, soil, mining and waste policies. There is not much clarity in regulation, particularly when it comes to disposal and reuse of dredged material from the reservoirs. Ministry of Environment, Forest and Climate Change has issued Sustainable Sand Mining Management Guidelines (2016) which, inter-alia, addresses the issues relating to regulation of sand mining. One of the salient features of the Guidelines is as follows:

Exemption of certain cases from being considered as mining for the purpose of requirement of environment clearance such as (among others) "**dredging and desilting of dam, reservoirs, weirs, barrages, river, and canals for maintenance and upkeep and avert natural disaster provided the dredged material is used departmentally. If the dredging activities are under taken for the purpose of winning mineral and selling it commercially it will be considered mining**."

Remark: Removed material must have values for its beneficial reuse. This shall be a part of Circular Economy concept. Therefore, the regulation related to beneficial reuse of sediments from reservoirs must be flexible and may not be strictly considered as mining of rivers.

Table 4-2. Reuse of dredged materials (DM) in some countries (Sheehan et al., 2009)

Country	Reused (% of total DM)	Remarks
Japan	90	Engineering uses (e.g. Construction of airport with DM stabilized with cement) and environmental enhancement e.g. Tidal Mudflats (DPC, 2009)
Spain	76	Used primarily for land reclamation and beach nourishment projects (Vidal, 2006)
USA	20-30	Uses include: habitat development; development of parks and recreational facilities; agricultural, forestry, and horticultural uses; strip-mine reclamation/solid waste management; shoreline construction; construction/industrial; and beach nourishment (USACE, 2007)
Netherlands	23	4% of this material is treated before reuse, 4% has a direct reuse and 15% is spread on land (Palumbo, 2007)
Ireland	20	Insignificant use of maintenance DM; 44% of capital DM reused (Sheehan et al., 2009)

4.3.2 Supporting Circular Economy Concept

In many countries, construction of new dams has become difficult due to various reasons, particularly environmental and social. India is one of them. Therefore, rehabilitation of existing reservoirs has become priority in many countries with large number of dams. There is a need to approach the sediment-induced problems in an integrated way and with a paradigm shift in thinking that sediments in reservoirs are not wastage and can be used beneficially as a natural resource, and thus can support the concept of Circular Economy (CE). The CE is the approach towards restorative concept rather than conventional concept of "Take, Make and Waste".

The beneficial reuse (Figure 4-49) shall bring not only direct economic values, but also favorable social and environmental merits (that can subsequently be incorporated in CE concept). Complementing sediment management in reservoirs with beneficial use of removed materials, will have dual advantages, namely (i) minimizing sediment-induced problems, leading to storage gain, water security, improvements and restoration of aquatic environment, structural safety, flood safety, and (ii) gaining from sediment reuse, thus supporting circular economy ("Hitting two targets with one shot!"). The concept could be equally valid for planned dams and reservoirs as well given the fact that the sediments can be treated as a valuable material, stored in a reservoir, just as water right from the beginning. Consequently, this shall be incorporated in sediment management plan and feasibility study considering social, environmental and economic impacts.

4.3.3 Problems and Constraints

Following are the problem and constraints, particularly related to removal, disposal and reuse of existing reservoir deposits:

- Location and accessibility (remote areas, preserved and protected areas)
- Lack of space and technology for disposal facilities and recycling
- Lack of industries for processing, treatment, and beneficial uses (particularly in nearby areas)
- Transportation (without technical, social and environmental impacts, distance and infrastructures)
- Quantity (usually huge amount of deposits) and quality of deposits (polluted, contaminated particularly in

Figure 4-49. Managing sediment-induced problems considering beneficial reuse

Figure 4-50. Land reclamation and improvement using dredged sediment *(Hull, 2016)*

the area of industrial effluent)

- Cost and budget limitation as well as economic viability (justification of high investments)
- Lack of market for products as secondary raw material
- limitations for beneficial use due to standards for the products
- Legal aspects and regulations in India, particularly related to reuse of dredged materials (they are considered as mining)
- Stakeholders' priorities and interests (hydropower, irrigation, water supply, recreation)

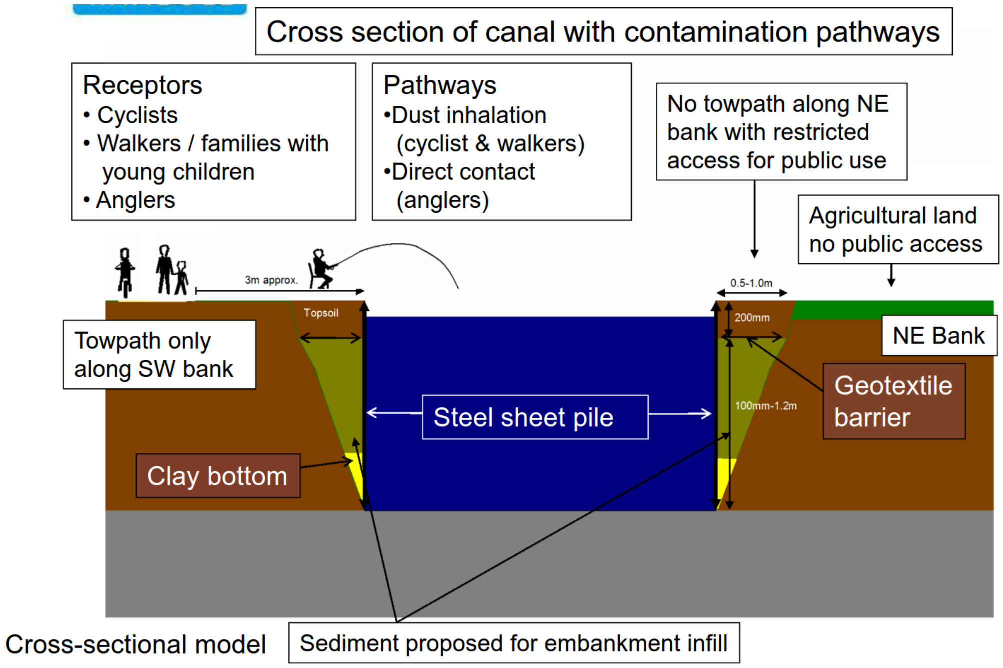

Figure 4-51. Reuse of contaminated sediment for embankment infill along the canal *(Studds and Miller, 2010)*

4.3.4 Application and Technology

Some existing applications and technology, demonstrating large possibilities for beneficial reuse of sediments, removed from rivers, seabed and reservoir, are briefly described in sections below. In addition, some of the options of beneficial reuse of dredged materials including their advantages and disadvantages are outlined in Table F-2 (**Appendix F**).

Land Reclamation, Improvement and Filling

- Reclamation of land such as polders, filling, raising and protection of sub-merged and low-lying areas as well as extension of lands (Figure 4-50 shows an example of land reclamation)
- Using material to areas where the quality of existing land is poor, such as mine-land or brownfields reclamation
- Land creation and improvement with dredged material is often associated with other benefits, such as capping or habitat creation (Great Lakes Commission, 2013).
- Use of dredged material to replace soils or other materials moved or removed for construction and landscaping projects (replacement fill)
- Use of dredged material as infill in the canal bank stabilization and pathways as shown in Figure 4-51. This reuse option saved the cost of transportation and disposal of hazardous landfill (Studds and Miller, 2010).

Capping

- Capping is the placement of clean or relatively clean dredged material on top of other sediment in the aquatic environment (Figure **4-52**).
- Usually this is done to provide a layer of cleaner material over slightly more contaminated material so that the contaminated material will not be harmful to human health or the environment (Great Lakes Commission, 2013).

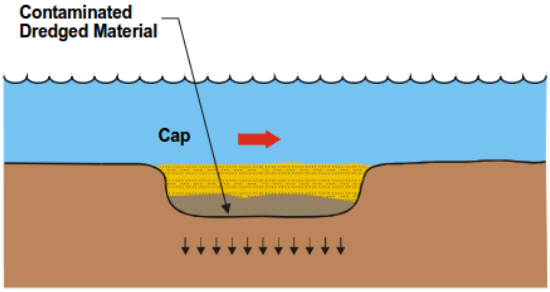

Figure 4-52. Simplified scheme of capping of contaminated material

Construction and Protection Materials

- Use of the sand component of dredged material in road construction and rip-rap
- Using as ingredient in the manufacture of bricks, ceramics, and concrete
- Use to fill geotextile bags and tubes which is used for protection, flow diversion, recreation (sometimes by growing vegetation on them) and other purposes (as shown in Figure **4-53**, Figure **4-54** and Figure **4-55**).

Figure 4-53. An example of use of geo-tubes (filled with dredged material) for bank protection *(http://erosionbarrier.com)*

Top Soil Enhancement and Agricultural use

- Dredged material is commonly composed of silt, clay and organic matter - all important and fertile components of topsoil to be used for agriculture and other purposes

Figure 4-54. Bank protection in Brahmaputra (Bangladesh) using geo-bags and blocks (as products of dredged sand)

Figure 4-55. Use of geotextile bags and tubes to recreate a lake (the dredged material of the same lake is relocated and used for recreation) *(http://deltaproof.stowa.nl)*

- Drying out finer dredged material and applying it alone or mixing it with other materials to make topsoil
- Dredged material often also requires the addition of other components such as bio-solids (manure) or processed municipal yard waste (Great Lakes Commission, 2013).
- It is also possible to reuse slightly polluted dredged sediment for agriculture by optimizing the process to decontaminate dredged sediments using plants (phyto-treatment) and the identification of crops suitable for growth in the recycled land. See *https://ec.europa.eu/environment/eco-innovation/projects*

Habitat Creation and Restoration

- Use of dredged material in aquatic, wetland or upland environments for habitat creation or restoration
- Upland wildlife habitats can be created in pre-existing dredged material containment areas that are no longer used, as well as by placement of dredged material on degraded lands or habitats. Native vegetation is then re-established to provide food and cover for wildlife
- In aquatic or wetlands environments, dredged material can be used to nourish, restore or improve habitats.
- Aquatic placement of dredged material to create shoals or shallower areas for fish habitat, or to create/enhance wetlands or aquaculture ponds for fisheries (Great Lakes Commission, 2013)

Beach Nourishment and Shore Protection

- Placement of sandy dredged material in the nearshore area or along the shore to provide a source of nourishment for natural sand movement as well as to protect the coastline and to restore a beach.

- A couple of examples of beach nourishment for management of dynamic coastline in Netherlands and Australia are depicted in Figure **4**-**56** and Figure **4**-**57** respectively.
- *Environmental impacts (Wikipedia)*: Beach nourishment has significant impacts on local ecosystems. Nourishment may cause direct mortality to sessile organisms in the target area by burying them under the new sand. Seafloor habitat are disrupted, e.g., when sand is deposited on coral reefs or when deposited sand hardens. Imported sand may differ in character (chemical makeup, grain size, non-native species) from that of the target environment. Light availability may be reduced, affecting nearby reefs and submerged aquatic vegetation. Imported sand may contain material toxic to local species. Removing material from near-shore environments may destabilize the shoreline, in part by steepening its submerged slope. Related attempts to reduce future erosion may provide a false sense of security that increases development pressure.

Figure 4-56. Sand nourishment along the coastline in North Sea *(www.dezandmotor.nl)*

Figure 4-57. Narrowneck beach before (upper) and after (lower) nourishment *(www.goldcoast.qld.gov.au)*

River Training (Soft Measures)

Dredged sand can be used to build some soft and recurrent measures for river and reservoir training and management purpose. For example, a recurrent measure of active floodplain management (AFPM) was developed and tested as a part of river management project in Bangladesh. A combination of fixed surface screens (or high-water bandals), floating surface screens, and an erodible sand plug was used (Figure **4**-**58**). This was executed to influence the morphological development of the Jamuna River in such a way that an aggressively eroding channel located adjacent to the mainland floodplain would be closed by silting its entrance.

Figure 4-58. Sand plug with brick cover in Jamuna near Katlamari *(E. Mosselman, personal communication)*

Japanese Practice on Sediment Reuse for Artificial Islands

Beneficial reuse of dredged sediment from the reservoirs is a normal practice in Japan (some examples of some good practices is presented in 0Japan has a number of airports that are located on artificial island, constructed within water body by filling dredged soil and sediment into the area separated by revetment. They are one of the best artificial islands in the world in terms of scale and technology (*www.umeshunkyo.or.jp*). Some impression about the artificial islands in Japan as well as a schematic sketch with the workflow and features of dredged material recycling system is shown in Figure 4-59.

Some alternative options of sediment reuse, practiced in some countires, are presented in Table F-3 in Appendix F.

4.3.5 Treatment Methods and Applicability

Treatment Methods

Dredged materials can be used directly or they need special treatment if they are waste sludge or contaminated. The removed materials are treated either ex-situ or in-situ, and thus the treatment methods are site specific. There are different treatment and disposal methods and technologies, being used worldwide. One of the most important treatment aspects is dewatering, particularly for the fine sediments/mud/sludge. For example, ripening of dredged material, which is a natural dewatering or drying process (Figure **4**-**60**). Raw dredged material transforms into soil influenced by chemical and physical processes. The aim of ripening is to obtain clay or soil, which complies with environmental legislations and geotechnical specifications for application in earthworks (e.g. dikes, noise reduction banks, landfill covers). In The Netherlands, ripening is applied in rural areas on a small scale and mainly for clean or lightly contaminated dredged material from regional waterways. The obtained clay or soil is locally used to raise the land for construction or for improvement and recreation (*http://deltaproof.stowa.nl*).

Some of the sediment treatment methods and technology are briefly mentioned in Table **4**-**3**.

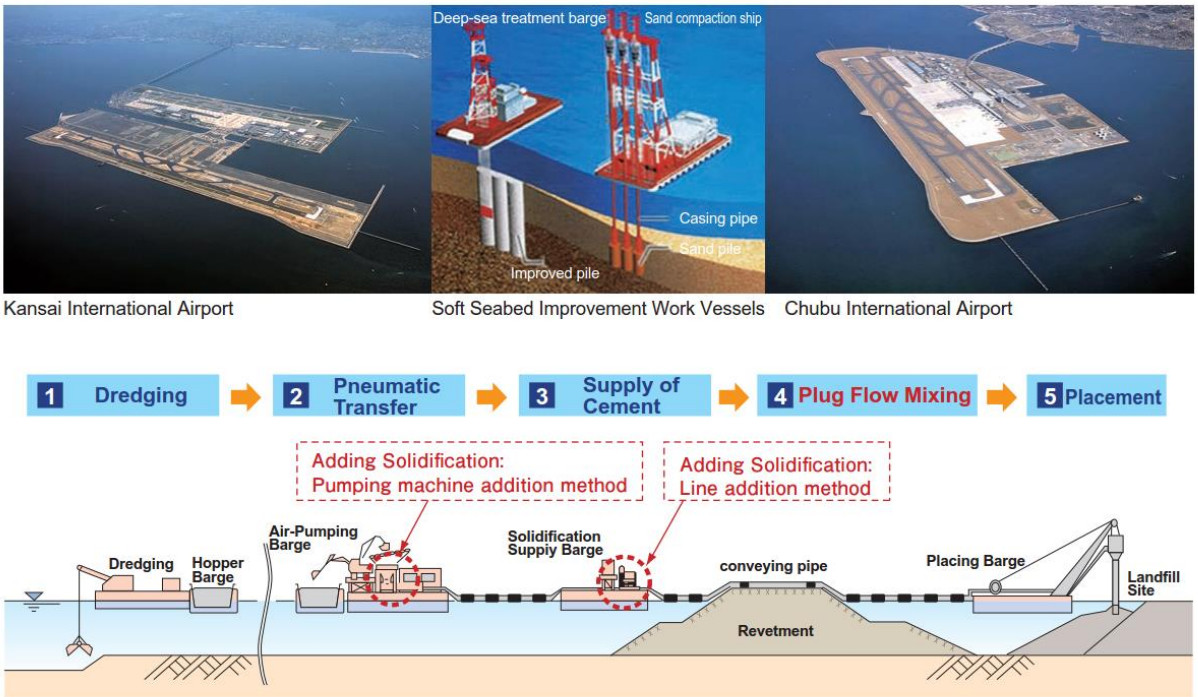

Figure 4-59. Some examples of artificial islands in Japan (upper pictures) and the workflow and features of dredged material recycling system *(www.umeshunkyo.or.jp/english/english.pdf)*

Figure 4-60. Ripening of dredged material *(Honders et al.)*

https://rwsenvironment.eu/publish/pages/126603/sediment_treatment_24_310101.pdf

Table 4-3. Sediment treatment methods and technology *(adapted from G. Bortone, 2004)*

Relocation	Open water disposal
	Injection dredging
Mechanical separation	Classification
	Sorting
Dewatering	Evaporation
	Mechanical dewatering
	Geotube with additives
Contaminant separation	Chemical extraction
	Thermal oxidation
Contaminant immobilization	Biological reduction
	Chemical immobilization
	Thermal oxidation
Disposal	Sub-aquatic confined disposal
	Upland disposal

See also Table F-4 in **Appendix F** for some treatment methods, practiced in Ireland.

Applicability and Legislation

The applicability of treatment methods depends on different factors that are mainly related to sediment type as well as level and type of contamination. Table 4-4 shows the applicability of each method. An example of Ireland's experience on different treatment options and their applicability for different type and sediment quality is presented in Table F-4 (**Appendix F**). Similarly, applicability of different options of beneficial use based on sediment quality and type is presented in Table F-5 (**Appendix F**).

In order to have an impression about the existing legislation, an example of European legislation, relevant for beneficial reuse of dredged material, is presented in Table F-6 (**Appendix F**). Similarly, a summary of some relevant DM legislation and regulation, existing in some selected EU countries is presented in Table F-7 (**Appendix F**). Some methods and practices of sand mining in some states and union territories of in India is presented in Table F-8.

4.3.6 Economics of Sediment Reuse

- The economics of removal and re-use of dredged material are highly variable and depend largely on the type of sediment supplied and required. This would also depend on the region and the country given the societal and human resource conditions.
- When very coarse material is present this can either be used directly for construction locally or be sold with profit, which will help projects financially.
- When fine sediment with a high percentage of organic matter is used, often this material will need to ripen first. This not only requires time but also space.

- Costs are also determined by the way of contractor involvement and regulation. When contractors are allowed more flexibility in organizing both the dredging activities and disposal of the material, the type of material for dredging and constructing can be matched optimally, lowering the costs of the overall project (*http://deltaproof.stowa.nl*).
- Social and environmental benefits shall be considered in economic analysis, such as navigation, aquaculture, agriculture, recreation, ecology, urban environment, drinking water, flood safety and so on.
- Detailed information about economic values, business model and regulations regarding sand mining in general in different states of India can be found in a recently published draft document "Sand Mining Recommendations" (2018), available at https://mines.gov.in/writereaddata/UploadFile/sandmining16022018.pdf.
- There is still knowledge gap and lack of proper methodology on how to make economic analysis of long-term explicit and implicit benefits owing to consideration of sediments in the reservoirs as a resource.

4.3.7 Knowledge Gap

- Since coarse materials are more widely re-used, the knowledge gaps mostly concern questions about soft dredged material, sludge, contaminated materials as well as stakeholder involvement.
- Beneficial re-use of sediments often needs further experimentation and pilot-applications before it can proceed to actual implementation.
- Geochemical and (micro-) biological processes are natural processes underlying the ripening process. However, understanding on the optimal use and interaction between these processes is limited. Research and experiments are needed to further understand these processes for improvement and accelerating ripening (dewatering).
- Further knowledge and research is necessary to improve understanding of the impact of geotechnical characteristics of sediment in the ripening process. This may lead to development of innovative technologies.
- Knowledge of boundary conditions and limitations for the reuse, the stability of the different types of sediment under different hydrodynamic and

Table 4-4. Applicability of treatment methods based on sediment type and contamination *(G. Bortone, 2004)*

	Type of sediment			Level of contamination			Type of contamination	
Process principle	**Silty**	**Silty / Sandy**	**Sandy**	**Low**	**Medium**	**High**	**Organic**	**In-organic**
1.1. Open water disposal	+	+	+	+	+/–	–	+	+
1.2. Injection dredging	+	+/–	–	+	+/–	–	+	+
2.1. Classification	+/–	+	+	+	+	+	+	+
2.2. Sorting	+/–	+	+	+	+	+	+	+
3.1. Evaporation	+	+	+	+	+	+	+	+
3.2. Mechanical dewatering	+	+	+	+	+	+	+/–	+
4.1. Chemical extraction	+	+	+	+/–	+	+	–	+
4.2. Thermal desorption	+	+	+	+/–	+	+	+	–
5.1. Biological reduction	+/–	+	+	+	+	+/–	+	+/–
5.2. Chemical oxidation	+	+	+	+/–	+	+	+	–
5.3. Thermal oxidation	+	+	+	+/–	+	+	+	–
6.1. Chemical immobilisation	+	+	+/–	+	+	+	+/–	+
6.2. Thermal immobilisation	+	+	+/–	+	+	+	+/–	+
7.1. Sub-aquatic disposal	+	+	+	+	+	+	+	+
7.2. Upland disposal	+	+	+	+	+	+	+	+

\+ Process is technically available or not negatively affected
+/– Process is technically mostly available or mostly not negatively affected
– Process is technically not available or negatively affected

geotechnical conditions, is required. Best practices around the world shall be reviewed.

- (Early) involvement of stakeholders contributes to generating public support for the beneficial reuse. In addition, a participatory approach may yield in the development of a supported knowledge base to which stakeholders have contributed.
- One of the main challenges is linking different stakeholders across institutional levels and sectors, which is required to match demand and supply.
- A second important challenge is matching demand and supply in terms of time. Dredged material may be available only at a certain moment in time. Therefore, there long-term sustainability shall be explored, particularly considering the reservoirs.
- Assessment and investigation of quantity and quality of deposited sediments in most of the reservoirs across the country shall be carried out as well as the reservoirs and the regions, where reuse is possible, shall be explored.
- Methods for evaluating the societal benefit of using sediment need to be developed. These benefits can be compared to using traditional solutions for river management including flood protection (*http://deltaproof.stowa.nl*).
- There are not much practices around the world for reusing the dredged material from the reservoirs. In India, particularly this is practiced only for limited cases (usually in rivers and coastal areas, but not much for the reservoirs).

Remarks: Please make use of **Appendix F** and the reference list (there is a separate reference list related to sediment reuse) of this handbook, "Sustainable Sand Mining Guidelines 2016", available at *www.moef.nic.in*, as well as recently published draft document "Sand Mining Recommendations" (2018), available at *https://mines.gov.in/writereaddata/UploadFile/sandmining16022018.pdf*

4.4 Sediment-Induced Problems in Hilly Region and Their Handling

4.4.1 Introduction

In Himalayan and hilly region of South Asia (like in India, Nepal, Bhutan, Pakistan and others), dams, weirs and barrages are of following types (mainly for hydropower purpose, and sometimes for multipurpose like irrigation and flood control as well, particularly in lower foothill areas):

- *Storage dam and reservoir*: High dams in hilly areas with large storage volume (usually for large hydropower production and sometimes used for irrigation and flood control as well)
- *Peaking Run-of-the-River (PROR)*: Hydropower plants, which run under natural stream flow condition, but some small storage for peaking (usually few hours in a day)
- *Run-of-the-River (ROR)*: Hydropower plants, which run under natural stream flow condition without any peaking requirement.
- *Barrages*: Low crest spillways with large hydraulic gates (usually for flood control, but also used for small hydropower production and irrigation)

4.4.2 Project Types: Advantages, Disadvantages and Problems

The mid-mountain areas of Himalayan region are very fragile and erodible. The rivers that are originated from these regions carry large amount of sediments. Therefore, sediment-induced problems are major problems for reservoirs, forebays and barrages. Some examples are published by Darde (2016). Some advantages and disadvantages as well as sediment-induced problems for each type of structures in hilly areas are briefly outlined hereafter.

High Dams and Reservoir

Advantages

- Beneficial for multiple water use
- Valuable storage under large seasonal variation (high peak, low base flow)
- Water transport possibility in hilly region due to large backwater length and reservoir depth
- Recreation and aqua-culture development
- Large dead storage and slow sediment delta migration due to large backwater effect

Disadvantages

- Inundation and loss of land
- Downstream impacts like changes in flow regime, sediment transport, morphology, bank erosion problem
- Large social and environmental impacts
- High geomorphological and technogenic risks (slope failure, landslides, dam failure, wrong operation and flow release)
- Ecological and water quality problem (like eutrophication)
- Very difficult to decommission
- Large investment

Sediment-induced problems

- Deposition of suspended sediment due to less sluicing
- Large deposition and storage loss during extreme events like flash floods with debris flow, GLOF and LDOF
- Overflow due to landslide or slope failure in reservoir area
- Problems near intake and under-sluices
- Sediment contamination

ROR and PROR HPP

Advantages

- Minimum social and environmental impact
- Minimum downstream impacts
- Economically viable in hilly regions
- Low risk for downstream settlements
- Easy to decommission
- Lower investment

Disadvantages

- No water storage, so suitable for hydropower only
- Large diversion structures, usually underground like tunnels, penstock pipes, canals
- Larger impacts of sediment-induced problems
- Necessity of sediment handling structures and facilities (like desilting basin, dredging pumps etc.)
- Regular damages of structural components and apparatuses (spillways, intakes, sills and inverts of outlets, guide wall, under-sluices, gates, turbines etc.)
- Project life and sustainability issue
- Higher operation and maintenance cost (comparing to the initial investment)

Sediment-induced problems

- High sediment load (debris) during monsoon (high rainfall period) due to higher and steeper location
- Abrasion of headwork structures and damages of apparatuses
- Turbine erosion due to high content of quartz in the Himalayan and hilly region (higher the head, larger the impact)
- Abrasion of bypass tunnels and canals (particularly sediment bypass system)

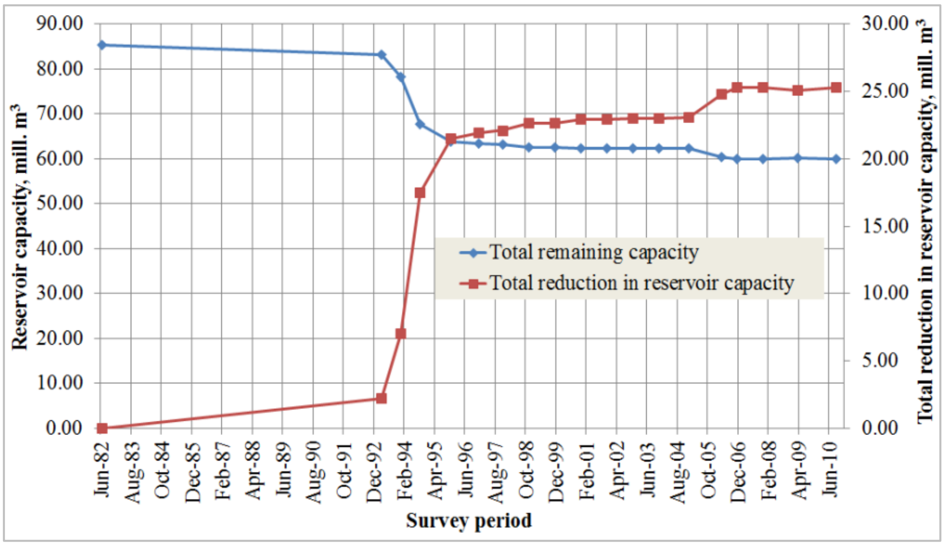

Figure 4-61. Abrupt loss of reservoir storage during flood in 1993 in Kulekhani reservoir, Nepal *(Shreshtha, 2012)*

- Example of sediment-induced problem due to LDOF in two of the PROR HPPs in Nepal is depicted in Figure 4-61 and Figure **4-62**. Similarly, the abrasion of spillway and damages of gates in one of the PROR HPP in Uttarakhand (India) is depicted in Figure 4-63.

Barrages

Advantages

- Minimum social and environmental impact
- Minimum downstream impacts
- Better possibilities for flow and sediment management using gate operation strategies
- Easier to decommission
- Lower investment

Disadvantages

- Possible in lowland areas and foothills
- Low storage
- High risk of damages and difficulties in sediment-laden rivers
- Abrasion and damages of structures and gates

- **Sediment-induced problems**
- Large sediment load may create hindrance in gate operation
- Abrasion and damages of spillways and gates
- Sedimentation and erosion problems at immediate downstream

Figure 4-62. Sediment accumulation in a hilly HPP in Nepal *(Picture: S. Giri)*

4.4.3 Handling Sediment-Induced Problems

Sediment management related descriptions and information, described in all other sections of this chapter are largely valid for the reservoirs and dams in hilly areas as well. Some of the differences are for ROR (PROR) projects and barrage due to the different sediment-induced impacts, such as abrasion and damages of structures, turbines and other apparatuses.

Figure 4-63. Abrasion of spillway glacis (left picture) and malfunctioning of gates (right picture) in Maneri Bhali Stage I (India)

High Dams and Reservoir

- Due to large dead storage as well as large backwater length in narrow hilly areas, there is relatively less problem of sedimentation in large reservoirs. However, there is an example of sedimentation problem in Salal dam in Jammu and Kashmir (India). The rock fill and concrete dams are 118 m and 113 m high, and the reservoir length was about 35-40 km long reservoir. It was silted up to the crest level just in 5 years of operation, mainly because of two major floods (Darde, 2016).
- Large reservoirs must be sustainable to be used for indefinite period, so there must be sediment management plan for such reservoirs as well.
- Availability of under-sluices is one of the requirements.
- Regular sluicing and density current venting (if applicable) during high flows with high sediment concentration to release the suspended sediments and avoid their gradual deposition
- Periodic (careful) flushing depending on the sedimentation magnitude
- Maintenance dredging (syphoning, pumping)
- Establishment of Reservoir Morphology Monitoring System for monitoring flow and sediment management operation and performance (as described in Section 4.6)

See all other sections in this chapter as well.

ROR/PROR HPP and barrages

For existing and planned projects, following points can be outlined:

- Exploring better operation of the gates, such as more uniform opening of all gates, or operation of alternate gates to have proper approach flow and morphological pattern as well as to reduce the immediate downstream impacts
- Usually, the spillway gate near the intake is operated to avoid the debris from entering to the intake. However, for certain reservoir configuration, the proper gate operation can be analyzed and checked. It is good to review the problem of Maneri Bhali – I (Giri & Pillai, 2016), which is a typical problem for many ROR projects.
- Sluicing and flushing: Usually the gates are open during high flows in ROR/PROR headworks as well as barrages, so sluicing and even flushing usually do take place. However, differently operating gates can improve the effectiveness of the flushing. Therefore, such possibilities have to be explored, first by analyzing observation

data and modelling tools, and then by testing in the field.

- Sediment removal and maintenance using dredging, pumping and syphoning
- Plant operation optimization according to the inflow sediment load based on real-time monitoring
- Sediments in Northern hilly area of India are very useful construction material, so it is possible to use excessive sediments (that are transported during extreme events) for construction and river protection works (see Section 4.3 for sediment reuse approaches)
- For new projects, the proper selection of location of the headworks with favorable flow and morphological processes as well as properly located intake (horizontally and vertically) is very important to minimize sediment-induced problems. For example, orientation of the intake slightly into the flow is essential to help reduce coarse sediment concentration by establishing a flow pattern similar to that illustrated in Figure 4-64 (Annandale, 2017).
- Innovative headwork design may also help to minimize the sediment-induced problems, but usually complex headworks are not always cost effective, particularly in developing countries (Lysne et al. 2003).
- There are several measures, which have been proposed to reduce abrasion impacts such as (Annandale et al., 2016): (i) provision of at least 0.5 m high-strength sacrificial concrete without steel reinforcing, (ii) use of hard stone granite with staggered joints, (iii) use of steel lining. The use of high-strength concrete with annual repair, and steel plate on the lowest meter of sidewalls, is found to be an economical approach at some sites. Besides, the arrangements has to be made to ensure that guard gates or stoplogs can be placed upstream, and also downstream if necessary, to enable the abrasion-prone area to be dewatered and repaired during the dry season.
- Besides such structural measures, it is very important to understand the reason for large transport of bed materials over the spillways. For example, a case study of Maneri Bhali Stage 1 has shown that the transport of large materials over the spillway have been enhanced due the high bed level of the reservoir (filled up almost up to the crest level of the spillway). The high bed level has created favourable condition for debris and large bed materials, entering from upstream during floods, to be transported over the spillway during flood passage. Additionally, in case of Maneri Bhali, such adverse impacts can be attributed to river planform (with bend) at location of the spillway and apparently gate operation rule. The detailed study can be found in Giri and Pillai (2016).
- Some research works can be found that

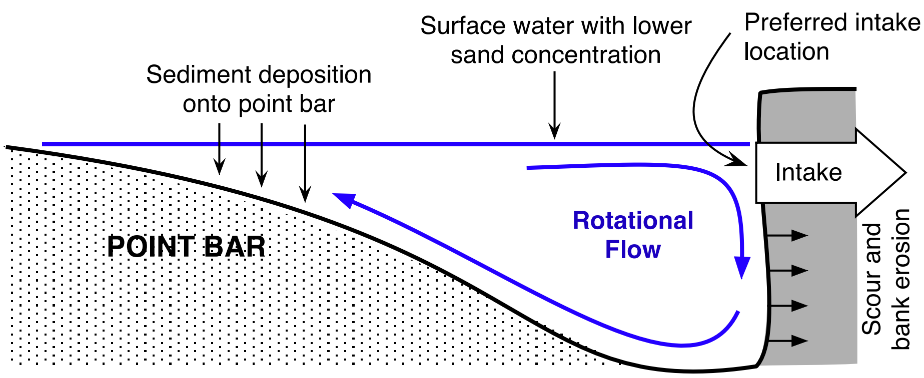

Figure 4-64. Horizontal (plunging) flow pattern at a river bend, and possibly favorable location for the intake *(Annandale et al., 2017)*

deal with high performance construction materials as well as turbine blades to minimize the abrasion.

- Establishment of Reservoir Morphology Monitoring System for monitoring flow and sediment management operation and performance (as described in Section 4.6)

See other sections of this chapter that are relevant as well.

A publication by Annandale et al. (2017) has described some key aspects of sediment-induced concerns and their handling for ROR HPP. Some real-world examples of sediment management in Hilly region can be found in 0.

4.5 Sediment Management in Planned Reservoirs

There is a complex process of feasibility study for planning and design of a reservoir. Most of the chapters of the handbook are valid for planned reservoirs as well.

One of the important aspects for an envisaged dam project is associated with consideration of morphological aspects while selecting the site, planning and designing a dam/reservoir and headworks. A concept of sustainable of reservoirs is very important to consider for planned projects. This includes consideration of integrated and multidisciplinary approach including sediment management as an integral part for sustainable utilization of reservoirs by making use of innovative tools and technologies.

4.5.1 Site Selection

Apart from other criteria, some important aspects in terms of consideration of morphological features and dynamics, and resulting sediment-induced problems should be thoroughly investigated while selecting the site. This is an important prerequisite to apply the concept of safety and sustainability of the planned project.

- Selection of a project site considering river morphological and sediment management aspects can be crucial, particularly in regions with high sediment load (like Himalayan region). For example, the project site of Middle Marsyangdi HPP (Nepal) appears to be rather unfavourable from river morphological perspective. Due to strong bend configuration of the river reach, a large deposition at inner bend in

Figure 4-65. A Google earth image of dry Middle Marsyangdi reservoir with pictures of inner bend deposition near the intake and toe erosion at outer bend protection near the spillway

front of intake has become a big problem. Moreover, toe erosion at outer bend during flow release through spillway (e.g. for flushing/sluicing) has become problematic as it seems to be leading to risk of slope instability and failure (Figure 4-65 provides an impression about these problems).

- Sediment-induced problems and their management shall be considered in the design of the dams and headworks like low-crest spillway with gates, under-sluices, bottom outlets, scour-vent etc. Also, effectiveness of new technologies and construction materials shall be investigated while updating about on-going advancement of the technology and approaches. Some publication and recent design experiences can be of help to review, such as a series of design books (Volume 8 is relevant for hydraulic design and sediment management) by Lysne et al (2003) and a book on sediment management by Annandale et al. (2017).
- Consideration of extreme episodic events is important, like in Himalayan region, where one flood event may bring a large amount of sediment (as shown an example in Figure 4-61). Therefore, it is very important to consider extreme and episodic sediment load as one of the major design criteria and thus cautiously investigate and estimate as it affects not only storage volume but also cause malfunctioning of the civil structures as well as hydro-mechanical equipment and apparatuses.
- Site selection must be based on proper deliberation, careful expert judgment complement with some detailed replication and analyses of extreme synthetic scenarios and hypotheses including uncertainties in terms of sediment loads and impacts. This is particularly vital in the region where data is scarce.

4.5.2 Sediment Analysis and Prediction

Most of the sections, presented in Chapter 3 on assessment of reservoir sedimentation are valid for planned projects as well, so are described some relevant aspects only very briefly.

Sediment Yield, Transport and Characteristics

Design estimation of sediment load is one of the crucial factors for proper design of dams and reservoirs, which might be effective for sediment management.

Following aspects shall be considered:

- Facts and figures on catchment condition and origin of sediment load
- Quality, accuracy and consistency of available data and information
- Availability of data and/or estimation of sediment load during extreme conditions. The approach must include quantification under extreme events and uncertainties.
- Data and analysis of flow as this is a basis for sediment transport estimation and morphological development
- Proper sediment sampling and characteristics (grain-size, composition, under-layers/strata, concentration)
- Consideration of major future uncertainties due to land use change, climate variation etc.
- Effects of uncertainty range on project efficiency and viability.
- Proper estimation of trap efficiency (see chapter)
- Modelling exercises with synthetic scenarios and sensitivity analysis is helpful.

Section 3.3.2 and Section 3.4.4 in Chapter 3 can also be seen.

Trap Efficiency

When a natural water and sediment flow is disturbed by creating a dam and reservoir, part of the water as well as sediments are trapped in the reservoir. Some part of sediment, however, passes during flow release through the spillway and/or under sluices. A parameter trap efficiency (TP) is used, which is defined as a ratio between amount of sediment deposits in the reservoir and total amount of sediment inflow. Commonly used empirical curves to estimate the trap efficiency are Churchill curve (1948), a sediment index method mostly used for small reservoirs, Brune curve (1953), a capacity-inflow method mostly used for large reservoirs, and Brown's curve, a capacity-watershed method as well as other methods.

Section 3.4.4 in Chapter 3 as well as Appendix B can also be seen.

4.5.3 Morphological Analysis and Prediction

Rapid Morphological Assessment

Rapid feasibility assessments of the river and reservoir responses after interventions, which also include structural, recurrent or/and non-structural measures, are rather important and desirable. The responses are usually immediate (short-term) after the interventions, and the long-term response, which is described by the new equilibrium configuration. The immediate response gives an insight in to the initial impacts as well as the temporal changes that occur during the transition period until the system attains new dynamic equilibrium state. The new equilibrium configuration describes the final state (theoretically) of the river.

The simple methodologies (presented in Crosato, 2015) are mainly focused on the reach-scale changes and apply to rivers and reservoirs, which respond to human interventions on adapting their longitudinal bed slope rather than their planform. Rivers with low and easily erodible banks respond by adjusting their planforms (widening, narrowing, and forming a braided or meandering configuration) rather than their longitudinal profiles. In particular, the method to assess the new morphological equilibrium does not apply to gravel-bed rivers, in which changes of the grain composition at the river bed take place, such as sediment sorting and armouring (due to erosion of fine and exposure of coarse sediments on the river bed) as well as hiding-exposure effects (reduction of fine sediment transport due to hiding and increase of coarse sediment transport due to exposure). In the extreme cases, the presence of an armoured or non-erodible bed layer can restrict the morphological evolution. A simple methodology is given in Crosato (2015) to assess the longitudinal bed slope for cases in which the river develops permanent riverbed armouring, as it may occur if the discharges are permanently lowered by the construction of a dam upstream.

For details, see the published lecture note of A. Crosato (2015)

Detailed Morphological Assessment

Detailed morphological analysis can be carried out based on data, information and different techniques as described in Sections 3.3 and 3.4 of Chapter 3.

4.5.4 Sediment Management Measures

Most of the approaches of screening sediment management option for existing dams are applicable to planned projects as well. However, for the planned projects, there is additional degree of freedom to check the feasibility of having sediment management option in the design phase, such as under-sluices, bottom outlets, desilting (desander) basins and sediment traps as well as some innovative technologies for efficient sediment removal from the desilting basins such as sluicers (Figure **4-66**), HSR system (shown in Figure **4-67**).

Sections 4.2, 4.3 and 4.6 in this chapter as well as other chapters below are relevant for planned projects as well.

Figure 4-66. Sluicers, installed in the desilting basin *(Courtesy: SediCon)*

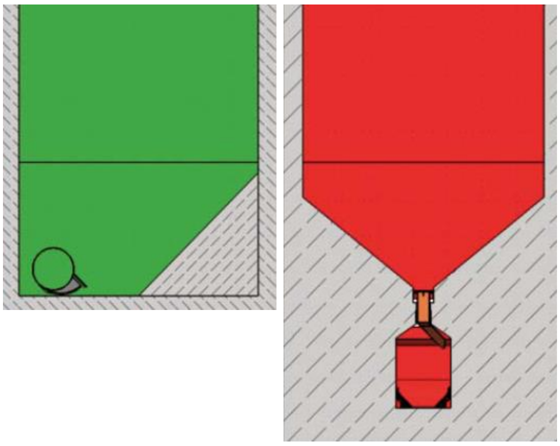

Figure 4-67. A comparison of a cross section of a conventional desander basin (right plot) with the opportunities opened up by the installation of an HSR sediment removal system (left plot): Digging and excavation savings, significantly higher positioning of the rinsing pipe. This makes it possible to install rinsing pipelines, even in very flat terrain. (*www.sitec.hsr.ch/fileadmin/user_upload/sitec.hsr.ch/pdf/zekHydro_Mai_2015_HSR-Sandfang_e.pdf*)

4.6 Reservoir Morphology Information System (RMIS)

For all kind of projects (planned, existing, small, large, storage, ROR), it is important to have an information system, which includes regular flow and sediment monitoring (real-time when applicable), data processing, analyses and database management system, flow and morphological calculations and modelling (empirical analytical and/or mathematical), dissemination and decision support system.

This section describes procedure and required reporting and documentation related to possessing a Reservoir Morphology Information System (RMIS). This is based on some good practices and a longstanding experience of U.S. Army Corps of Engineers on setting up the Sediment Studies Work Plan (SSWP) for rivers and reservoirs (USACE, 1989; Pinson et al., 2016) as well as USGS on setting up Reservoir Sedimentation Survey Information System (RESIS) (Ackerman et al, 2009).

4.6.1 Objectives of RMIS

The main objective of the RMIS is to establish an integrated system to monitor, study, support and improve the reservoir flow and sediment management of the reservoir and associated decision-making processes.

In the context of India, the proposition is to integrate RMIS into Dam Health And Rehabilitation Monitoring Application (DHARMA). DHARMA has been developed under Dam Safety and Rehabilitation Project to enhance the capacity of dam personals and authorities throughout India to manage their dam assets scientifically and professionally so as to sustain advantages of dams (irrigation and water supply, flood control, hydropower etc.) and prevent disasters. DHARMA will address four main challenges: (i) Bring stakeholders together, (ii) ensure completeness of information, (iii) assess soundness of dam health, and (iv) effectively manage asset inventory (*https://damsafety.in*).

Therefore, the objective shall be to integrate flow and sediment-induced database, monitoring and information system into DHARMA platform.

Some of the purposes of the RMIS are as follows:

- Regular (and real-time) monitoring of flow and sediment-induced phenomena on a scale relevant for the reservoir or group of reservoirs
- Regular assessment of flow, sediment transport and morphological processes in the reservoir
- Quantifying reservoir storage loss in a regular basis
- Monitoring and assessing performance of sediment management measures
- Supporting adaptation plan for sediment management when necessary
- Enabling development of integrated reservoir operation strategy considering sediment management

4.6.2 Inventory of Data and Information

First activity would be to review the current state of affairs regarding flow and sediment information system for the reservoir (or group of reservoirs) under consideration. Following are the steps:

- Synthesizing and reviewing available information and data (or database) for each reservoir, e.g. type of data and information, storage methods and institutions/organization
- Preparing a sheet, which includes catchment specific data and information to be used for RMIS: A list of necessary data and information is given in Table 4-5. This sheet is also useful for field reconnaissance and interviews.

Table 4-5. Data and Information Needs for RMIS

<table>
<tr><th colspan="3">Data Type</th></tr>
<tr><td>1.</td><td>Original design data and information</td><td rowspan="5">Most Important</td></tr>
<tr><td>2.</td><td>Topographic and bathymetry surveys</td></tr>
<tr><td>3.</td><td>Area-capacity analysis</td></tr>
<tr><td>4.</td><td>Satellite imagery/photography</td></tr>
<tr><td>5.</td><td>Sediment samples/characteristics (cores and surface samples)</td></tr>
<tr><td>6.</td><td colspan="2">Sediment quality (physical and chemical)</td></tr>
<tr><td>7.</td><td colspan="2">Project information (pools, authorized purposes, water control)</td></tr>
<tr><td>8.</td><td colspan="2">Incidental evidences/observations</td></tr>
<tr><td>9.</td><td colspan="2">Measured discharge, water levels, water surface and sediment load</td></tr>
<tr><td>10.</td><td colspan="2">Flow rating curves</td></tr>
<tr><td>11.</td><td colspan="2">Sediment rating curves</td></tr>
<tr><td>12.</td><td colspan="2">Flow and sediment gauge station/ locations, other information</td></tr>
<tr><td>13.</td><td colspan="2">Past morphological studies</td></tr>
<tr><td>14.</td><td colspan="2">Morphological modelling</td></tr>
<tr><td>15.</td><td colspan="2">Volume depletion at different pools</td></tr>
<tr><td>16.</td><td colspan="2">Sediment management activities (e.g., dredging, flushing, sluicing, etc.)</td></tr>
<tr><td>17.</td><td colspan="2">Funding over time, sources</td></tr>
<tr><td>18.</td><td colspan="2">Flow and sediment monitoring system</td></tr>
<tr><td>19.</td><td colspan="2">Environmental factors driving data collection</td></tr>
<tr><td>20.</td><td colspan="2">Operational impacts, e.g., stage-frequency shifts, reallocation of pools/ storage</td></tr>
</table>

Remark: *The frequency of the measurement shall be site specific based on severity of the sediment-induced problems as well as technical and financial possibilities.*

4.6.3 Primitive Project Data Sheet and Data Gap Summary

For a first evaluation of the problem and rapid assessment, a primitive project data summary sheet can be prepared in the same way it used to be in US (by U.S. department of agriculture). The data sheet is accessible at the USGS (RESSED) website: *https://water.usgs.gov/osw/ressed/datasheets/32-4.pdf* . This sheet has been slightly modified and presented in Appendix C. It also includes a checklist (Table C-1), which provides information mostly related to safety, social and environmental aspect. The datasheet, checklist and additional notes can be used for data availability as well as data and information gap summary. This should include also the reasons for the data and information gap, such as funding source and other technical and/or institutional problems.

4.6.4 Database Tables and Descriptions

The database may contain a number of tables. This database system is based on the data and information, which were manually prepared in form of the project data summary (mentioned in the section above). The formats of database tables, used for Reservoir Sedimentation Survey Information (RESIS-II) (Ackerman et al., 2009), can be adapted for the data management purpose at the first stage. It is a relational database (prepared by USGS), stored in MS Access format in 15 tables. The template and the contents of these tables are useful to adapt as it will be a basis for further improvements in regards to the database format and management system (more advanced database management system can be created later). The description of the each table is as follows:

Table 4-6. Description of tables in database *(adapted from Ackerman et al., 2009)*

Table	Description
Location	Coordinates of each reservoir
Description	Descriptions of the all field in all tables
RMIS01	Details of the location, top of dam and spillway crest elevations, dates of operation, drainage area, and climate of reservoir drainage
RMIS02	The pool elevations, surface area, and capacities of the pools by purpose of operation
RMIS03	The elapsed time since the previous survey for each survey on each reservoir
RMIS04	Details of the survey method and scope for each survey date on each reservoir
RMIS05	Precipitation and water inflow for each survey period for each reservoir
RMIS06	Aerated, submerged, and total sediment deposits, sample number, and average dry weight estimates for each survey date
RMIS07	Definition of reservoir pool layers denoted by elevation for areal sediment distribution
RMIS08	The percentage of sediment deposits occurring in each depth layer for each survey
RMIS09	The percentage of the sediment deposits occurring by distance segment and reach for each reservoir and for each survey date
RMIS10	Water inflow and maximum and minimum reservoir elevations by water year
RMIS11	the storage capacity by elevation stage for each reservoir (may have multiple dates)
RMIS12	Footnote explanations and other remarks
RMIS13	Agencies collecting and reporting data

Remarks: The older version of the RESIS database did include a table of land use areas (urban, crop/pasture, range, forest, water) for each USGS hydrological sub-region. Since land use changes through time as well as the source and date of the land use calculations were not documented, this table is not included in new version. Besides, older version also included a table with the county, major land resource area (MLRA) and hydrological sub-region of each reservoir (Ackerman et al., 2009). Therefore, such information can be included if they are available, updated and consistent.

The content and description of the each table as well as some other useful information and details are given in Ackerman et al. (2009).

4.6.5 Data Management, Analysis and Visualization Platform

All the data and information records must be organized and presented using a data management and visualization platform with their further utilization, and not simply in form of hard and/or soft copies of individual files that are stored standalone. Such platform and system can be of different level of complexity and possibilities, some of which are as follows:

- A simpler database platform with only for storing the pre-processed data and information with an online (or offline) access to them in interactive way like Reservoir Sedimentation Database (RESSED) at USGS: *https://water.usgs.gov/osw/ressed/index.html*
- A data management platform that fully or partly automated and connected with the data acquisition systems and instruments with pre- and post-processing and visualization possibilities like a dash board
- A data management platform which, in addition to afore-mentioned option, can also be integrated and coupled with different tools and models (like statistical analysis tool, real-time control tool, hydrologic, hydraulic and morphological models and tools, forecasting systems and tools)

4.6.6 Existing Practices and Experiences

Many reservoirs around the world have their own monitoring and information system. However, most of them do not include sediment related data and observation (also not available as online platform). Some of the available existing practices are as follows:

- Reservoir Storage Monitoring System in Andhra Pradesh (this does not incorporate sediment related data):

  http://cadarsms.cgg.gov.in/Login.do
- Real Time Streamflow Forecasting and Reservoir Operation System for Krishna and Bhima River Basins in Maharashtra (this does not incorporate sediment related data):

  http://nhp.mowr.gov.in/Docs/HP-2/Manuals/Krishna%20RTDSS%20flyer.pdf
- The Reservoir Sedimentation Database (RESSED) at USGS

  https://water.usgs.gov/osw/ressed/index.html
- A publication with some case studies on Real-Time Integrated Operation of Reservoirs, published by Central Water Commissions, can be of use: *http://cwc.gov.in/main/downloads/Real%20Integrated%20Operation%20of%20Reservoirs%20.pdf*
- Experience of Hydrological Information System (HIS), developed under Hydrology Project, can also be useful (*http://hydrology-project.gov.in/GuidesandManuals_GeneralHISDataManagement.html*)
- An open source platform for data management, data analysis, model coupling and real-time operation use, the Delft-FEWS can be of use also for RMIS. Owing to its unique

characteristics in regards to data importing and processing and model coupling, Delft-FEWS has been applied in a wide range of different operational situations. Examples are water quality forecasting, reservoir management, operational sewer management optimization, and even peat fire prediction (*http://oss.deltares.nl/web/delft-fews/home*).

- Some examples for individual reservoirs and sediment management options can be found in 0
- It must be emphasized that analysis of operational performance data must be regularly reviewed by operational personnel at the dam as well as their supervisors. If supervisors do not focus on performance records, then there will be little incentive for operators to take the trouble of collecting data and optimizing the reservoir operation. Operational performance is directly related to the interest that supervisors place on achieving efficient operation, as opposed to simply maintaining the equipment in good condition and similar housekeeping duties (Annandale et al., 2016).

Chapter 5. FEASIBILITY, IMPACT AND RISK ASSESSMENT

5.1 Feasibility Assessment

Sediment handling activities for an existing reservoir are usually rather complex and costly affair, particularly when there are needs for structural (e.g. building bypass system and check dams) and recurrent measures (e.g. sediment removal and disposal). Consequently, it is necessary to carry out technical and economic feasibility studies of such measures. This shall also consider social and environmental aspects.

5.1.1 Rapid Assessment Methods and Tools

During preliminary screening of the options, a rapid feasibility (pre-feasibility) assessment shall be made. This is particularly the case when the sediment management option is ambiguous for the reservoir under consideration.

- Usually, a tailored analysis for a particular reservoir may already provide sufficient idea about the pre-feasibility of the selected option(s).
- A detailed impact study is usually not justifiable during pre-feasibility study, since there may be lack of data and information. However, all associated impacts shall be considered as a first approximation (usually the impacts are obvious).
- There are some methods and tools, which can be used for pre-feasibility assessment of reservoir sediment management measures. They are briefly described hereafter.
- It should, however, be noted that the result and outcomes of such simplified methods and tools shall be interpreted with care under specialists' judgment.
- In general, a tailor-made approach shall be considered for each reservoir considering many other aspects like regional specificity (like cultural and societal needs and requirements), age of the problem and other nuances.

Assessment by RESCON-2

- The RESservoir CONservation (RESCON-2) is a tool for rapid assessment of technical and economic feasibility of sediment management measures in reservoirs (Efthymiou et al. 2017; Annandale et al., 2016). Figure 5-1 shows a basic program structure of RESCON-2.
- The palette of the evaluated techniques includes the state-of-the-art methods of sediment yield reduction, sediment routing and deposit removal.
- The tool includes an economic optimization function, supported by engineering relationships that allow the quantification of basic parameters.
- It helps to evaluate at the pre-feasibility-level the technical and economic feasibility of implementing the life cycle management approach.
- The results from the economic optimization routine identify the preferred sediment management technique for sustainable use of the water resource infrastructure. Where sustainable use cannot be achieved, the model computes the annuities as required for the retirement fund (Palmieri et al., 2003). The issue of intergenerational equity and dual nature of reservoir storage is considered through the incorporation of the option to perform the financial analysis with a declining discount rate.

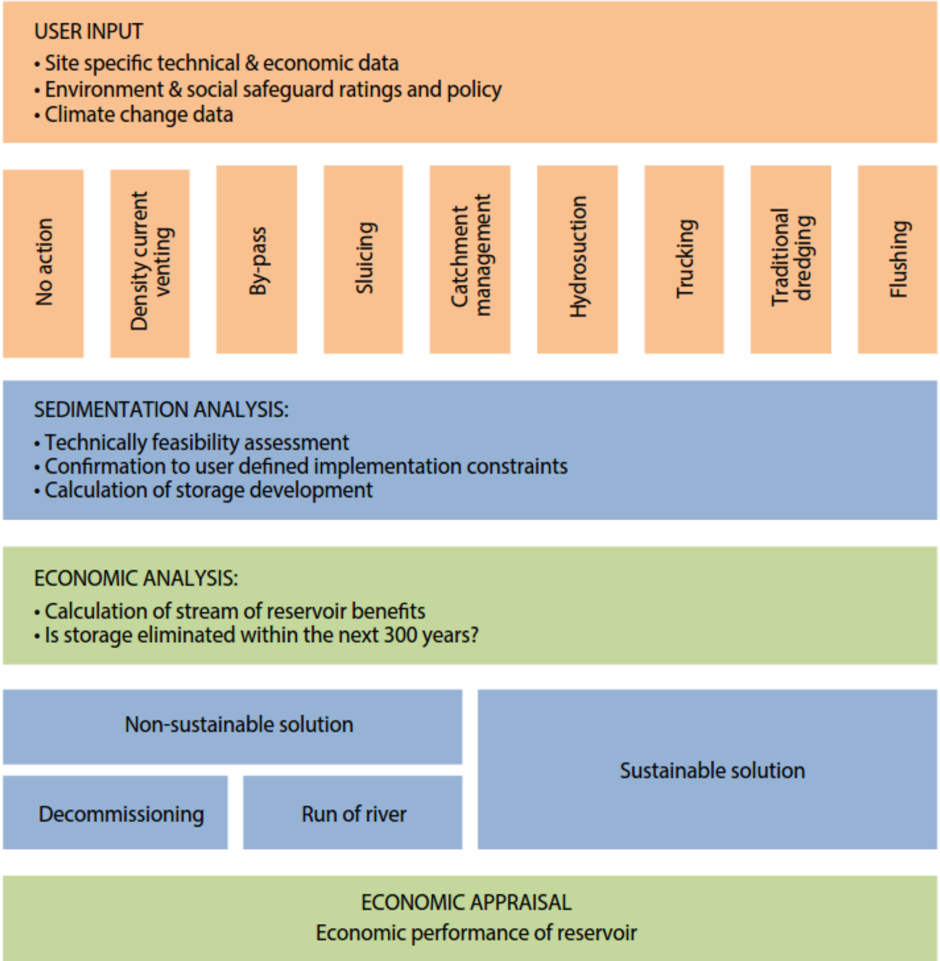

Figure 5-1. Structure of the program RESCON-2 *(Efthymiou et al. 2017)*

- The tool incorporates a climate change analysis which is based on data retrieved by the World Bank Climate Change Knowledge Portal *www.climateknowledgeportal.worldbank.org* The analysis performs an assessment of sediment management as an adaptation strategy for increasing the resilience of the water infrastructure.

- It must be noted that RESCON 2 is not intended to replace detailed studies. The program is based on empirical methods and therefore sound engineering judgment is required for interpretation of the results with specialists' support. Furthermore in more advanced project development stages, the analysis shall be substantiated by detailed techno-economic studies and numerical and/or physical modelling. The tool has several limitations (Efthymiou et al. 2017). Therefore, the evaluation must be made with specialists' support and may only be useful for pre-feasibility phase of study.

- The publications on RESCON and RESCON-2 (Efthymiou et al. 2017; Annandale et al., 2016; T. Aras, 2009, Palmieri et al., 2003 and Kawashima et al., 2003) include detailed materials on approach, case studies as well as user manual. RESCON-2 is updated version of RESCON with some additional improvement including among others the improvement of the prediction of the reservoir storage time path, the allocation of deposits between active and inactive storage, the partitioning of sediment inflow to suspended load and bedload. Furthermore, the model set-up and result processing is substantially easier through a more user friendly GUI.

Basson's Diagram

The Basson's diagram (Basson and Rooseboom, 1997) on applicability of sediment management options gives an experiences around the world. An example indicating sediment removal option for USBR reservoirs is depicted in Figure 5-2. According to their guidance, if the relative storage loss rate, K_t is less than 50, the

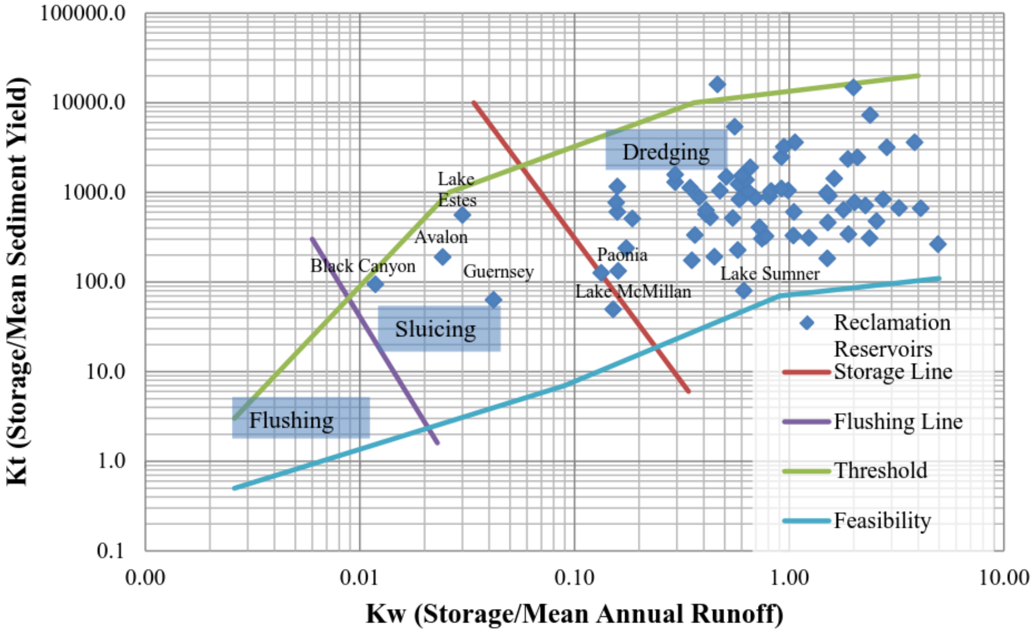

Figure 5-2. Basson's diagram for preliminary sediment removal options (examples for existing reservoirs of *USBR*)

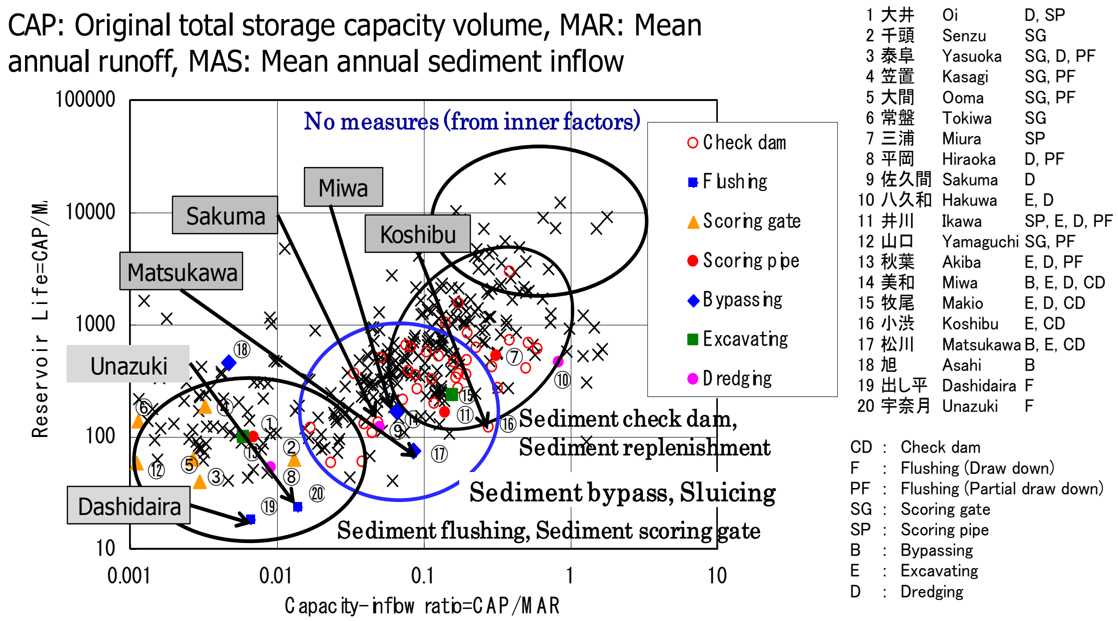

Figure 5-3. Japanese experiences of sediment management (adapted to the Basson's diagram) *(Sumi, 2008)*

initial idea about the applicability of the flushing operation, which is based on the reservoir sedimentation problem is considered serious, which implies that sediment management actions need to be undertaken.

This diagram cannot be used as a design tool, but maybe useful in some cases for preliminary assessment if there are several options available. In general, the Basson's diagram shows the relationship between two parameters, i.e. a parameter, indicating the Reservoir Life (Total capacity/Mean annual runoff) and a parameter, indicating Capacity- Inflow Ratio (Total capacity/Mean annual sediment inflow). An example of usability of the Basson's diagram for Japanese cases (based on existing sediment removal options and measures in 20 Japanese reservoirs) can be seen in Figure 5-3. It is found that the ratio of reservoir storage to mean annual flow should not exceed 4% for the successful flushing due to the fact that the reservoir cannot be easily drawn down with larger storage (Sumi, 2008).

5.1.2 Detailed Feasibility Study

- A reservoir is usually a complex system and it is not always possible to use generic approach and tool for feasibility assessment.
- This requires a tailor-made approach, in which each reservoir (or a system of reservoirs) shall be assessed separately without any generalization.
- A tailor-made approach does not always mean a sophisticated approach. It can also be simple if analyze all available data, information and past experiences specifically on the reservoir under consideration.
- A detailed feasibility study is not always a simple task as it involves more complex investigations and studies, such as field measurements, rigorous analysis, process-based hydraulic and morphological modelling, economic analysis and modelling, environmental and social impact assessment (see Section 5.2 below) and so on.
- An example of a comprehensive feasibility study on sediment management of John Compton dam in St. Lucia can be found in a report by DB Sediment (2013). Some of the content of the report is as follows: (i) Introduction and Background, (ii) Project Reconnaissance and Consultation, (iii) Bathymetric and Topographic Survey, (iv) Hydrology, (v) Present Reservoir and Sediment Management, (vi) Options to Restore Reservoir Capacity, (vii) Dredging Dimensioning and Equipment, (viii) Future Reservoir Management, (ix) Hydropower Assessment, (x) Timeframe and Cost Estimate, (xi) Conclusions, (xii) Annexes (field survey, images, data, calculations, sediment management design drawings and sketches)

Table 5-1. Feasibility analysis of sediment management in Millsite reservoir in USA
(Utah State Water Plan report, 2010)

Alternative	Technical Potential	Economic Feasibility	Environmental Feasibility	Comments
Reduce Erosion	Not feasible	-	-	Not feasible
Dredging (dry)	High	$33.5 million	Low impact	Extends life about 15 years
Sediment Bypass	Medium	$805,000 Capital $650,950 Annual O&M	Low impact	Extends life indefinitely
Flushing & Sediment Pass-through	Not feasible	-	-	Not feasible
Hydrosuction Dredging (barge)	High	$302,000 Capital $13,790 Annual O&M	Desirable	Extends life indefinitely
Hydrosuction Dredging (hydraulic)	High	$637,000 Capital $13,790 Annual O&M	Desirable	Extends life indefinitely

- Another example of outcomes of a feasibility analysis of sediment management in Millsite reservoir is depicted in Table 5-1.
- Some case studies on financing reservoir sediment management can be found in a recent publication (Hotchkiss, 2018).

5.2 Impact and Risk Assessment

Impacts and risks are different for planned and existing projects that can be outlined as follows:

- For the planned projects, the problems do not exist yet. Therefore, the impact and risks (social, environmental, economic and maybe others) are anticipated, and assessed to fulfill the established criteria (based on existing laws and regulations).
- For the existing projects, the sediment-induced problems do exist. On the one hand, these existing problems already have impacts; while on the other hand, the handling of these problems may have impacts and risks as well, which have to be assessed.
- A general idea about sediment-induced impacts and risks can be gotten from the different types of sediment-induced problems that are partly outlined in Section 4.4.2. In addition, there are existing guidelines, rules and regulations for impact and risk assessment and mitigation for planned projects. Therefore, comprehensive guidelines with a focus on said problems are beyond the scope of this handbook.
- In this guideline, the emphasis is on the impacts, associated with sediment management of existing dams and reservoirs (although some part of them may be valid for planned dams and reservoirs as well). All relevant impacts and risks as well as methods and tools to assess them are descried briefly in sections below and also outlined in tabulated form.
- Review of previous experiences, incidents and hazards is very important. For example, the desiltation of Kallarkutty reservoir in Kerala caused pollution of downstream reach of the river Periyar (Figure **5**-**4**), obstructing the water supply. The desiltation was carried out after 18 years despite the regulation for cleaning the reservoir once in every two years. The deposits in the reservoir were polluted mostly due to the industrial effluent. This is described also in 0
- Another example of sediment hazard during flushing operation in 1991 in Pillur reservoir (Tamil Nadu, India). Figure **5**-**5** gives a pictorial impression. The details are presented in 0
- Another example of impact of sediment flushing in upstream reservoir on downstream reservoir is depicted in Figure 5-6. The details can be found in Peteuil et al. (2013), and are presented in 0This case study also shows how the reservoirs can be flushed in synchronized and environmental friendly manner.

Figure 5-4. Polluted Periyar as a result of flushing of Kallarkutty dam *(www.indiatogether.org/periyar-environment--2)*

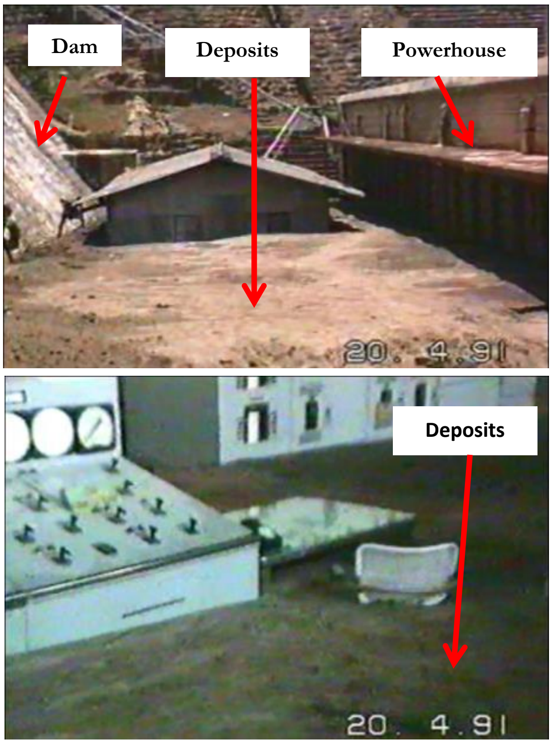

Figure 5-5. Sediments, deposited in and around powerhouse premises, showing the scale of hazard during flushing through scour sluice in 1991 *(Giri et al., 2016)*

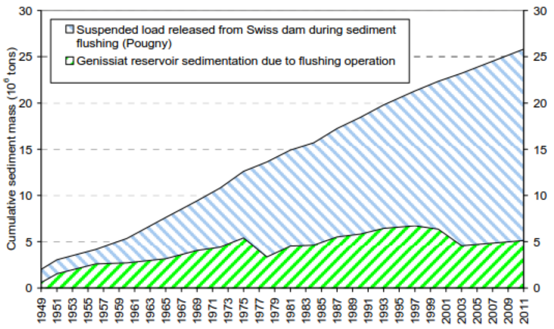

Figure 5-6. Cumulative suspended sediment fluxes released downstream of Swiss dams and Genissiat reservoir sedimentation due to flushing operation *(Peteuil et al., 2013)*

5.2.1 Social, Environmental and Economic Impacts

- A sediment management plan is supposed to address social and environmental impacts and associated legal issues and challenges. The impacts can be short-term and/or long-term.
- Some of the positive (social, environmental and economic) impacts of rehabilitation and improvement of the reservoir condition by handling sediment-induced problems are as follows: (i) Water availability, (ii) flood safety, (iii) structural safety (dams, headworks etc.), (iv) capacity building and employment, (v) quasi-natural water and sediment supply, (vi) agriculture and aquaculture, (vii) energy production, (viii) recreation, (ix) water transport, (x) upstream and downstream eco-hydraulics and morphology, (xi) circular benefit (if there is possibility of reuse of materials).
- The adverse impacts and risks of sediment management measures are as follows: (i) Structural safety and stability concerns, (ii) upstream impacts (e.g. retrogressive erosion (Figure **5**-7), bank erosion, disturbance to wildlife and habitats), (iii) downstream impacts (hyper-concentrated or turbid flow, polluted flow, contaminated sediment transport, downstream morphological changes), (iv) water quality, (v) high cost.
- A brief outline of impacts associated with each sediment management measure is presented in Table 5-2. Also, a checklist related to social and environmental aspects is presented in Table C-1 (Appendix C).
- It is to be noted that it is not always straightforward to assess economic feasibility and impact. Many aspects shall be analyzed thoroughly that depend on local situation (Plummer et al., 2005).
- Some relevant publications are Palmieri et al. (2003), K-State Research and Extension publication (2008) and others (see references).

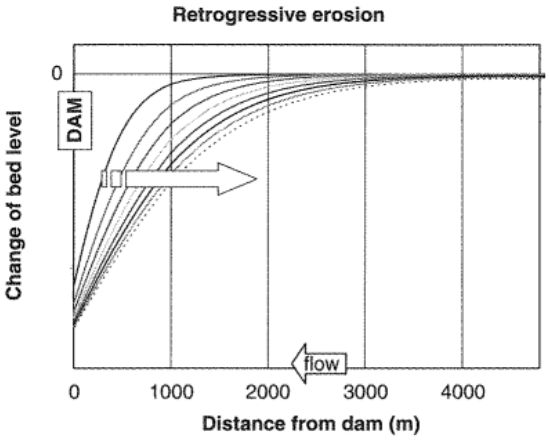

Figure 5-7. Definition sketch of retrogressive erosion

5.2.2 Impact Assessment and Risk Management in a Cascade System

- Mekong River Commission has recently developed new guidelines and manuals for Hydropower Environmental Impact Mitigation and Risk Management in the Lower Mekong Mainstream and Tributaries. This handbook and manuals consist of five major themes, namely: (i) Hydrology and downstream flows, (ii) geomorphology and sediments, (iii) water quality, (iv) fisheries and aquatic ecology; and (v) biodiversity, natural resources and ecosystem services.
- The guidelines provide guidance for selecting approaches for the entire life cycle of the project (from master planning to operation and can be adapted to existing projects as well). A prior assessment of risks and vulnerabilities is followed by selecting mitigation approaches, and by modeling to optimize the power output while maximizing the efficiency of mitigation (Sloff et al., 2018). The approach can well be applied to multipurpose dams as well as to assess the cumulative impacts and risks of sediment management measures and their minimization.
- The models, proposed for sediment mitigation in the guideline, cover full sediment pathways, starting from catchment, to detailed reservoir, and to the large-scale river as a backbone (Sloff et al., 2018).
- During the optimization, the different aspects (such as hydrology, fisheries, and economics) are jointly evaluated (Sloff et al., 2018).
- The application of this handbook to the planned Mekong mainstream dams shows that flushing and sluicing operations may not sufficiently bring (coarse) sediments through the cascade. Mitigation in the Mekong requires large-scale jointly-operated sluicing and flushing events to retain the important flow and sediment pulses. The guidelines provide useful tools and insights to manage these basin-scale impacts (Sloff et al., 2018).
- It is suggested to review the guidelines (MRC, 2017; Sloff et al., 2018) for their usefulness and application in the context of India.
- It is also suggested to review the sample guidelines and a useful report on Cumulative Impact Assessment, since this has been a preferable impact assessment concept in recent years *(www.esmap.org/node/2964, www.moef.nic.in/downloads/public-information/CH-11.pdf).*

5.2.3 Methods and Tools

- The methods and tools for the impact assessment are similar to those that are used for the assessment of sediment-induced problem, described in Chapter 3. The only difference is that in this case we consider the sediment management measures and quantify the resulting effects on similar processes.
- While carrying out impact assessment studies, it is necessary to quantify the reference (baseline) scenario, i.e. 'do-nothing' scenario under the same forcing. Subsequently, the results of the reference scenario shall be compared

with the results of scenarios with sediment management measures. This will reveal whether the situation has been improved or worsened.

- While carrying out impact study, it is necessary to consider the options and alternatives on minimizing the negative impacts of sediment management measures as well as optimizing the effectiveness and viability (technical, environmental and economic) of the selected measures.
- Some of the possible impacts due to each sediment handling measure, and methods and tools to quantify the impacts are presented in Table 5-3.
- Figure 3-39 (presented in Chapter 3.) gives an impression about dominant processes, and relevant tools and models to assess impacts of reservoir sediment management measures in a cascade system of dams.
- A case study by M. van der Vat (2015) provides an example of integrated approach and use of several simplified models including economic model to optimize multipurpose reservoir operation (however, this does not include the sediment management option), shown in Figure 5-8.
- Relevant materials and information can be found in other guidelines as well (see reference lists).

5.3 Existing Regulations and Mitigation Options

5.3.1 Regulations & Guidelines

Ministry of Environment, Forest and Climate Change has issued Sustainable Sand Mining Management Guidelines (2016) which, inter-alia, addresses the issues relating to regulation of sand mining. One of the salient features of the Guidelines is as follows:

Exemption of certain cases from being

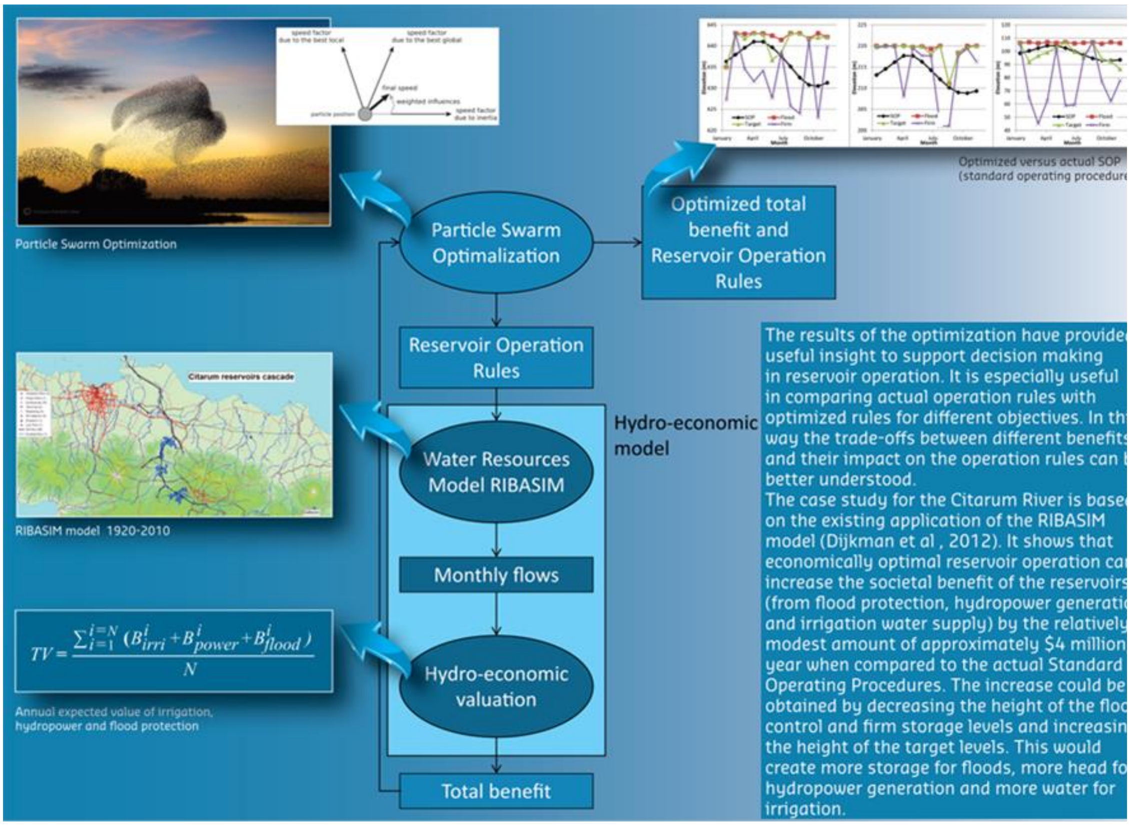

Figure 5-8. Optimizing reservoir operation for flood storage, hydropower and irrigation using a hydro-economic model for the Citarum River, West-Java, Indonesia *(M. van der Vat, 2015)*

considered as mining for the purpose of requirement of environment clearance like: *(i) extraction of ordinary clay or ordinary sand manually by hereditary Kumhars (Potter) who prepare earthen pots on a cottage industry basis; (ii) extraction of ordinary clay or ordinary sand manually by earthen tile makers who prepare earthen tiles on a cottage industry basis; (iii) removal of sand deposited on agricultural field after flood by owner farmers; (iv) customary extraction of sand and ordinary earth from sources situated in Gram Panchayat for personal use or community work in village;(v) community works like desilting of village ponds /tanks, rural roads under taken in MGNREGS and other Government sponsored schemes; (vi)* ***dredging and desilting of dam, reservoirs, weirs, barrages, river, and canals for maintenance and upkeep and avert natural disaster provided the dredged material is used departmentally. If the dredging activities are under taken for the purpose of winning mineral and selling it commercially it will be considered mining.***

See also Section 4.3 of this guideline regarding treatment and beneficial use of dredged materials and relevant practices around the world, "Sustainable Sand Mining Management Guidelines 2016", available at *www.moef.nic.in* as well as "Guidelines for Assessing and Managing Social and Environmental Impacts", published by CWC-DRIP.

5.3.2 Impact Mitigation Conditions

Mitigation options are usually identified based on the assessment of relevant impacts. Sediment management interventions/ measures, their impacts and assessment methods are briefly outlined in Table 5-2 and Table 5-3. Several social, environmental, economic and safety requirements and conditions shall be fulfilled to mitigate adverse impacts of sediment management interventions and options. Some of them are outlined in Table 5-4.

Table 5-2. Sediment management options and associated impact

Measures	**Impacts (positive and negative)**		
	Social/Safety	Environmental	Economic
Catchment treatment	○ Improved catchment condition ○ Better land use ○ Reduced sediment inflow ○ Employment	○ Better environment (forestation, land-use)	○ Moderate cost ○ Implicit gains (depending on size and problems)
Catchment/ river erosion control structures	○ Interventions in landscape and basin system ○ Safety and sustainability concerns ○ Reduced sediment inflow ○ Employment	○ Environmental concerns due to structural intervention	○ Noticeable cost ○ Implicit gains (depending on size and problems)
Dam height raising	○ Upstream inundation ○ Dam stability problem ○ Downstream impacts ○ Some gains (employment, water availability, flood control)	○ Upstream and downstream hydraulic and morphologic changes and impacts	○ Higher cost ○ Some storage gain (water use, energy, flood control)
Fusegates	○ Similar but less concerns comparing to dam height raising	○ Less concerns comparing to dam height raising	○ Higher cost ○ Some gains (storage and controlled flow release)
Additional	○ Land-use	○ Land use changes	○ Higher cost (land, di-

Measures	Impacts (positive and negative)		
	Social/Safety	Environmental	Economic
storage reservoir	o Landscape intervention o Flood control	o Basin intervention o Flow diversion	version/pumping facilities) o Some gains (storage, energy, flood safety)
Storage reallocation	o Changes in flow release frequency and water use o Safety and risk	o Changes in flow frequency and quantity (downstream impacts)	o Lower cost o Some gains (water, energy), implicit loss (e.g. flooding pool)
Sluicing/ venting	o Flow and sediment supply to downstream (water and silt for agriculture and aquaculture) o Sometimes safety concern	o Quasi-natural flow and sediment supply o Morphological and environmental impacts (positive, but sometimes negative)	o Low cost o Water loss (energy, water supply)
Flushing	o Retrogressive erosion o Bank erosion o Increase in turbidity o Water and silt for agriculture and aquaculture o Storage gain o Safety concern (downstream sediment hazards)	o Downstream impacts (high concentrated flow, contaminated sediment)	o Low cost o Water loss (energy, water supply)
Bypass tunnel/ channels	o Structural intervention o Safety concern o Storage gain	o Flow and sediment balance o Landscape intervention	o High cost o Storage gain and other indirect benefits
Sediment replenishment	o Storage gain o Employment** o Noise and pollution (if trucking) o Downstream sediment supply	o Less environmental impact (can be controlled)	o Higher cost o Low storage gain o Indirect benefits
Hydro-suction removal	o Storage gain o Employment o Less safety concerns	o Less environmental impact (can be controlled)	o Moderate cost o Low (no) energy cost o Low storage gain
Hydraulic dredging	o Storage gain o Employment o Noise and other pollution, o Less safety concerns	o Pollution o Upstream and downstream impacts (can be controlled)	o Higher cost o Some gains (storage, safety)
Dry dredging and trucking	o Storage gain o Employment o Noise and air pollution o Safety concerns (during trucking)	o Air pollution (trucking) o Disposal sediment	o Higher cost (removal, trucking , disposal) o Storage gain o Reuse possibilities
Non-structural measures	o Less encroachment o Employment o Resource o Knowledge and capacity development	o Control of environmental impacts	o Lower cost o Implicit and long-term benefits

Table 5-3. Sediment management options and impact assessment methods

Measures	Resulting Impacts to Quantify	Methods & Tools
Catchment treatment	Reduction of erosion rate, morphological changes in channel(s) and reservoir due to sediment inflow reduction, cost and benefit	Catchment erosion calculation and/or modelling, river and reservoir erosion-sedimentation calculation and/or modelling, economic analysis (calculation/modelling), review of other experiences, data analysis
Catchment/ river erosion control structures	Reduction of erosion rate, effectiveness of control structures, morphological changes in channel(s) and reservoir due to sediment inflow reduction, cost and benefit	-ditto-
Dam height raising	Backwater, hydraulic load, reduction in downstream flow, modified flow release and dam break analysis, cost and benefit	Hydrodynamic and morphological computations, economic analysis, review of other experiences, data analysis, economic analysis (calculation/modelling)
Fusegates	-ditto-	-ditto-
Additional storage reservoir	Hydraulic and morphological changes in the river and reservoir due to water diversion, effectiveness of additional storage, cost-benefit analysis	Hydraulic and morphological calculations and computation, economic analysis, review of other experiences, data analysis
Storage allocation (for multipurpose reservoir)	Changes in reservoir operation, flood risk (e.g. due to reducing the flood control pool), downstream flow and morphology, reservoir morphology	Calculations/computations of reservoir operation and optimization, river and reservoir hydraulics, downstream flow and morphology, flood inflow and risk
Sluicing/ venting	Effectiveness of sluicing/ venting, sediment transport and morphology of the reservoir and downstream reach	Morphological calculation/ computation of the upstream reach, reservoir and downstream reach, economic analysis
Flushing	Effectiveness, quantity and quality of deposits, sediment transport and morphology of the reservoir including upstream and downstream changes, cost and benefit	Analysis of quantity and quality of deposits, review of other experiences, modelling of flushing operations including upstream and downstream sediment transport and morphology, calculation/computation and analysis of retrogressive and bank erosion, economic analysis (calculation/modelling)
Sediment replenishment	-ditto-	-ditto-
Hydro-suction removal	-ditto-	-ditto-
Hydraulic dredging	-ditto-	-ditto-
Dry dredging and trucking	-ditto-	-ditto-
Bypass tunnel/ channels	Effectiveness, flow and sediment transport in the tunnel/channel, sediment transport and morphology of the reservoir, upstream and downstream reaches, abrasion, maintenance, cost and benefit	Calculation/computation of the flow and sediment transport at the upstream river, bypass, reservoir and downstream reach, abrasion calculation, economic analysis (calculation/modelling)

Table 5-4. Impacts of sediment management interventions/measures and mitigation options and conditions

Possible Impacts	Mitigation Options & Conditions
Upstream inundation (due to dam heightening)	○ Quantification (computation, expert judgment) of the upstream inundation, their social and environmental impacts ○ The option shall not be considered if the impact is large (given the condition at specific location) ○ Economic calculation
Changes in downstream hydraulic and morphologic regime (due to various measures and interventions)	○ Quantification (computation, expert judgment) of the downstream hydraulic, sediment transport and morphological conditions to keep aquatic environment and ecologic impact within permissible limits, specified under the law. ○ Optimization of operation of spillways, bypass and other outflows (computation, expert judgment) ○ Flow/flood and sediment management in downstream region
Structural stability (due to dam heightening)	○ Stability analysis (computation) under changed scenario of hydraulic load ○ Opting for safer heightening option, like Fusegates, which can be used to release water in case of problems in upstream ○ Dam break analysis, hazard and risk maps including update of Emergency Action Plan (if deem necessary)
Downstream turbidity and pollution (during sluicing, flushing, replenishment)	○ Assessment and analysis of quantity and quality of depositions, age of the deposited material (from last sediment management operation) ○ Investigation on downstream infrastructures such as water supply intakes, dams and barrages, recreational spots, settlements; consideration and measures for their safety ○ Quantification and analysis (computation and expert judgment) of the sediment transport condition (mainly concentration) during flushing, sluicing and replenishment (considering downstream reservoirs as well, if exist) ○ Water turbidity shall meet permissible limits, specified under environmental law. ○ Real-time measurement of turbidity to control the environmentally hazardous quantity, make use of balance between sediment and flow release, for example additional flow release from the spillway or other outlets during flushing operation to dilute the downstream flow and reduce the concentration
Upstream retrogressive erosion, downstream changes in hydraulic and morphological regime (due to dry and hydraulic dredging, trucking)	○ Quantification of upstream retrogressive erosion (computation, expert judgment) due to sediment removal from the reservoir (this is particularly important if there are river and reservoir infrastructures nearby like bridge, embankments, earthen dams) ○ Quantification of downstream changes (computation, expert judgment) if the slurry is supplied to downstream reach ○ No dredging/sediment removal during extreme flow period (e.g. monsoon period)

Possible Impacts	Mitigation Options & Conditions
	○ No diversion and disturbance of natural flow of the streams during sediment removal operation
Stability of reservoir banks (due to different operation and measures with reservoir level lowering and high current through deep channel in the reservoir that may hit the curved outer bank of the reservoir)	○ Observation of the bank/toe conditions and deep channel pattern in the reservoir (from topo-bathymetry measurement), for example deep channel formation along the curved outer bank ○ Quantification of deep channel pattern in the reservoir during sediment management operation, toe erosion (computation, expert judgment) and slope stability analysis ○ Assessment and analysis of the reservoir bank stability due to sediment removal from the toe (computation, expert judgment), particularly in hilly and landslide prone areas.
Air (dust) and water pollution, noise pollution, impacts on wildlife, aqua-life, visual impact, safety concerns, social impacts, hurdles and disturbances (during dry/hydraulic dredging, trucking, slurry transport, dumping)	○ Dredging and dumping activities in reserved forest area require forest clearance in accordance with the provisions and rules under the Forest Conservation Act. ○ Dredging and dumping activities shall not disturb water supply and irrigation, otherwise proper arrangements for alternative options shall be made. The losses in energy revenue (for hydropower dams) due to the disturbance shall be assessed (economic calculation) ○ Real-time measurement and observation (in complement with expert judgment) of water turbidity and pollution to keep them within permissible limits, specified under environmental law. ○ The operation shall be carried out in systematic manner with regular cleaning, water sprinkling and repairing of the site and the transport route. ○ Site clearance and tidiness is strictly required to have less visual impact of dredging and dumping activities ○ Transportation shall be carried out through covered trucks only and the vehicles carrying dredged material shall not be overloaded. Wheel washing facility should be installed and used. ○ Vehicles used for transportation of dredged materials shall meet prescribed emission norms, i.e. they shall have Pollution Under Control (PUC) Certificates. ○ Road shall not be damaged, and no stacking is allowed along the road side ○ Noise impact (due to equipment as well as transportation) on wildlife shall be avoided. ○ Transport of dredged material shall not be done through villages/ habitations. ○ Junction at takeoff point of approach road with main road be properly developed with proper width and geometry required for safe movement of traffic ○ Protection of aqua life shall be ensured. For example, mi-

Possible Impacts	Mitigation Options & Conditions
	grating birds shall not be disturbed, therefore the sediment management operations shall be carried out beyond the period of migrating birds. o Spring sources should not be affected due to mining activities. Necessary protection measures shall be incorporated. o Site specific plan with eco-restoration should be in place and implemented. o Environmental friendly equipment shall be used. o Health and safety of workers should be taken care of. o Effect of reservoir depletion shall be assessed properly, such as effects on wildlife (as they come to drink water to the reservoirs in forest area that is the case in many reservoirs in India) o The dumping site shall be properly designed. If slurry pipe is used, dewatering and water passage arrangements shall be checked and properly made based on the site condition o The slurry pipe shall not disturb or damage other infrastructures and dam apparatuses. It should not disturb people's and vehicles' movement. The pipe should not be laid through sanctuaries, ecologically sensitive and recreational areas (like forest, flora-fauna areas, parks, etc.) as well as unsafe areas shall be avoided. o Overhang at the dredging and dumping areas shall not be allowed for safety reasons. o Rubbish and waste material burial shall not be done in the rivers and reservoirs o Restricted working hours depending on the site condition (like forest area, areas with busy transportation). Trucking shall not disturb regular transportation and shall avoid rush hours with dense traffic (like peak office/school hour, hours of wildlife activities) o Restoration of flora affected by dredging and dumping activities should be done immediately (like additional plantation of trees, destroyed at dumping sites). o Regular monitoring of the dredging and dumping activities to ensure effective compliance of all stipulated conditions
	o The natural course of other rivers and streams shall not be disturbed and obstructed o Making use of technology to monitor and manage the activities, such as Bar Coding, Information and Communications Technology (ICT),Web based and ICT enabled services, mobile SMS and Applications etc. o Different levels of monitoring, such as (i) reach level monitoring, (ii) transportation monitoring, (iii) Dumping/end consumers/usage, (iv) indirect monitoring (e.g. marketing, trend of consumption and sales record of byproducts and reuse) o Disaster management plan, emergency helpline, signs and signals shall be in place

Possible Impacts	Mitigation Options & Conditions
	○ Availability of Occupational Health Specialist for regular and periodical medical examination of the workers engaged in the Project and records maintained; also, occupational health check-ups for workers having some ailments like BP, diabetes, habitual smokers, etc. shall be undertaken once in six months and necessary remedial/preventive measures taken accordingly. Recommendations of National Institute for Labour for ensuring good occupational environment for workers would also be adopted.

Remarks

- All the permits and approvals must be in place during screening and planning, and then only it is suggested to start contractual processes and execution sediment management measures and interventions.
- It is important to check carefully all the regulations related to sediment-induced activities in reservoirs. There is not much documentation/regulations about sediment removal from the reservoir and its reuse. Nevertheless, sand mining guidelines and regulations are useful to consider and adapt.
- It is recommend to study and explore the possibilities of the beneficial reuse of the deposited sediments in the reservoir in more details, and subsequently prepare detailed and dedicated regulatory document and guidelilnes on reservoir desilitation and reuse (shall be incorporated in the current sand mining guidelines). Other existing experiences and practices around the world would be useful to consider (described in Section 4.3 and **Appendix F**).
- Make use of the "Sustainable Sand Mining Management Guidelines 2016" and recently published draft document "Sand Mining Recommendations" (2018), available at *https://mines.gov.in/writereaddata/UploadFile/sandmining16022018.pdf*

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Chapter 6. Real-World Examples

This chapter contains some real-world examples of good sediment management practices (also in India), failure examples in India and some case studies that were carried out under DRIP project. These examples are rather useful for dam authorities in India to consider while screening the sediment management options for their reservoirs.

6.1 Good Sediment Management Practices

Some examples of effective sediment management practices around the World have been presented hereafter.

6.1.1 Sakuma Reservoir (Japan)

Sakuma dam is one of the dams in a cascade system of dams in Tenryu River basin. The geology of the basin is characterized as fragile, thus the sediment load is rather high particularly during flood season.

The dam is a concrete gravity dam with a crest length of 293.5 m, dam height of 155.5 m, reservoir volume of 1.12 million m^3. The am was completed in 1956. The water used for power generation at the Sakuma Power Station is reused for power generation at five hydropower stations located downstream (Sakuma No. 2 Hydropower Station, Akiba Nos. 1, 2 and 3 Hydropower Stations, Funagira Hydropower Station), agricultural and industrial purposes, waterworks, and for maintaining normal discharge of the river (personally provided note by Chigasaki Research Laboratory J-Power).

The Electric Power Development Co. Ltd. (EPDC) has implemented a sediment management plan for the reservoir to reduce the level of sedimentation to the riverbed level of 1970. One of the reasons for this is to reduce the flood impacts at the upstream reach. A schematic sketch, depicted in Figure 6-1, provides an impression about the approach. As it can be seen in the figure, the reservoir is divided in three reaches, namely upper, middle and tail reaches. The implemented sediment management plan is outlined as follows (see also Figure 6-1):

(1) *Flow-induced transport within the reservoir*: This is to create the condition for sediment transport from the upper and middle reaches to the tail reach portion by lowering the water level during dry season to have natural flow in upper reaches and facilitate

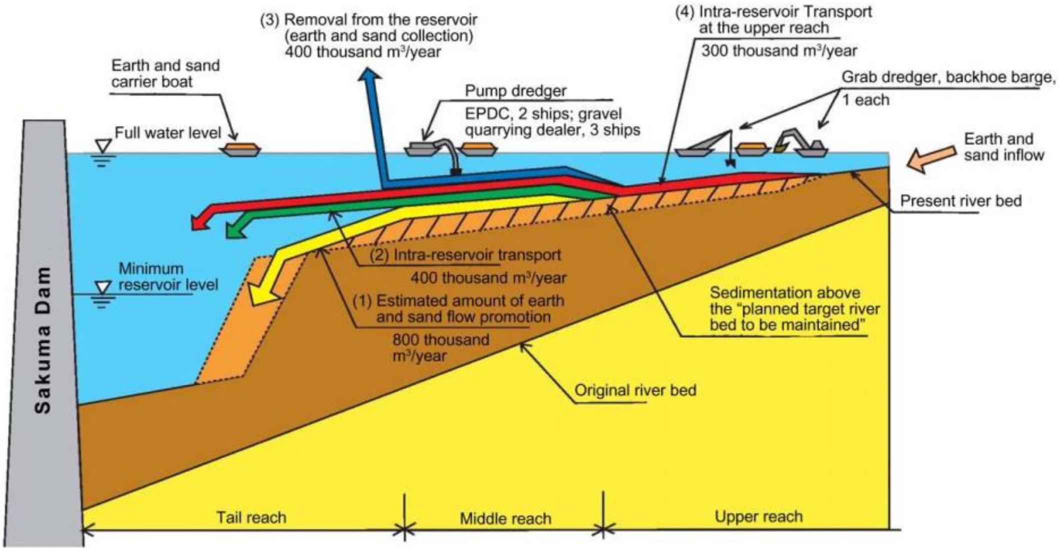

Figure 6-1. Sediment management at the Sakuma Dam *(J-Power, personal communication)*

transport towards the lower tail reach. The transport volume is limited to the effective volume of the tail reach. The annual transport (estimated by EPDC) is about 800 thousand m^3 (denoted by a yellow arrow in Figure 6-1). This is implemented by EPDC.

(2) *Intra-reservoir transport*: This is realized by dredging and dumping of the sediment from the middle reach to the tail reach within the limit of the effective volume. The target annual volume is 400 thousand m^3 (denoted by a green arrow in Figure 6-1). As an additional measure to accelerate the realization of the plan, the dredging operation is started to be carried out at the upstream reach as well with the target annual volume of 300 thousand m^3 (denoted by red arrow in Figure 6-1). This is also implemented by EPDC.

(3) *Removal from the reservoir*: This includes removal of sand and gravel by dredging from the tail reach and transported outside the reservoir. The dredging and removal operations are carried out by sand dealers. The target annual volume of removed material is 400 thousand m^3. The dealers get right to use dredged sand and gravels as construction material and for other purposes, such as making concrete, asphalt, using sand for golf course preparation and others.

The dredging and removal arrangement is depicted in Figure 6-2.

6.1.2 Miwa Reservoir (Japan)

The Miwa is one of the dams in Tenryu basin. It is a gravity concrete dam of 69 m high and having gross storage reservoir volume of 29.95 million m^3 with 311 km^2 of catchment area.

Due to several extreme events and sediment loads, the reservoir suffered from sedimentation problems. There was a sediment removal plan in place already in 1966, and deposited materials have been regularly removed since then. Approximately 5.32 million m^3 sediment have been dredged in 33 years (until 1998). If there were no sediment removal, the total sedimentation would be approximately 19.47 million m^3 (Sumi and Kantoush, 2011). Furthermore, as a part of long-term sediment management plan, a bypass system (Figure 6-3) that comprises 20.5 m high

Figure 6-2. Sediment dredging and removal arrangement *(J-Power, personal communication)*

diversion weir and a 4.3 km long bypass tunnel with a maximum discharge capacity of 300 m^3/s was constructed in 2004. This bypass system designed mainly to capture the wash load given the fact that about 34th of the deposited sediment in the reservoir was found to be wash load smaller than 74 µm (Sumi and Kantoush, 2011).

Following is the target plan of the project:

- The annual average sediment inflow is estimated to be 685 thousand m^3 (525 thousand m^3 of wash load and 160 thousand m^3 of bed material load).
- First, 160 thousand m^3 of bed material load is expected to be trapped by the check dam with sediment storage capacity of 200 thousand m^3. This trapped material is removed and transported for beneficial use as construction material or for other purpose.
- The bypass tunnel is expected to divert 399 thousand m^3 of wash load (out of 525 thousand m^3).
- A part of the remaining volume of the wash load will be flushed or removed from the dam and part will be deposited in the reservoir (estimated to be 26 thousand m^3).

The sediment management scheme is depicted in Figure 6-4.

Monitoring System and Operation Improvement

Along with the structural measures in the Miwa reservoir, non-structural adaptive measures are also considered like developing monitoring system and improvement of reservoir operation for sediment management. They have established real-time monitoring system to measure rainfall, reservoir inflow, turbidity and suspended sediment concentration in the upstream as well as downstream areas. Based on the observation, the operation mode can be adapted as follows (Sumi and Kantoush,, 2011, see also Figure 6-5):

- Mode 1: This is the normal operation mode in which all incoming flood will overflow the diversion weir into main reservoir.

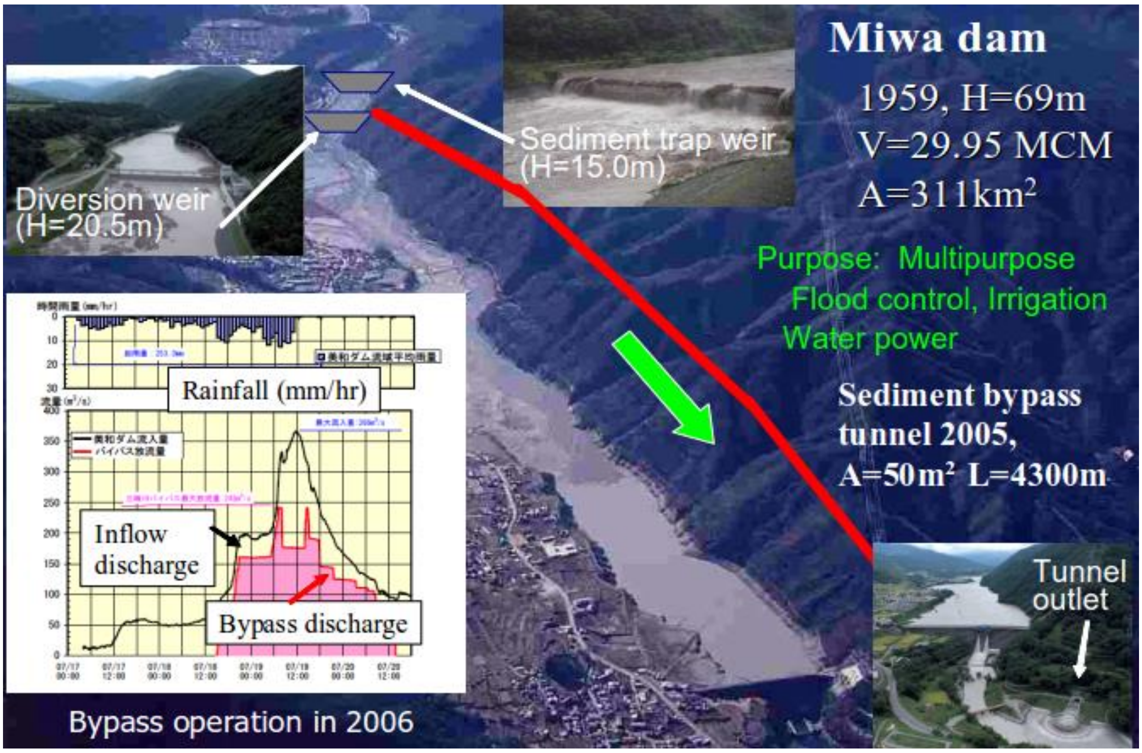

Figure 6-3. Sediment bypass system in Miwa reservoir *(Sumi and Kantoush, 2011)*

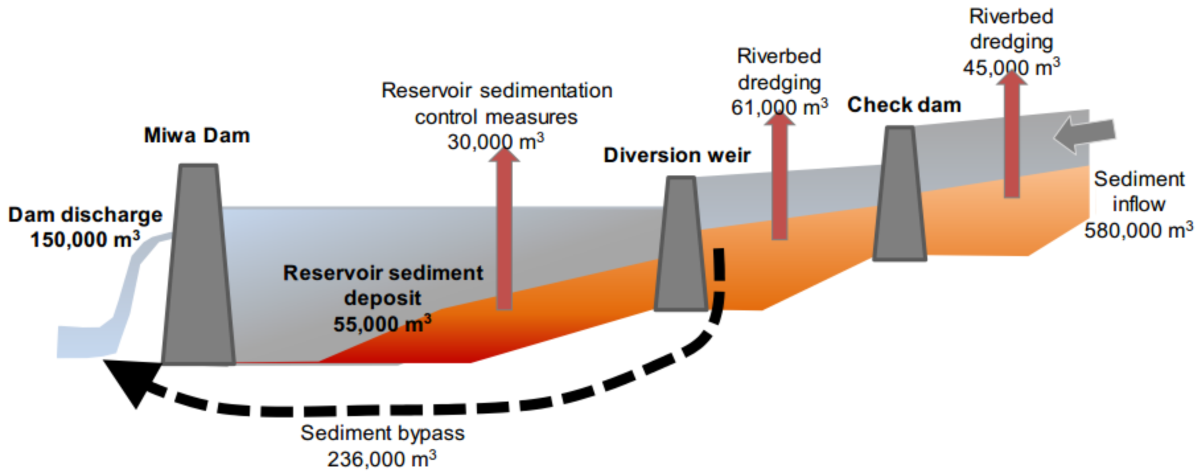

Figure 6-4. Sediment management in Miwa reservoir *(Sawagashira et al., 2017)*

- Mode 2: In this mode, some part of the flow is diverted to the bypass tunnel.
- Mode 3: This is refilling mode by closing the bypass main gate.
- The observed inflow discharge can be used to plan the timing for switching these operation modes. However, the maximum sediment concentration has usually a time lag with flow discharge, i.e. the maximum sediment concentration does not coincide with peak flow and usually higher during rising stage of flood. Therefore, the monitoring of suspended sediment concentration is also important.

The operation modes and monitoring arrangement in the Miwa reservoir is depicted in Figure 6-5.

6.1.3 Chamera-I and II (India)

National Hydroelectric Power Corporation (NHPC) carried out sediment management of two HPPs. Both HPPs are located on Ravi River - a tributary of Indus River in North part of India.

Chamera - I is a medium size reservoir with a gross storage of 412.8 Mm^3 (at FRL) and submergence area of 9.5 km^2 and reservoir length is 15 km. Total catchment area for is 4725 km^2. Chamera-II is a small size reservoir with a gross storage of 2.25 Mm^3 (at FRL) and length of the reservoir is 3.6 km. Total catchment area for I is 2593 km^2 (Dayal et al., 2016). A comparison between these two reservoirs is presented in Table

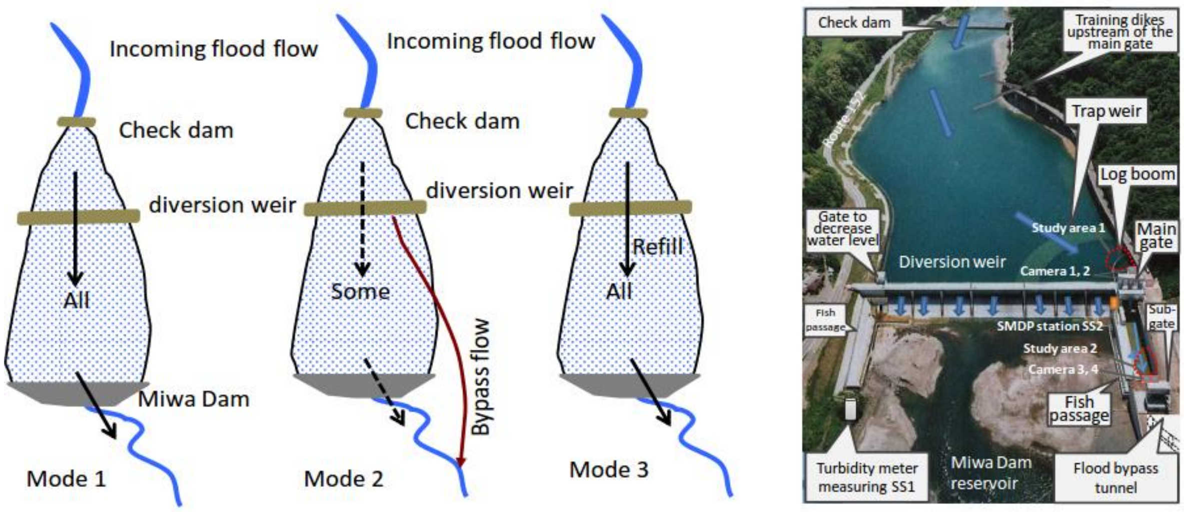

Figure 6-5. Operation modes (left) and monitoring arrangement (right) at the Miwa reservoir *(Sumi and Kantoush, 2011)*

6-1, showing general features of these two reservoirs (NHPC data, Internet Source).

A schematic layout of both reservoirs is depicted in Figure 6-6.

losses in live storage capacity are still insignificant so far. This may be owing to regular sediment management as mentioned hereafter.

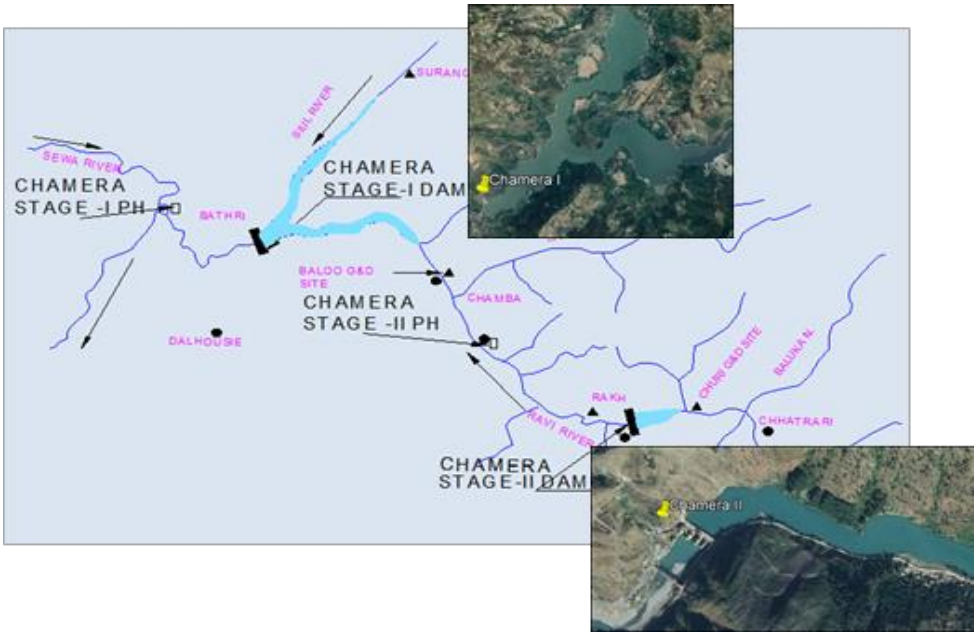

Figure 6-6. Schematic layout of Chamera-I and Chamera-II projects *(Dayal et al., 2016; Google Earth)*

Table 6-1. General features of Chamera-I and Chamera-II

	Chamera-I	Chamera-II
Gross storage at FRL (Mm^3)	412.8	2.25
Total catchment area (km^2)	4725	2593
Length of reservoir (km)	15	3.6
Design flood (m^3/s)	26500	8950
Sluices/gates	4 sluices (4 m × 5.5m)	4 gates (15 m × 21 m)
Annual average suspended load (Tons)	9.5	2.43

Changes in reservoir storage capacity in the course of years (NHPC, Internet Source) are depicted in Figure **6-7** and Figure **6-8** for Chamera-I and Chamera-II respectively. The data reveals that the gross storage has been reduced in both reservoirs, although

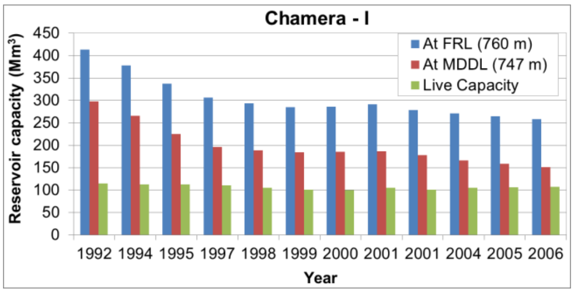

Figure 6-7. Changes in reservoir storage capacity over the years in Chamera-I

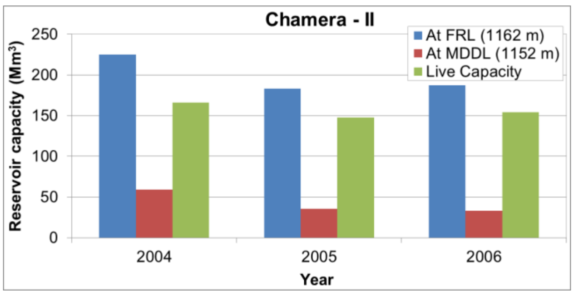

Figure 6-8. Changes in reservoir storage capacity over the years in Chamera-II

Sediment Management in Chamera - I

The sediment management practices and operation guidelines for Chamera-I and Chamera-II, reported by Dayal et al. (2016) are outlined as follows:

- Due to the larger size of Chamera-I, the flushing operation is carried out by maintaining the reservoir level at lower level and operating the undersluices (i.e. pressure flushing) rather than drawdown flushing (as it takes several days to deplete and refill the reservoir).
- The operation rule during high flow season considering sediment management is depicted in Table 6-2.
- This operation rule is found to be effective and optimal considering both sediment management and power generation regardless the fact that there is some short-term generation loss during high flow period, which is compensated by long-term advantage of sediment management (Dayal et al., 2016).

Table 6-2. Operation rule during flood season in Chamera-I

Period	Reservoir Level (m + Datum)
1 June to 20 June	757 m
21 June to 31 Aug	753 m
1 Sep to 15 Sep	754 m
16 Sep to 30 Sep	754 m to 757 m
1 Oct to 15 Oct	757 m to 760 m

- There is also regular sluicing in Chamera-I through four low level sluices. The sluicing appears to be effective to keep the intake area cleaner.
- Despite sediment management in Chamera-I, the reservoir storage capacity is decreasing. This could be attributed to several factors such as: (i) the reservoir is relatively large, (ii) it is located after the confluence of two rivers, which is not very favorable planform in terms of morphological condition, (iii) the spillway (and thus the underslucies) is not aligned well against the flow direction, and (iv) the undersluices are relatively small (low crest spillway with large gates could be more effective)
- Nevertheless, the sediment management seems to be effective enough to maintain the reservoir storage to some extent as well as to avoid the sediment related problem near the intake area in a highly sediment laden river.

Sediment Management in Chamera - II

- Given relatively small and narrow reservoir, it appears to be easier and effective to carry out sediment management operation in Chamera-II. Besides, it has large gates that allow free flow flushing.
- The sediment management in Chamera-II is carried out by maintaining the lower reservoir level during flood season, which is synchronized with Chamera-III (upstream reservoir) as well.
- Furthermore, free flow flushing is carried out in Chamera-II. The flushing operation is carried out when excess discharge is available during monsoon.
- The minimum discharges during 1 June to 31 August and 1 September to 30 September shall be 350 m^3/s and 250 m^3/s respectively. In former case, even if discharge does not exceed 350 m^3/s flushing is carried out around the last day of each month irrespective of the inflow discharge. While in latter case, the flushing operation is carried out between 26 to 30 September irrespective of the inflow discharge.
- The minimum interval between two successive flushing operations is defined to be 10 days. In case there is higher discharge immediately after such regular flushing (particularly, when the discharge is more than 1.5 times the proposed flushing discharge), then the

excess water is supposed to be used for continuation of flushing operations.

- The flushing operation is supposed to be started during rising limb of flood wave to ensure effective utilization of peak flow.
- Water level must be lowered gradually by keeping all the gates equally open. The water level must be as lower as possible to get better flushing effect.
- The flushing operation is allowed for the period until upstream and downstream sediment concentration is about equal. However, the flushing operation should be continued for at least 12 hours.
- Continuous observation and measurements of inflow, spillway outflow, reservoir level, and sediment concentration must be carried out at upstream and downstream locations. Besides, reservoir cross-section is measured at the end of monsoon (i.e., after flushing operations) at specified locations.
- The powerhouse must be shut down during flushing operation. The power generation restarts after closing all the gates and attaining desired reservoir level.

The results of flushing operations that have been carried out since 2008 are presented in

Table 6-3.

There is also a numerical and physical modelling studies on sediment flushing in Chamera-II reservoir, which can serve as an example how such studies are taken place in India as well (Isaac et al., 2014).

6.1.4 Shihmen Reservoir (Taiwan)

Shihmen reservoir is located in the middle of Dahan River in Taiwan. The dam was commissioned for exploitation in 1963. The dam height is 133 m, crest length is 360 m. The design storage capacity of the reservoir is 309 million m^3 at the Maximum Reservoir Level (245 m) with the design effective storage of about 252 million m^3 (while it was 209 million m^3 in 2011). The length of the reservoir is 16.5 km and the surface area is 8.0 km^2 (at FRL).

The reservoir is very important considering the fact that it is used for multiple purposes, i.e. power generation, irrigation, urban water supply, flood protection as well as for recreational use.

Most of the presented information, facts and figures are based on a recent publication by Lai and Wu (2018).

Reservoir Sedimentation Problem

- The sedimentation rate, observed during last two decades, shows the higher value than the design estimate. The major reason was the combined effect of two extreme events, namely a typhoon in 1996 and an earthquake in 1999.
- There were larger number of landslides and surface erosion as an effect of 1999 earthquake.
- There were more than 100 check dams in upstream reaches (about 35 million m^3 of sediment storage capacity). All these check dams almost fully filled up after a typhoon in 1996. Only during this typhoon, about 8.7 million m^3 of

Table 6-3. Results of flushing operations in Chamera II *(Dayal et al., 2016)*

Year	No of flushing operation	Cumulative hours of flushing	Observed sediment concentration (max) during flushing (ppm)	Total flushed sediment (M tonne)
2008	4	44	102250	2.5
2009	4	53	143560	2.7
2010	8	156	76450	5.7
2011	4	67	134330	4.3
2012	4	21	256940	2.66

sediments were transported into the reservoir.

- The bed level near the dam increased by about 25 m during the period of 1964 to 2005, and the reservoir lost about 35% of its storage capacity (as observed in 2009).
- Coarse sediments deposit at the upstream part, forming a delta. The fine sediments move towards the dam mainly due to the density current near the bed. The turbidity layer appears on the surface only when the typhoon is very large.
- A large typhoon in 2004 led to the interruption of the water supply for 18 days, affecting more than one million people. Moreover, it has been reported that this typhoon brought about 27.9 million m^3 of the sediment load into the reservoir, leading to the loss of about 11% of the reservoir capacity.
- After these events, various sediment management studies have been carried out as well as various options to deal with sedimentation problems have been proposed. A sediment bypass tunnel is one of them as a part of long-term sediment management strategy.

Existing and Planned Sediment Management Measures

- There was only a spillway for flood release with a maximum capacity of 11,400 m^3/s. An additional flood diversion outlet with the discharge capacity of 2,400 m^3/s was constructed in 1984.
- Other facilities that are usually used for sediment release are powerhouse intake, the permanent channel outlet and the Shihmen intake (as shown in Figure 6-9). The design feature of these facilities are presented in Table 6-4.

Table 6-4. Design features of existing facilities

Facilities	Parameters	Values
Spillway	Design discharge	11,400 m^3/s
	Crest elevation	235 m
	Gate H×W (6 numbers)	10.6 m × 14 m
Flood diversion	Design discharge	2400 m^3/s
	Sill elevation	220 m
	Tunnel pipe diameter (2)	9 m
Power-house	Max. discharge	137.2 m^3/s
	Bottom elevation	173 m
	Pipe diameter (2)	4.57 m
Perma-nent channel	Max. discharge	34 m^3/s
	Bottom elevation	169.5 m
	Pipe diameter	1.372 m
Shihmen Intake	Design discharge	18.4 m^3/s
	Bottom elevation	193.55 m
	Pipe diameter	2.5 m

- Several modification and rehabilitation of the facilities have been carried out since 2006 for increasing sediment release capacity, such as rehabilitation of permanent channel outlet as it was

Figure 6-9. Location of existing outlets that may be used for sediment release *(Google Earth image)*

clogged, modification of powerhouse intake to use one of the two pipes exclusively for sediment sluicing (which allows increasing the sluicing capacity from 137 to 380 m^3/s).

- As a next phase of sediment management strategy, new bypass tunnels have been proposed. Comprehensive studies have been carried out to assess the technical, economic and environmental feasibilities and impacts. Figure 6-10 gives an impression about the function and operation of the bypass tunnel. A detailed modelling study has been reported in Lai and Wu (2018).
- There is also real-time monitoring system to detect the turbidity current in the reservoir, which allows to sluice them by opening the gate right in time (see the work of Commandeur, 2015 on turbidity current in Shihmen Reservoir). The measurement technique is called Time Domain Reflectometry (TDR) for automatic monitoring of suspended sediment concentration over the depth (works with solar power). The details about this technique are given in Appendix A.
- Catchment management, forecasting and decision support systems, that are very useful for sustainable reservoir management, are in place as well.
- Figure 6-11 provides a good impression about the existing and proposed sediment management options and their effectiveness.
- Some relevant studies can be found in Tsai et al. (2012) and Lee et al. (2016).

6.1.5 Genissiat Reservoir (France)

Sediment Management Practice

The sediment management by using, so called, environmental-friendly flushing is practiced in Genissiat reservoir, which is located on the upper Rhone River in France. The case study, described here, is extracted from a published paper by Peteuil et al. (2013).

- There are other dams in the upstream reaches of this river in Switzerland. Therefore, there is impact of the sediment release from these upstream reservoirs, particularly from the Verbois dam (Figure **6-12**). In the French part of the reach, the sediment transport is relatively lower due to the trapping effect of upstream dams.

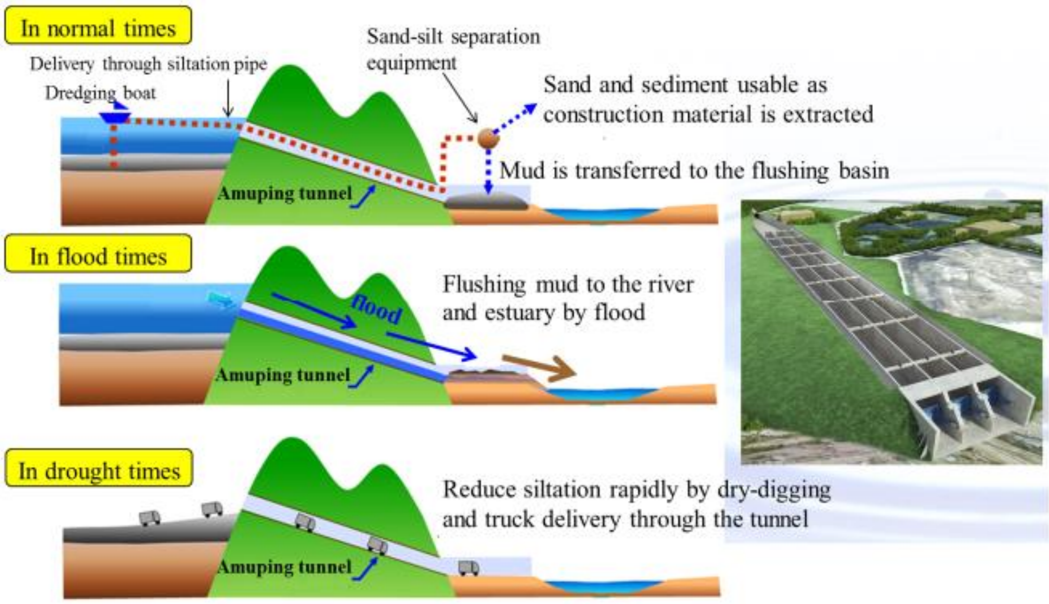

Figure 6-10. Function and operation of designed bypass tunnel *(Lai, 2017)*

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

Figure 6-11. Existing and proposed sediment management measures in Shihmen reservoir and expected results of their implementation
(www.rvo.nl/sites/default/files/2014/06/Jinn_Chuang_Yang_DWPE_Taiwan.pdf)

- The basin area is 95,500 km² and the mean annual discharge at the outlet of the catchment is 1700 m³/s. There is an Alpine tributary, namely Arve River, meets Rhone at upstream reach (see Figure **6-12**). In fact, the Arve River brings larger amount of sediment (estimated to be between 1-3 Mm^3 per year). Figure **6-13** gives an impression about this.
- As reported, 19 sediment flushing operations have been organized in the upper Rhone River since the commissioning of the Genissiat dam in 1948. There is a French-Swiss agreement for planning of the frequency of the operation.

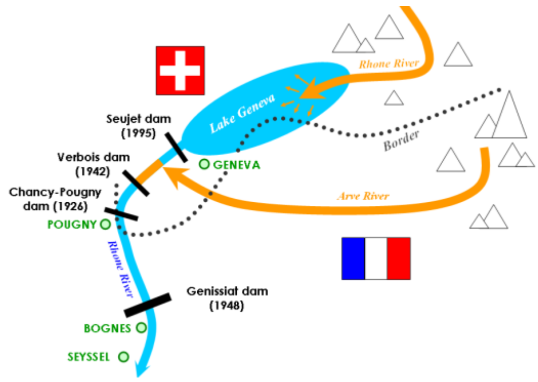

Figure 6-12. A schematic overview of the dams in the upper Rhone across French-Swiss boarder *(Peteuil et al., 2013)*

Figure 6-13. Confluence of the Rhone (cleaner) and the Arve (turbid) rivers *(Peteuil et al., 2013)*

According to the agreement, the flushing operation has to be carried out every three years between the end of May and the beginning of June.

- The dam authority has to consider following aspects while conducting flushing operation: (i) Ensure safety of the dam by avoiding clogging of the under sluices and bottom outlets, (ii) sluicing of sediment coming from the upstream, (iii) regulate the concentration of suspended sediment, released from the Swiss dams in order to limit the impact of the flushing operation on the fluvial environment, (iv) preserve the natural reach of the Rhone (Old-Rhone), and (v) limit the impact of flushing on human activities and infrastructures closely connected with the river like the water intake of Bugey nuclear power plant, several well-field for drinking water and some swimming areas

- The Genissiat dam includes 3 hydraulic intakes and outlets (like bypass), located at different levels and location, namely a bottom intake-outlet (intake level at 262.60 m), a half depth intake-outlet (intake level at 285.90 m) and a surface spillway (intake level at 316.80 m). Such an arrangement is very effective to control the sediment concentration during flushing. The Figure **6-14** provides an impression about the design and location of intakes and spillway.

- There is a monitoring station at the downstream reach (at Seyssel, see Figure **6-12**) to monitor the sediment concentration. The criteria for the sediment concentration at this location, set forth by the French authorities (based on longstanding experience, successes and failures), are as follows: (i) average concentration during the entire operation shall be below 5 g/l, (ii) average sediment concentration during a continuous period of 6 hours shall be below 10 g/l, and (iii) average concentration during a continuous period of 30 minutes shall be below 15 g/l

- For the sake of comparison - the maximum value observed during natural floods is around 3 g/l for the period between 1988 and 2009.

- Following is the approach of reservoir operation for sediment concentration control: (i) The reservoir level is lowered to mobilize the bed, which causes a vertical gradient of concentration of the fine materials, (ii) this high concentration flowing through the bottom outlet is diluted by the less turbid water provided by the upper layer of the reservoir through 'half depth' outlet to obtain the appropriate concentration downstream of the dam (Figure **6-15**), and (iii) the surface spillway can also be used for providing more clear water if necessary.

- In addition, a sequence of reservoir operation during flushing is followed that includes following steps: (i) a slow drawdown of the water level until a free flow state keeping it for several days, allowing transport of deposited bed materials, (ii) thanks to the real time monitoring of suspended sediment fluxes, an appropriate concentration is obtained by manipulating with the different intake gates of the dam, (iii) the water level in the reservoir is partially raised during the period when Swiss reservoirs are drawn down, releasing a great amount of sediments in the river, (iv) this uncontrolled (flushed) sediment supply from the upstream is once again regulated based on real time monitoring, (v) water level in the reservoir is raised to decrease the transport capacity towards the reservoir, (vi) in the meantime, water and sediment discharges flowing from the different hydraulic outlets are carefully controlled to obtain an appropriate sediment concentration at the downstream reach, and (vii) at the end of the operation, all intakes are closed and the reservoir is refilled.

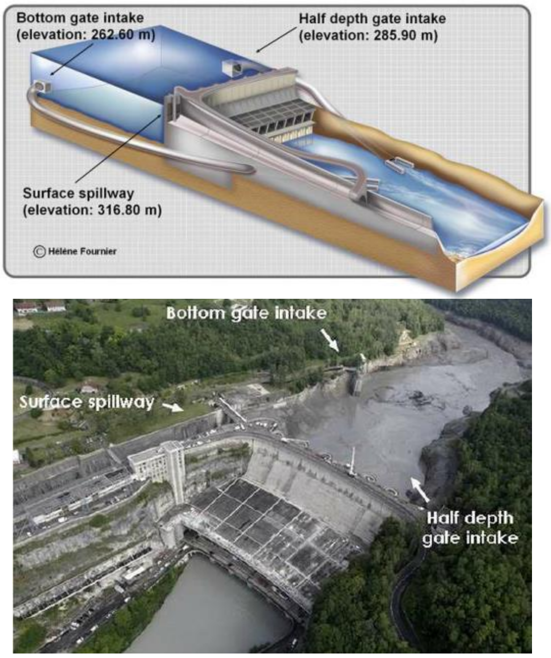

Figure 6-14. Schematic and real-world overview of the intakes and spillway of the Genissiat dam *(Peteuil et al., 2013)*

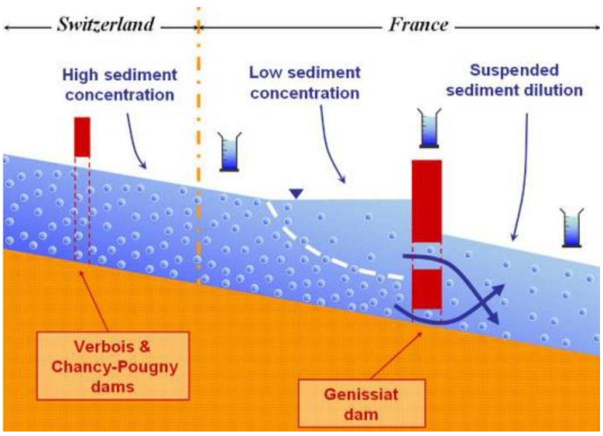

Figure 6-15. A schematic sketch of sediment dilution process while flushing in the Genissiat dam *(Peteuil et al., 2013)*

Monitoring System and Equipment

- The Genissiat dam has a comprehensive monitoring network, which is a key factor for good sediment management practice in this reservoir. Following parameters and objects are measured and monitored: (i) suspended sediment concentration (real-time monitoring during flushing operation), (ii) bathymetry, (iii) grain size analysis, (iv) bedload sampling (first time in 2012), (v) physical and chemical parameters (Temperature, Dissolved Oxygen, PH, NH4, Conductivity and Turbidity), (vi) toxicity and ecotoxicity, and bacteriology.
- Specific surveys are conducted for well-fields for drinking water, natural reserved areas, bypass river channel (so called Old-Rhone) and sensitive areas for aqua life (like fish).
- Suspended sediment concentration was measured by X-Ray densimetry and other complementary field methods like Specific Gravity Bottle and Filtration Method.
- Two bedload samplers were also tested during flushing operation of 2012 at different stage of the operation to measure the bedload fluxes both entering into the reservoir and released downstream of the dam.
- Review of the original paper (Peteuil et al., 2013) can be useful for further details.

Effect of the Sediment Flushing

- For the Genissiat dam authority the flushing operation is turned out to be costly. The experience of flushing operation in 2003 reveals that the cost is around 1.4 million Euros, among which 62% for energy losses, 15% staff costs and 23% for subcontracted services (impact surveys, specific monitoring, communication and others). Nevertheless this is found to be much cost effective than dredging given the 1.8 M tonne of flushed amount of sediment.
- For the flushing operation of 2012, about 400 people were mobilized from for the period of approximately 10 days. The cost is evaluated around 8 million Euros, among which bit less than 50% for energy losses. About 2.1 M tonne of sediment load were flushed downstream during the operation, which shows that

the method is still economically effective than dredging.

- It is inferred that regular sediment management efforts since last 40 years have resulted in significant improvement of the storage capacity allowing the gross deposition of only 4.5 M tonne in the reservoir. While the sedimentation rate suggests that the amount of sediment deposit in the reservoir could have been 23 M tonne since its commissioning.

6.1.6 Utah's Reservoirs (USA)

A report by Utah State Water Plan (USWP, 2010) gives a good overview of ongoing efforts on sediment management of Utah State's reservoirs.

Hereafter, the summary of sediment management strategies for ten reservoirs and watersheds in Utah are presented. The summary provides an impression about some characteristic features and relevant sediment management strategy. The details can be found in USWP report (2010).

<u>Wide Hollow Reservoir</u>

Built: 1954
Dam: Earth fill
Dam Height: 50 feet
Surface Area: 145 acres
Original Storage Capacity: 2,325 acre-feet
Watershed: 10 mi^2 *
Maximum Depth: 23 feet
Mean Depth: 16 feet
Length/Width: 0.61/0.42 miles
Off-stream Source: Escalante River
On-Stream Source: Wide Hollow Wash (ephemeral)
Current Uses: Irrigation and recreation

Sedimentation Rate/Loss of Capacity: Average annual loss of 0.91% of original capacity per year (1954-2007) or 48% lost capacity as of 2007
Sediment Characteristics: Fines with sand. 90% of sand is over 0.15 mm diameter

Management Strategies: Sediment basin and sluice gates installed in initial reach of canal. A dam-safety rebuild and concurrent enlargement are proposed.

Benefit: Raising the dam will restore almost all of the original reservoir capacity.

*Natural drainage watershed is roughly 4% of the total watershed of 273 mi^2 (Utah Department of Water Quality).

<u>Gunlock Reservoir</u>

Built: 1971
Dam: Earth fill
Surface Area: 266 acres
Original Storage Capacity: 10,884 acre-feet
Watershed: 306 mi^2
Maximum Depth: 115 feet
Mean Depth: 77 feet
Length/Width:1.8/0.7 miles
On-Stream Source: Santa Clara River
Current Uses: Irrigation and recreation

Sedimentation Rate/Loss of Capacity: 0.86% per year (1971-2004) or 28% as of 2004
Sediment Characteristics: Fines and sand

Management Strategies: Trap and excavate sediments upstream. Drain and excavate sediments near outlet.

Benefit: Restore outlet works function.

<u>Millsite Reservoir</u>

Built: 1971
Dam: Earth fill
Dam Height: 125 feet
Surface Area: 435 acres
Original Storage Capacity: 18,000 acre-feet
Watershed: 157 mi^2
Maximum Depth: 102 feet
Mean Depth: 46 feet
Length/Width: 1.38/0.66 miles
On-Stream Source: Ferron Creek
Current Uses: Recreation and irrigation

Sedimentation Rate/Loss of Capacity: 0.44% per year (1971-2004) or 14% as of 2004
Sediment Characteristics: Fines
Sediment Load: 441 tons/day

Current Management Strategy: Sediment pass-through to remove sediment around intake structure during high flow
Recommended Management Strategy: Hydro-suction Dredging
Cost: $302,000 capital, $14,000 annual

Benefit: Maintain current reservoir capacity and possibly restore some original capacity.

Piute Reservoir

Built: 1908
Dam: Earth fill
Dam Height: 90 feet
Surface Area: 2,508 acres
Original Storage Capacity: 81,200 acre-feet
Watershed: 2,440 mi^2
Maximum Depth: 66 feet
Mean Depth: 33 feet
Length/Width: 6.9/0.9 miles
On-Stream Source: Confluence of Sevier and East Fork Sevier River
Current Uses: Recreation and irrigation

Sedimentation Rate/Loss of Capacity: 0.32% per year (1910-1938); 0.21% (1961-2004)/ 18% as of 2004.
Sediment Characteristics: Fines from alluvial and volcanic rock

Management Strategy: Dam upgrade. Indirect sediment mitigation.
Project Completion Date: 2005
Cost: $8.2 million (dam upgrade)

Benefit: Dam was upgraded for dam safety reasons. This increased storage capacity to about 71,826 acre-feet.

Otter Creek Reservoir

Built: 1897
Dam: Earth fill
Surface Area: 2,520 acres
Current Storage Capacity: 52,660 acre-feet
Watershed: 364 mi^2
Maximum Depth: 37 feet
Mean Depth: 20.6 feet
Length/Width: 6.55/0.73 miles
On-Stream Source: Otter Creek
Off-Stream Source: East Fork Sevier River (East Fork Canal)
Current Uses: Recreation and irrigation

Sedimentation Rate/Loss of Capacity: 0.21% per year (1961-2004) or an estimated 9% as of 2004
Sediment Characteristics: Fines from alluvial and volcanic rock

Management Strategy: Raise spillway to regain capacity
Cost: $224,000 (estimate)

Benefit: Raise water level two feet. Restore some of original storage capacity and increase water

First Dam Reservoir

Built: 1914
Dam: Compacted concrete-fill
Dam Height: 30 feet
Crest Length: 250 feet
Original Storage Capacity: 70 acre-feet
Watershed: 226 mi^2
On-Stream Source: Logan River
Current Uses: Recreation, Irrigation Hydropower, and Research Lab

Sedimentation Rate/Loss of Capacity: 0.74% per year (1914-2001) or 64% as of 2001

Management Strategy: Sluicing

Benefit: Maintains current storage capacity

Cost: Difficult to manage. Potential environmental impacts and current turbidity & water quality requirements are difficult to achieve.

Quail Creek Diversion

Built: 1984
Dam: Concrete gravity
Dam Length: 95 feet
Original Storage Capacity: 295 acre-feet
Watershed: 1,000 mi^2
On-Stream Source: Virgin River
Current Use: Divert water to the Quail Creek and Sand Hollow reservoirs for agriculture, recreation and drinking water.

Management Strategy: Follow sediment management plan. Sluicing and mechanical cleanout

Gebidem Reservoir

Built: 1967
Capacity: 7,460 acre-feet
Dam Height: 400 ft
On-stream Source: Massa River
Current Use: Hydropower
Reservoir Length: 0.93 mi

Sedimentation Rate/Information: 324 acre-feet per year
Sediment Characteristics: very fine sand to gravel

Management Strategy: Emptying and Flushing
Sediment Removed: About equal to annual accumulation
Cost: 0.8 franc per 35 ft^3 sediment removed (1970 currency)

Benefit: Substantially increased longevity of the hydroelectric facility

North Fork Feather River Watershed

Size: 656,600 acres
Management Strategy: Watershed restoration
Projects Completed: Over 30
Cost: Varies per project. 10 projects were completed in Pumas County at a cost of $2,063,000.
Benefit: 50% decrease in sediment yield over 30 years. Increased environmental quality. Increased power production.
Lower maintenance costs.

Benefit: Substantially increased longevity of the hydroelectric facility

Valentine Mill Pond

Built: Early 1890s
Size: 37 acres surface area
Maximum Depth: 12 feet
On-stream Source:
Minnechaduza Creek
Current Use: Recreation

Sedimentation Rate/Information: By the 1970s over half the capacity was lost
Sediment Characteristics: Sand

Management Strategy: One-time dredging. Hydrosuction bypass sediment removal system
Sediment Removed: 160,000 yd^3
Project Completion Date: Summer 2002
Cost: $1.6 million

Benefits: Improved water quality, recreation, aquatic life, & aesthetics. Sediment reduction.

6.1.7 Case Studies Database

There is a knowledge hub, published in website of International Hydropower Association (IHA). There are a number of useful information including a database of case studies around the world. The link to the webpage of the hub (the case studies) is given below:

www.hydropower.org/sediment-management

The site could be updated in future with more case studies, experiences and practices and useful information.

6.2 Failure Examples in India

6.2.1 Sediment Disaster

There was an attempt to flush the Pillur reservoir (see below in Section 6.3.2 for the details about the reservoir) using scour sluice by depleting it (pressure flushing) in 1991. However, it had ended up with a huge sediment disaster, since there were no regular sediment management measures in place before that. The deposited amount was huge, thus the slurry during flushing got highly concentrated, and did not seem to behave like normal sediment-water mixture, but rather as a body of fluidized sediment mass (or like hyper concentrated turbidity current). At the same time, there was an unforeseen trouble with the clogging of scour sluice (apparently due to the hindrance, induced by some debris), which led to the mass of sediment bursting towards powerhouse (which is located on left side of the scour sluice at downstream area). Powerhouse area was covered with large amount of sediments, and thus the generation had to be stopped for considerable period. Figure **6-16** and Figure **6-17** provide an impression about the deposition near the dam and the effect of the hazard, revealing its scale. Since then the scour sluice has never been used for flushing, and it appears that most part of it has been clogged again.

Figure 6-16. Deposition in front of power intake and scour sluices (in 1991)

C

Figure 6-17. Sediments, deposited in and around powerhouse premises as a result of hazards during the flushing

6.2.2 Downstream Pollution

General

The available information on a serious incident caused by the uncontrolled desiltation of Kallarkutty reservoir in Kerala, leading to environmental havoc causing pollution of downstream reach of the river Periyar, and thus obstructing the water supply and affecting the aqua life, has been synthesized. This reservoir is the downstream-most one in the Mudirapuzha basin. The spill from upstream reservoirs Kundala, Maduppetty, RA Head works, Anayirankal, Ponmudi and Sengulam also reaches this reservoir. The water from Kallarkutty reservoir is diverted through a water conductor system to the Powerhouse of Neriyamangalam HEP located on the right bank of Periyar River. After generating power, the water is released to Periyar River (PST, DRIP). Figure **6-18** gives an impression about the location and surrounding area.

This case has been mentioned here in order to consider as a learnt lesson, which will be very useful for future consideration while dealing with such problems.

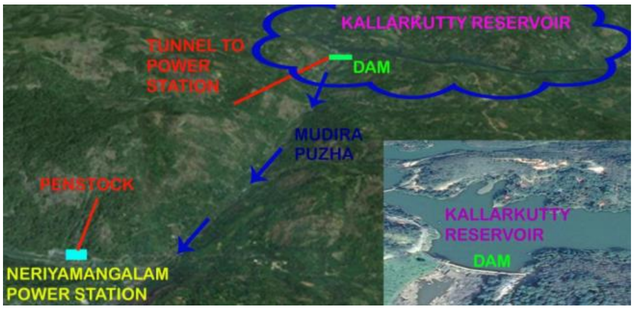

Figure 6-18. Location of Kallarkutty Reservoir *(adapted from Google Earth)*

Issues and Action Plan

There were no sediment management plan and operations, and nothing had been done for more than 18 years (Paimpillil, Internet Source). After such a long period, a desiltation operation was carried out without proper investigation of sediment quantity and quality. A case study was performed by Paimpillil (Internet Source), in which the water quality hazard due to release of contaminated sediment was described. Following severe impacts, issues and action plans for water quality and sediment management have been mentioned in the report (Paimpillil, *Internet Source*):

- Water color in lower reaches of the river Periyar was reddish (as shown in Figure **6-19**). It is apparent that area near the river Pariyar and its banks have already been polluted due to the industries. This seems to have led to contamination of sediment deposits in the reservoir.
- The turbidity level varied between 58 and 68 NTU (comparing to original level of 1 NTU before the flushing). (Note: NTU stands for Nephelometric Turbidity Units).
- Discoloration was found to be occurring 25 times in nine months. No toxicological testing was done during this period.

- Probably there was an issue with reservoir eutrophication.
- Moreover, polluted water spread over upstream of the delta area due to tidal effect, e.g. in Eloor, which is only 17 km from the Arabian Sea.
- Polluted sediment and water got into several rural water supply pumping system downstream.
- As reported, the water supply system in the entire Kochi region seemed to be affected.
- Aquatic and habitat life was affected severely.
- Growing public concerns over polluted water in Periyar forced government authorities to take steps to organize remedial measures for improving the water quality as well as future action plan.
- The Kerala State Pollution Board proposed action plan to investigate and safeguard the river, check and control dumping of chemical effluents from industries.
- Following actions and measures have been included in the action plan: (i) setting up of an online water quality monitoring system, (ii) road construction along the river banks in the industrial areas, (iii) setting up of a common effluent treatment plant for the nearly 200 small-scale industries in the Edayar area, (iv) launching of "Save Periyar" initiative, (v) a River Protection Authority under Water Resources Ministry, (vi) patrolling the river etc.
- Community participation and involvement in restoration of the Periyar, monitoring the river and spot incidents of pollution, contribution by local community as environmental surveillance wardens etc.
- Catchment treatment plan, river bank protection, planned and viable desilting operations, option for sand mining and reuse of sediment etc.

Figure 6-19. Impact of reservoir flushing in downstream of the river Periyar
(www.indiatogether.org/periyar-environment--2)

6.3 Case Studies under DRIP

Reservoir sedimentation issues, particularly sediment removal operations, were considered on case to case basis within the scope of Dam Rehabilitation and Improvement Project (DRIP) in India. They were supposed to be addressed only in circumstances when the regained reservoir volume would have a high economic value. There were concerns from some State Electricity Boards and Public Water Department to explore sediment removal possibilities for some reservoirs, which are losing the storage capacity with the threat of malfunctioning of apparatus and structures due to significant siltation including consolidation of the deposited silt and clay as well as large debris flow.

The four selected reservoirs to investigate the sediment management options are located in Tamil Nadu (owned by TANGEDCO) and Uttarakhand (owned by UJVNL).

6.3.1 Kundah Palam (Tamil Nadu)

General

Kundah Palam is one of the DRIP dams, located in Tamil Nadu. The dam is mainly a forebay to Kundah Power House-2 for the Kundah Hydro-electric scheme, constructed across the Kundah River. The catchment area of the dam is 113.96 sq. km. The Catchment drains at Kundah River and Sillahalla. Dam has scour vent, but it was hardly ever used for sediment removal (except for some minor sediment removal due to severe deposition). Some characteristic features of the reservoir are presented in Table 6-5. Figure **6-20** gives an impression about the reservoir. Table 6-5.

Table 6-5. Features of Kundah Palam reservoir

Particulars	Details
Water Spread Area	1.61 km²
Gross Capacity	1.76×10^6 m³
Effective Capacity	1.56×10^6 m³
Spillway Capacity	1556 m³/s
Scour Vent Capacity	28.3 m³/s

Figure 6-20. Kundah Palam reservoir with dam and upstream powerhouse *(Image source: Google Earth)*

Problem Statement

Following points are outlined based on a field reconnaissance and other available information on Kundah Palam sedimentation issue (Giri et al., 2016):

- Sediment management was never a priority given that the forebay is used predominantly for power generation. So, despite the fact that the dam has a scour vent, it has been seldom used for regular sluicing and flushing purpose.
- There is no proper study on reservoir sedimentation.
- The scour vent was almost clogged during 2016. Moreover, 2/3rd of the trash rack at the tunnel entrance has been silted up. The reservoir has been filled up almost 50% in last 50 years. Figure **6-21** provides impression about the siltation near entrance of the tunnel and scour vent entrances.
- Source of the problem is poor catchment management (e.g. bare cultivated lands on hill slopes), but more importantly, due to the absence of regular maintenance and negligence of sedimentation issues in the reservoir. Basically, there is no sediment management plan whatsoever despite a number of past events, awareness and recommendations. A major desiltation operation has never been conducted so far. Only cleaning of the deposits in front of scour vent and entrance of the tunnel was carried out in 2014.
- The current situation is rather acute not only in terms of storage loss, but also the malfunctioning of structures and apparatus (e.g. trash rack at tunnel entrance) that could be leading to conceivable occurrence of emergency situation including failure of power generation and other damages.
- A sediment removal activity was carried out to clean the deposits near the dam area, particularly near tunnel entrance and scour vent. It was carried out by depleting the reservoir first and then 'washing' by using tailrace discharge of upstream powerhouse (see Figure **6-20** above for the location of upstream powerhouse).
- In fact, the inflow sediment transport rate does not appear to be significant given the magnitude of storage loss in last 50 years without any sediment management measure. This implies that the removal of silt deposits from the reservoir has long-term benefit.
- Section below provides some impression about how the concerns have been identified and quantified based on morphological and sediment transport patterns.

Figure 6-21. Sediment deposits at the dam (scour vent and intake)

Morphological Feature of the Reservoir

Based on the morphological feature, the Kundah Palam reservoir can be divided in to three characteristic reaches. It should be noted that the bathymetry survey was carried out in 2009 only, and no digital data is available. Figure **6-22** provides an impression about these reaches, while pictures depicted in Figure **6-23** and Figure **6-24** give a clear impression of the morphological patterns and deposits (as most of them were taken during depletion of the reservoir). It is interesting that different silt concentration and color was observed in two tributaries (i.e. Reach I and Reach II), which can be seen from the pictures (taken during monsoon at the same time), depicted in Figure **6-25**. It was found that Reach II had larger turbidity and different colour of sediment. Also, the discharge from Reach II seems to be higher (including the tailrace discharge of the powerhouse which is located in this reach as shown in Figure **6-20**), since we found that the turbid reddish water was entering to Reach I. Lower discharge at Reach I appears to be the reason why sediment deposit at Reach I is migrating slowly towards the confluence (as shown in lower picture of Figure **6-23**).

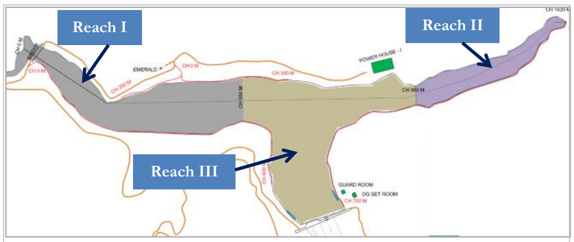

Figure 6-22. Division of reservoir reaches based on morphological features

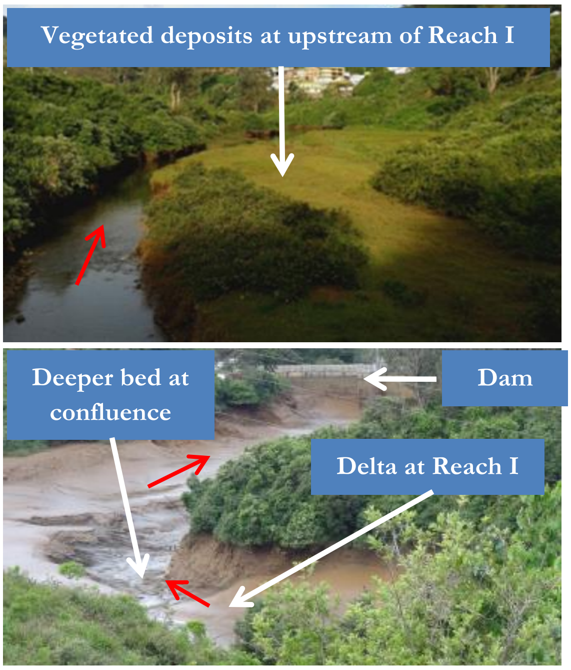

Figure 6-23. Vegetated deposition at upstream (upper) and sediment delta migrating towards the confluence (lower)

Figure 6-24. Sediment deposits in Reach III, looking upstream from the dam (upper) and Reach II (lower)

Figure 6-25. Different turbidity and colors of water in two reaches during high flow (observed in monsoon), showing that Reach II brings highly suspended load, eroded from the slopes of cultivated lands and gullies

Proposed Sediment Management Plan

Sedimentation issues are associated with not only technical aspects, but also specificity of the locations/region/country, local constraints and regulations, social and environmental issues etc., which have to be considered while selecting remedial measures. In case of Kundah Palam, there were not much alternatives, so following aspects had been considered while selecting the sediment removal approach: (i) size of the reservoir (small), (ii) volume of the deposited material (moderate), (iii) sediment inflow (insignificant), (iv) downstream condition (presence of Pillur reservoir in the same cascade), (v) availability of land for silt disposal (valley for landfill owned by the dam authority), (vi) morphological feature of the reservoir (three characteristic reaches), (vii) minimum generation loss, (viii) environmental and social impacts, (viii) location and accessibility.

Based on these aspects and constraints, dry dredging and trucking as well as hydraulic dredging options (using environmentally friendly dredging pump or hydro-suction technology) with partial downstream removal through scour vent and/or slurry pipe was proposed.

The sediment removal plan was divided in to three main phases based on three reaches. So, following three phases were recommended to be considered while carrying out destilting operation:

- Phase 1: In this phase, the water level is recommended to keep at minimum level, i.e. at 1620 m+ datum. At this level the power generation is not interrupted. At the same time, lowering of water level to this level will create quite some dry areas, particularly in Reach I and II. These areas shall be excavated by mechanical means and subsequently to trucking to the dump site.
- Phase 2: This phase is related to the desilting operation near the dam area (Reach III) with a focus on cleaning of the reservoir near the entrance of tunnel and the scour vent as well as deepening of the approaching channel. Hydraulic dredging using light and environmental friendly equipment is recommended, since the depletion (causing generation loss) is not allowed for more than 10 days during lean period.
- Phase 3: This phase of sediment removal operation has been proposed for all remaining areas. The deeper and inaccessible areas of the reservoir (particularly in Reach III, and if necessary also in Reach I and II) shall be desilted by means of hydraulic dredging. This is particularly desirable given the fact significant generation loss is not viable economically and socially. All remaining dry and reachable areas shall be desilted by means of dry excavation and trucking. All the deposits, which are not possible to be removed by means of

dry excavation and trucking, shall be relocated to upstream area (in Reach I and II) by means of hydraulic dredging and slurry pipe for dewatering and later trucking to the dump site.

- While sediment disposal plan can briefly be outlined as follows:
- Landfill: There is a small valley, located at about an average distance of 5 km away from the reservoir site, where the removed materials can be disposed. The area is owned by TANGEDCO and rather suitable for landfill, which can later be used as a playground or for other purpose (see Figure **6-26**).
- Transportation of removed materials: Most of the removed material shall be transported by trucking, since other option like slurry pipe and conveyer belt is technically and economically less viable given the hilly location.
- Disposal through slurry pipe and scour vent: A part of the deposited material (not more than 50.000 m^3), particularly near the dam area of the Reach III (to be carried out mainly in Phase 2) shall be discharged through the scour vent (referred to in these works as washing). Since the depletion is not allowed for long period (maximum allowable period may be less than 10 days), other effective dredging alternative shall be considered, such as using hydraulic dredging equipment (e.g. a light dredging pump), by means of which silt deposits can be removed to downstream through the slurry pipe over the dam. This could be more efficient and effective, and the silt removal activity can be carried out during monsoon without affecting the powerhouse generation.
- The volume of sediment, discharged to downstream, should not exceed 50, 000 m^3 given the fact that most of these materials will eventually reach Pillur reservoir. Increasing the volume of downstream disposal would be possible only after monitoring of the first discharged volume including detailed assessment of loss of water, propagation of removed material along the downstream river as well as sediment management plan to be implemented in the Pillur reservoir.
- The overall sediment removal and disposal approaches would remain the same; nevertheless, the methodology can be improved in case of availability of more data, measurements and elaborative studies. Also, it is recommended to consider the other cascade dam (upstream and downstream), particularly for assessing effectiveness of flushing operation.
- For more detailed technical specification of proposed sediment management, the report (Giri, 2015) can be referred.

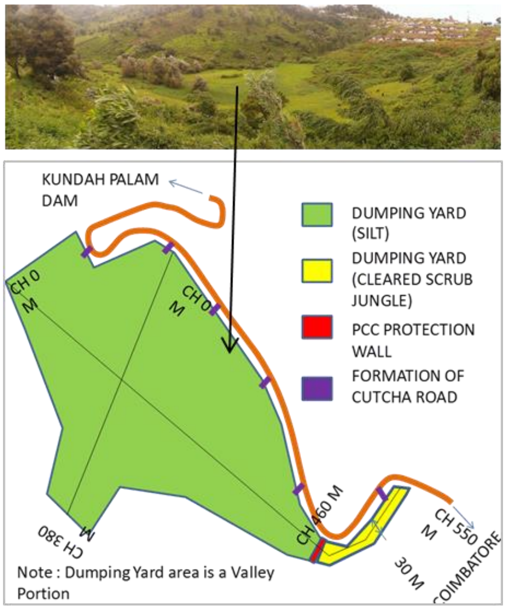

Figure 6-26. Image and schematic plan of the dumping yard

6.3.2 Pillur (Tamil Nadu)

General

- Pillur is one of the reservoirs within Kundah Hydro Electric System, located downstream of the Kundah reservoir in Nilgiris. The reservoir is located 5 km downstream of the confluence between the rivers Bhavani and Kundah (constructed in Bhavani River).

- The Water Spread Area of the reservoir is 2.6 km^2, while gross and effective capacities are 44.4×106 m^3 and 34.97×106 m^3 respectively. The dam level and crest level of the spillways are 429.16 m and 417.58 m respectively. The Full Reservoir Level (FRL) and Minimum Drawdown Level (MDDL) are 426.72 m and 396.25 m respectively.
- The catchment area of the reservoir is 1191.40 km^2 (about 10 times bigger than that of Kundah reservoir), which includes not only Tamil Nadu, but also Kerala state. The main rivers, contributing to the reservoirs are Bhavani, Kundah, Nirala Pallam and Katteri rivers. Besides, all upstream reservoirs, located in Nilgiris basin, contribute to this reservoir. Consequently, not only water but also sediment sources are diverse.
- The impoundment type powerplant is located in the dam, which makes the sedimentation issue more relevant and important to be considered.
- Another important aspect is that the reservoir is being used for water supply to the city of Coimbatore. Therefore, the loss of storage capacity and deposition near water supply intakes could be of great concern in future. In effect, it appears to be already an issue, since sedimentation at the area of one of the intake levels is already rather high (only about 10 m below the maximum water level of the reservoir and merely about 1.5 m below the crest level of the spillway).

Past Efforts and Problems

- Some studies regarding the capacity and sedimentation issues at Pillur reservoir were made by Institute of Hydraulics and Hydrology, Poondi. One of these studies has been carried out recently (in 2014). Earlier study was made in 1982 as described in the report (I.H.H. Poondi Report No. 4, 2014). Based on these studies, some plots have been made, revealing the storage loss over the reservoir level (as shown in **Figure 6-27**.
- As it can be seen from the **Figure 6-27**, the lower level near the bottom (up to about 380 m) of the reservoir filled up completely (about 25 m thick layer, although the initial storage volume within this layer is about 7% of maximum capacity.
- As result reveals, the loss of storage (under the condition of FRL) in first 16 years is 27.88%, while the storage loss during second 32 years is 13.76%, and thus the total loss with respect to initial capacity (after 48 years) is 41.64%.
- The faster loss of storage capacity during initial periods after the construction is a logical result, since the trap efficiency of the reservoirs tends to decrease with time.
- Following is a summary based on past studies: (i) Loss of reservoir storage = 41.64%, (ii) Annual storage loss = 0.87%, (iii) Trap efficiency = 68%, (iv) Annual rate of sedimentation = 1.4%.
- Furthermore, sediment sampling and grain size analysis were carried out for several locations along the reservoir (as shown in **Figure 6-28**). From the result, it can be inferred that the content of coarse sand (0.6 – 0.212 mm) is predominant in almost all locations, even near the dam (e.g. locations S2, S3, S17, S18 etc.).
- Some of the samples from upstream location show the content of gravels as well (S4, S6), which is logical. The contents of fine sand, silt and clay are very small even near the dam (only samples from the locations S3 and S18 contain about 11% and 10.5% of silt/clay and fine sand respectively).

- It is possible that the bed material at deeper layer near the dam has been consolidated during past years. This does not reflect in the sediment analysis as it shows low content of silt in the area near the dam.
- The collected sediment sample appears to represent merely the newly deposited thin surface layer and not the core sample, which could give information about the deposits in deeper layer.
- There was an attempt to flush the reservoir through scour sluice by depleting (pressure flushing) in 1991. However, it ended up with a huge sediment disaster. This is explained in Section 6.2 above.
- There is no information about the sediment management efforts other than the flushing attempt of 1991.
- The problem is due to absence of proper sediment management, and thus it has been accumulating since decades. Moreover, the preserved forest area, downstream reservoirs as well as not that easy accessibility due to hilly area (particularly for big machineries etc.) make the sediment management efforts very difficult.

Recommendations for Sediment Management

- The reservoir is relatively large, and the volume of deposited material is about 20 Mm^3 (the layer thickness of deposited material appears to be varying between 20-40 m). Moreover, the reservoir is located inside the preserved forest area.
- In effect, there are not many options for removing the sediment easily and fast. Consequently, a long-term (more than 10 years) sediment removal plan was proposed as a first quick plan.

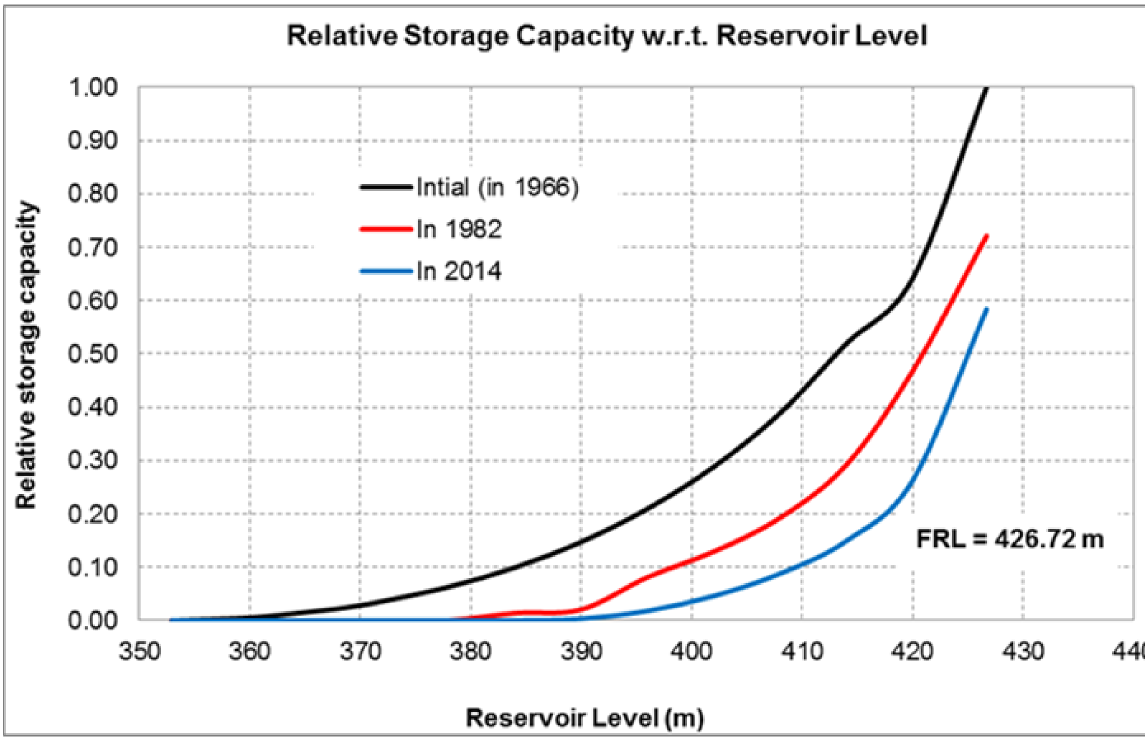

Figure 6-27. Changes in Reservoir Storage capacity w.r.t Reservoir Level (Pillur Dam)

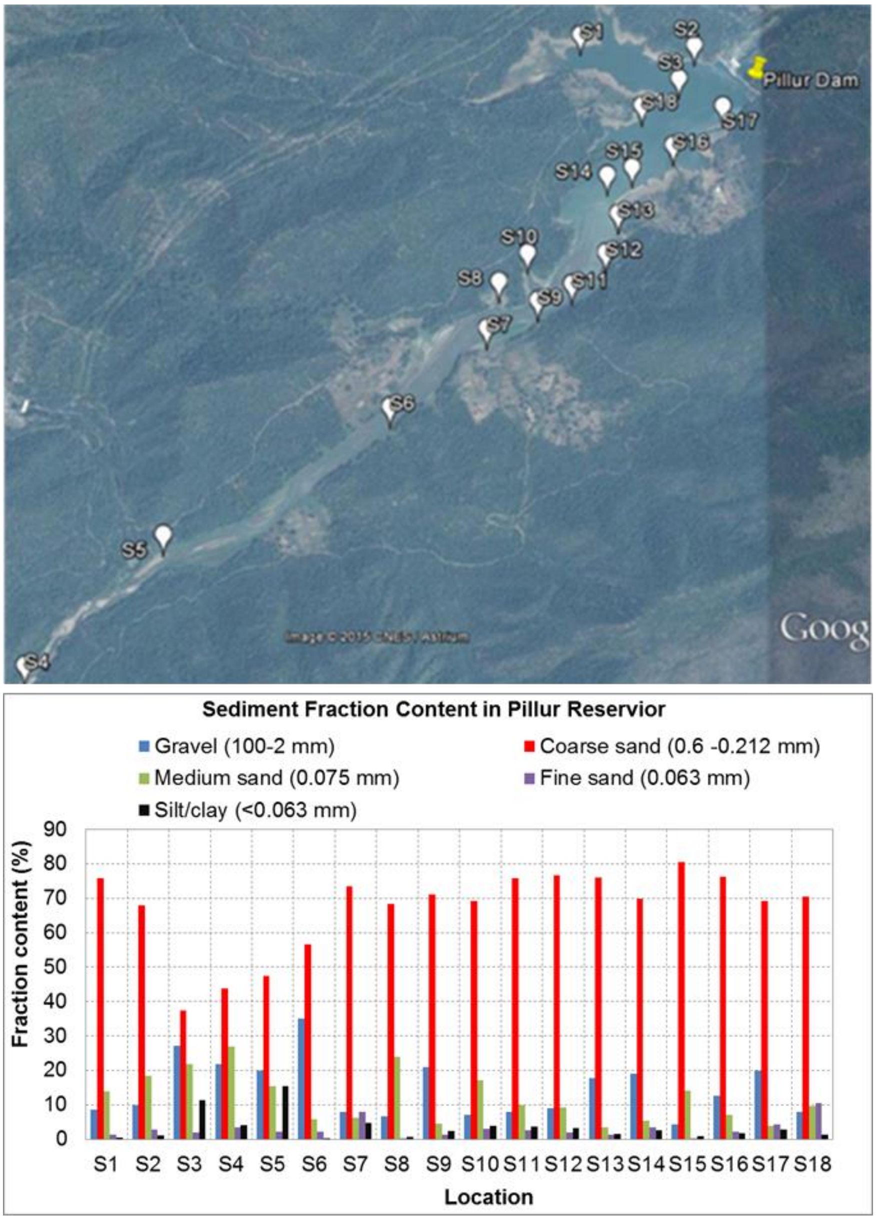

Figure 6-28. Location (only indicative) of sediment sampling (upper Google Earth image) and fraction content of sediment sample for each location (lower plot)

- The sediment removal plan includes hydraulic dredging using a light environmentally friendly equipment (like dredging pump or hydro-suction) and downstream transport using slurry pipe in a controlled manner to avoid adverse environmental impacts in downstream area. Also, presence of barrages in downstream area has to be considered while discharging sediment downstream.
- It is proposed to discharge the removed material through a slurry pipe to the downstream with a limited amount. For example, start with 200, 000 – 300, 000 m^3 during first year (spread over the year) and monitor the erosion-sedimentation pattern and migration of removed discharge given the fact that there is another barrage in the downstream (Bhavani barrage). Since the downstream reservoirs are barrage, removal of sediment from those reservoirs is not a problem in case of synchronized release of flood flows.
- The important areas like water supply intake, powerhouse intake, near the

scour sluices shall be considered while preparing the sediment removal plan.

- It is suggested to carry out comprehensive study including bathymetry and sediment measurement to assess the current condition. Also, such study shall include upstream and downstream dams and barrages.
- In addition, it is suggested to assess the possibility for beneficial reuse of deposited material.
- It is suggested to carry out impact assessment, particularly downstream impact of sediment removal. A simplified morphological modelling study has been carried out to assess the propagation of released flow and sediments in downstream reach (see Giri et al., 2016).
- The detailed technical specification for the sediment management is presented in a report (Giri, 2015).

6.3.3 Papanasam (Tamil Nadu)

This case study is not included in this handbook. The study can be found in the DRIP report (Giri, 2015).

6.3.4 Maneri Bhali Stage-I (Uttarakhand)

General

- The Maneri Bhali Stage – I HPP, located in the river Bhagirathi (15 km upstream of Uttarkashi), is a Run-of-the-river hydropower plant (90 MW capacity). It has a concrete gravity dam with the elevation of 1298 m (above datum) and the minimum foundation level is at 1259 m.
- There is a spillway with crest elevation of 1280.2 m having 4 bays (13 m wide each, separated by 4m wide piers). The size of each radial gate is 13 m (width) by 14.55 m (height).
- The energy dissipation arrangement consists of a dented roller bucket at the level of 1261 m in all the four bays. The design discharge of the dam is 5000 m^3/s.
- The river carries large amount of sediments/debris during monsoon period. Particularly, during 2012 and 2013 flood events, there were landslides, bank erosion and significant morphological changes in the river causing disaster and fatality in upper Ganga basin.
- The region is very fragile as it can be seen from the picture of one of the roadside slope erosion along the Bhagirathi river (upstream of the dam), depicted in **Figure 6-29**.
- Large amount of sediment has been supplied into the river reach, upstream of the reservoir, during the road construction as shown in **Figure 6-30**.
- Significant changes in river planform and channel shifting were occurred in a number of locations along Bhagirathi River as well including just upstream of the Maneri Bhali I dam as can be seen in the images, depicted in **Figure 6-31** (a bridge was swept away from this area).
- Large amount of debris containing rubbles, boulder and gravels, transported over the spillway causing abrasion and damages of the spillway as well as other structures and apparatuses.

Figure 6-29. Roadside slope erosion, revealing the outlier of fragile alluvial deposits

Figure 6-30. Large amount of sediment, inflowing in to the upstream reach during road construction

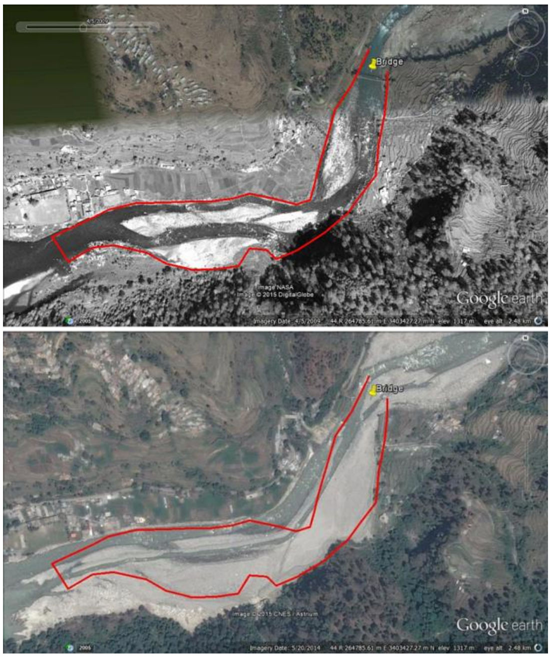

Figure 6-31. Large morphological changes at upstream of the reservoir (upper image: before 2012 flood, lower image: after 2012 and 2013 floods) with significant erosion and sedimentation

Problems and Challenges

- The major issues at the dam site are associated with debris flow, reservoir sedimentation, abrasion and cavitation damages of the structures, e.g. spillway glacis, roller buckets, cut-off walls, gates etc. Particularly, the spillway has been severely damaged by the floods during two consecutive years (in 2012 and 2013).
- Abrasion on the spillway glacis (as depicted in right picture in Figure 6-32) due to transport of large sediments/debris over the spillway during high flow period is a major issue. Moreover, the problem appears to be related to cavitation resulting in damage of the spillway glacis due to high current, adverse flow pattern upstream and immediately downstream.
- Sedimentation of the reservoir leading to loss of storage capacity is another major issue (in effect, interrelated to the structural damages). Even though the HP is a run-of-the-river type, sedimentation has reached up to crest level of the spillway creating an adverse flow and sediment transport condition over the spillway during flood passage, and thereby causing its abrasion. During the depletion of the reservoir for the rehabilitation of the spillway, the deposition was found to be almost up to the spillway crest.
- Sediment deposits are evident in upstream part of the reservoir as well (within reservoir spread area). These sediment bars and delta (as shown in Figure **6-33**) would be propagating further towards the reservoir, particularly during high flows when all gates are in operation. This would eventually lead to further filling up of the reservoir.
- Current gate operation during monsoon period appears to be one of the aspects to be checked carefully, since asymmetric opening of the gates may cause complex flows over and in the vicinity of the spillway (both upstream and downstream). This also causes sedimentation in front of the gates (at right side near the inner bend), which are closed most of the time except during high floods.

Figure 6-32. Severe damages on the spillway glacis

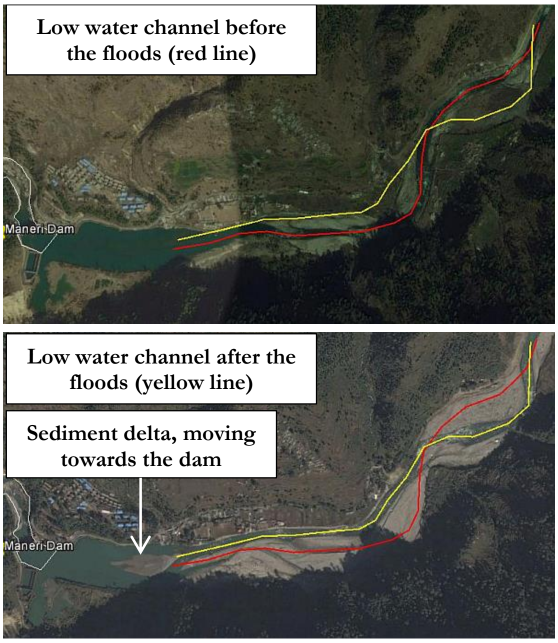

Figure 6-33. Large morphological changes near the Maneri-I dam, caused by 2012 and 2013 floods *(Google Earth)*

Analysis and Approach

Based on field reconnaissance, available information as well as some numerical modelling exercises (Giri and Pillai, 2016), a brief analysis has been carried out, which is outlined as follows:

- The damage of spillway glacis' due to abrasion appears to be one of the major consequences of gravels and bounders transport over the spillway. This effect appears to have been enhanced due the high bed level of the reservoir (up to the crest level of the spillway), which creates favourable condition for these debris, entering from upstream during floods, to be transported over the spillway during flood passage. The numerical simulation also shows that the velocity magnitude is significantly higher when the reservoir bed is in current condition.
- Current gate operation rules might be somewhat unfavorable, triggering the adverse conditions. The opening during high flows starts with gate no. 4 then 3 (located at left side, i.e. near the outer bend and intake); while gate 1 and 2 are opened only during flood condition (when inflow discharge exceeds about 200 m^3/s). Consequently, sediment deposition in front of these spillways occurs due to the infrequent opening of the gate 1 and 2. For instance, opening of gates 3 and 4 (or only 4) during moderate flows creates dead (or recirculation) zone in front of the bays 1 and 2, leading to sedimentation predominantly in front of these bays. This seems to be further triggered by the river planform as these bays (1 and 2) are located near the inner bend of the river. As it is well known, inner bend has more deposition due to the secondary flow effect and deceleration. Opening of these two gates (1 and 2) only during higher flows appears to cause transport of a large amount of all accumulated material through these gates causing larger damages on the spillway glacis of these bays due to abrasion.
- In addition to the transportation of accumulated deposits, the river planform at the spillway location may also cause transport of bedload and debris, brought from upstream during flood, predominantly through right bays along the inner bend (as a result of secondary flow effect). The numerical model also shows larger velocity magnitude near the right side of the spillways (this is valid for flatbed condition at the bend, which could be the case in front of the spillway, particularly when all gates are open during flood). This is shown in the paper (Giri and Pillai, 2016).

- Cavity flow is rather indicative phenomenon for the situation with high flow velocity through the spillway, particularly with control gates. Usually such flow induces negative pressure zones caused by discontinuities in the flow path, and forming bubbles. These bubbles may result in the impact zone of very high pressure and collapse against a concrete surface, leading to damage of concrete surface and creating further continuation of the damage. There is almost no prevention other than some remedial measure against cause of the cavitation. One of these remedial measures could be to improve flow over the spillway, e.g. by optimizing gate operation as well as proper rehabilitation of the glacis (maintaining proper profile to minimize the cavity flow).

- Flow distribution pattern in transverse direction can create cavity flow effect near the inner (right) part. Moreover, if the bend morphology with deep outer bend and shallow inner bend is not very pronounced in front of the spillway (i.e. a case with more or less flat cross-section, which seems to be the case with this reservoir), then the inner bend has flow with higher magnitude (simulated by the numerical model as well). Consequently, the occurrence of larger damage along the right corner of the spillway glacis can be attributed to combination of these adverse conditions. In a normal river bend with strong bend profile, the boundary shear stress is larger in outer bend, making it deeper, which does not seem to be the case in the reservoir, particularly in front of the spillway (although this is visible in the picture, depicted in Figure **6-34**, but there is no measurement).

- The asymmetrical opening of the gates may result in more damage in bays 1 and 2. It has to be checked if the flow through the gates is uneven due to asymmetrical opening and/or malfunctioning of the gates, creating more possibility for occurrence of cavitation damages.

- As past experiences show, the magnitude of abrasion damage depends on many factors, such as flow magnitude, direction and pattern, duration of impact, shape and feature of the concrete surfaces, aggregate loading etc. Obviously, it is difficult to predict concrete performance under such conditions. Usually hydraulic model studies (computational and/or laboratory) are carried out to assess these effects, and subsequently test the required modification.

- Another adverse condition is the complex flow patterns at the immediate downstream of the spillway due to the narrow and sharp bend with large deposits. This appears to be creating adverse flow condition causing damages of spillway glacis, sidewalls and roller bucket. As model result shows, the most favorable downstream flow is when all the gates are open. In addition, opening of alternate gates maybe favorable, since the unit discharge at downstream is reduced due to larger flow width, although under such condition the upstream flow pattern has to be analyzed as well.

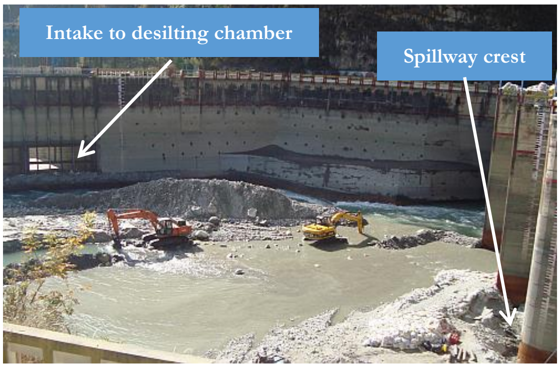

Figure 6-34. Sediment deposition in front of the spillway and the intake

Recommendations

The problems, associated with debris flow, reservoir sedimentation and structural damages at Maneri Bhali I dam, have been investigated and analyzed based on site reconnaissance, available information as well as by carrying out some basic and simplified numerical model simulations of synthetic scenarios. The following comments and recommendations are provided for consideration in developing plan to address these issues:

- The reservoir bed contains deposited layer of fine/coarse sands and gravels in addition to rubbles and boulders. Therefore, removal of sand deposits within the reservoir area using a light and environmental friendly hydraulic dredging pump is necessary in order to bring the reservoir bed level few meters below crest level of the spillway. Such sediment removal operation, followed by regular sediment management has following advantages:

(i) This will increase the reservoir storage capacity, which will avoid the situation when storage level has to be increased due to exhausted capacity given that the current bed level is almost 5 m above dead storage level. Moreover, there are deposits and sandbars in upstream of the spillway/intake area, which will eventually reach the spillway and intake area.

(ii) Lowered bed level in the reservoir will lead to reduction of flow magnitude within the reservoir area, which will be favorable for the spillway as well as for deposition of large material in the reservoir rather than transport over the spillway (as shown by numerical analysis as well)

(iii) In case of deeper reservoir, rubbles/boulders/gravels will be trapped in front of the spillway, consequently transport of large sediments over the spillway glacis will be reduced, thereby reducing the adverse effects due to abrasion.

(iv) Lowered bed level near the trash rack of desilting chamber may also reduce the transport of sediment in to the chamber.

(v) In case of gaining extra storage, the reservoir operation can be optimized for flood release and sluicing.

(vi) Planned and controlled sediment discharge towards downstream has positive environmental, social and ecological impacts in the downstream river.

(vii) Removal of fine and coarse sand and gravels appears to be easier than removing large boulders and rubbles from reservoir level. Moreover, it may not require depletion of the reservoir. Although boulders can be used for river engineering and bank protection works, planned to be carried out in Bhagirathi River. Most of these deposits appear to have been transported by the river during 2012 and 2013 floods. In effect, mining of these boulders and large gravels would not have adverse social and environmental impact. However, studies and assessment have to be made before carrying out such activities).

(viii) Sediment management appears to be more sustainable than recurrent maintenance of the spillway and other structures, which is a costlier affair.

- A field experiment (‘no regret’ approach) is recommended to carry out by using relatively cheaper and soft structural measure to trap boulders at immediate upstream of the reservoir (where the area is almost dry during low flows). These soft measures shall be used together with monitoring instruments and visualization techniques as possible. This will provide some quantitative impression about the debris transport as well as durability and usability of soft measures under such flow and sediment transport condition (even if they would be ineffective and eventually failed). An impermeable structure should not be used so as to avoid substantial flow resistance and upstream impact (our numerical simulation shows some qualitative assessment of such effects).

- There could be a potential risk for the spillway and intakes in case the traps are swept away and transported towards the reservoir during flood. Therefore, this fact must be considered and analyzed while selecting type and material for the traps.
- Regular and planned release of turbid flow during monsoon should be a part of sediment management plan.
- It is recommended to carry out measurement and analysis of reservoir bathymetry as well as sediment characteristics and sorting process. This will be of help to further exploring the effect of river planform and gate operation on reservoir morphology and sediment sorting process in upstream vicinity of the spillway. Based on detailed data and measurements, more rigorous and elaborative numerical model study can be performed to develop and improve appropriate safety and remedial measures as well as for effective management and maintenance.
- Regular/real-time monitoring and forecast of the flow (to a possible extent considering very low lag/lead time and extreme condition), sediment transport and reservoir morphology is necessary as a part of non-structural measures.
- More detailed about the study can be found in the report (Giri, 2015) and DRIP Transmittal (*PIC No: UA25HH0010*).

6.4 Lessons Learnt

- A problem, which has been accumulated since decades, is not possible to be assessed and managed simply and quickly.
- Sediment-induced problems in reservoirs are generally very complex and ambiguous, and there is no "Elixir" to resolve them in a straightforward and easier ways.
- Sediment management measures and interventions can cause serious disaster as well. Consequently, it is very important to carry out thorough investigation considering all possible threats and impacts. This is in particular valid when the problem has been accumulated for a long period.
- Such complex problems can only be managed by putting proper efforts, capacity and resources in a justifiable manner. For example, the flushing operation at Genissiat reservoir (in France) in 2012 required mobilization of 400 people for about 10 days, and it did cost around 8 million Euros.
- There are experiences, practices, examples (successes and failures), knowledge and technology that are very useful to consider, although it is not always possible to adapt them easily and straightforwardly.
- There are also knowledge gaps and lack of adequate experiences, which imply that there are needs for further exploration, experimentations and research in a regular basis as well as "Learning by doing".
- Building capacity, developing professional human resources and specialized institutions are some of the key prerequisites to handle the problems related to sediments. Assessment and management of sediment-induced concerns in rivers and reservoirs are associated with multiple disciplines that require widespread specialization and knowledge integration.

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Appendix A. Sediment & Bathymetry Measurement Techniques

Bedload Transport Measurement

While planning and designing a reservoir, it is important to have an estimation of bedload transport as accurate as possible. However, it is extremely difficult to measure bedload transport directly. So, it is not always justifiable to put efforts on measuring the bedload transport. The bedload samplers usually give quite different results depending on river characteristics. So, a combination of sampling methods should be used and it is important to use the same type of sampler throughout the sampling duration in order to achieve consistent results (IAEA, 2005).

There are several approaches to track and measure the bedload transport process depending upon the type and location of the rivers (IAEA, 2005). In addition, for sediment transport measurements, among others, the design manual (volume 5) of Hydrology Project can be used (*http://nhp.mowr.gov.in/docs/HP1/MANUALS/Surface%20Water/5014/SW%20Design%20Manual%20Volume%205%20Sediment.pdf*).

Only a few relatively new techniques have briefly been descried here.

Acoustic Monitoring Techniques

The method is mainly applied for steep rivers with large bedload transport. A review work of Rickenmann (Internet Source) provides a good overview of passive acoustic methods. Geophones and hydrophones have been recently developed in Switzerland and Japan. Several studies have been summarized in this publication, which includes Swiss impact plate geophone, Japanese pipe hydrophone, other impact plate systems, and underwater microphones. Some of these acoustic measuring systems were successfully calibrated for total bedload flux under field conditions. Figure A-1 gives an impression about the devices, installed on fields. Figure A-2 shows plot of bedload transporting flow event of 29 July 2013 at the Erlenbach, showing acoustic measurements along with discharge over time.

Among other acoustic methods, load cell system and acoustic bottom tracking can be mentioned. Figure A-3 shows field monitoring technique for debris flows and bedload in the field using load cell systems (Itoh et all, 2013). Vericat et al. (2013) presented an indirect approach that relates local bedload transport to apparent bed velocity, determined by comparing the Doppler-derived bottom track and GPS-based position of an acoustic current-profiler.

Owing to the difficulties and challenges involved with direct bedload measurements and the large natural variability of transport rates, the necessary data to systematically test, calibrate and validate laboratory-derived equations for natural streams is not currently available. Indirect methods to measure bedload transport can provide useful high-resolution data of value for fluvial sediment transport studies. Non-invasive techniques have the additional advantage to minimize local and temporal changes in the flow field near the sensor. The need for surrogate measuring techniques has been recently discussed for example at the International Bedload Surrogate Monitoring Workshop, held in April 2007 in Minneapolis, USA (Gray et al. 2010) and at the International Workshop of Acoustic and Seismic Monitoring of Bedload and Mass Movements (Rickenmann et al. 2013). Following are the conclusions from these past experiences and investigations (Rickenmann et al., 2013):

- Indirect bedload measuring methods have the advantage of providing continuous records of bedload transport activity both in time and over a cross section.
- Controlled laboratory experiments are important for a better understanding of the factors influencing the calibration of these measuring methods.

- Additional field calibration of the sensors is still necessary to obtain a reasonable measuring accuracy.

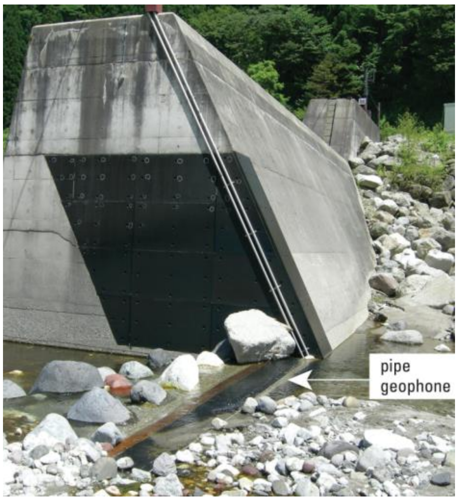

Figure A-1. Bedload measurement using pipe geophone (left), located on a stable bed surface of a slotted debris dam on the Joganzi River, Japan (Gray et al., 2010) and bedload impact plates and sensors, installed on the Elwha River, USA in 2009 *(Hilldale, 2013)*

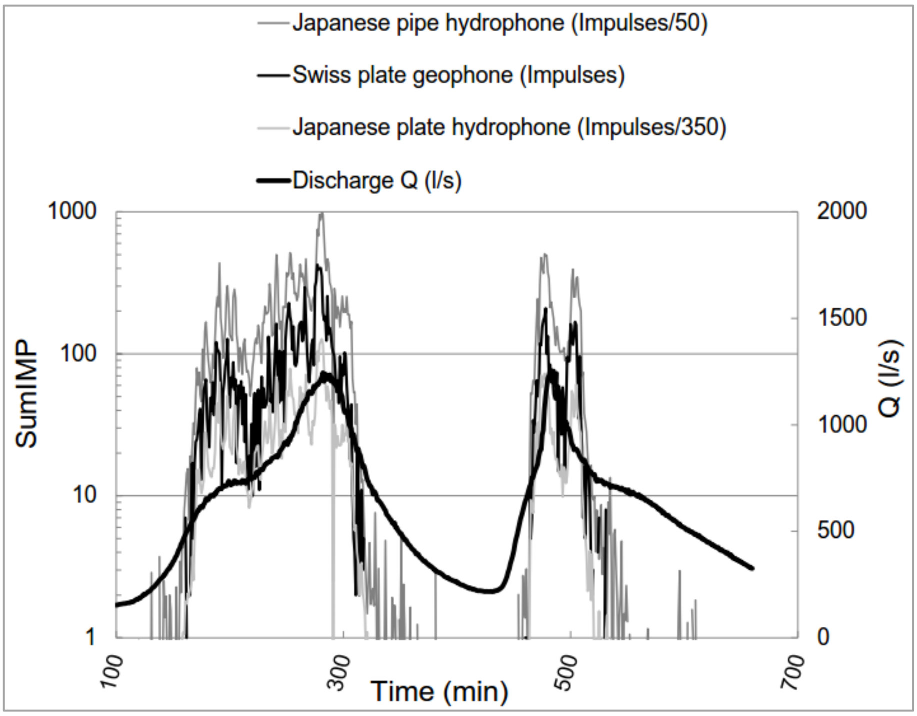

Figure A-2. Bedload-transporting flow event of 29 July 2013 at the Erlenbach, showing acoustic measurements along with discharge over time. The plate hydrophone (a variant of the pipe hydrophone) was fixed under the same steel plate as one geophone, thus covering only a width of 0.5 m. The plate geophone data are the values of two neighboring plates, covering 1 m. Also the pipe hydrophone covers 1 m of channel width. The impulse count is made according to the procedure implemented for the Swiss plate geophone system (SumIMP). The scaling factors for the hydrophone data were chosen arbitrarily, to better illustrate the similarity of the signal responses *(Rickenmann, Internet Source)*

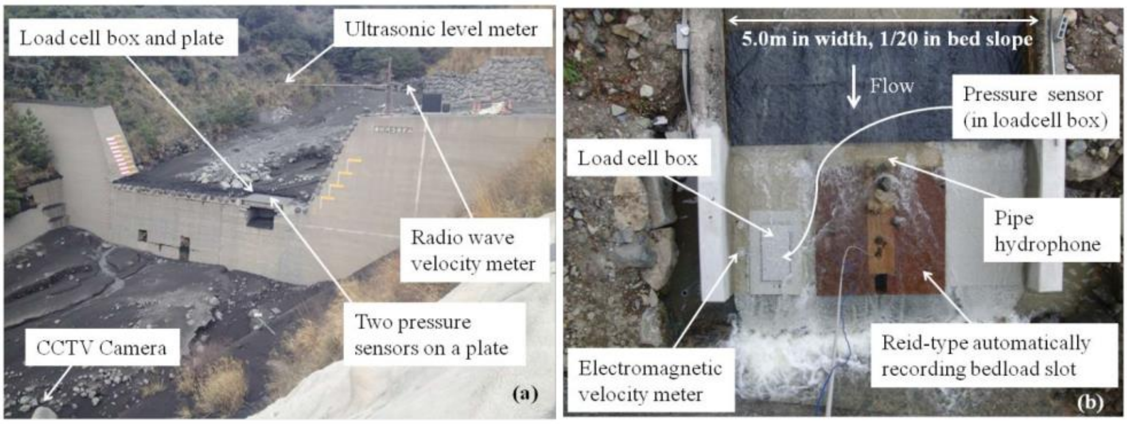

Figure A-3. Field monitoring for debris flows and bedload using load cell systems. (a) Debris flow monitoring at the Sakurajima dam; (b) Bedload monitoring at the Ashi Arai dani, Hodaka Sedimentation Observatory of Kyoto University *(Itoh et al., 2013)*

Despite difficulties and complexities, these techniques and applications provide new opportunities for a better understanding of the interaction between sediment supply, flow hydraulics, sediment transport and channel morphology, and the effects on physical habitat conditions at multiple spatial and temporal scales.

Trench Filling and Dune Tracking

Monitoring the filling of a trench in a river allows estimating the sediment transport rate at that particular location and at that particular time interval. This can be done in complement with a numerical model (at least a 1D model), reproducing the observed filling process. The model should be able to simulate the evolution of the trench. In general, the part of sediment transport that contributes to trench filling is the bedload component as well as a part of the suspended load, in particular the particles travelling in the lowest layers near the bed that easily fall in the trench. The longest the trench is, the more suspended sediment is trapped. Consequently, in order to include the contribution of all bed material loads (suspended plus bed load, but excluding washload), the trench should be designed as an efficient sediment trap, longer than the distance covered by the sediment travelling in the upper layers near the water surface (Crosato, 2015).

The advantage of this method lies in the fact that trench filling is a relatively long process, if the excavated trench is large. It is the result of the cumulative contribution of all sediment transport rates occurring in the time of trench filling, at both high and low discharges. Trench filling may therefore give an indication of the yearly sediment transport rate.

Recent days, high resolution measurement of river bathymetry can be performed using single- or multi-beam eco-sounder. Such measurement is able to detect the micro-scale bed forms like dunes. So, successive measurements of bathymetry can provide their size and celerity, which can be roughly translated to bedload transport rate. The sediment that contributes to the formation and propagation of dunes is the bedload component and the sediment that is transported in suspension in the lowest layers near the bed. So the amount sediment transport estimated using this method will not include the bed material load travelling in suspension in the upper layers of the water column and of course the washload that is eventually present.

The method requires the knowledge of the average dune height and celerity. It is based on the integration of the Exner's equation (Crosato, 2015) for a bed form of average height, assumed across the entire channel width, and leads to the following relation (Simons et al., 1965):

$q_s = (1-p)\ c\ \beta\ h_b + C$

where, q_s = volumetric transport rate per unit width excluding pores (m^3/sm); h_b = average bed form height; c = celerity of bed form (m/s); β = coefficient to average the cross-sectional area of the bed form ($0.55 \leq \beta \leq 0.6$); and C = an integration constant to account for the material not associated with the migration of bed forms (with dominant bedload C = 0).

The general application of this method is complicated by the fact that bed form characteristics, such as height, wavelength and celerity, change with the flow condition. This means that the bedload rate can only be computed for specific flow condition (e.g. discharge). In order to have an overview of the yearly bedload transport, the bed form characteristics and evolution process under variable flow condition shall be determined. Besides, there are hysteresis effects, i. e. under the same discharge during rising and falling, the bed form size usually different. Recently, some noticeable physics-based modelling works have been carried out, which provides insight into these processes and applicable to real-world situation as well (Nabi, 2012; Giri and Shimizu, 2006; Neumann et al., 2012).

Suspended Load Measurement

Particularly during high flows, river carries large amount of suspended load, which in case of limited flow release may be settled in the reservoir. It is also useful to measure real-time turbidity to detect density current and manage its release from the reservoir. There are several techniques for measurement of suspended sediment, which can be found in other guidelines as well (e.g. IAEA, 2005). Here, we have briefly described some of the available measurement techniques. Some of these techniques are relatively new, which can be applied to measure real-time sediment concentration in reservoirs.

Multiple Frequency Acoustic Method

One of the recently developed techniques is multiple frequency acoustic method. Sound of multiple frequencies (usually 3 or more, in the megahertz range) is propagated simultaneously through the water column where it is scattered from particles in suspension. Since different acoustic frequencies interact with particles of a given size in different ways, the backscatter data can be used to estimate the average size of particles in suspension. If perfected, this technique could minimize or eliminate the need to collect pump samples together with acoustic data. However, it is very difficult to convert multi-frequency backscatter data into particle sizes and concentrations. This technique has successfully been applied in marine environments, but has seen little use in river environments. This is likely due to the wider particle size and concentration ranges present in rivers. By sweeping the acoustic beam across a channel cross-section, one instrument could potentially measure particle size, particle concentration, and bathymetry in a channel cross-section, provided that the cross-section is small enough for the signal to propagate across (IAEA, 2005).

Pressure Differential Method

Another technique is pressure differential, in which the inlets of a differential pressure transducer are vertically separated by a known distance in the water column. The difference in pressure measured at the two inlets will be affected by particles suspended in the fluid between the ports. This difference can be used to infer the particle concentration. This technique has been successfully tested in the laboratory. Local changes in pressure caused by turbulent velocity fluctuations make field deployment difficult; however, a device of this type may be useful for measuring high concentrations (say, >20 g/l) of suspended particles. The relatively low cost of the pressure transducers make this an interesting technique (IAEA, 2005).

Digital Imaging

Digital imaging is another new technology that is being developed to quantify suspended sediment concentration. In digital imaging, charge coupled devices (the sensor of a digital camera) are used to collect images of the water sediment mixture that has either been pump sampled or directed isokinetically into some type of conduit. These images can be subjected to various numerical algorithms to count and size the imaged particles. One major advantage of this technique is that it yields images of the sediment/water mixture that can be used to visually confirm the analysis results (IAEA, 2005).

Time Domain Reflectometry (TDR)

There is another new technology, namely Time Domain Reflectometry (TDR), which has been developed (Chung et al., 2014) and being applied in real-world condition as a part of sediment management, particularly to detect density current and venting. TDR is a monitoring technique based on transmission lines, and wherein various TDR sensing waveguides can be designed to monitor different physical quantities, such as soil moisture content, electrical conductivity, and water level. By improving TDR method, a new travel time analysis method with temperature correction procedure is proposed. The SSC accuracy is improved drastically to 1500 ppm and the measurement is insensitive to electrical conductivity and soil particle size. An extensive SSC monitoring program which includes TDR automatic monitoring and manual sampling is established at the Shihmen reservoir in Taiwan. SSC hydrographs are obtained for several typhoon events. In addition, the automatic monitoring station, featured by floating installation and multi-point measurements at depths, provides data for analyzing transportation velocity and thickness of venting density current (Chung et al., 2014).

Compared with traditional SSC method, the measurement range of the TDR method is theoretically unlimited, and the TDR probe is simply a waveguide which can be easily made to fit different environments. The field testing results further supported feasibility and great potential of TDR SSC measurement (Chung et al., 2014). Figure A-4 provides an impression about floating installation and multi-point measurements at depths in a reservoir in Taiwan. While Figure A-5 shows a comparison between the measurements of SSC using direct sampling and TDR during typhoon in Shihmen reservoir.

There are some other references, which can be considered for the guidelines regarding sediment measurement techniques, such as Rasmussen et al. (2011), Morris and Fan (2010), Gray et al. (2010) etc. (see References).

Figure A-4. Time Domain Reflectometry (TDR) automatic monitoring station for measurement of suspended sediment concentratio. Picture shows floating installation and multi-point measurements at depths *(Chung and Lin, 2011)*

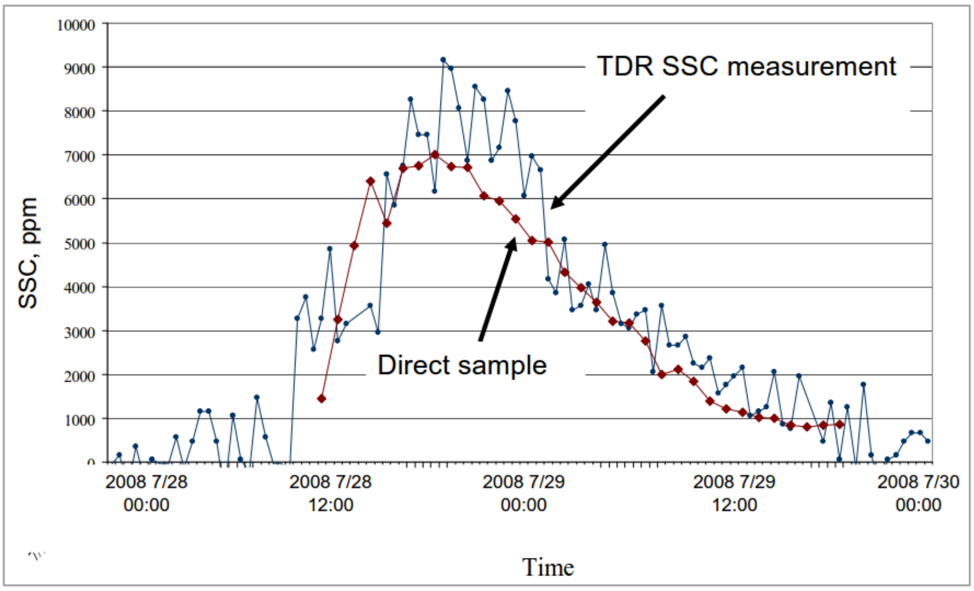

Figure A-5. Real-time record of SSC at Shihman outlet of the reservoir in Taiwan during Fung Wong typhoon *(Chung et al., 2014)*

Interferometric Multibeam Technology for Bathymetry Measurement

This portable surveying equipment can be described as a hybridized hydrographic surveying system (Figure **A**-**6**). It combines the advantages of conventional beamforming multibeam echosounder (nadir coverage, deep range ~60m) with those of interferometric technology (large swath width, collocated side scan) in a single motion-compensated unit that can be deployed on a variety of boats. The disadvantages of beamforming technology (small swath width, relatively poor shallow water performance) and interferometric technology (potential nadir gap, relatively poor deep water performance) are solved with this integrated approach (Figure **A**-**7**). Two different frequencies are used so cross talk between transducers is not a concern.

SONAR measures the range from the transducer to the bed; converting this measurement to a bed elevation can be accomplished in either of two ways. In the first method, real time kinematic (RTK) GPS corrections must be available (centimeter level vertical precisions) so the dynamic elevation of the GPS antenna on the surveying vessel can be collected simultaneously with the SONAR. In this case, bed elevation is easily determined because the GPS antenna has a known height above the acoustic sensor. In the second method, several stationary pressure sensors with known locations are used to record continuous water level measurements during the hydrographic survey throughout the reach of interest. These water-surface elevations combined with the draft of the acoustic transducer below the water surface and the SONAR range then provides the bed elevation. The elevation of each water level logger must be known, which requires a separate, accurate ground-based survey of the pressure transducer locations. RTK-GPS is the preferred method for accuracy, ease of use, and range but conventional surveying or leveling can also be used. The importance of implementing one of these two methods must be emphasized because in absence of these measurements the SONAR only records a range to the bottom, not absolute bed elevation.

The hydrographic survey data is processed using the Hypack software for the Odom transducer and the Grid Processor software for the Bathyswath transducers. Data can be exported from both software packages in simple text files and subsequently imported into a geographical information system or hydraulic modeling software.

Figure A-6. Photograph of the system from the top which includes the Odom conventional multibeam transducer (left) and interferometric Bathyswath transducers (right). Motion compensation unit is located between the transducers (*Courtesy of USGS- Geomorphology & Sediment Transport Laboratory)*

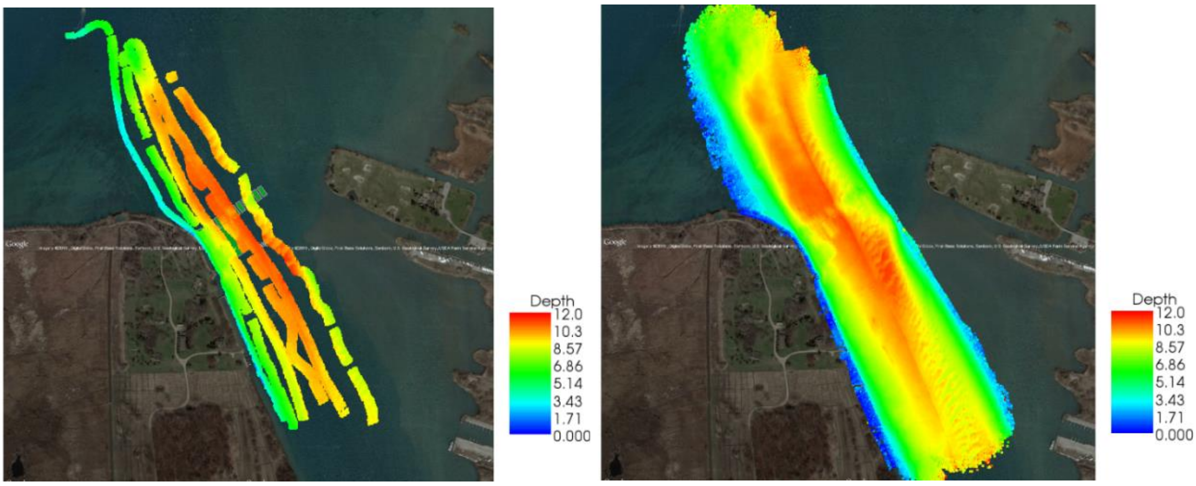

Figure A-7. Comparison of survey coverage with Odom conventional multibeam transducer (left) and Bathyswath transducers (right) for the same number of boat passes. Data is from a survey of the Detroit River, Michigan, USA *(Courtesy of USGS- Geomorphology & Sediment Transport Laboratory)*

Surveys can be carried out from a boat using GPS-RTK or GPS beacon-based positioning along with the conventional and interferometric multibeam acoustic sensor, navigational system, and data collection/processing equipment. The bathymetric surveys focus on complete coverage such that the dense data can be used directly or processed into appropriate Digital Elevation Models (DEMs). The navigation and data collection system provides an interactive map showing the boat location and data track overlain on the reach or reservoir of interest, so the boat pilot can simply follow preset tracks or navigate to provide complete coverage.

The information has been provided by Jonathan Nelson from USGS- Geomorphology & Sediment Transport Laboratory.

Remote Sensing Technique: Satellite-Derived Bathymetry

The ability to derive bathymetry from multispectral satellite imagery is a topic that has received considerable research attention since the 1970s. Typical multispectral satellite platforms (e.g., Landsat, Ikonos, SPOT, and WorldView) collect data in multiple spectral bands that capture a broad spectral range (40 to 150nm). Collectively, these bands typically span the visible to infrared portions of the electromagnetic spectrum. The physical concept underlying the ability to estimate bathymetry from multispectral imagery is the wavelength-dependent attenuation of light in the water column.

Although the accuracy of SDB does not meet current International Hydrographic Organization (IHO) S-44 standards, results from this technique suggest that SDB can be a useful tool for survey planning and prioritisation, especially for national hydrographic offices with limited resources. However, this application has two main requirements: 1) the data must be referenced to a chart datum (typically a tidal datum), and 2) the procedures must be based on readily available, low-cost data and software.

www.hydro-international.com/content/article/satellite-derived-bathymetry

Available Resources

Figure A-8. Freely available sources of satellite images *(Snyder, 2013)*

The Procedure

The key steps for SDB procedure are as follows (Snyder, 2013):

1- Pre-processing - Satellite imagery is downloaded based on the geographic location and environmental conditions (e.g., cloud coverage and sun glint) had to be used.

2- Spatial filtering - 'Speckle noise' in the Landsat imagery is removed using spatial filtering.

3- Water separation - Dry land and most of the clouds are removed.

4- Glint/cloud correction

5- Identifying the extinction depth - The optic depth limit for inferring bathymetry (also known as, the extinction depth) is calculated.

6- Applying the bathymetry algorithm - The bathymetry is calculated using algorithm on the blue and green bands (e.g. the Stumpf et al., 2003).

7- Vertical referencing - A statistical analysis between the algorithm values to the chart soundings references the Digital Elevation Model (DEM) to the chart datum.

Figure **A-9** provides a visual impression of the steps for SDB procedure. All the procedures and techniques for data and image post-processing is described in the IHO-IOC GEBCO Cook Book (*www.star.nesdis.noaa.gov/sod/lsa/GEBCO_Cookbook*).

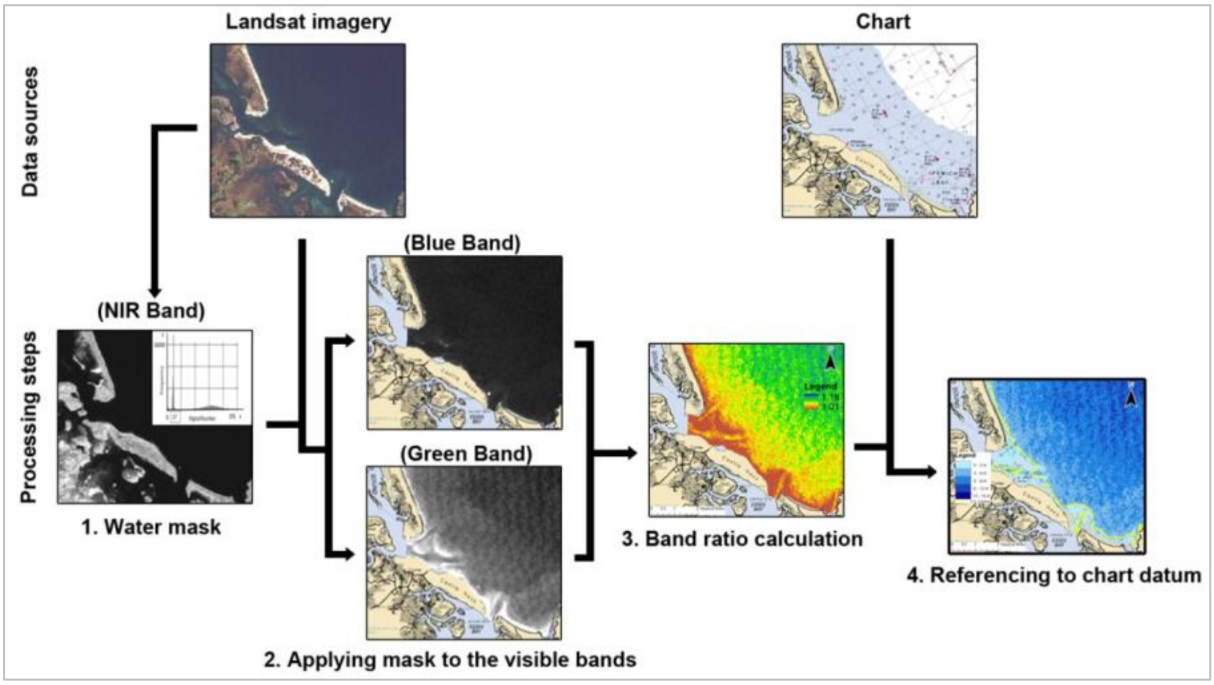

Figure A-9. Key steps of the SDB procedure *(Snyder, 2013)*

Result

An example, showing the comparison between Landsat-derived bathymetry of 30 m resolution and Worldview2 bathymetry of 2.4 m resolution is depicted in Figure **A-10**.

Remarks

Most of the application is related to shallow sea areas. Therefore, the method shall be tested for large reservoirs. The method may not be appropriate for deep reservoirs, but could still be good for reconnaissance purpose.

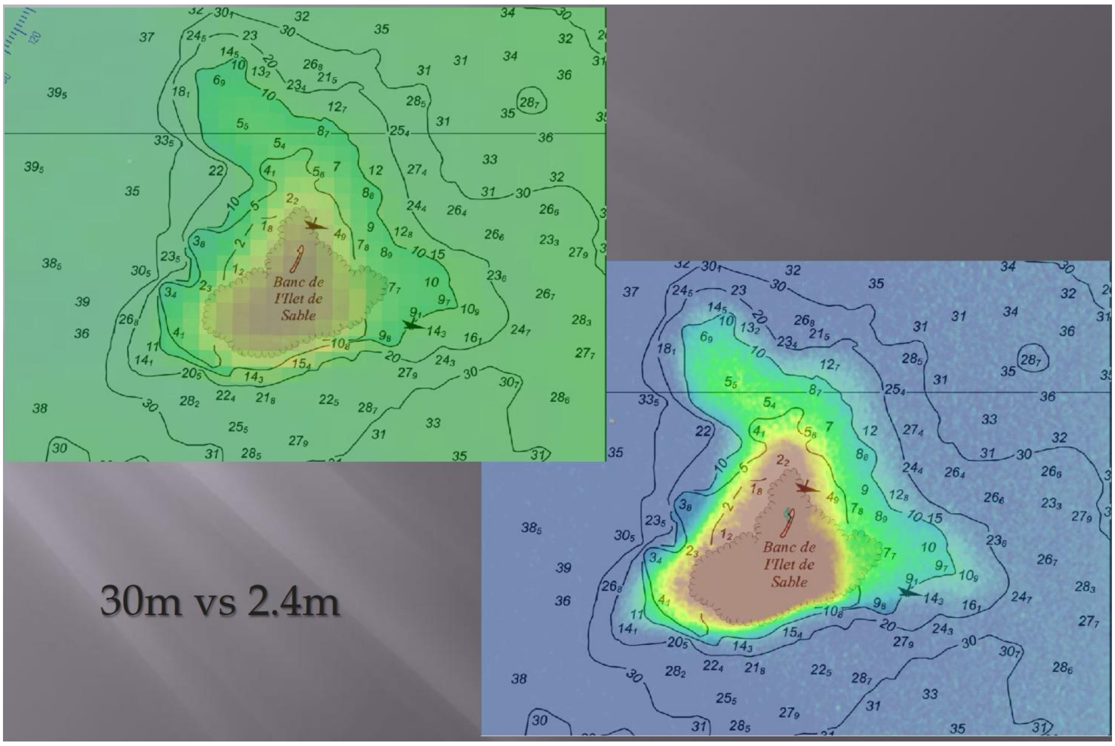

Figure A-10. Bathymetry comparison between Landsat-derived with 30 m resolution (upper left plot) and Worldview2 with 2.4 m resolution (lower right plot) *(Snyder, 2013)*

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Appendix B. CALCULATION OF TRAP EFFICIENCY & SEDIMENTATION: SIMPLE APPROACHES

Trap Efficiency

When a natural water and sediment flow is disturbed by creating a dam and reservoir, part of the water as well as sediments are trapped in the reservoir. While some part of sediment passes during flow release through the spillway and/or under sluices. A parameter trap efficiency (TP) is used, which is defined as a ratio between amount of sediment deposits in the reservoir and total amount of sediment inflow. Commonly used empirical curves to estimate the trap efficiency are Churchill curve (1948), a sediment index method mostly used for small reservoirs, Brune curve (1953), a capacity-inflow method mostly used for large reservoirs, and Brown's curve, a capacity-watershed method.

Figure B-1 provides an idea about the factors, which may influence the trap efficiency of reservoirs.

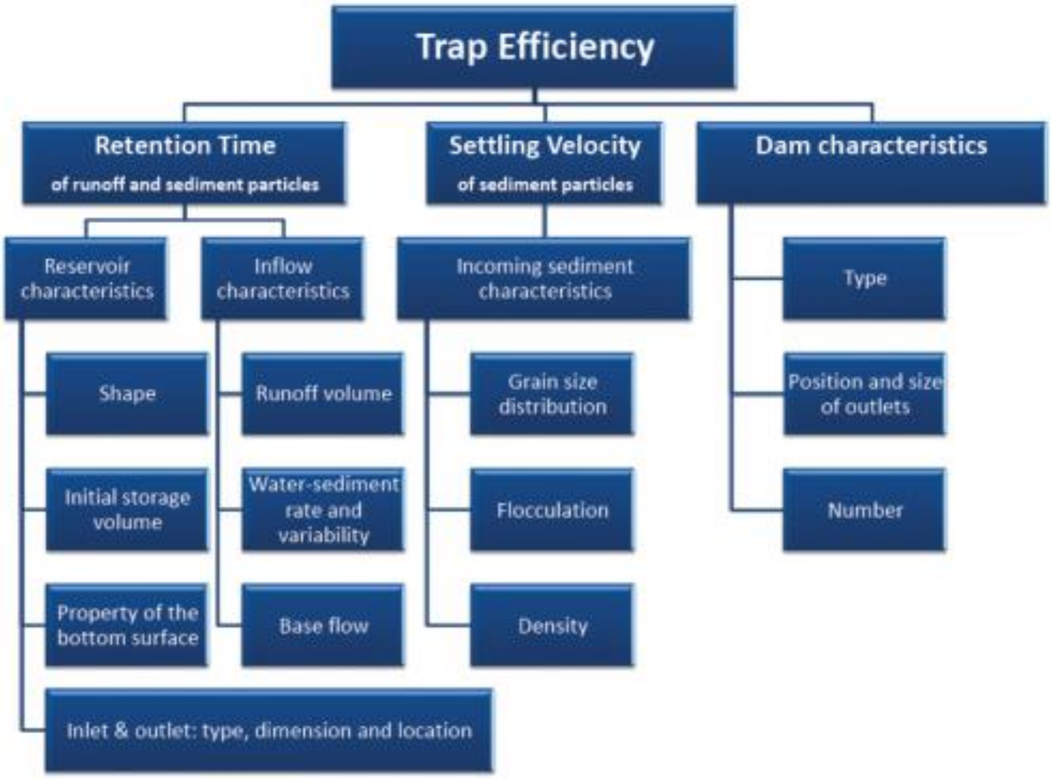

Figure B-1. Factors influencing the trap efficiency of reservoirs *(Kantoush and Schleiss, 2014)*

Churchill's Curve

Churchill's curve represents a relationship between sedimentation index (SI) and trap efficiency. The sedimentation index of a reservoir is the period of retention divided by the reservoir mean velocity. If the retention time or mean velocity cannot be obtained from field data, approximation can be made by assuming the effective retention time to be equal to the retention time as computed by using the ratio between reservoir capacity and average daily inflow rate, which gives period of retention. The mean velocity is obtained by dividing the average daily inflow rate by the average cross-sectional area in which the average cross-sectional area is obtained by dividing the capacity by the reservoir length (at the mean operating pool elevation). This can be written as follows (Klik et al., 2010):

S.I. = R/V; R = C/I; V = I/A; A = C/L

S.I. = $(C/I)^2/L$

where, S.I. = sedimentation index; C = capacity of the reservoir at mean operating level (m^3); I = average daily inflow rate (m^3/s); R = period of retention (sec); V = mean velocity (m/s); A = average cross-sectional area (m^2); and L = reservoir length at mean operating level (m).

Churchill's relationship has "percentage of incoming silt passing through reservoir" on the ordinate, which necessitates determining the difference between the value obtained and 100% to get the trap efficiency. The term "silt" on the ordinate axis meant all the size classes of sediment when Churchill developed this relationship.

The Churchill's curve can be represented by following equations for trap efficiency with accuracy of 5% and 10% respectively (Van Rijn, 2013):

$E_{res} = [-20 + 0.95\times SI^{0.63}]/[7500+SI^{0.63}]$ for $SI > 6\times10^4$ (2.5a)

$E_{res} = -1.1 + 0.25\times\log(SI)$ with $E_{res} = 0$ for $SI \leq 2.6\times10^4$, and $E_{res} = 1$ for $SI \geq 2.5\times10^8$ (2.5b)

Figure B-2 shows the Churchill curve and equation (2.5a) and (2.5b).

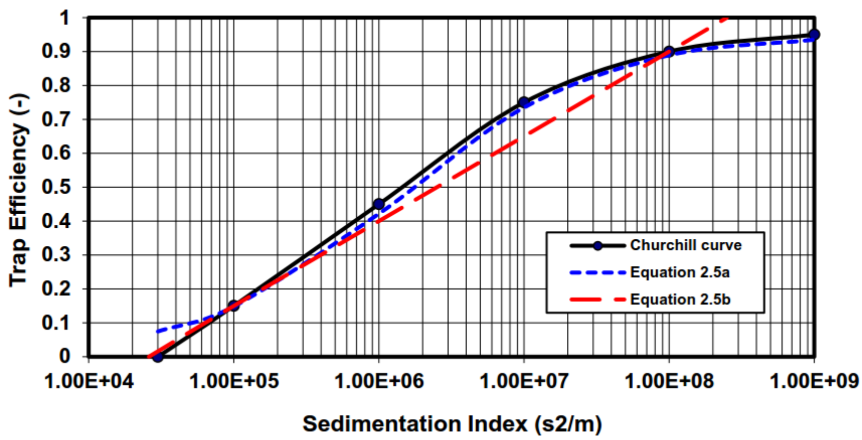

Figure B-2. Trap efficiency of the reservoir: Comparison of the Churchill's curve with equations *(Van Rijn, 2013)*

Brune's Curve

Brune developed an empirical relationship between trap efficiency and the ratio of reservoir capacity to mean annual inflow, both in the same volume units. Since the curves were generated by the use of data from normal ponded reservoirs, they are not recommended for use in determining trap efficiencies of de-silting basins or dry reservoirs. Dendy added more data to Brunes's curve and developed a prediction equation for the median curve:

$TE = 100\times0.97^{0.19\log(C/I)}$

The variations, as shown by the envelope curves, are due to the same factors that influence the K coefficient in Brown's curve; however, Brune's curve is considered to be more accurate than Brown's curve, described below (Klik et al., 2010).

The trapping efficiency is independent of sediment properties (size, fall velocity). Brune's curve can be represented by following equation with the accuracy of about 10% (Van Rijn, 2013):

E_{res}= $[0.000085 + (V/V_w)^{1.1}]/[0.0085 + (V/V_w)^{1.1}]$ for $V/V_w>0.003$ (2.6)

Figure B-3 shows the Brune's curve and representation of equation (2.6).

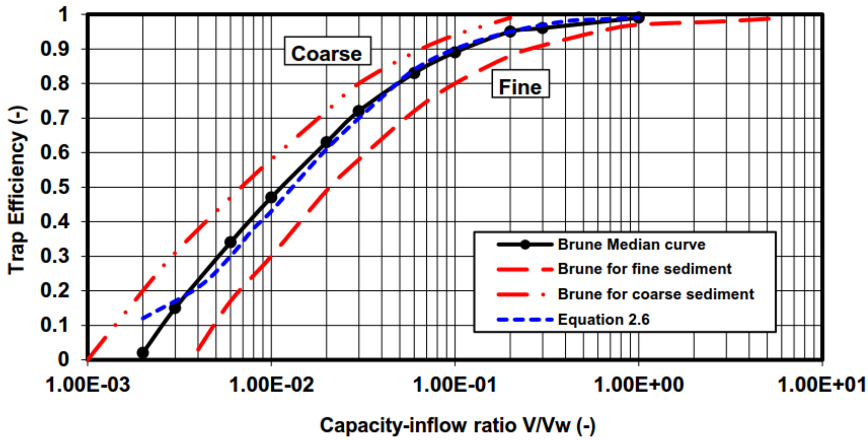

Figure B-3. Trap efficiency according to Brune's curve and the equation *(Van Rijn, 2013)*

Siyam et al. (2001) found that the Brune's curve can be very well represented by $E_{res}=e^{-\beta(Vw/V)}$

in which, V_w= average annual inflow volume, V= storage volume of reservoir below line through bed level at upstream boundary (x=0 m, see Figure B-4), β=empirical coefficient=0.0079. The β-coefficient is not a universal coefficient, but it depends on settling velocity of the sediments, reservoir shape, reservoir area and reservoir operation. They suggest to determine the annual sedimentation volume by summation of all monthly contributions to better include the reservoir operation procedures (Van Rijn, 2013)

Borland (1971)

He proposed following equation:

E_{res}= 1 - $\exp[-A_b(L/h)(w_s/u)]$ (2.7)

in which, L=length scale (m), w_s= settling velocity of sediment, h= mean flow depth of reservoir (or section of reservoir), u= mean flow velocity in reservoir, A_b= coefficient (=1.055).

Eysink and Vermaas (1981) & Van Rijn (2013)

The trap efficiency can also be estimated by using the deposition formulae of Eysink and Vermaas (1981) as follows:

E_{res}= 1 - $\exp[-A_{ev}L/h]$ (2.8a)

L= length of reservoir, h= mean flow depth of reservoir (or section of reservoir), (see Figure B-4), $A_{ev}=\alpha_s(w_s/u^*)(1+2w_s/u^*)$= deposition parameter, α_s= 0.06= coefficient (in range of 0.04 to 0.08; assuming k_s/h= 0.003 (k_s = roughness height) and Chezy coefficient C= 65 $m^{0.5}/s$), w_s= settling velocity of sediment, u*= mean bed-shear velocity in reservoir.

Van Rijn (2013) proposed following equation for trap efficiency:

E_{res}= 1 - exp[-A_{vr}L(h-h_0)/h^2] (2.8b)

in which, L= length of reservoir, h_0= flow depth at upstream reservoir boundary (x=0 m), h= mean flow depth of reservoir (or section of reservoir) (see Figure B-4), A_{vr}=α_s(w_s/u*)(1+2w_s/u*)= deposition parameter, α_s= 0.25= coefficient (in range of 0.2 to 0.3), w_s= settling velocity of sediment, u*= mean bed-shear velocity in reservoir.

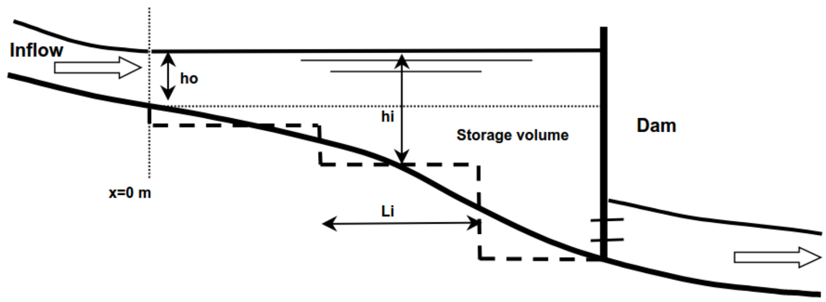

Figure B-4. Schematization of reservoir into compartments (storage volume is volume below line through bed level at x=0 m) *(Van Rijn, 2013)*

If necessary, the incoming sediment load can be divided into a series of representative sediment fractions and the sedimentation can be computed for each fraction. The total sedimentation can be obtained by summation over the fractions: ΔS= Δt ∑($E_{res,i}$ $Q_{s,o,i}$), in $Q_{s,o}$ = incoming sediment transport at x = 0 (Van Rijn, 2013).

Using one single fraction with w_s= 0.1 mm/s (sediment of about 10 μm), u*= 1 mm/s, u= 50 mm/s, the following trap efficiency values according to Eysink-Vermaas and Borland are obtained (Van Rijn, 2013):

Eysink-Vermaas (A=0.007; α_s=0.06)	**Borland** (w_s/u=0.002)
E_{res} =0.07 for L/h=10,	E_{res} =0.02 for L/h=10,
E_{res} =0.50 for L/h=100,	E_{res} =0.19 for L/h=100,
E_{res} =0.88 for L/h=300,	E_{res} =0.47 for L/h=300,
E_{res} =0.97 for L/h=500,	E_{res} =0.65 for L/h=500,
E_{res} =0.999 for L/h=1000,	E_{res} =0.88 for L/h=1000.

The trap efficiency of large-scale reservoirs (L/h>500) will be about 90% to 100%; thus nearly all sediments entering the reservoir will be trapped. The coarse fractions will be deposited in the upper part of the reservoir (backwater region), while the finer sediments will be deposited in the lower part (region with horizontal water surface). The proportion of sediment passing through the reservoir will depend primarily on the average flow velocity in the reservoir and the settling velocity of the sediment. In small-scale reservoirs the fine sediments may remain in suspension long enough to pass through the reservoir.

The length scale of the settling process is: L_s=h u/w_s, in which h= mean depth, u = mean velocity and w_s= settling velocity. A particle at the surface of the reservoir will settle after L_s (assuming no upward mixing).

Example Calculation

A reservoir has the following dimensions: L= 25000 m, depth below bed at x=0 m from 0 to 40 m (mean depth $h\text{-}h_0$=20 m), width from 100 to 500 m (mean width= 300 m), yielding a reservoir storage volume of V=25000×20×300=1.5×10^8 m^3. The river just upstream of the reservoir (x=0 m) has a depth h_0= 5 m and width= 100 m.

The discharge is Q= 500 m^3/s. The settling velocity of the sediment is 0.1 mm/s. The Chézy-roughness in the reservoir is assumed to be C=65 $m^{0.5}/s$.

What are the trap efficiency values?

1) Trap efficiency according to Churchill: V=1.5×10^8 m^3, SI=$V^2/(Q^2L)$=3.6×10^6 s^2/m, yielding E_{res} = 0.55

2) Trap efficiency according to Brune: V=1.5×10^8 m^3, V_w=365×24×3600×500=1.57×10^{10} m^3, yielding E_{res} = 0.45

3) Trap efficiency according to Borland: h_{mean}=20 m, u_{mean}=500/(300×20)=0.0833 m/s, yielding E_{res} = 0.80

4) Trap efficiency according to Eysink-Vermaas: u* = ($g^{0.5}u_{mean}$/C)=0.004 m/s, A=0.0016, yielding E_{res} = 0.87

5) Trap efficiency according to Van Rijn: u*=0.004 m/s, A=0.0066, $(h\text{-}h_0)/h$=20/25 yielding E=0.99

The settling length of a particle at the surface is roughly: L_s=h u/w_s ≅ 17000 m (assuming no upward mixing).

Calculation of sediment thickness along the reservoir using trap efficiency

Large-scale reservoirs should be divided into a series of compartments to estimate the sedimentation thickness along the reservoir. The trap efficiency formulae can be applied from compartment to compartment ($E_{res,i}$) as per Figure B-4.

For example, if a reservoir is schematized into three compartments (see Figure B-4) with L_1,b_1, h_1; L_2, b_2, h_2 and L_3, b_3, h_3, the sedimentation in each compartment and the total sedimentation can be expressed as (since the sedimentation volume in the reservoir can be expressed as ΔS= E_{res} $Q_{s,o}$ Δt, see Van Rijn, 2013)

$\Delta S_1 = E_{res1}\ Q_{s,o}\ \Delta t$

$\Delta S_2 = E_{res2}\ Q_{s,1} = E_2\ (1-E_1)\ Q_{s,o}\ \Delta t$

$\Delta S_3 = E_{res3}\ Q_{s,2} = E_3\ (1-E_2)(1-E_1)\ Q_{s,o}\ \Delta t$

The total sedimentation is: $\Delta S = \Delta S_1 + \Delta S_2 + \Delta S_3 = [E_1 + E_2(1-E_1) + E_3(1-E_2)(1-E_1)]\ Q_{s,o}\ \Delta t$.

This approach can be expanded to more compartments (if necessary).

A similar expression can be derived while taking equilibrium transport in to account. In this case, the general expression reads as (Van Rijn, 2013):

$\Delta S = E_{res}\ (Q_{s,o} - Q_{s,eq})\ \Delta t$

in which, E_{res}= trapping efficiency of reservoir (percentage of sediment trapped in reservoir or reservoir section), $Q_{s,o}$= incoming sediment transport (m^3/s or kg/s), $Q_{s,eq}$=equilibrium sediment transport at end of reservoir or reservoir section and Δt= period considered (s).

The equilibrium transport can be estimated as:

$Q_{s,eq}=(u/u_o)^3 Q_{s,o}$

in which, u_o= mean flow velocity at upstream reservoir boundary (x=0 m), u =mean flow velocity at end of reservoir or reservoir section.

Brown's Curve

Brown developed a curve (depicted in Figure B-5) showing the ratio between reservoir capacity (C, in acre-ft) divided by watershed area (W, in square miles) and trap efficiency (E, in percentage). This curve can be represented by the following relationship (Klik et al., 2010):

E = 100 [1-1/ (1 KC/W)]

where, K = coefficient ranges from 0.046 to 1.0 with a median value of 0.1.

Coefficient K increases: (i) for regions of smaller and varied retention time (calculated using the capacity-inflow ratio); (ii) as the average grain size increases; and (iii) for reservoir operations that prevent release of sediment through sluicing or movement of sediment toward the outlets by pool elevation regulation.

Variations are mainly due to the fact that reservoirs having the same C/W ratio can have different capacity inflow ratios. Brown's curve is useful when only watershed area and reservoir capacity are known.

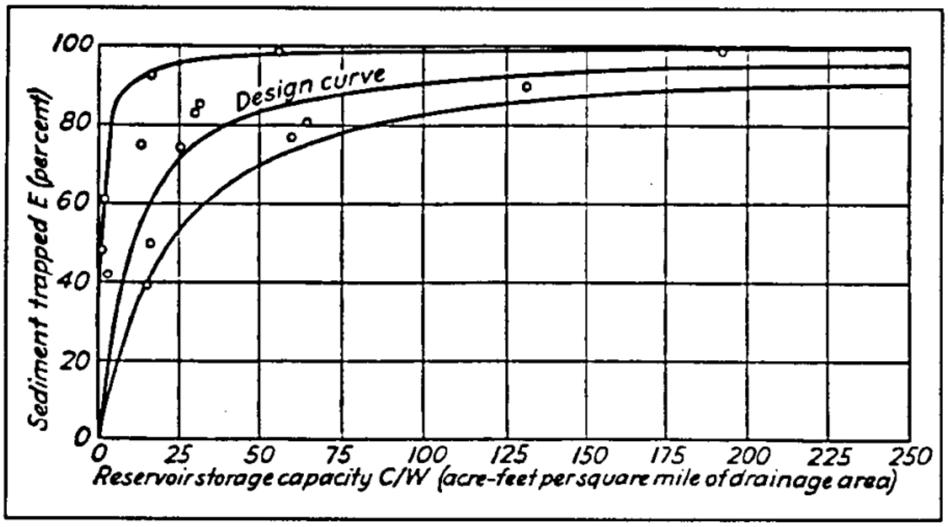

Figure B-5. Brown's curve for trap efficiency for different values of coefficient K *(Klik et al., 2010)*

Simple Approach to Calculate Sedimentation in Reservoirs (Van Rijn, 2013)

A simple spreadsheet approach (SED-RES) is available to compute the sedimentation in a reservoir for given sediment transport and sediment characteristics at the upstream reservoir boundary (x=0 m).

Three sediment fractions are considered:

Clay with settling velocity, $w_{s,clay}$ = 0.0001 m/s (input value)

Silt with settling velocity, $w_{s,silt}$ = 0.001 m/s (input value)

Sand with settling velocity, $w_{s,sand}$ = 0.01 m/s (input value).

The reservoir is schematized into five sections (or compartments) A, B, C, D and E, each with length L, width W and depth do=h-ho=depth below line through bed level at x=0 m, h=flow depth, ho=flow depth at x=0 m. The total storage volume is: $V=\sum(L_iW_i\ (h_i\text{-}h_0))$.

The upstream transport rates are defined as:

$Q_{s,clay} = C_{clay}\ Q_0$,

$Q_{s,silt} = C_{silt}\ Q_0$,

$Q_{s,sand} = C_{sand}\ Q_0$,

in which, Q_0 = flow discharge (input value in m^3/s), C = depth-mean concentration (input values in kg/m^3).

The sedimentation (ΔSi) in each Section i is computed as:

- $\Delta S_{i,clay} = E_{i,clay}\ (Q_{s,i,in,clay} - Q_{s,i,eq,clay})\ \Delta t$
- $\Delta S_{i,silt} = E_{i,silt}\ (Q_{s,i,in,silt} - Q_{s,i,eq,silt})\ \Delta t$
- $\Delta S_{i,sand} = E_{i,sand}\ (Q_{s,i,in,sand} - Q_{s,i,eq,sand})\ \Delta t$,

in which, $Q_{s,i,in}$ = sediment transport at upstream boundary of Section i, $Q_{s,i,eq} = (u_i/u_0)3$, $Q_{s,0}$ = equilibrium transport in Section i, E_i = trap efficiency in Section i according to the methods of Van Rijn, Eysink-Vermaas and Borland (see above).

These methods have been implemented, because the type of sediment is explicitly represented by the settling velocity. The equilibrium transport rates can be included or excluded by a correction factor (1or 0).

The total sedimentation mass in Section i is: $\Delta S_{i,tot} = \Delta S_{i,clay} + \Delta S_{i,silt} + \Delta S_{i,sand}$.

The total sedimentation volume in Section i is: $\Delta S_{i,tot}$, volume= $\Delta S_{i,tot}/\varrho_{i,bulk}$.

The bulk density (ton/m^3) in Section i is represented by: (i) a constant input value (in range of 0.4 to 1.5 ton/m^3); or a formula; $\varrho i,bulk= (\Delta S_{i,clay}/\Delta S_{i,tot})(0.415+0.43\times0.255\gamma) + (\Delta S_{i,silt}/\Delta S_{i,tot})(1.12+0.43\times0.09\gamma) + (\Delta S_{i,sand}/\Delta S_{i,tot})(1.55)$, in which $\gamma=[\{(T/(T\text{-}1))\ln(T)\}\text{-}1]$ = consolidation factor (T in years) and 'always submerged values' from Table B-1 (see below).

The deposition layer thickness in Section i is: $\Delta h_i=\Delta S_{i,tot,\ volume}/(L_i\ W_i)$.

The new flow depth in Section i at time t+Δt is $h_{i,t}+\Delta t = h_{i,t} - \Delta h_{i,t}$. The maximum sedimentation thickness can be somewhat larger than the maximum storage thickness due to sedimentation in last time period just before the maximum sedimentation volume is reached; time periods should be smaller than about 6 months to minimize this effect.

The sediment transport rates at the upstream boundary of Section *i*+1 at time *t* are:

- $Q_{s,i+1,clay} = Q_{s,i,clay} - E_{i,clay} (Q_{s,i,clay} - Q_{s,i,clay,eq})$
- $Q_{s,i+1,silt} = Q_{s,i,silt} - E_{i,silt} (Q_{s,i,silt} - Q_{s,i,silt,eq})$
- $Q_{s,i+1,sand} = Q_{s,i,sand} - E_{i,sand} (Q_{s,i,sand} - Q_{s,i,sand,eq})$

Bulk Density of Deposited Sediment

The bulk density (unit weight of dry sediment material in kg/m^3) of the deposits will vary with the proportions of sand (>0.05 mm), silt (0.01 to 0.05 mm) and clay materials (<0.01 mm), the type of reservoir operation (exposed or submerged sediment deposits) and the consolidation period. The variation range is about 300 to 1600 kg/m^3. The lower densities generally occur in the vicinity of the dam under submerged conditions, while the higher densities generally occur in the upstream part of the reservoir and exposed regions after drawdown of the reservoir. Based on data from reservoirs in the USA, Lara and Pemberton (1963) derived an expression for the initial (at t=0) bulk density:

$$\rho_{bulk} = p_{clay}\,\rho_{clay} + p_{silt}\,\rho_{silt} + p_{sand}\,\rho_{sand}$$

in which, p= percentages of clay, silt and sand in sediment deposits, the values of ρ_{clay}, ρ_{silt}, and ρ_{sand} are given in Table B-1.

Murthy (1977) presents many data of bulk density values from reservoirs (mostly submerged sediments in reservoirs with moderate drawdown) in India. Based on a total of 380 samples (taken by a corer sampler):

$\rho_{clay, initial} = 480$ kg/m^3, $\rho_{silt, initial} = 1040$ kg/m^3, $\rho_{sand,initial} = 1470$ kg/m^3.

The bulk density increases with time due to compaction. Lane and Koelzer (1943) proposed an expression, which gives the bulk density of the first year's deposition after T years of compaction due to later deposits (on top of the first year's deposit):

$$\rho_{bulk} = \rho_{initial} + K \log(T)$$

in which, $\rho_{initial}$ = initial bulk density (see Table B-1), K= coefficient (see Table B-1), T= time (years).

Miller (1953) developed an expression representing the average density of the total deposited sediment package in the reservoir from one to T years:

$$P_{bulk} = \rho_{initial} + 0.43K\,[\{(T/(T-1))\ln(T)\}-1]$$

The value according to this equation is always smaller than that according to Lane and Koelzer (1943).

Table B-1. Characteristic values of bulk density (initial and after compaction)

Reservoir type	Initial (t=0)			Compacted after time t		
	ρ_{clay} (kg/m^3)	ρ_{silt} (kg/m^3)	ρ_{sand} (kg/m^3)	$\rho_{clay,initial}$; K (kg/m^3)	$\rho_{silt,initial}$; K (kg/m^3)	$\rho_{sand,initial}$; K (kg/m^3)
Always submerged	415	1120	1550	480 K=255	1040 K=90	1550 K=0
Normally moderate to considerable drawdown	560	1140	1550	735 K=170	1185 K=45	1550 K=0
Normally empty	640	1170	1550	960 K=100	1265 K=15	1550 K=0
River bed sediment	960	1170	1550	1250 K=0	1310 K=0	1550 K=0

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Appendix C. Reservoir Assessment Datasheet Template and Checklist

RMIS: Sediment Data Summary

Name of Reservoir

Dam	Authority	River	State & Town
	Coordinate		
	Bed Elevation [m]	Dam Crest Elevation [m]	Spillway Crest Elevation [m]

Reservoir	Storage Allocation	Pool Elevation [m]	Original Surface Area [m²]	Original Capacity [m³]	Gross Storage [m³]	Date Storage Begin/Date Normal Operation
	a) Multiple Use					
	b) Flood Control					
	c) Power					
	d) Water Supply					
	e) Sediment					
	f) Inactive					
	Length of Reservoir [m]		Average Width of Reservoir [m]			

Watershed				
	Total Drainage Area [m²]		Mean Annual Precipitation [mm]	
	Net Sediment Contributing Area [m³]		Mean Annual Runoff [m³/s]	
	Length [m]		Average Width [m]	
	Max. Elevation	Min. Elevation	Climatic Classification	

Flow, Sediment & Bathymetry Data

Date of Survey	Period Years	Type of Survey	Measurement Resolution [m]	Surface Area [m²]	Capacity [m³]	Trap Efficiency [%]	
						Orig.	Meas.
…. …. ….							

Date of Survey	Period Annual rainfall [mm]	Period Inflow Discharge [m³/s]			Water Inflow To Date [m³/s]	
		Mean Annual	Max. Annual	Period Total	Mean Annual	Total to Date [m³]
…. ….						

Date of Survey	Period Sediment Deposits [m³]			Total Sediment Deposits to Date [m³]		
	Period Total	Av. Annual	Per km²-Year	Total to Date	Av. Annual	Per km²-Year
…. ….						

Date of Survey	Av. Dry Weight [kg/m³]	Grain Size [mm]			Storage Loss [%]		Suspended Sediment Inflow [ppm]		Annual Bedload [m³]
		D50	D10	D90	Av. Annual	Total to Date	Period	Total to Date	
…. ….									

Water and Sediment Quality

Date of Survey	Metals	Solids	pH	Temperature	Odour	Dissolved Oxygen (DO)
…. ….						

<table>
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<tr><td rowspan="14">Basic Analyses</td><td rowspan="3">Date of Survey</td><td colspan="14">Depth Designation Range Above and Below Crest Elevation [m]</td></tr>
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<tr><td colspan="14">Part of Total Sediment Located Within Depth Designation [%]</td></tr>
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<tr><td rowspan="3">Date of Survey</td><td colspan="14">Reach Designation Percentage of Total Original Length of Reservoir</td></tr>
<tr><td>0-10</td><td>10-20</td><td>20-30</td><td>30-40</td><td>50-60</td><td>60-70</td><td>70-80</td><td>80-90</td><td>90-100</td><td>100-105</td><td>105-110</td><td>110-115</td><td>115-120</td><td>120-125</td></tr>
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<tr><td colspan="15">Range in Reservoir Operation</td></tr>
<tr><td colspan="4">Water Year</td><td colspan="4">Max. Elevation [m]</td><td colspan="4">Min. Elevation [m]</td><td colspan="3">Inflow [m³/s]</td></tr>
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<tr><td colspan="15">Elevation – Area Capacity Data</td></tr>
<tr><td colspan="5">Elevation [m]</td><td colspan="5">Area [m²]</td><td colspan="5">Capacity [m³]</td></tr>
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</table>

Additional Notes:

- All data must be available in digital format as well.
- All elevations and height data must be with respect to standard datum.
- The table is indicative for the guidance purpose only, so it can be modified as per the data standard and competence. The table indicates a minimum data summary, which is required for first assessment.
- The bathymetry map shall be included if the measurement is of high resolution.
- Data and analysis shall be presented in charts and graphical plots as well.
- Include satellite images, pictures, videos, report, models (year, location)
- For water and sediment quality testing and requirements for beneficial reuse of sediment, see the **Appendix F**.

Reservoir Assessment Checklist

Table C-1. Checklist for social and environmental conditions of the reservoir

S. No.	Questions	Yes/No/ Unknown
	Is there any practice, adopted earlier for sediment removal?	
	Is periodicity of clearing the silt from reservoir less than 5 year?	
	Are the catchment treatment activities undertaken for erosion protection?	
	Are they useful/successful?	
	Is quantity of sediment likely to be generated due to proposed desiltation activities known?	
	Are properties (quality) of sediments to be removed/disposed known?	
	Is the location of reservoir with respect to Tiger Reserve, Wildlife Sanctuary or national park, reserved forest etc. within 10 km radius from the reservoir?	
	Are there faunal population/wild animals in and around the dam area?	
	Does the reservoir form the part of wetland of ecological importance?	
	Is there presence of aquatic animals in the reservoir and whether identification of impact on such aquatic population has been carried out or not?	
	Are there clearance and approvals for sediment removal and disposal necessary?	
	Are there options for potential disposal sites available for disposal of sediment?	
	Is the reservoir and dumping sites easily accessible to carry large equipment and vehicle?	
	Are there acceptable transportation facilities?	
	Are there risks of pollutions (noise, dust, dirt) and traffic disturbance during transportation?	
	Are there any possibilities for the sediment reuse?	

Note: This checklist is mainly related to safety, social and environmental aspects. More will be added to this in future.

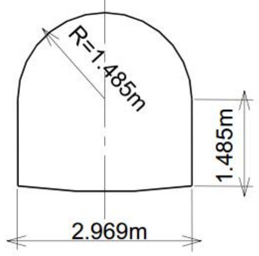
Appendix D. EXAMPLES OF EXISTING AND PLANNED BYPASS SYSTEMS

Some examples of existing and planned bypass tunnel systems in three counties, namely Japan, Switzerland and Taiwan, are presented here. These works are published in Proceedings of the 2nd International Workshop on Sediment Bypass Tunnels (2017).

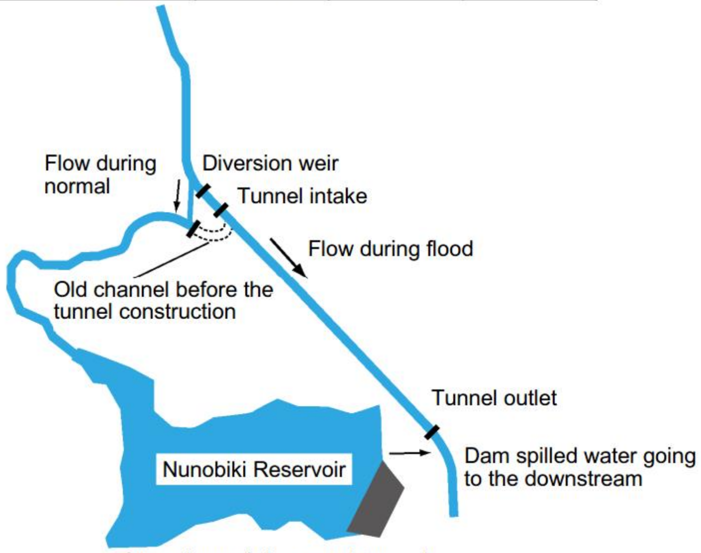
Nunobiki-Gohonmatsu Dam (Japan)

Bypass tunnel specifications

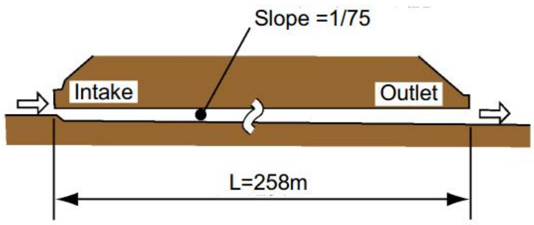
Completion Year	Purpose	Cross Section Shape	Length (m)	Longitudinal Slope
1908	Sediment discharge /Water utilization bypass	Hood-type 2.9m×2.9m	258	1.30% (1/75)



Typical tunnel cross-section



Overview of dam and tunnel



Longitudinal profile


Diversion weir

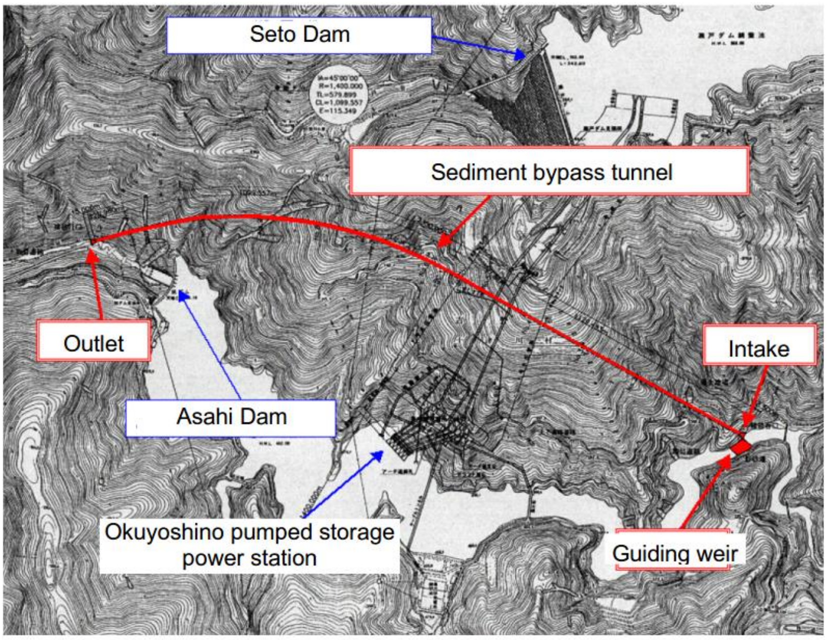

Tunnel intake

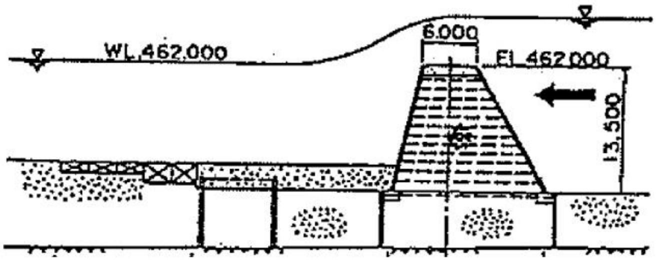

Tunnel outlet

Asahi Dam (Japan)

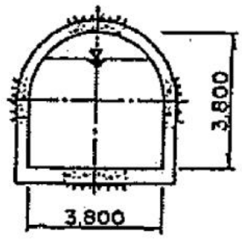
Bypass tunnel specifications

Completion Year	Purpose	Cross Section Shape	Length (m)	Longitudinal Slope
1998	Sediment discharge (Turbid water discharge)	Hood-type 3.80m×3.80m	2,350	2.90% (1/35)





Guiding weir



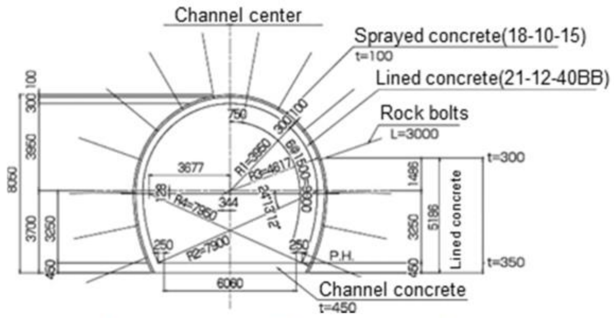
Typical tunnel cross-section

Koshibu Dam (Japan)

Bypass tunnel specifications

Completion Year	Purpose	Cross Section Shape	Length (m)	Longitudinal Slope
2016	Sediment discharge (Flood control)	Horseshoe shape 2r=7.95m	3,999	2.00% (1/50)

Overview of sediment bypass facilities

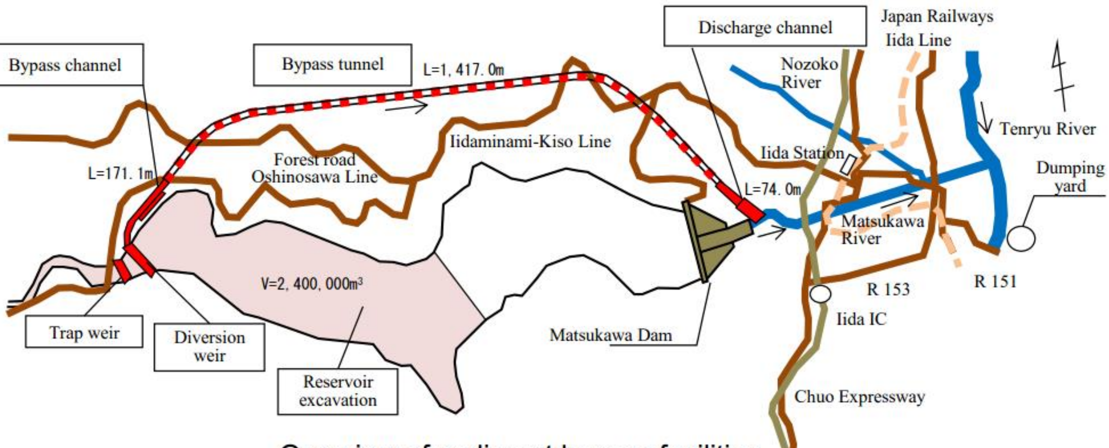


Tunnel cross-section (major section)

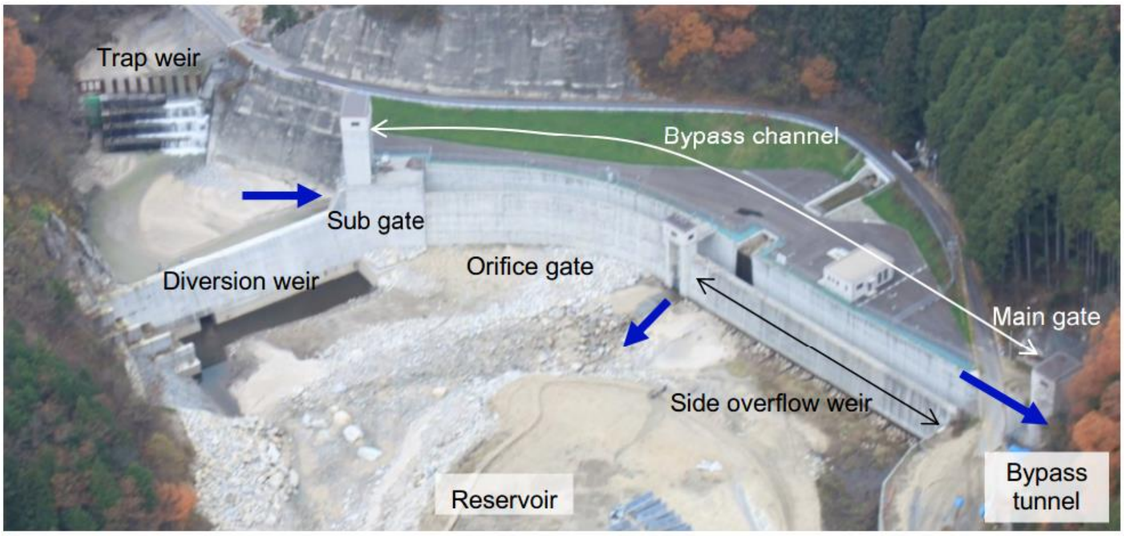
Matsukawa Dam (Japan)

Bypass tunnel specifications

Completion Year	Purpose	Cross Section Shape	Length (m)	Longitudinal Slope
2016	Sediment discharge (Flood control)	Hood-type 5.20m×5.20m	1,417	4.00% (1/25)



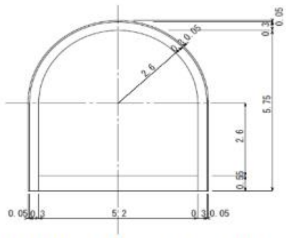
Overview of sediment bypass facilities



Intake part of bypass facilities

Outlet

Energy dissipator

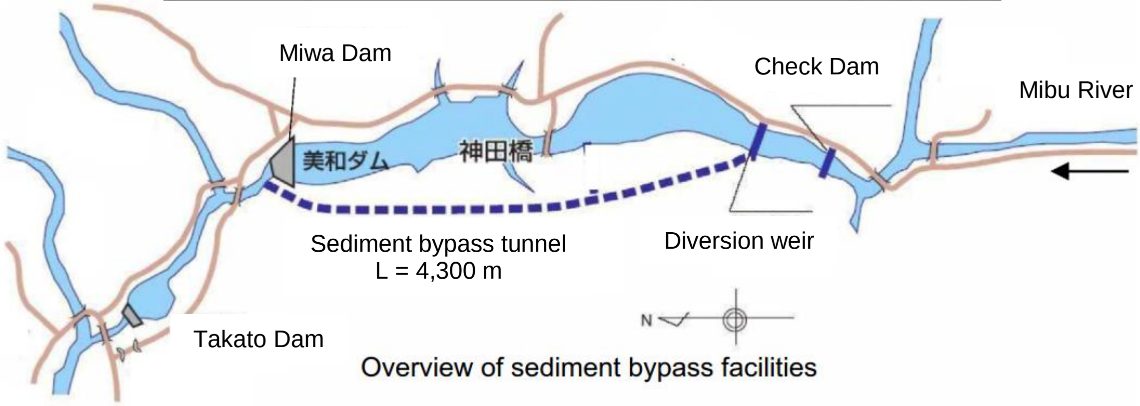


Typical tunnel cross-section

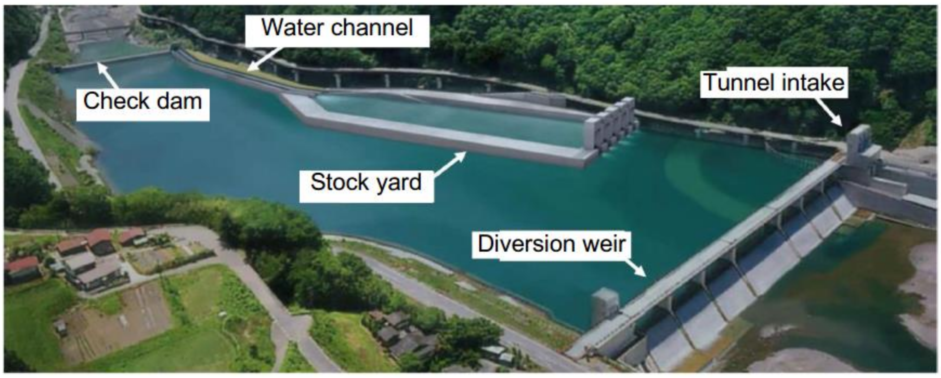
Miwa Dam (Japan)

Bypass tunnel specifications

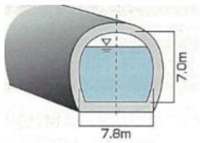
Completion Year	Purpose	Cross Section Shape	Length (m)	Longitudinal Slope
2005	Sediment discharge	Horseshoe shape 2r=7.8m	4,308	1.00% (1/100)



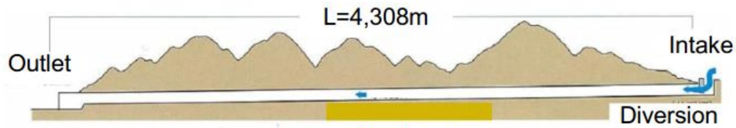
Overview of sediment bypass facilities



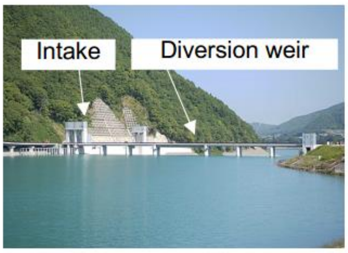
The auxiliary sediment measure facilities



Typical tunnel cross-section



Longitudinal profile

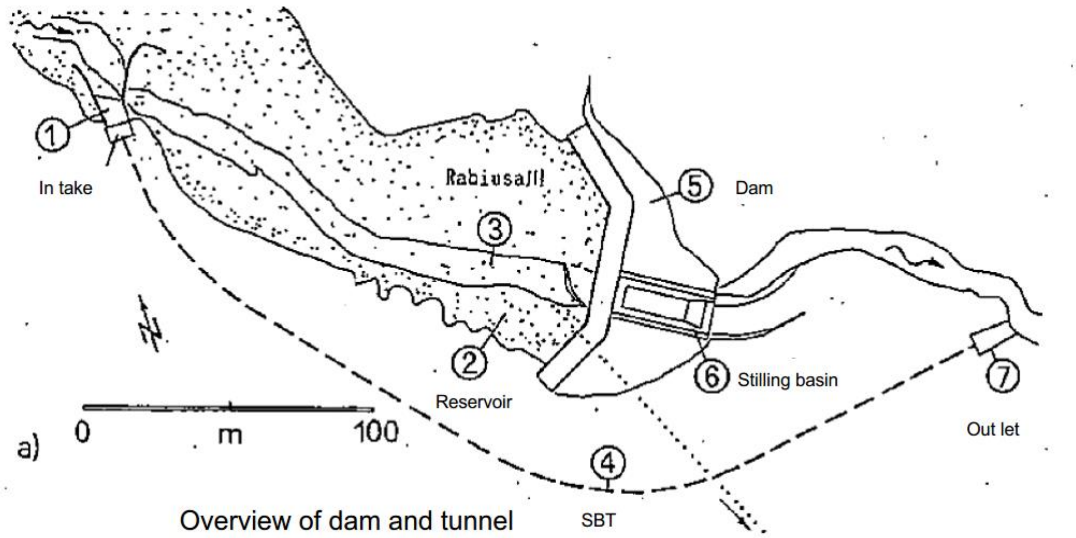


Tunnel outlet and energy dissipator

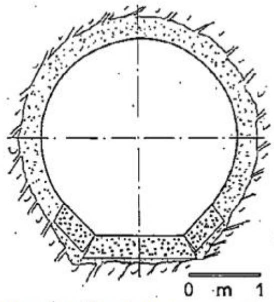
Egschi Dam (Switzerland)

Bypass tunnel specifications

Completion Year	Purpose	Cross Section Shape	Length (m)	Longitudinal Slope
1976	Sediment discharge	Circle D=2.80m	360	2.60% (1/38.5)



Overview of dam and tunnel



Typical tunnel cross-section

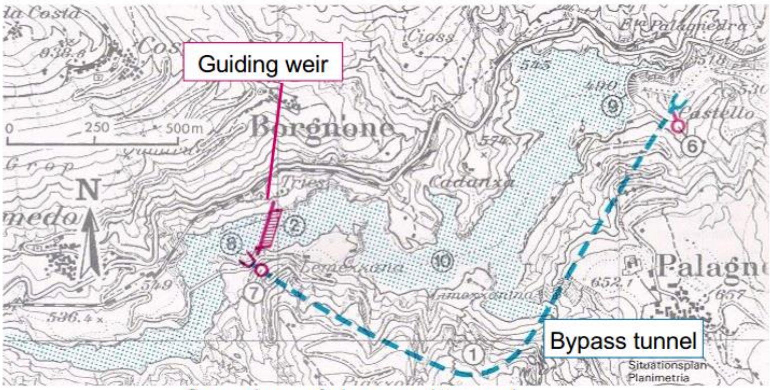
Upstream of dam

Downstream of dam

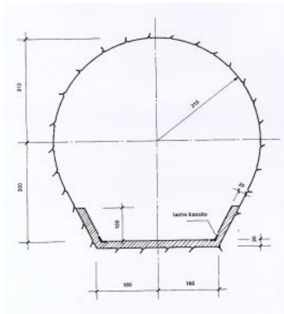
Palagnedra Dam (Switzerland)

Bypass tunnel specifications

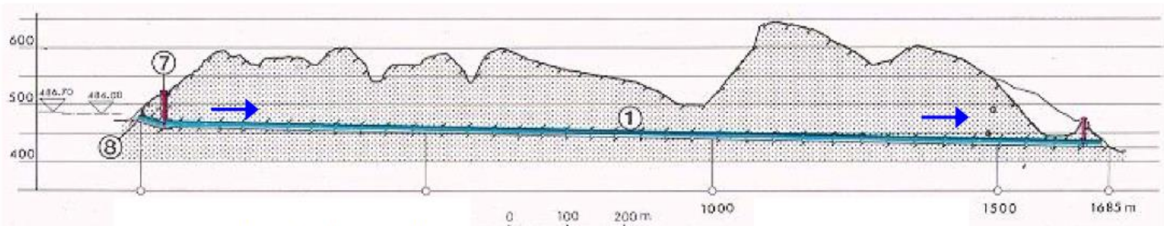
Completion Year	Purpose	Cross Section Shape	Length (m)	Longitudinal Slope
1977	Sediment discharge	Horseshoe shape 6.20m×6.13m	1,760	2.00% (1/50)



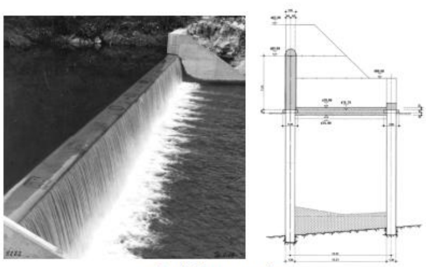
Overview of dam and tunnel



Typical tunnel cross-section



Longitudinal profile



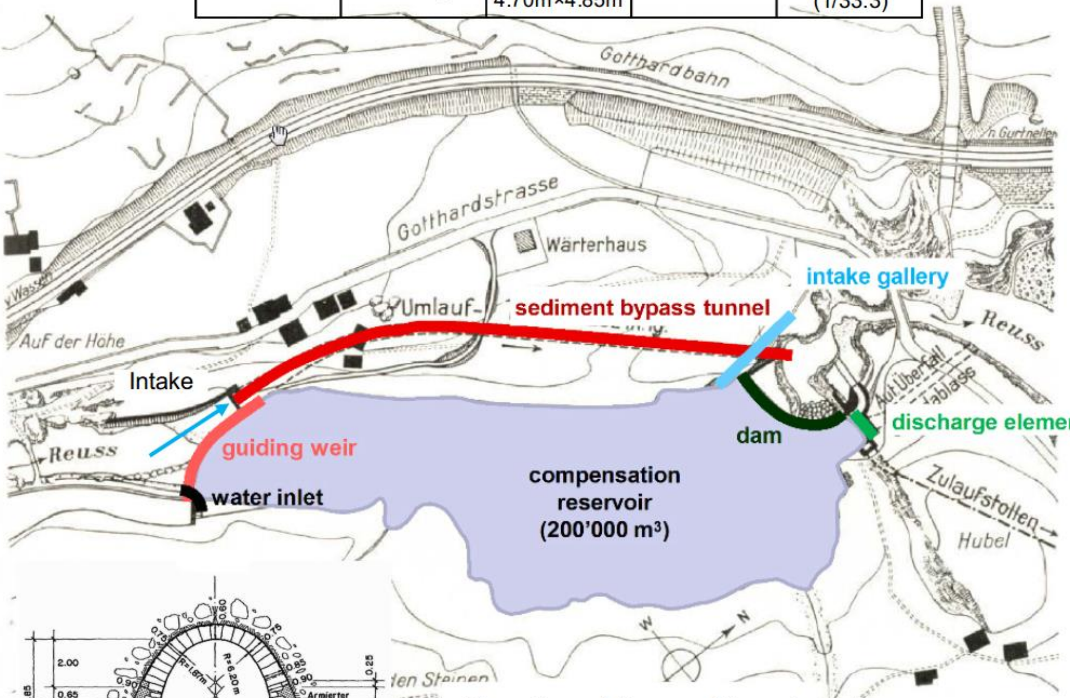
Guiding weir

Downstream of dam (near the outlet)

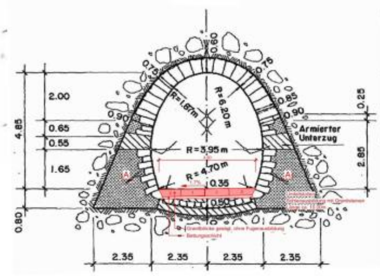
Pfaffensprung Dam (Switzerland)

Bypass tunnel specifications

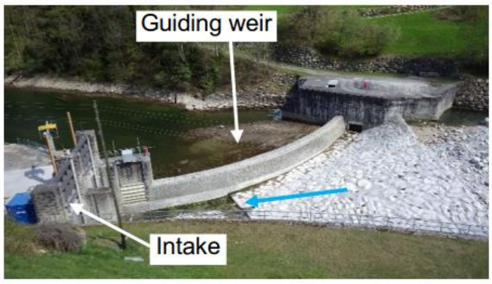
Completion Year	Purpose	Cross Section Shape	Length (m)	Longitudinal Slope
1922	Sediment discharge	Horseshoe shape 4.70m×4.85m	282	3.00% (1/33.3)



Overview of dam and tunnel



Typical tunnel cross-section



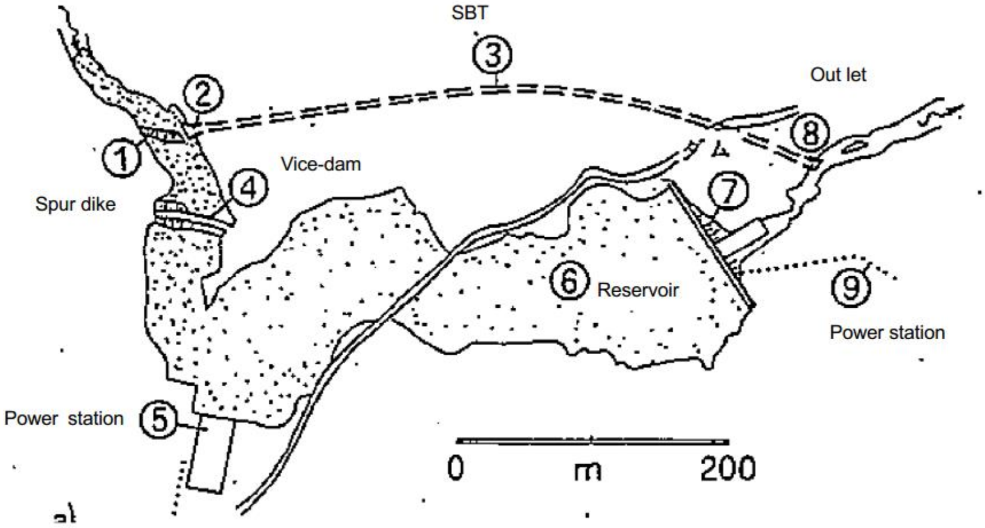
Downstream side of dam

Intake

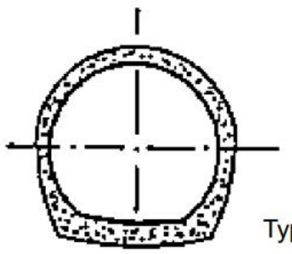
Rempen Dam (Switzerland)

Bypass tunnel specifications

Completion Year	Purpose	Cross Section Shape	Length (m)	Longitudinal Slope
1986	Sediment discharge	Horseshoe shape 3.45m×3.42m	450	4.00% (1/25)



Overview of dam and tunnel



Typical tunnel cross section

Upstream of dam

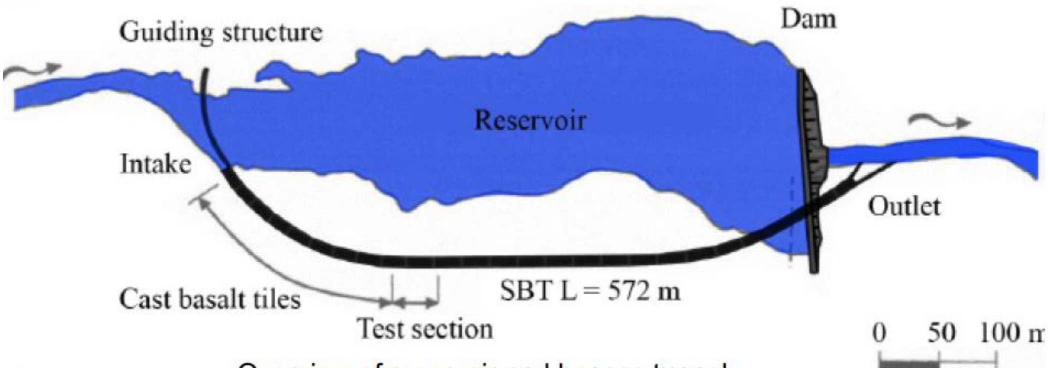
Downstream of dam

Runcahez Dam (Switzerland)

Bypass tunnel specifications

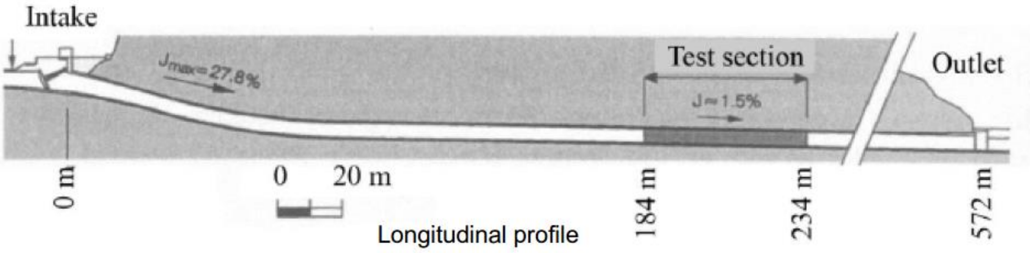
Completion Year	Purpose	Cross Section Shape	Length (m)	Longitudinal Slope
1962	Sediment discharge	Hood-type 3.80m×4.50m	572	1.40% (1/71.4)

a)

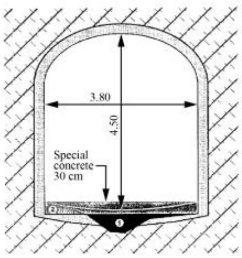


Overview of reservoir and bypass tunnel

b)



Longitudinal profile



Typical tunnel cross-section

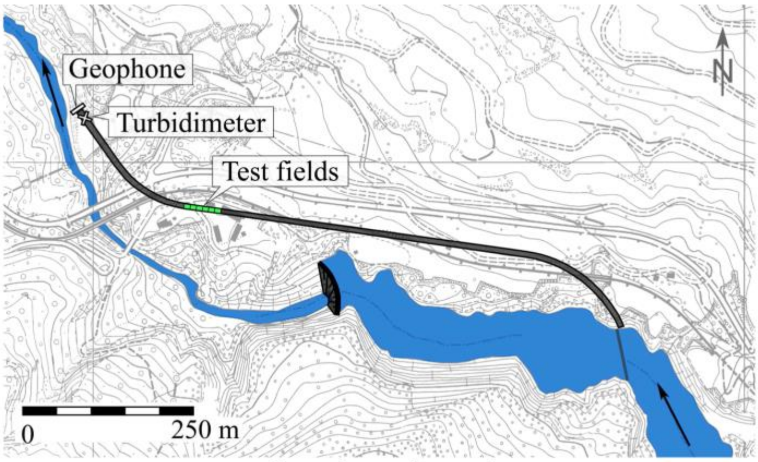
Downstream of dam

Upstream of dam

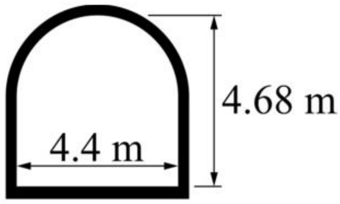
Solis Dam (Switzerland)

Bypass tunnel specifications

Completion Year	Purpose	Cross Section Shape	Length (m)	Longitudinal Slope
2012	Sediment discharge	Hood-type 4.40m×4.68m	968	1.90% (1/52.6)

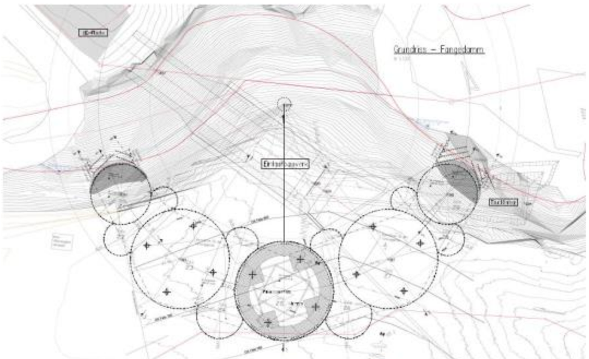


Overview of tunnel



Typical tunnel cross section

Intake



Circular-cell cofferdam (plan view)

Circular-cell cofferdam
(under construction)

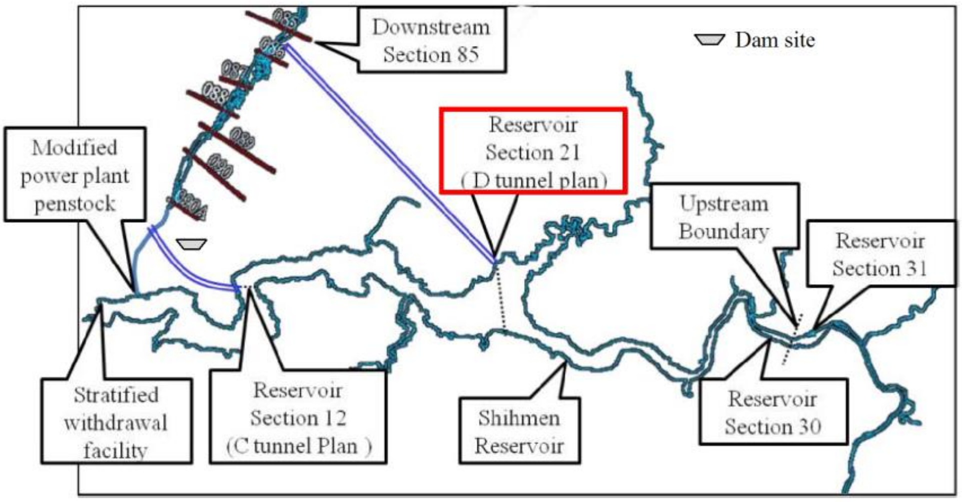
Guiding structure

Outlet

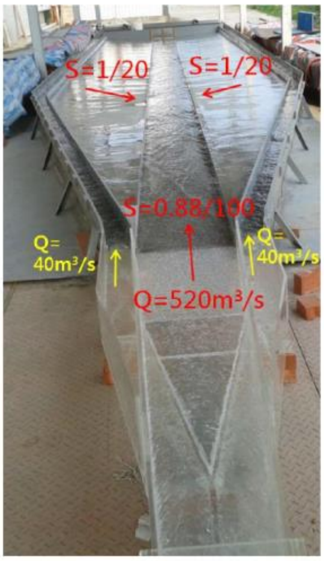
Shihmen Dam (Taiwan)

Bypass tunnel specifications (PlanD)

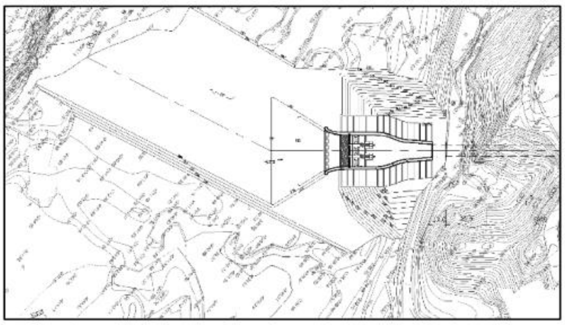
Completion Year	Purpose	Cross Section Shape	Length (m)	Longitudinal Slope
In planning	Strengthen release capability, sediment discharge	Hood-type 8.00m×9.00m	3,685	2.86% (1/34.9)



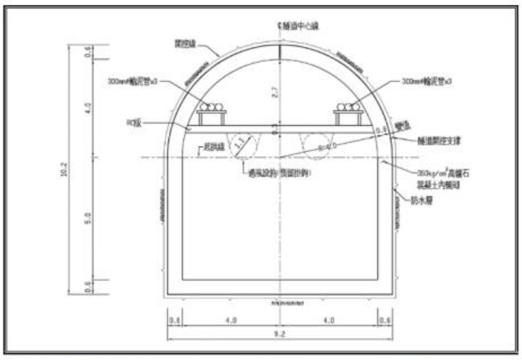
Overview of reservoir and bypass tunnel



Physical model of the settling basin at the outlet of Plan-D tunnel



Intake of Plan-D tunnel (Plan view)

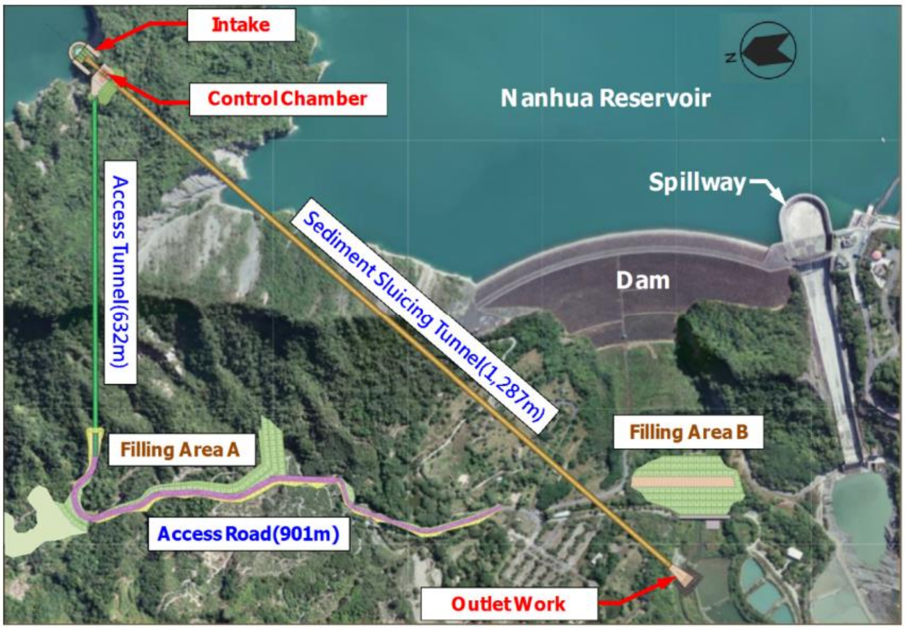


Plan-D typical tunnel cross section

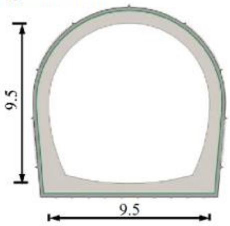
Nanhua Dam (Taiwan)

Bypass tunnel specifications

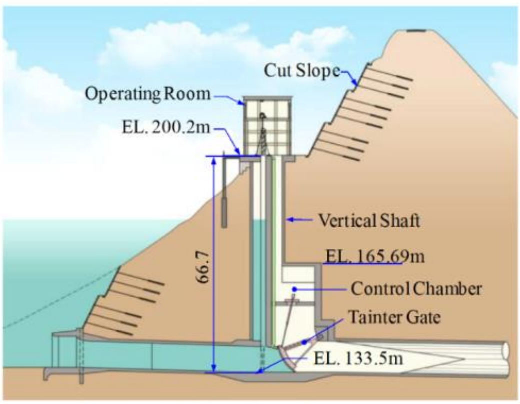
Completion Year	Purpose	Cross Section Shape	Length (m)	Longitudinal Slope
2018	Strengthen release capability, sediment discharge	Horseshoe shape 9.50m×9.50m	1,287	1.85% (1/54.1)



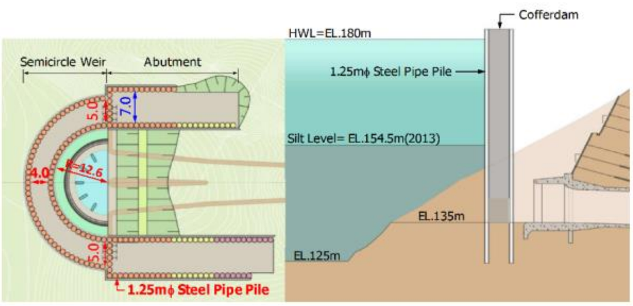
General arrangement of the sediment sluicing tunnel



Typical tunnel cross-section



Vertical shaft and control chamber

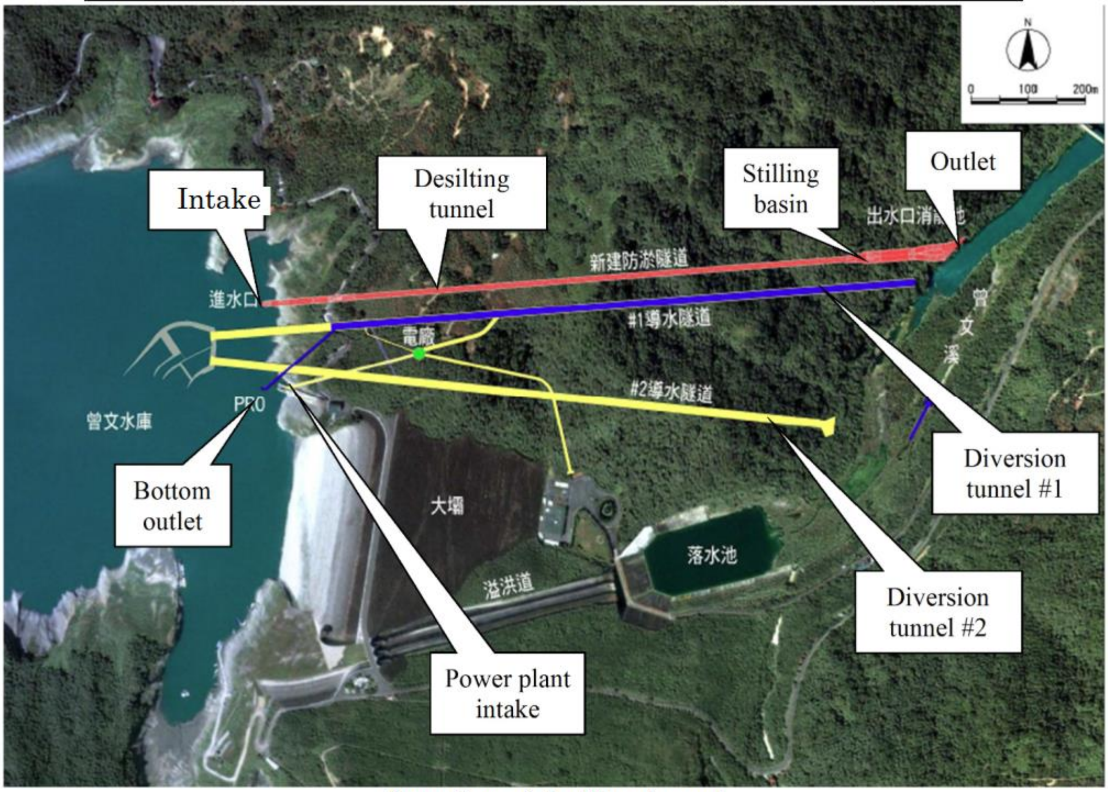


Plan view and profile of the cofferdam

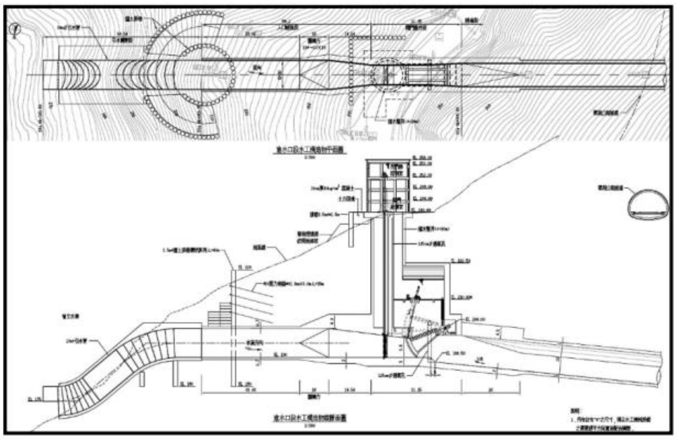
Tsengwen Dam (Taiwan)

Bypass tunnel specifications

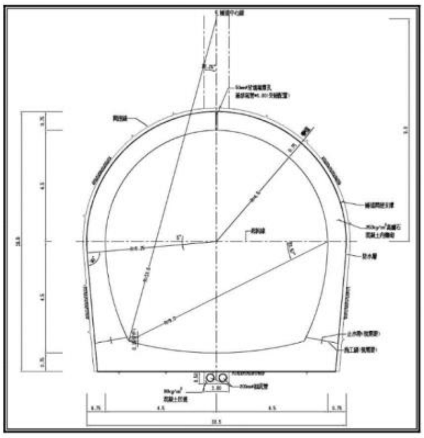
Completion Year	Purpose	Cross Section Shape	Length (m)	Longitudinal Slope
2017	Strengthen release capability, sediment discharge	Horseshoe shape 9.50m×9.50m	1,235	5.32% (1/18.8)



Overview of desilting tunnel



Plan and vertical view of tunnel intake



Typical tunnel cross-section

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Appendix E. TEMPLATE FOR THE REPORT ON RAPID HANDLING OF SEDIMENT-INDUCED PROBLEMS

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Central Water Commission

Dam Rehabilitation & Improvement Project

Template for the report on

Rapid Handling of Sediment-Related Problems in *(name of the reservoir)*

(Name and address of involved organization/institutes)




YEAR
2018

Quality Control:

Version	Date	Writers/Contributors	Checked by
1			
2			

Issued/Copied to:

I/C	Date	Name	Organization
Issued			Central Water Commission

Table of Contents

Abbreviations

CDSCO	Central Dam Safety Organisation
CPMU	Central Project Management Unit
CWC	Central Water Commission
DFR	Design Flood Review
DSRP	Dam Safety Review Panel
ICOLD	International Commission on Large Dams
PST	Project Screening Template
SDSO	State Dam Safety Organisation
SPMU	State Project Management Unit
TD	Tender Documents
WB	World Bank
WP	Work Package

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Summary

- ✓ Summary about the sediment-induced problems, their history, results of measurements, magnitude of problems, constraints, proposed management options and alternatives, conclusions and recommendations.

- ✓ Key outcomes can be summarized in table forms.

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1 Introduction

1.1 General Background

Some relevant sediment-induced problems in dams and reservoir (*assess which of them are relevant for the reservoir(s) under consideration*):

- ✓ Reduction of storage volume in reservoirs
- ✓ Flood level increase in upstream of the reservoir
- ✓ For flood control dams and reservoirs, reduction of storage implies altered regulation and operational strategies leading to less effectiveness of flood management, and thus more risk
- ✓ Erosion and shifting of river banks and bed incision in downstream areas due to lack of sediment supply in downstream area
- ✓ Coastline erosion due to the lack of sediment supply from rivers
- ✓ Adverse effects on agricultural activities in downstream areas due to lack of fertile silt and nutrient supply
- ✓ Impact on aquaculture like fisheries, aquatic plants etc. at downstream areas
- ✓ Possible alteration in static and dynamic loads on structures due to large deposition in front of dam/spillway
- ✓ Erosion of turbines and its accessories
- ✓ Malfunctioning and clogging of hydro-mechanical equipment, such as flow control gates, sluice outlets and vents
- ✓ Abrasion and cavitation of concrete structures like spillways, roller buckets, cut-off wall, sediment bypass tunnels and channels etc.
- ✓ Deterioration of aquatic environments, ecology, water and sediment quality leading to eutrophication, contamination of sediments in the reservoir ((this is usually the case due to industrial effluents, reaching the reservoir)
- ✓ Concerns related to random sediment removal activities (like uncontrolled and irregular flushing) with large turbidity may have an effect on water quality as well as on aquatic environment in downstream area.
- ✓ Any other concerns?

1.2 Organization of Report

- ✓ Chapter 1: This chapter includes Introduction, general background, objective and scope.
- ✓ Chapter 2: This chapter includes assessment of sediment induced problems that includes field reconnaissance and data inventory related to all relevant processes like catchment hydrology and erosion, river and reservoir hydraulics (inflows, outflows), sediment transport and morphology, other past information on sediment management efforts. Furthermore, the chapter includes

analysis of collected data and information to identify the severity and magnitude of the problems, existing constraint (technical, social, environmental, economic) and priorities for sediment handling. The outcomes of the chapter shall help to categorize the sediment-induced problems, whether it is LOW, MEDIUM, HIGH or EXTREME (see handbook)

- ✓ Chapter 3: In this chapter, rapid screening of sediment management options and alternatives, based on rapid assessment of sediment-induced problems (outcomes of chapter 2), shall be described. If the problems are clear, a preliminary sediment management plan can be proposed and described in this chapter. This chapter shall also include recommendations, for example on measurement and monitoring systems (as described in Handbook), sediment management alternatives like possibilities for beneficial use of sediment for various purposes (as described in the Handbook)
- ✓ Chapter 4: This chapter includes pre-feasibility (technical and economic) assessment of the proposed sediment management option(s) and alternative(s), rapid assessment of associated impacts (social, environmental, economic) outlying compliances and conditions for the impact mitigations (see Handbook)
- ✓ Chapter 5: This chapter includes conclusions and recommendations that are related to assessment and management of sediment-induced problems, knowledge, information and data gaps as well as recommendations on how to make a way forward, what is necessary (e.g. measurement and monitoring systems, human resources, capacity building etc.) based on severity and urgency of the problems.
- ✓ The report shall include reference list and appendices with relevant materials, information and data.

1.3 Objective and Scope

The main objective is to carry out a rapid assessment of sediment-induced problems in a reservoir (or a group of reservoirs) to: (i) understand and explain underlying processes associated with sediment-induced problems in the reservoir(s) under consideration, (ii) assess and quantify severity of the sediment-induced problems, (iii) screen and propose (preliminary) sediment management option(s) and alternative(s), and (iv) rapid assessment of feasibility, impacts and compliances related to proposed sediment management interventions and measures

2 Rapid assessment of Sediment-Induced Problem

- ✓ If sedimentation studies have been carried out in the past, the results can be readily used for this chapter!
- ✓ Bathymetry measurement and sediment sampling are important for the rapid assessment as well (particularly for the reservoir with sediment-induced problems
- ✓ This chapter is basically sedimentation study of the reservoir(s) under consideration.
- ✓ Make use of the Handbook (Chapter 3)

2.1 Background

2.2 Site Information

- ✓ Most of the information are in Project Screening Sheets (PST), being used in DRIP project.

2.2.1 Location

- ✓ Coordinates, maps, pictures

2.2.2 Infrastructures and access

- ✓ Available infrastructures, facilities, accessibility

2.2.3 General Features and Information of Dam and Reservoir

- ✓ Salient features, dimensions, apparatuses,
- ✓ Sketches, drawings, maps, images

2.3 Field Reconnaissance, Data Inventory and Review

2.3.1 Site Condition

- ✓ Site condition, revealed during field trip (not only at dam and reservoir site, but also upstream and downstream areas)

- ✓ Quick assessment of the problems in the spot, observation of flow and sediment features and conditions (quick sampling, pictures, depth measurement using portable sounding if possible)
- ✓ See some examples of case studies under DRIP (Chapter 6, section 6.3 of the Handbook)

2.3.2 Hydrology

- ✓ Catchment condition (land use), rainfall, snowfall
- ✓ Graphs, charts

2.3.3 Hydraulics

- ✓ Discharges (inflow hydrographs), water levels at inflow point and near the dam, dam (gate) operation rules, other inflow (tailrace of upstream reservoirs) and outflows (power, irrigation, water supply, environmental flows)
- ✓ Graphs, charts

2.3.4 Sediment Characteristics, Erosion and Transport

Catchment Erosion

- ✓ Catchment condition, surface erosion, mass failure, gully erosion, landslides
- ✓ sediment yield
- ✓ If data and information are not available, mention the reason and problems,
- ✓ Make necessary recommendations

Sediment Characteristics

- ✓ Grain-size distribution and analysis (what kind of data is available - surface layer, core sampling)
- ✓ Spatial distribution of sediment in the reservoir (longitudinal variation, variation in some specific locations)

Sediment Transport

- ✓ Characteristic mode of sediment transport (suspended load, bedload)
- ✓ Sediment transport data and estimates (in reservoirs and upstream reaches)
- ✓ Dominant factor for sediment supply – catchment surface erosion and/or river bed and bank erosion, mass wasting and landslides

2.3.5 Reservoir Morphology

- ✓ Bathymetry measurement data if available (past measurement and analysis)
- ✓ Morphological pattern of the reservoir
- ✓ Image analysis (maybe satellite/radar images can give some ideas, pictures of dry areas or while reservoir was empty etc.)
- ✓ Make use of *Handbook*

Example of bed topography of the Kundah forebay, measured in 2014

2.3.6 Sediment Management Measures

- ✓ Data and information about past sediment management activities
- ✓ Catchment treatment, sediment handling in river(s) and reservoir(s) etc.
- ✓ Outcomes, problems (success, failures)

2.3.7 Physical and Mathematical Modelling

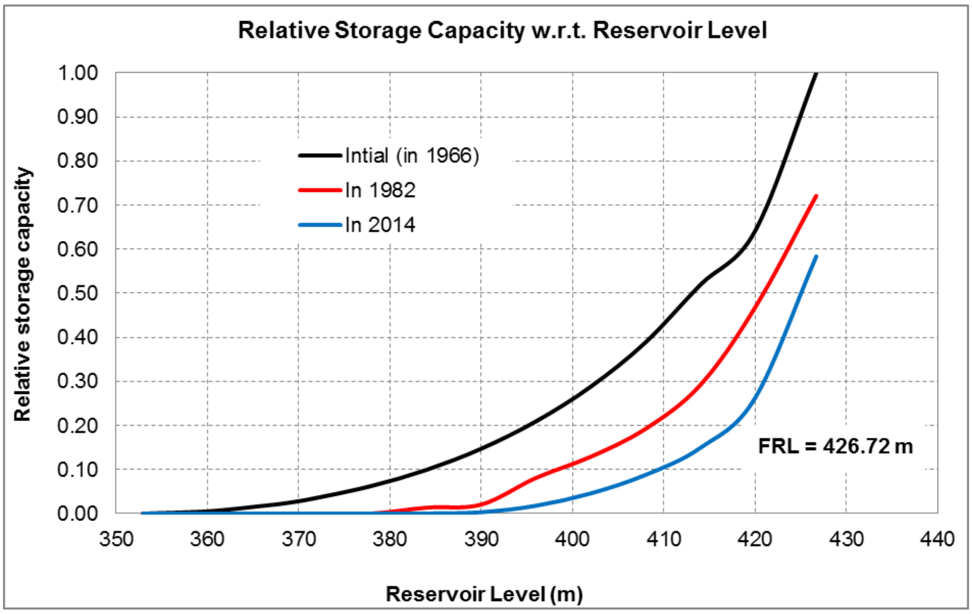
- ✓ Include information and results about physical and mathematical modelling that were carried out in the past.

Note: Fill up the reservoir information data sheet and checklist (see **Appendix C** in the Handbook for the template)

2.4 Problem Identification and Rapid Analysis

2.4.1 Reservoir Feature and Storage Loss

- ✓ Amount of storage loss (capacity curve)
- ✓ Calculate sedimentation rate, trap efficiency, reservoir life etc.
- ✓ Morphological analysis based on field reconnaissance, available data and information (see example of Kundah Palam and Pillur in Chapter 6 of the Handbook)
- ✓ Plots (preferably spatial plot of the bathymetry), graphs, charts, pictures



Storage capacity relative to the initial capacity with respect to the reservoir level (for Pillur reservoir)

2.4.2 Other Sediment-Induced Problems

- ✓ Condition of civil structures (abrasion, damages)
- ✓ Condition of outlets, Intakes, gates, turbines (clogging, abrasion, damages)

2.4.3 Constraints and Priorities for Sediment Handling

- ✓ Technical, economic, social and environmental constraints
- ✓ Necessary approvals
- ✓ What are the priorities? How many reservoirs with the problems, their level of urgency and available resources….

2.4.4 Categorization of Problems

- ✓ Categorize the sediment-induced problem (LOW, MEDIUM, LARGE, EXTREME, see Handbook)
- ✓ Last measurement, recommendation for detailed measurements and study based on category of the problems

2.5 Summary

- ✓ Results and findings of the assessment of sediment-related problems.

3 Rapid Screening of Sediment Management Options

- ✓ Make use of the Handbook (Chapter 4)

3.1 Approach and Techniques

- ✓ Describe about screening process for sediment management options, applicable techniques and approach based on the results of the assessment and available ground condition and resources.
- ✓ Describe about possible option(s) and alternatives based on review of best practices and problems
- ✓ Preferably present in table forms about approach and techniques with their advantages and disadvantages
- ✓ Make use of Handbook (Chapter 4, section 4.1, Chapter 6, Appendix D)

3.2 Sediment Removal Options

- ✓ Describe in more details selected options and alternatives of sediment removal (see Kundah case in Chapter 6, section 6.3 of the Handbook)
- ✓ Make use of Chapter 4 (section 4.2) of the Handbook

3.3 Sediment Disposal/Reuse Options

- ✓ Explore various sediment transport (downstream) and disposal options, weight their advantages and limitations
- ✓ Explore options for beneficial reuse of sediments for various purposed (make use of Chapter 4, section 4.3 of the Handbook)
- ✓ Make use of Chapter 4 of the Handbook

4 Rapid Screening of Impacts and Compliances

4.1 Pre-Feasibility Assessment

- ✓ Economic justification and technical possibilities
- ✓ Quick (expert) judgment for pre-feasibility assessment (technical possibilities as well as social, environmental, economic justification) based on assessments that have been described in previous chapter
- ✓ If capacity and resources allow, it is suggested to do some studies, calculations, numerical modelling
- ✓ Make use of Handbook for the descriptions, methods and tools as most of them are in table form so that it is easy to use and adapt to a specific reservoir (Chapter 5, section 5.1)

4.2 Impact Assessment

- ✓ Assessment of social and environmental impacts of proposed sediment management option(s) and alternative(s)
- ✓ Checking availability of Social and Environmental Impact Assessment reports in general
- ✓ Checking whether the proposed sediment management option(s) and alternative(s) need additional approvals and clearances
- ✓ Make use of Handbook (Chapter 5, section 5.2), particularly fill up the **Checklist** (Appendix C)

4.3 Possible Impacts, Mitigation Options and Conditions

- ✓ Make use of Handbook for the descriptions, methods and tools as most of them are in table form so that it is easy to use and adapt to a specific reservoir (Chapter 5, section 5.3)
- ✓ For monitoring and measurement (also helpful to mitigate or minimizing the impacts), sections 3.4 and 4.6 could be useful.
- ✓ Would be preferable to present in table forms (as shown in the Handbook as well, but here specifically for the reservoir(s) under consideration)

5 Conclusions and Recommendations

- ✓ Conclusions on assessment and management of sediment-induced problems for the reservoir(s) under consideration, the key outcomes,
- ✓ Conclusions on knowledge, information and data gaps, problems, constraints and priorities
- ✓ Conclusions on feasibility and impacts, and any relevant and key aspects (related to technical, social, environmental and economic)
- ✓ Recommendations on how to make a way forward to address the problem and minimize future degradation in case it cannot be resolved
- ✓ Recommendation on what would be necessary to manage the sediment-induced problems, e.g. design and planning of measurement and monitoring systems, human resources requirements, capacity building programs etc.) based on available resources and willingness as well as severity and urgency of the problems.

References

- ✓ List of all reviewed literatures, websites and other sources of information

Appendices

✓ Maps, sketches, design drawings, figures, pictures, data tables, previous reports, notes, memos etc.

Appendix F. Beneficial Reuse of Sediments: Methods, Technology, Practices, Advantages, & Limitations

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Table F-1. Brief summary of national strategy and practice for DM management in the EU and the USA (CIT, 2013)

Country	DM Management Strategy and Practice
The Netherlands	Annual DM production of 25-30 million m^3, with an annual average budget of €130 million, most of which is spent on maintenance dredging at the Port of Rotterdam. • Prioritize dredging activities with largest benefits and quantify economic and social revenues. • Introduction of subsidies for dredging in urban areas and financial incentives for maintenance dredging. • Adaptation of DM legislation to make it more coherent, simple and suitable to achieve policy targets. **Example Case Study Limburg, Zeeland** • Maintenance project in canals with contaminated silty-sand DM • Treatment and beneficial use of 50% of DM by ripening, sand separation and immobilization
Germany	Annual DM production of approximately 46 million m^3, 76% of which is from maintenance dredging in coastal areas. • Established a Working Group on Coastal Dredging (AKN)-to define management practices for maintenance dredging and improve economic efficiency of equipment and machinery. • Large scale contaminated treatment plant (METHA) in Hamburg. • Mechanical separation and dewatering of contaminated dredged material (CDMS). **Example Case Study Bremen Harbour** • Contaminated maintenance DM from the Harbour used for brick production • Containment layer in landfills and the production of Light Weight Aggregates (LWA).
Norway	Less than 100,000 m^3 is dredged annually but there are considerable issues with contaminated sediments. • Norwegian Pollution Control Authority (SFT) established to monitor and evaluate CDMS. • Policy to advance through pilot projects, research, monitoring and establishment of a national council to address sediment issues. • Impose obligation on polluters to conduct the necessary clean-up required **Example Case Study Sandefjord Seaport/bay** • Dewater CDMS using Geotubes deposited locally on seabed to act as a barrier • This is covered over with geotextile and clean sand.
Belgium	The main region for dredging activities is Flanders – annual DM production of 6.3 million m^3. • Introduction of TRIADE approach to DM classification; 4 pollution

Country	DM Management Strategy and Practice
	classes ranging from no pollution (class 1) to severe pollution (class 4). • Spreading of DM on rivers, canals and waterways to enhance navigable areas. • Flemish waste regulations (VLAREA) allow classification of suitable DM (after analysis) as "secondary raw material"; it is no longer considered a waste allowing for easier beneficial use application of DM. **Example Case Study** • 2.5 million m^3 of dry contaminated DM spread over 13 treatment facilities where it is dewatered and treated biologically to remove contaminants. • The remaining clean sediment (sand and fine aggregates) is certified by Flemish waste agency (OVAM) as either 'soils' or 'building material' for beneficial use.
France	Annual volume of DM production is approximately 56 million m^3; 89% of which comprises of marine sediments generated from the 6 main ports. • Developed the GEODRISK method of DM characterisation; gives geochemistry of DM and identifies potential hazards as well. • History of implementing a range of different beneficial uses for DM including: land improvement, agricultural fill material, beach nourishment, coastal erosion control, construction material and topsoil. **Example Case Study Charentes** • Maintenance DM used as beach nourishment to improve coastal regime and enhance recreational opportunities.
Italy	Approximate annual national dredging requirement of 6 million m^3. • National policy of viewing DM as a 'resource' instead of a 'waste' • National Program of remediation and environmental recovery of contaminated DM. • Testing of treatment technologies for contaminated sediments in order to identify environmentally sustainable management options. **Example Case Study** • Confined Disposal Facility (CDF) for containment of CDMS in the harbour of La Spezia. • Level of contamination required a 1m thick lining of impermeable material to the sides and bottom of the CDF.
United States	Approximate annual national dredging requirement of 200-300 million m^3 of DM. • Established National and Regional Dredging Teams (USEPA & USACOE's & RDT's) to facilitate communication, coordination, and resolution of national dredging issues. • Extensive and detailed national dredging management programme overseen by the EPA and DMMO (Dredged Material Management Office). • Published "Beneficial Use Planning Manual" which presents a frame-

Country	DM Management Strategy and Practice
	work for identifying, planning, and financing beneficial use projects in the US. • Committed to implementing beneficial uses of DM over the last decade under the "Action Agenda – 2003 to 2013" outlying the issues and principles of good DM Management. **Example Case Study San Francisco Bay** • The LTMS (Long-Term Management Strategy) of the RDT has developed several beneficial use programs for DM and aims to use 40% of all DM beneficially in the long term. • Current beneficial uses include: landfill daily cover, beach nourishment, sand for use by aggregate companies, and construction fill in separately approved upland or aquatic fill projects (for both material that is clean and that is unsuitable for aquatic disposal).

Table F-2. Advantages and disadvantages of dredged material (DM) reuse options (CIT, 2013)

Reuse Options	Advantages/Capabilities	Disadvantages/Limitations
Beach Nourishment	○ Helps to prevent localized flooding and control coastal erosion ○ Facilitates and supports local tourism by maintaining a wider beach area ○ Provides a ‘soft’ engineering approach instead of or in conjunction with traditional ‘hard’ engineering solutions such as construction of sea walls and groynes.	○ Detailed engineering analysis required to accurately assess the local wave climate and beach erosion rates. ○ If dissimilar material (texture, colour etc.) is used from the in-situ natural beach material then the aesthetics of the beach may be negatively impacted.
Land Creation/Reclamation or Land Improvement	○ Reclaimed land can provide an economic incentive for dredging stakeholders where benefits to tourism, ports and industry may be realized. ○ Potential profits to be made from reclaimed/improved land may be substantial ○ It may be less expensive to place the DM in a reclamation area than transport to a disposal site ○ The creation of reclaimed land may be more environmentally acceptable than disposal at sea.	○ Final land use of the reclaimed land may be restricted depending on the type of DM used. ○ Reclamation may not be possible where water depths are excessive. ○ Consolidation and drainage is slow, and the final strength achieved may be low. ○ Potential land ownership issues must be resolved ○ May require extensive environmental impact analysis
Landfill Cover	○ Potentially improves the aesthetics of the area upon completion of landfill cover ○ Creation of potential amenity and/or recreation area for local community. ○ Potential environmental benefits through the regeneration of plant life ○ Potential increase in surrounding land values	○ Contamination levels must be at a level suitable for the materials intended use. ○ Dewatering is typically required, desalination of DM may be required to stimulate plant growth

Reuse Options	Advantages/Capabilities	Disadvantages/Limitations
Offshore Berm Creation	o Established international technology (e.g. applied in Taiwan, USA, and Japan). o Recovery site and application may be close reducing DM transport costs. o Can provide an environmentally acceptable "soft-engineering" solution to coastal protection. o May be created by simple discharge of DM from hoppers	o For berms designed to be stable they may yet be prone to erode with the erosion rate dependent on the local wave climate. o May not be suitable for locations where conflict with fisheries, ports, outfalls etc. may arise. o Optimum placement area must be located and be sufficiently shallow to mitigate wave effects.
Coastal Protection Works (including geotubes)	o Versatile technology and relatively simple to implement o May provide an environmentally beneficial and economically viable alternative for elements of traditional rubble mound structures o Use of geotubes can retain and isolate some forms of contaminants	o Risk of tearing / distortion of geotubes with potential to lead to instability and undermining of coastal structure o Generally available in specific sizes which may not necessarily suit a particular application. Custom sizing may be expensive. o Hydraulic equipment is required for geotubes
Wetland Habitat Creation/ Enhancement	o Environmental benefit with preservation of endangered ecosystems/habitats o Restoration of wetland area can alleviate problems associated with flooding, erosion and reduced fish populations.	o Substantial physical, chemical and biological testing is required to determine feasibility o Assigning an economic value of beneficially using DM for wetland restoration is difficult and often subjective
Sediment Cell Maintenance	o Contributes to maintaining the natural sediment regime of an estuarine system which may be affected by dredging activities. o Relatively easy to implement with environmental benefits. o Subtidal and intertidal habitats can be enhanced for benthic macro-fauna.	o Extensive DM characterization and monitoring of the local ecosystem must be undertaken to ensure no negative impacts. o Likely to require advanced computer modelling and specialist involvement at the design stage.
Fill for Abandoned Mines/Quarries	o May be suitable for contaminated DM without a requirement for pre-treatment o May contribute to providing a solution to minimizing the potential environmental threat posed by abandoned mines/ quarries. o May be combined with other 'waste' products such as coal ash to provide a beneficial end use.	o Depending on the specific site; it may be seen as an alternate disposal route for DM as opposed to a beneficial use.

Reuse Options	Advantages/Capabilities	Disadvantages/Limitations
Concrete Manufacture	○ May provide an alternative to quarry sourced aggregate in concrete manufacture, potentially reducing construction costs ○ Dredged sediment is suitable for use in several types of concrete such as light weight and self-consolidating concrete. ○ May potentially provide a beneficial use for contaminated DM without requiring expensive pre-treatment.	○ The quantity of aggregate that can be replaced is dependent on the characteristics of the DM. ○ Results for the fined grained component of DM only based to date on results of research work.
Road Sub-base Construction	○ Offers a range of potential uses in road construction ○ Contaminated DM may be used in the road sub-base construction. ○ May contribute to providing a sustainable alternative to quarry sourced natural sand/aggregate.	○ Fine grained DM requires the addition of a stabiliser, such as lime or cement, to obtain the required mechanical characteristics for the sub-base layer. ○ Use of fine grained DM as a substitute still at experimental stage with pilot road construction in France an example of application
Landfill Liner	○ Can provide a less complex and less expensive alternative to bentonite-enriched soil (BES) or compacted clay liners (CCL). ○ Placing, testing and evaluating the DM will be similar to traditional liner materials, thus existing machinery and testing apparatus are appropriate for DM	○ Possible stabilisation and grading of DM may be required depending on physical characteristics. ○ Ideally only suitable for DM sourced from consolidated clay ○ To date reliance on research pilot-type schemes
Manufactured Topsoil	○ May provide a potential income stream for ports/harbours that produce significant quantities of maintenance DM on a regular basis. ○ Significant research has been undertaken with several projects completed in the U.S. and the U.K. ○ May contribute to reduced organic municipal waste disposal costs as it is used with DM in the manufacture of topsoil ○ Both hydraulic and mechanical dredging can be used	○ Relies on a market demand for the product near to the point of source ○ Stringent requirements apply to the characteristics of the DM ○ A reliable and consistent supply of suitable organic material is required

Reuse Options	Advantages/Capabilities	Disadvantages/Limitations
Production of Bricks/Ceramics	○ Contaminated DM may be used with contaminants becoming neutralized in the manufacturing process. ○ Selling the DM as a raw material for the brick/ceramic manufacturing industry may provide an income stream.	○ Consistency of the DM characteristics required for successful brick manufacture. ○ To date only small to medium scale pilot schemes have been undertaken in France and Germany.

Table F-3. Alternative options for the beneficial use of DM (CIT, 2013)

Options	Remarks	Countries of Application
Earthen Dams	Dewatered DM may be used for construction of either earthen or earth-filled dams.	USA, The Netherlands
Fertilizer	Suitable DM with appropriate quantities of nutrients may be used as a land based fertiliser; either on its own or combined with a traditional fertilizer.	USA
Forestry	Several studies have concluded that DM can be spread on afforested land to aid in the growth of certain species of trees (poplar, spruce and willow). Afforestation of polluted DM landfills may also provide environmental benefits such as soil stabilization and visual buffering combined with possible treatment of contaminants destroyed through the growth process of the trees/plants.	USA, Belgium
Aquaculture	Projects in the US have shown that marine disposal sites for DM can be structured to suit certain fish habitats providing new locations for aquaculture.	USA, U.K.
Construction of Tidal Flats/ Shallows	Construction of tidal flats/shallows combined with 'sand capping' for environmental restoration using DM with potential benefits to the local benthic ecosystem.	USA, Japan
Offshore Mounds	Construction of offshore mounds formed from DM may provide refuge for different fish species.	USA
Decorative Landscaping Product	DM can be blended with recycled residual materials such as glass, gypsum, plastic bottles etc. to manufacture decorative garden ornaments including statues, water fountains and artificial rocks.	USA
Capping	This involves the placement of clean DM in open water over deposited contaminated material to form a wave and current resistant layer of material. This may allow the formation of suitable aquatic habitats. Capping may also be used in upland locations to isolate contaminated material.	Belgium, Germany, USA
Filler for Polymer Composites	Polymers, tyres, plaster and mortar may benefit from the addition of clay/sand filler from DM. Traditional inorganic fillers modify properties such as permeability, corrosion and durability; DM may potentially provide an alternative, organic filler additive.	USA

Table F-4. Treatment options for dredged materials (DM), practiced in Ireland (CIT, 2013)

Treatment Methods & Remarks		Applicability									
		For Common Contaminants				For Sediment Type					
		Heavy metals	PAH[1]	TBT[2]	PCB[3]	Saltwater	Soft Clay	Silt - Soft Clay	Sand - Silt	Consolidated Clay	Gravel – Sand Mix
Soil Washing	Contaminated sediment is separated from the reusable DM. The left-over CDMS[4] is stabilized as a filter-cake ready for further treatment/disposal.	√	√	√	√	√	×	√	√	×	√
Mechanical Dewatering	Filter presses are used to reduce the water content of DM by up to 80%, removing suspended/soluble contaminants. Filter-cake is produced. Commonly used as a pre-treatment for other treatment methods.	√	√	√	√	√	√	×	√	√	×
Geotextile Tube Dewatering	Tubes are fabricated from synthetic geotextile that 'sieves' the DM, reducing contaminant concentrations and allowing the treated water to filter out, whilst retaining and consolidating the solid matter of the DM.	√	×	√	×	√	√	√	√	×	×
Thermal Desorption	Hazardous organic compounds, and some volatile metals, are heated and converted into gases/liquids which are collected for safe disposal.	+	√	+	√	×	√	√	√	×	√
Landfarming or Ripenning	DM is spread over land and undergoes natural aerobic degradation removing organic contaminants. Heavy metals may also be removed using additional treatments (see 11 & 12).	×	√	×	√	√	√	√	√	×	×
Bio-reactors	Varying sizes of vessels are used to contain the DM whilst it undergoes various microbiological processes to degrade organic contaminants. % degraded depends on the length of treatment time.	×	√	+	√	√	√	√	√	√	√

Treatment Methods & Remarks		Applicability									
		For Common Contaminants				For Sediment Type					
		Heavy metals	PAH[1]	TBT[2]	PCB[3]	Saltwater	Soft Clay	Silt - Soft Clay	Sand - Silt	Consolidated Clay	Gravel – Sand Mix
Stabilization	Chemical compounds (e.g. cement) are added to the CDMS; stabilizing &/or immobilizing the material for use in construction or to reduce leachability and bio availability on disposal. May require pre-treatment dewatering.	√	+	√	+	√	√	√	√	√	×
Thermal immobilization	Dewatered DM is melted and crystallised. Organic contaminants are destroyed in the process whilst inorganics are accumulated for safe disposal or treatment.	√	√	√	√	√	√	×	√	√	×
Thermal-Chemical Immobilizatio using Cement Kiln	DM is mixed with fuel, air, and modifiers in a cement kiln. Organic contaminants are destroyed and heavy metals are immobilized in the cement matrix. A clinker-material is produced which can form cement.	+	√	√	√	√	×	√	√	×	√
Pyrolysis	Organic contaminants are destroyed in anaerobic conditions. Organic and inorganic compounds are separated in the process. Requires extensive pre-treatment dewatering.	×	√	+	√	√	√	×	√	√	×
Super-Critical Water Oxidation*	New technique currently being researched in Ireland. DM is heated under high pressure causing the water content to enter 'super-critical' stage which destroys all organic contaminants. Inorganics are mineralized into sterile compounds which may have beneficial uses.	√	√	√	√	√	√	√	√	√	√
Dewatering using Wetland Plants*	Studies have concluded that certain species of wetland plants are adept at dewatering and sub-	×	√	×	√	√	√	√	√	×	√

Treatment Methods & Remarks		Applicability									
		For Common Contaminants				For Sediment Type					
		Heavy metals	PAH[1]	TBT[2]	PCB[3]	Saltwater	Soft Clay	Silt - Soft Clay	Sand - Silt	Consolidated Clay	Gravel – Sand Mix
	sequently removing contaminants from DM.										
Electro-osmotic De-watering*	A small electric potential is applied across the DM inducing rapid flow of water as a result of physio-chemical and electro-chemical processes. Hydraulic conductivity and shear strength of consolidated DM are also increased.	√	√	√	+	√	√	√	√	√	√
Electro-kinetic Extraction*	Electro-kinetic technology is a technique that employs a low direct current to facilitate the ionic metal transport through porous media (DM).	√	+	√	+	✕	√	√	√	✕	√

***Symbol**:* *√ Suitable* *+ Partially suitable* *✕ Unsuitable*

* Treatment method still undergoing research as to its applicability in practical DM treatment on an industrial scale

[4]CDMS: Contaminated Dredge Material Sediment

Remark: The chemicals that are considered to be the most detrimental to the aquatic environment are those that are persistent, toxic and bio-accumulate in the food chain and include (CIT, 2013):

Heavy metals (e.g. mercury, lead, arsenic, zinc, cadmium)

[1]Polynuclear Aromatic Hydrocarbons (PAHs) (e.g. Oils, diesel, hydraulic fluid)

[2]Tri-Butyl Tin (TBT) (organic compound)

[3]Polychlorinated Biphenyls (PCBs) (e.g. paints, plastics, adhesives)

Table F-5. Applicability of DM for beneficial use based on type and quality (Sheehan, 2012)

Category of Beneficial Use	Type of Beneficial Use	DM Applicability									
		Uncontaminated	Contaminated	Freshwater	Saltwater	Soft Clay	Silt - Soft Clay	Sand - Silt	Consolidated Clay	Gravel - Sand	Rock
Engineering Uses	Beach Nourishment	√	×	√	√	×	×	×	×	√	+
	Land Reclamation	√	+	√	√	√	+	√	√	√	√
	Landfill Cover	√	+	√	√	√	√	√	×	×	×
	Offshore Berm Creation	√	×	√	√	√	√	√	√	√	√
	Coastal Protection Works	√	√	√	√	×	×	√	√	√	√
Environmental Enhancement	Wetland Habitat Creation/ Enhancement	√	×	√	√	+	+	√	√	√	×
	Sediment Cell Maintenance	√	×	√	√	√	×	√	√	+	×
	Fill for Abandoned Mines/Quarries	√	√	√	√	√	+	√	×	×	×
	Upland Habitat Restoration/ Creation	√	×	√	×	+	√	+	√	√	√
Agricultural/ Product Uses	Concrete Manufacture	√	+	√	+	×	√	√	×	√	×
	Road Sub-base Construction	√	√	√	×	×	+	√	√	√	×
	Landfill Liner	√	+	√	√	×	+	×	√	×	×
	Manufactured Topsoil (MS)	√	+	×	√	√	√	√	×	×	×
	Production of Ceramics/Bricks	√	√	√	√	√	×	√	√	×	×

Table F-6. Relevant European Legislation for Beneficial Use Options (CIT, 2013)

Legislation	Engineering Uses					Environmental Enhancement			Agricultural/ Product Uses				
	Beach Nourishment	Land Reclamation	Landfill Cover	Coastal Protection	Offshore Coastal Protection (Berms)	Wetland Habitat	Sediment Cell Maintenance	Mine/Query Fill Material	Landfill Liner	Manufactured Top Soil	Concrete Manufacture	Brick Production	Road Sub-Base
Foreshore Act	√	√		√	√	√	√						
Planning Permission	√	√		√	√	√	√						
Waste Management Act		√	√			√		√	√	√	√	√	√
Article 5 & 6 EU Directive 2008/98/EC on Waste Management			√					√	√	√	√	√	√
Waste Management Collection Permit Regulations		√	√					√	√	√	√	√	√
Landfill of Waste			√						√				
Directive on Environmental Quality Standards	√	√		√	√	√	√						
Fisheries Act	√	√		√	√	√	√						
Water Framework Directive	√	√		√	√	√	√						
Marine Strategy Framework Directive	√	√		√	√	√	√						
EC Quality of Shellfish Waters Regulations 2006	√	√		√	√	√	√						
Birds and Natural Habitats Regulations 2011	√	√		√	√	√	√	√					

Legislation	Engineering Uses					Environmental Enhancement			Agricultural/ Product Uses				
	Beach Nourishment	Land Reclamation	Landfill Cover	Coastal Protection	Offshore Coastal Protection (Berms)	Wetland Habitat	Sediment Cell Maintenance	Mine/Query Fill Material	Landfill Liner	Manufactured Top Soil	Concrete Manufacture	Brick Production	Road Sub-Base
Bathing Water Directive[1]	√												
Quality of Salmonid Water Regulations 1988[2]													
EC Environmental Objectives (Surface Water) Regulations 2009[3]													

[1]Specific Beneficial Use Projects may impact on the Quality of Bathing Waters

[2]Specific Beneficial Use Projects may impact on migrating Salmonid populations

[3]Specific Beneficial Use Projects may impact on Surface Waters

Remark: Legislation Decision Tree for each type of beneficial use options is given in ICT (2013).

Table F-7. Summary of some relevant DM legislation and regulations for some selected EU states (CIT, 2013)

Country	Summary of DM Legislation/Regulation
UK	• Main National Agency dealing with DM disposal and re-use is the Centre for Environment, Fisheries and Aquaculture Science (CEFAS) • Regulatory agency is the Marine Management Organisation (MMO) • Separate license required for sampling of seabed in addition to any dredging licensing granted • Main legislative instrument governing DM re-use is the Environmental Permitting Regulations (2010) but does not provide specific guidance on DM • The Contaminated Land: Applications in Real Environments (CL:AIRE) code of practice (2008) outlines regulations for re-use of suitable DM on land • CIRIA currently developing guidance document on the re-use and disposal of dredged material to land with a focus on legislation and regulation governing DM
The Netherlands	• National guidelines in place outlining the different pathways for handling DM based on National policy and strategy for DM. • DM still generally regarded as a 'waste material', however, certain categories of DM are exempt from waste regulations. • Dutch Building Materials Decree has been adapted for several parameters leading to simplified application of suitable DM in construction etc. • Prioritization of the EU Water Framework Directive; DM is incorporated in the water legislation
Germany	• No specific National documentation on DM disposal options • DM regulated by various laws for water, waterways, soil and waste • Directive for Dredged Material Management in Federal Coastal Waterways (HABAK); incorporates majority of coastal DM – gives guidance on testing, evaluation and disposal of DM
Norway	• Government report released in 2002 entitled "Protecting riches of the sea" outlined strategic plans to protect and improve the marine environment. • No specific guidance on DM/sediment management. • Dependent on guidelines established in OSPAR Convention (1992).
Belgium	• Waste legislation and strategies can vary in each designated region; Brussels, Walloon or Flanders. • Flemish legislation for waste prevention and management (VLAREA) established concise set of guidelines/rules for beneficial use of DM; periodically updated since 2004 • DM still considered a waste in the first instance; after analysis it may be categorized as "secondary raw material" and is no longer considered a waste. • Established public waste products organization (OVAM) which controls the entire process of applying for DM to be used beneficially as a construction material

Country	Summary of DM Legislation/Regulation
France	• Still heavily dependent on the International regulations established in the OSPAR Convention (1992) for guidance on DM management • No specific national legislation directly related to DM • Various Decrees in French law encompassing DM as a waste for disposal • Special measures must be taken to beneficially re-use DM in accordance with current French Law
Italy	• Legislative Decree 152/99 states that disposal of DM may only be approved once alternatives for beneficial use cannot be implemented • Contaminated DM addressed under national laws and Ministerial Decrees. • Ministry of the Environment established national research organization to define DM characterization (ICRAM)

Table F-8. Common methods and practice of sand mining in some states and union territories of India (Sustainable Sand Mining Guidelines, Ministry of Environment, Forest and Climate Change, (2016); ***www.moef.in*****)**

State/UT	Summary of DM Legislation/Regulation
Andaman & Nicobar	• The Apex Court in its order dated 7.5.2002 in I.A. No. 502 in WP (C) No. 202 of 1995, had directed that extraction of sand be phased out @ minimum 20% per year on reducing balance basis to bring the sand mining to a level of 33% of the present level of mining within a maximum period of five years. • Since the level of extraction of sand in the territory in the year 2001-02 i.e. the base year, was 68909 cubic meter, the quantity of extractable sand is fixed at 22581 cubic meter. • The quantity of sea sand so allowed by MoEF is extracted from the identified and approved sites having such deposits on the sea beaches (identified accreting area) with adequate environmental safeguards so as to prevent any damage to the sensitive coastal eco-system including corals, turtle/ bird nesting sites and the protected areas. • The allotment of sea sand is made to the individuals by the Sand Allotment Committee constituted by the Lieutenant Governor under the Chairmanship of Chief Secretary who also heads the A&N CZMA. The quantum of sea sand allotted is fixed by the Committee on the basis of availability of sea sand and the number of applicants (local) applied for their bonafide use.
Arunanchal Pradesh	• Mining of sand restricted to foothills only that too for a very short period. • Grant of mining lease is kept in abeyance, short-term mining permits are issued to various Central and State agencies for carrying out developmental works under the strict supervision of the departmental officers.
Himanchal Pradesh	• Manual. The mining lease areas are sanctioned on the river bed if the area is approved in survey document. The mining activities are allowed strictly in accordance with the approved working cum Environment Management Plan and after the environment clearance.
Jharkhand	• Manual
Karnataka	• Manual
Madhya Pradesh	• Manual
Meghalya	• Hill quarrying in private areas
Mizoram	• Extraction of sand limited mainly for domestic purpose in the state. • The produce extracted illegally is seized as per the Mizoram Forest Act, 1955. • Mining is only limited to river banks and riverbeds with improvised equipment like spade, shovel, small canoes, etc.
Puducherry	• Manual
Rajasthan	• Sand is available in seasonal streams and rivers except Chambal, which is perennial but mining is banned because of Chambal

State/UT	Summary of DM Legislation/Regulation
	Crocodile Sanctuary. • Mining is done up to 3 meters and is open cast. It is filled in trucks either manually or semi mechanized method. In Bikaner no river exists and mining for sand is being done from palaeo-channel. In this palaeo-channel the sand deposit occurs at the depth of 5 meter to 20 meter below ground level with an over burden of 5 to 20 meters. • The mining here is done open cast benching method, where overlying blown sand, gravel, pebble etc. is removed, the sand is further sieved, graded and washed upto 12 to 18 mesh size.
Tamil Nadu	• Manual mining is carried out in certain quarries. • In most of the sand quarries two poclains are used by the PWD.
Uttar Pradesh	• Manual and semi-mechanized

Remarks:

- States/UTs, which are not mentioned, have not provided the data.
- Please check the Table -6 in Appendix of this handbook (*www.moef.in*) that includes suggestions and recommendations from the states for environmentally sustainable sand mining. Also, other information are useful to consider.
- Please note that this handbook are mostly focused on mining activities other than reservoir dredging (although there is a section on "Desilting of Reservoirs/Barrages/Annecuts/Lakes/Canals).

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Central Dam Safety Organisation
Central Water Commission

Vision

To remain as a premier organisation with best technical and managerial expertise for providing advisory services on matters relating to dam safety.

Mission

To provide expert services to State Dam Safety Organisations, dam owners, dam operating agencies and others concerned for ensuring safe functioning of dams with a view to protect human life, property and the environment.

Values

Integrity: Act with integrity and honesty in all our actions and practices.

Commitment: Ensure good working conditions for employees and encourage professional excellence.

Transparency: Ensure clear, accurate and complete information in communications with stakeholders and take all decisions openly based on reliable information.

Quality of service: Provide state-of-the-art technical and managerial services within agreed time frame.

Striving towards excellence: Promote continual improvement as an integral part of our working and strive towards excellence in all our endeavours.

Quality Policy

We provide technical and managerial assistance to dam owners and State Dam Safety Organisations for proper surveillance, inspection, operation and maintenance of all dams and appurtenant works in India to ensure safe functioning of dams and protecting human life, property and the environment.

We develop and nurture competent manpower and equip ourselves with state of the art technical infrastructure to provide expert services to all stakeholders.

We continually improve our systems, processes and services to ensure satisfaction of our customers.

DRIP
Dam Rehabilitation & Improvement Project