DRAFT

Deltares

TIPPING POINT RESOURCES GROUP

Management of sediment-induced problems at Tuyamuyun Hydro-Complex

A desk study

Funded by the European Union

nexus

carec

CAWEP CENTRAL ASIA WATER & ENERGY PROGRAM

THE WORLD BANK IBRD • IDA | WORLD BANK GROUP

EUROPEAN UNION

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

Swiss Confederation

Federal Department of Economic Affairs FDEA
State Secretariat for Economic Affairs SECO

UKaid from the British people

July, 2022

Disclaimer

This work was produced under the European Union funded project "Central Asia Nexus Dialogue Project: Fostering Water, Energy and Food Security Nexus and Multi-Sector Investment (Phase II)" implemented by the Regional Environmental Center for Central Asia (CAREC) and the financial support of the project "Laboratory of Innovative Solutions for the Water Sector of Central Asia" under the Central Asia Water and Energy Program (CAWEP).

Its content of this work is the sole responsibility of authors and do not necessarily reflect the views of the European Union, CAWEP and CAREC.

Authors:

Sanjay Giri
Eric Stern

Summary

Within the scope of this assignment, we first have carried out a comprehensive review of the previous studies and data available as well as a rapid analysis of the sediment-induced problems at the Tuyamuyun Hydro Complex (THC). The review of the current state of the THC watershed system has revealed that the sediment-induced problems at the Channel (Ruslovoe) reservoir of the THC are rather severe and need to start being addressed. This has been in the making for the last 40 years. The sedimentation of the reservoir has resulted in not only storage loss but also has increased the risk for the safety of the populace and the in-water dam structures. A large layer of sediment deposition near the hydropower and irrigation intakes and spillways has resulted in the malfunctioning of the hydropower and irrigation structures and facilities as well as in increasing risks of flood and sediment hazards.There is also a significant storage loss leading to a water stress induced situation affecting the livelihood of more than 5 million people being benefited from the THC in the region (in Uzbekistan and Turkmenistan). Hence, by inaction, this resource can ultimately be lost.

We have categorized the problems as per their impacts and the urgency to address them. Accordingly, the measures have been characterized in two categories based on their types and scale. The 1st-category problem is related to the large deposition near the headworks (intakes and spillways) adversely affecting the functionality and safety of the structures (e.g., hydropower and canal operation) as well as the safe flood passage. Consequently, the problems must be addressed urgently. Particularly for addressing this problem, we have proposed a technical concept and framework that details a comprehensive sediment management program with the beneficial reuse of sediments. The concept includes four main components: (1) sediment removal in the Channel reservoir and canals (i.e. major operation & maintenance measures) in conjunction with sluicing and flushing (i.e.; supplementary measures); (2) erosion and sediment inflow management in the Tuyamuyun catchment, the river, tributaries, and the Channel reservoir (i.e. mitigation measures); (3) a commercial pilot campaign for potential options of beneficial reuse of removed sediment (i.e.,. the scoping and prefeasibility assessment); and (4) establishment of monitoring, information, forecasting and early warning systems for water (quantity and quality), sediment (quality, quantity and reuse) and reservoir morphology (i.e. non-structural adaptive measures). These first-tier measures do not require a very large financial investment (compared to the losses that the THC has been suffering from for last few years). Additionally, within this category, we have proposed toassess a storage recovery measure that includes a technical assessment of the possibility to increase the maximum reservoir operation level by 1.5 - 2 m (i.e., from the current level of 130 m to the level of 131.5-132 m). Most likely that this will require certain soft structural measures to strengthen and enhance some part of the critical structures (i.e, embankments, spillways). Moreover, this measure should only be adapted in conjunction with the proper sediment management program.

The 2nd-category challenge is related to the storage loss of the Channel reservoir itself (almost 1.5 billion m^3) due to significant sedimentation. Addressing this problem requires large-scale storage recovery efforts or alternative structural solutions. We have proposed several options to consider for their feasibility assessment, viz. (i) capital dredging in the Channel reservoir with beneficial reuse of sediment (Option 1); (ii) construction and/or extension of the off-channel reservoir(s) (Option 2); and (iii) renovation/reconstruction of the structures (e.g., dam heightening, replacement) (Option 3). All these options require a large amount of technical, engineering, and financial resources. Moreover, a comprehensive and careful feasibility and impact assessment should be carried out before the selection of any of these measures.

Deltares

It should be noted that the implementation of the measures to address the 1st-category problems will eventually be useful to assess the feasibility of the large-scale measures to address the 2nd-category problems, thereby to help facilitate proper decisions that can sustain an environmental management program.

In regard to the beneficial reuse of removed sediments from the Channel reservoir, we have proposed some potential options for the THC for further consideration, viz. (i) manufactured topsoil production and/or improvement and fertilizer production for agriculture and afforestation; (ii) creation and restoration of ecological zones that support livelihood functions;
(iii) establishment of commercial industries for producing building materials, landscape design, engineered fill (structural and non-structural) and environmental applications; and (iv)river and reservoir training structures (bank protection, berms, sand plugs, earthen dams, etc.) for flow and sediment management. We have suggested to carry out a commercial pilot campaign (as a part of comprehensive sediment management program) to assess the technical feasibility for their real-world application. This should also include market drivers and cost-benefit analysis as well as the detailed impact and risk assessment (social, economic, and environmental).

One of the important components related to addressing both 1st- and 2nd-category problems is the non-structural adaptive measures. These measures are associated with the regular and systematic monitoring in the catchment and the reach scales (contributing to the THC). The monitoring and measurement should include various processes and parameters in various spatial (from catchment to river, tributaries and reservoir reaches) and temporal resolution and frequency. However, only monitoring and collection of data will not add much value if they are not properly managed, stored, analysed, and utilized for the purpose of further improvement and adaptation of the measures including sustainable management of the THC. Moreover, the data should be used to establish an information, forecasting and early warning systems in conjunction with some prediction methods (e.g., empirical, data-driven) and/or physics-based computational models. These systems can be used not only for the dissemination of the information but also for decision-making processes during critical and extreme situations.

In this report, we have also provided several examples of global practices and references that could be useful while selecting and designing the measures for the THC. However, there is no one generic method and technique. Thus, the proposed solution(s) and measure(s) should be designed specifically as per the local/ regional situations at the THC based on a comprehensive investigation on social, technical, environmental, engineering, and economic feasibility and impacts. This is most important since there will be a significant volume of sediments over the long-term (10-15 years) that will need to be removed and a long-term sediment management program put in place to keep the THC at steady state over time to come. All the selected measures and interventions should be properly studied for their adverse impacts that may lead to water- or sediment-induced hazards and risks affecting not only the THC but also downstream reaches, infrastructure, ecosystem, and habitants.
Furthermore, it is important to reveal and explore properly the constraints and challenges for an optimal selection of the measure (or a combination of the measures). It should be emphasized that the benefits and feasibility of the 1st-category measures are obvious as they are urgent and inevitable. The important aspect is to assess the impacts and safety issues during the assessment, planning, design, and execution of the measures. Regarding the 2nd-category problems and the measures, at first, there should be a high-level scoping study based on a preliminary exploration and discussions with the stakeholders on the possibilities to acquire financial and technical resources. All potential 2nd-category measures require a comprehensive feasibility and impact assessment in case they are considered after the scoping study. The feasibility and impact assessment are beyond the scope of this study.

Nevertheless, we have briefly outlined the impacts and prefeasibility of all the proposed measures in a generic way that can be applied and specific to the THC complex with follow-up assessments. We have also attempted to complement the proposed measures with the Nexus approach and reservoir sustainability that eventually contributing to the Sustainable Development Goals (SDGs).

Contents

	Summary	**4**
1	**Introduction**	**11**
1.1	Background	11
1.2	Objective of the assignment	11
1.3	Tasks and approaches	12
1.3.1	Review task	12
1.3.2	Recommendations for management of sediment-induced problems at THC	12
1.3.3	Development of concept(s) for the potential reuse of sediment at THC	12
1.3.4	Participation in discussions and brainstorming to develop a cost-benefit analysis on technical solutions	12
1.4	Organization of the report	13
2	**Study of information on the operation of the THC and its current state**	**14**
2.1	Introduction	14
2.2	Revisiting the sediment-induced problems at the THC	16
2.2.1	Study area – THC and its functions	16
2.2.1.1	Reservoir complex and headworks	16
2.2.1.2	Agriculture, aquaculture, and drinking water supply	19
2.2.1.3	Flood management	20
2.2.2	Analysis of hydraulic and sediment data	20
2.2.2.1	Data availability and usability	20
2.2.2.2	Flow and sediment yield	21
2.2.2.3	Morphological changes at Channel reservoir	24
2.2.2.4	Sediment composition and beneficial reuse potential	26
2.2.2.5	Reservoir operation	30
2.2.2.6	Water losses	31
2.2.3	Economic loss	31
2.2.4	Data uncertainties and inaccuracies	31
2.3	Characterization of the sediment-induced problems and impacts at the THC	32
2.3.1	1st-category problem: Functionality and safety of the structures at headworks	32
2.3.2	2nd-category problem: Reservoir storage loss	33
2.4	Concluding remarks	34
3	**Management of sediment-induced problems at THC**	**35**
3.1	Introduction	35
3.2	Screening possible measures for THC	35
3.2.1	Recurrent measures	36
3.2.1.1	Sediment removal and disposal	36
3.2.1.2	Sluicing and flushing of Channel reservoir	37
3.2.1.3	Downstream sediment replenishment	37
3.2.2	Structural (soft and hard) measures	38
3.2.2.1	Raising the full reservoir level (FRL)	38
3.2.2.2	Additional off-channel reservoirs	40

3.2.2.3 Renovation and/or relocation of (hard) structures 41
3.2.3 Non-structural and supplementary measures 42
3.2.3.1 Improving reservoir operation considering sediment management 42
3.2.3.2 Improving technology, practices, monitoring and management 42

3.3 Screening of possible options for beneficial reuse of sediment at THC 43
3.3.1 Manufactured topsoil improvement and fertilizer production for agriculture and afforestation 43
3.3.2 Creation and restoration of ecological zones and livelihood 44
3.3.3 Establishment of industries for producing building/engineering materials 45
3.3.4 River training and guiding structures 45

3.4 Development of preliminary recommendations for the solutions at THC 45
3.4.1 Urgent and essential sediment management and storage recovery program 45
3.4.1.1 Regular maintenance dredging 45
3.4.1.2 Regular flushing and sluicing of the reservoir 46
3.4.1.3 Raising Full Reservoir Level (FRL) above design value 48
3.4.1.4 Pilot cases on beneficial reuse of sediment 48
3.4.1.5 Non-structural measures 50
3.4.2 Large-scale measures and interventions 50
3.4.2.1 Option 1: Capital dredging in Channel reservoir with beneficial reuse of sediment 51
3.4.2.2 Option 2: Construction and/or extension of the off-channel reservoir(s) 51
3.4.2.3 Option 3: Renovation/relocation of structures 52

3.5 Development of a technical concept of sediment management with beneficial reuse at THC 53
3.5.1 Background 53
3.5.2 Technical concept 53
3.5.3 Sediment removal plan and execution 54
3.5.3.1 Maintenance dredging plan and technology 54
3.5.3.2 Sluicing and flushing operation 59
3.5.4 Sediment reuse pilot campaign 60
3.5.4.1 Sediment reuse options 60
3.5.4.2 Transport, disposal, treatment, and processing 60
3.5.4.3 The examples of dredged sediment placement facilities 64
3.5.5 Erosion and sediment inflow management 71
3.5.5.1 Catchment erosion and treatment 71
3.5.5.2 Erosion and sedimentation management in river and reservoir 72
3.5.6 Monitoring, information, forecasting and early warning systems 73

3.6 Concluding remarks 76

4 Feasibilities, impacts, benefits, and constraints 78

4.1 Introduction 78

4.2 Technical, economic, environmental, and social feasibilities and impacts 78
4.2.1 Approach and methods 78
4.2.2 Rapid assessment of proposed measures 79
4.2.3 Possible preventing measures and conditions 81

4.3 Contribution to the principles of Nexus and Sustainable Development Goals (SDGs) 83

4.4 Constraints and challenges 84
4.4.1 Physical constraints and challenges 84
4.4.2 Social and environmental constraints and challenges 85
4.4.3 Economic constraints and challenges 85
4.4.4 Legal and other constraints and challenges 85

4.5 Concluding remarks 85

5 Global practices and examples 87

5.1 Introduction 87

5.2 Management of sediment-induced problems in reservoirs 87
5.2.1 Shihmen reservoir (Taiwan) 89
5.2.2 Sediment management in Sakuma reservoir (Japan) 92
5.2.3 Sediment sluicing and flushing in Chamera-I and Chamera-II (India) 93
5.2.4 Managing water availability problem due to sedimentation at Khashm el-Girba dam (Sudan) 95

5.3 Examples of dam upgrading 98
5.3.1 Dam upgrading in Japan 98
5.3.1.1 General aspects and examples 98
5.3.1.2 Additional outlet facilities at the Tsuruda dam 100
5.3.1.3 Replacement of Oyubari dam 101
5.3.2 Heightening of Zhushou dam (China) 102
5.3.3 Heightening of the Roseires dam (Sudan) 102

5.4 Global practices on processing, treatment, and beneficial reuse of sediment 103
5.4.1 The Kubuqi Ecological Restoration Project (China) 103
5.4.1.1 General overview 103
5.4.1.2 Public-private partnership 105
5.4.2 Reservoir dredging and sediment reuse projects by the Great Lakes Dredge & Dock Company (USA) 105
5.4.2.1 John Redmond Reservoir dredging 106
5.4.2.2 Lake Decatur (Phase 2) dredging 106
5.4.2.3 Pass A'Loutre dredging 107
5.4.2.4 Mosaic dredging 107
5.4.3 Restoration projects in The Netherlands (Ecoshape) 108
5.4.3.1 Nature restoration project Marker Wadden 108
5.4.3.2 Clay ripening pilot 109
5.4.4 New Suez Canal project: An iconic dredging project 111

5.5 Concluding remarks 111

6 Conclusions and recommendations 113

6.1 General conclusions 113

6.2 On managing sediment-induced problems with beneficial reuse of sediment at THC 113

6.3 On sustainable management of THC 115

6.4 On constraints and challenges 115

6.5 Acknowledgement 116

References 117

Appendix 1: Water resources and reservoir sedimentation in Uzbekistan – some facts and figures 129

Appendix 2: Chemical and agrochemical compositions of sediment samples 131

Appendix 3: Summary of national strategy and practices for management of dredged materials in some countries 136

Appendix 4: Applicability of dredged sediments for beneficial use based on type and quality 139

Appendix 5: Treatment options for dredged sediments, practiced in Ireland 141

1 Introduction

1.1 Background

The Tuyamuyun hydrocomplex (THC) was constructed in the lower land reach of the Amu Darya River in 1980. It is a transboundary complex located in the territories of two countries – Uzbekistan and Turkmenistan. The THC is an important asset for their joint multipurpose water utilization (mainly drinking water, irrigation, and hydropower) and management. The THC has four interconnected reservoirs – one in-stream reservoir, referred to as Channel ("Ruslovoe") reservoir and three off-stream/filling reservoirs, namely the Kaparas, the Sultansanjar and the Koshbulak reservoirs. In the THC, there are more than 30 major hydraulic structures – dams, spillways, embankments, intakes and canals. The total design storage capacity is 7.8 km^3 (Olsson et al., 2011).

The THC has been selected as a site for a transboundary technical assistance demonstration project by the Ministry of Water Resources of the Republic of Uzbekistan and the State Committee of Water Resources of Turkmenistan. The objective of this project is to promote regional water and energy cooperation focusing on innovative and technical solutions, particularly for the management of the sediment-induced problems at THC due to very high sedimentation in the Channel (Ruslovoe) reservoir located in the Amu Darya River. The scope of the pilot assignment also includes the exploration of possibilities for beneficial (innovative) beneficial reuse of removed sediment from the reservoir by dredging. This should be an important component to consider while preparing the holistic management/mitigation plan to work through with the problems induced by a large magnitude of the deposited sediment in the reservoir (almost 1.5 billion m^3).

1.2 Objective of the assignment

The main objective of the assignment is to propose implementable and possible technical solutions to the sediment-induced problems at THC. To achieve the objective, it is required to carry out a quantitative assessment of sediment-induced problems at THC due to the large sedimentation in the Channel reservoir including the review of current practices and studies that have been and being carried out. One of the important aspects as a part of the solutions is an investigation of the possibility of beneficial reuse of the removed sediment. The activity also includes a demonstration of documented international practices that could be of relevance for the region in general, and for THC in particular- realizing that every project site differs and comes with it their own environmental, social, economic, and engineering challenges.

There are two main aspects of the assignment: (i) assessment of the sediment-induced problems (quantity and quality), and (ii) management of the sediment-induced challenges considering beneficial reuse of sediment. It is to be emphasized that handling the sediment-induced problem in the in-channel reservoir, particularly with large and long-term morphological changes, is a challenging task. Proper handling of sediment-induced problems requires detailed and careful assessment and analysis considering technical, engineering, economic as well as social and environmental feasibility and impacts. Consequently, this study assesses both structural and non-structural solutions as possible alternatives to particularly large-scale sediment removal plan that may not be efficient owing to social, economic, environmental, and large-scale engineering constraints and impacts in a project of this magnitude.

1.3 Tasks and approaches

1.3.1 Review task

This task is related to the review of the available information and reports associated with the THC. There is already a considerable amount of project documents and materials that helps to carry out a comprehensive assessment and analysis of the current state at the THC, its operation, and other past and ongoing activities. Moreover, there are data and technical reports on reservoir sedimentation (quantification of temporal variation of storage losses for several years) as well as analysis of mechanical and chemical properties of the deposited sediment in the Channel reservoir (Ikramova M., 2021; Shirokova Y.I., 2022). The quality of the data, especially the chemical classification of the sediment, could not be assessed. Also, we did not go into detailed chemical classification of the sediments. These reports also include forecasting methods for reservoir sedimentation as well as preliminary recommendations on technical solutions for reservoir operation and sediment beneficial reuse. Furthermore, we have briefly reviewed and presented several global practices on sediment management and beneficial reuse that could be relevant to start the solution formation discussion for the THC.

1.3.2 Recommendations for management of sediment-induced problems at THC

This task is focused on screening of options and alternatives (recurrent, structural, non-structural) for handling sediment-induced problems at THC due to the significant sedimentation of the Channel reservoir. Based on a thorough review of the problems, analysis of sediment characteristics, quantity, and quality in the Channel reservoir in complement with the discussions with various stakeholders and reservoir authorities, the recommendations for all potentially possible options and alternatives of the measures and solutions are made. The proposed methods and options are also based on the review of the state-of-the-art global experiences and practices.

1.3.3 Development of concept(s) for the potential reuse of sediment at THC

The focus of this task is to develop a set of recommendations with all possible options for beneficial reuse of sediments from the Channel reservoir based on the suitability of the deposited sediment, local situation as well as existing global practices. We develop a site-specific approach and a set of recommendations relevant to the THC based on a comprehensive analysis of the problems in complement with gathered information and findings on international good practices and experience. These recommendations should be used for technical, social, economic, engineering, environmental feasibility and impact assessment.

1.3.4 Participation in discussions and brainstorming to develop a cost-benefit analysis on technical solutions

As per the scope of the assignment, the expert from the Global Nexus Secretariat is required to develop a cost-benefit analysis on proposed technical solution(s). We have closely cooperated with the project stakeholders and have provided our inputs, comments and suggestions as required. Besides, we have an active participation in workshops, knowledge sharing, discussions and brainstorming on various aspects of the project related to sedimentation problems at the Channel reservoir, proposed technical solution(s) including beneficial reuse, their impacts and feasibility of further actions.

1.4 Organization of the report

Chapter 1 of the report is a general introduction. The review and study related to understanding of the system and the problems at THC are included in Chapter 2, in which we have characterized the problems that have to be addressed.

Global practices and examples on managing sediment-induced problems, beneficial reuse of sediment as well as other structural measures related to dam rehabilitation are included in Chapter 3. A rapid screening of possible measures including beneficial reuse of sediment, which could potentially be applicable to THC, to address sediment-induced problems is described in Chapter 4 (i.e. an overview of options is given in chapter 3 going into more detail in chapter 4). It also includes a succinct description of preliminary recommendations on the combination of measures and alternatives for THC. In Chapter 5, we discuss the feasibility, impacts, benefits, and constraints that are associated with the proposed measures and solutions. The Chapter also briefly includes some description about principles of Nexus and Sustainable Development Goals (SDGs), and how the measures at THC can contribute to these goals. Chapter 6 focuses on general conclusions and recommendations. The report also includes appendices with relevant supplementary information.

2 Study of information on the operation of the THC and its current state

2.1 Introduction

Amu Darya is the largest river in Central Asia (Figure 2-1), with a catchment area of 534,739 km^2 (however, this has reduced to 309 km^2 as river flow from Zeravshan and Kashkadarya does not reach Amu Darya anymore) and length of 2,620 km. The drainage of the river lies mainly in four central Asian countries, namely Tajikistan, Uzbekistan, Turkmenistan and Afghanistan. The main tributaries are Pyanj, Vaksh (the Amu Darya starts, when the river Panj flows into the river Vakhsh), Kafirnigan, Sherabad, Surkhan Darya, Kunduz (left tributary). As per some report, the annual volume of the river is about 78,4 km^3 with a storagecapacity of 29.8 billion m^3 (there are different numbers in various sources). The river is significantly regulated (about 80%) by over 35 reservoirs with a capacity over 10 billion m^3 (Dukhovniy et al., 2018). There are two large reservoir systems, namely Nurek and THC. There are other reservoirs and canals (e.g., Karakum, Karshi, Amu-Bukhara) along the main river and tributaries.

Commissioned in 1983, The THC is situated in the downstream reach of the Amu Darya River that divides two central Asian countries – Uzbekistan and Turkmenistan. It is a transboundary hydrocomplex with a vital importance for the surrounding region of both countries. It is a multipurpose hydrocomplex contributing to irrigation, water supply and hydropower that are very important for the livelihood of the 5.3 million people in both countries. The surrounding region is a desert area with mostly bare and sparse vegetation. The land-use and land-cover (LULC) map of the area is depicted in Figure 2-2 that shows theextent of the agricultural lands. The total agricultural production is about 117 billion UZ Sum being around 53% in crop sector and 47% in livestock sector (as recorded in 2018, reported in UzNCID, 2020). It is important to note that there is another large hydrostructure downstream of the Tuyamuyun in Karakalpakstan, namely Takhiatash (Figure 2-3) with the capacity of more than 10500 m^3/s (UzNCID, 2020). Some facts and figures on water resources as well as reservoir sedimentation issues are presented in Appendix 1 as well.

Figure 2-1 Amu Darya and Syr Darya as parts of Aral Sea basin (Source: https://en.wikipedia.org/wiki/File:Aral_Sea_watershed.png)

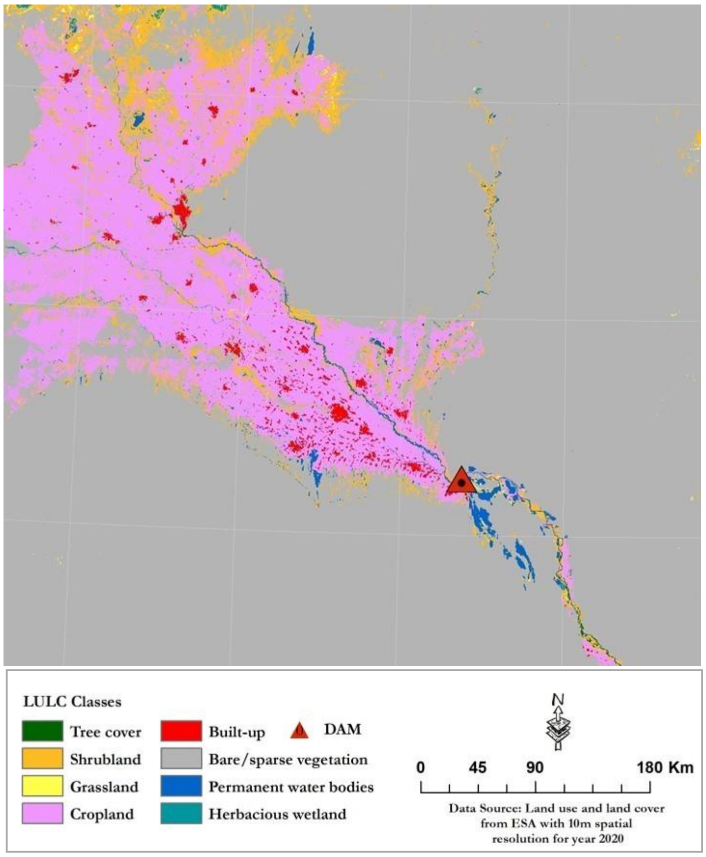


Figure 2-2 Land Use and Land Cover (LULC) map of the area around the THC

Figure 2-3 Takhiatash hydrostructure, located downstream of Tuyamuyun, in Karakalpakstan (UzNCID, 2020)

2.2 Revisiting the sediment-induced problems at the THC

2.2.1 Study area – THC and its functions

2.2.1.1 Reservoir complex and headworks

The hydrocomplex with all in- and off-channel reservoirs and the headworks are shown in Figure 2-4. The Channel reservoir is in the main river Amu Darya. There are three off-channel reservoirs on the left floodplain, located in Turkmenistan (the borderline between two countries passes almost along the middle of the Channel reservoir).

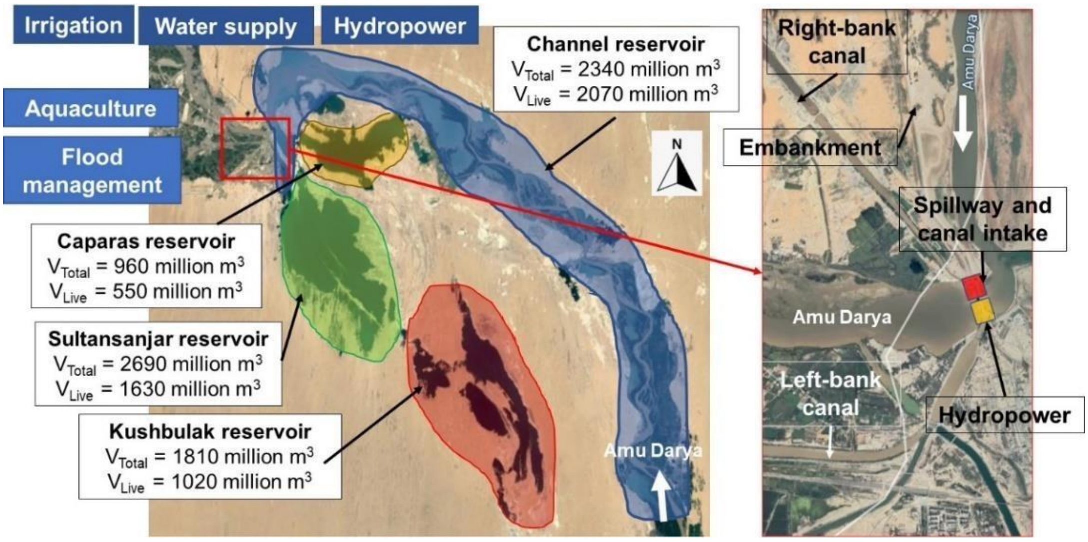


Figure 2-4 The reservoir complex (left) and the headworks (right)

The headworks include the spillway (Figure 2-5), the undersluices (Figure 2-6) and the hydropower plant (Figure 2-7). It also includes intakes of left- and right-bank canals as depicted in Figure 2-8 and Figure 2-9 respectively. The presence of the undersluices implies that the headworks is equipped with a flushing facility. The bottom of the undersluices, hydropower and canal intakes are at the same level, i.e., 110 m. Some salient features are outlined as follows:

- Commissioned year – 1980
- Full (operating) Reservoir Level (FRL) = 130 m (maximum/forced level is 131.5 m)
- Minimum Drawdown Level (MDDL) = 106 m
- Original bottom level near the dam = 110 -112.5 m
- Spillway length/ height = 141 m/ 34 m (Head = 24 m)

- Spillway (with 8 gates) capacity = 920 m^3/s (each gate)
- Spillway crest level = 118m (Figure 2-5)
- Undersluice capacity = 8700 m^3/s
- Sill level of undersluice = 110 m (Figure 2-6)
- Earthen dam height/ length = 34 m /900 m
- Earth dam crest level = 134 m
- Total hydropower capacity = 150 MW (25 MW*6 turbines).

The headworks also includes a lock for the passing of ships (however this is not clear). There are also other structures such as intake structures for the connection with other off-channel reservoirs.

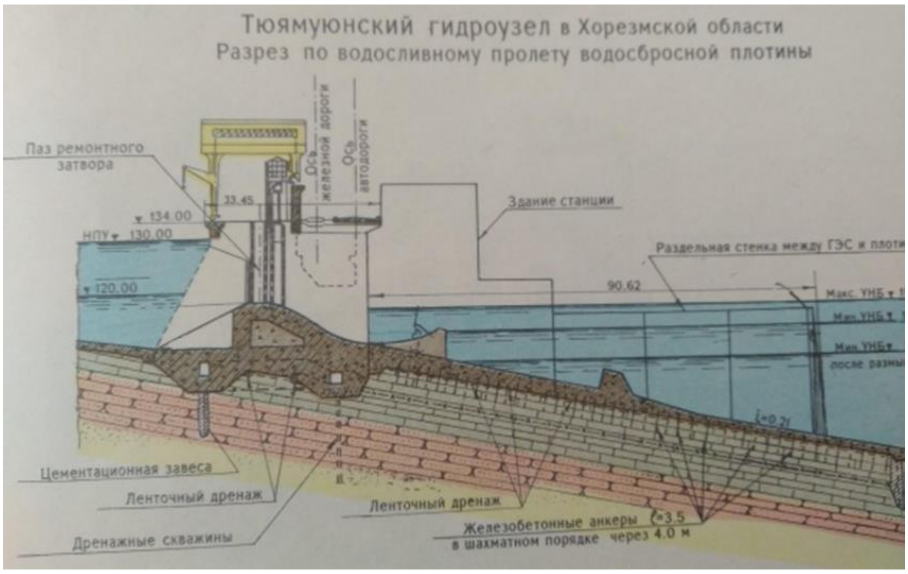


Figure 2-5 A longitudinal section along the spillway

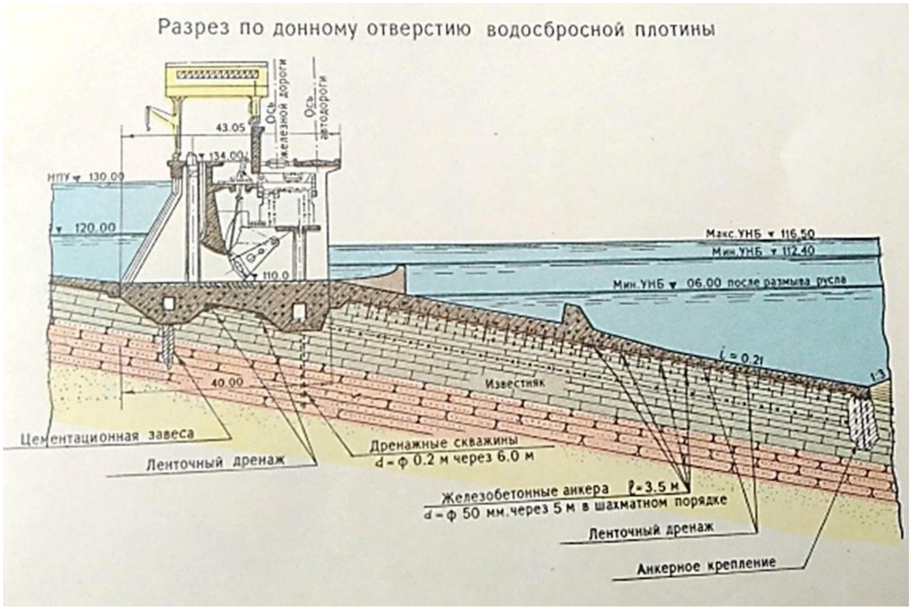


Figure 2-6 A longitudinal section along the undersluices

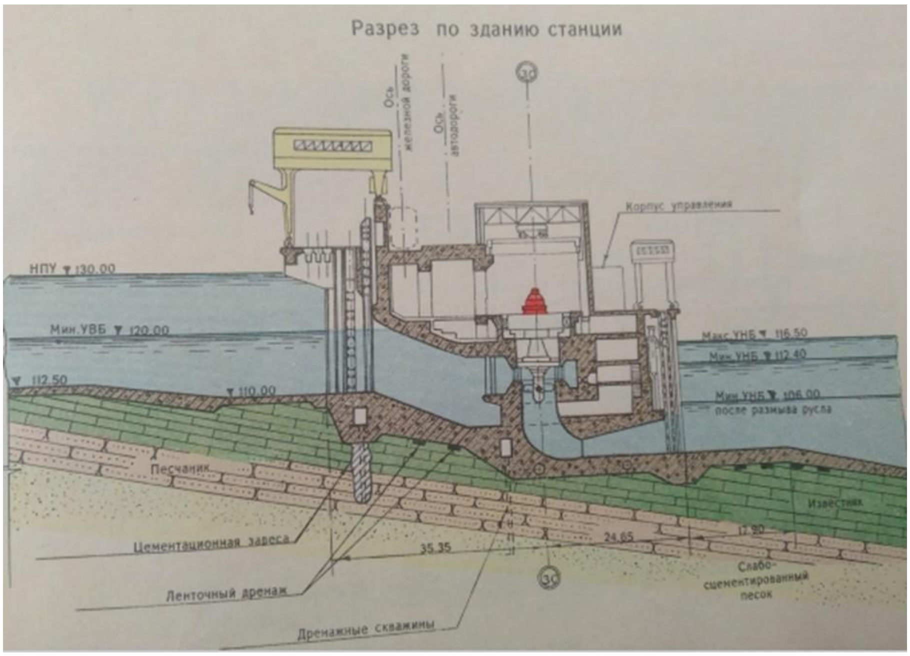


Figure 2-7 A longitudinal profile along the hydropower plant

Figure 2-8 A longitudinal profile along the left-bank canal

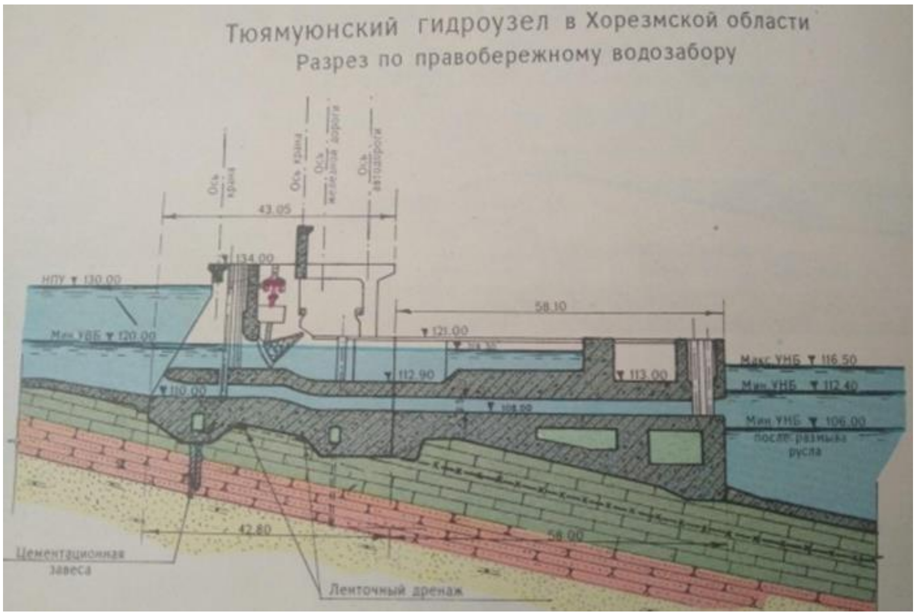


Figure 2-9 A longitudinal profile along the right-bank canal

2.2.1.2 Agriculture, aquaculture, and drinking water supply

Agriculture is a major sector that utilizes a large part of storage water resources in Uzbekistan, e.g., 2018 data shows more than 90% of water withdrawal was used for agriculture (UzNCID, 2020). There are also activities by farmers related to aquaculture in the complex area (supported by the authorities).

THC to Takhiatash hydrostructure along the Amu Darya river is regulated by the THC Authority, including the irrigated area, namely Khorezm region, Beruni and Turtkul DC in Karakalpakstan (Uzbekistan) as well as in Dashoguz (Turkmenistan) as shown in Figure 2-10(the irrigation systems in Turkmenistan and Uzbekistan are depicted in Figure 2-11 and Figure 2-12). The total area, irrigated by THC, are 782,257 and 273,734 hectares in Uzbekistan and Turkmenistan respectively (different sources provide different values). There are collector systems to return the water.

The supply of drinking water is one of the important functions of THC. For the drinking water supply, mostly the storage of Kaparas reservoir is used. It provides the guaranteed water supply of about 0.15 km^3 (as per 2011 record).

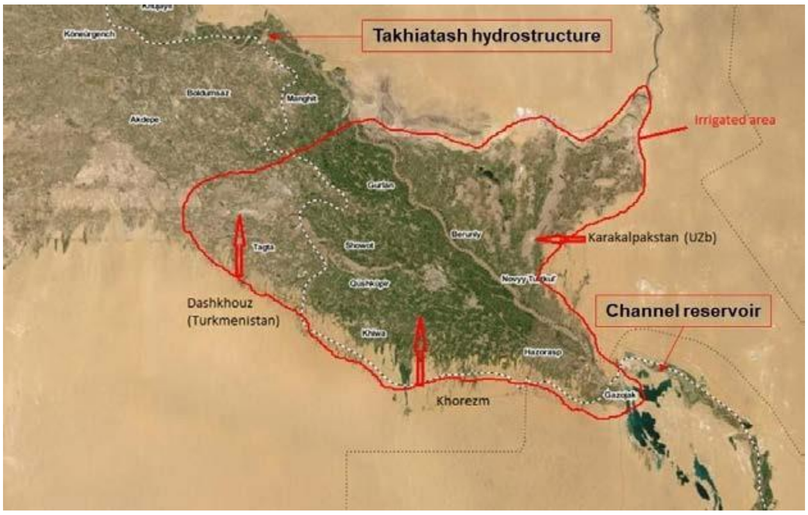


Figure 2-10 The area, irrigated by THC, in Uzbekistan and Turkmenistan

Figure 2-11 The irrigations system in Turkmenistan, covered by the THC

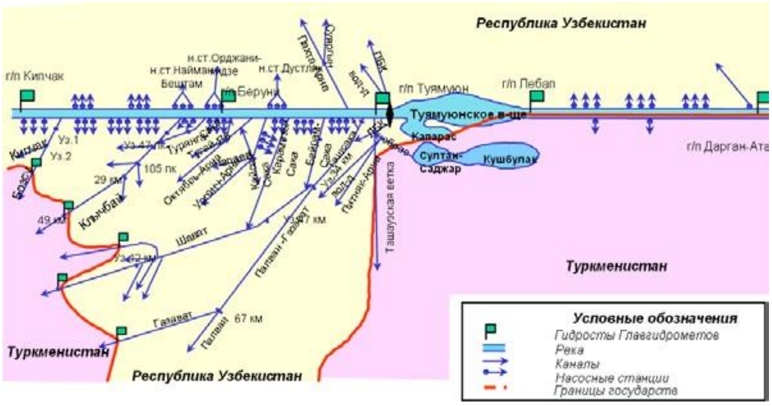


Figure 2-12 The irrigations system in Uzbekistan, covered by the THC

2.2.1.3 Flood management

The Tuyamuyun Hydro Complex controls the flow of the Amu Darya and regulates the seasonal hydrological regime of the river also considering downstream hydrocomplex Tahiatash in Uzbekistan. It is not clear whether flood management is considered well in the reservoir operation regulation. Due to the high-water demand for irrigation, water supply and hydropower, there may be no storage allocation for flood management. Nevertheless, the reservoir must be able to manage the flood discharge under extreme hydrometeorological conditions.

2.2.2 Analysis of hydraulic and sediment data

2.2.2.1 Data availability and usability

A brief outline about data availability and usability is as follows:

- There are a significant amount of reliable data and information related to flow and sediment transport that provides system understanding and processes relevant to the problem of THC and Channel reservoir.in particular.
- There are good measurements and analysis of sediment-induced problems and morphological changes, particularly related to storage loss that provide clear and quantitative idea about the problem.
- Some outcomes, presented in previous studies, require reanalysis to evaluate their consistency including data objectives relative to the THC.

- These data and analysis are important to prepare a sediment management program as well as sediment disposal with beneficial reuse plans.
- The most important data (mechanical and chemical characteristics of the sediment, deposited in the reservoir) is still missing (there is a 10-year-old measurement of chemical properties, covering a limited set of pollutants in reference to USA and EU sediment standards). There could already be quite some changes during this period). This is very important for the selection and analysis of the sediment removal, processing and beneficial reuse options and ultimately, technology selections.

2.2.2.2 Flow and sediment yield

Based on a review and rapid analysis of available data on flow and sediment transport characteristics, some key facets are outlined as follows:

- The variation of the annual-averaged discharge (inflow to the reservoir) is depicted in Figure 2-13. This shows that it varies between 400 m^3/s and 2000 m^3/s, revealing a decreasing trend during the last 15 years.
- The variation in annual volumes of water inflow at the Channel reservoir for the last 42 years is depicted in Figure 2-14. Following aspects can be inferred:
  - The difference between maximum (wet year) and minimum (dry year) annual inflow volumes during this period is almost four times (with max and min inflow volumes of about 54 km^3 and 13 km^3, observed in 1991 and 2021 respectively).
  - The average annual inflow volume during the period between 1979 and 2021 is about 31 km^3.
  - The variation in reservoir inflow volumes reveals a decreasing trend during the last 15 years. This could be due to the larger water retention/withdrawal in upstream reaches and catchments. This must be explored in detail as this is an important aspect for optimal management of sediment-induced problems in the Channel reservoir (some of the reasons appear to be the increased water retention and diversion in upstream catchment, e.g., Karakum as well as shrinkage of glaciers).
- Based on available data, the monthly-averaged flow volumes and sediment loads are calculated at inflow and outflow locations of the Channel reservoir, depicted in Figure 2-15. A few important observations are as follows:
  - The inflow and outflow of water volumes do not differ much, whereas inflow and outflow of sediment loads differ significantly. This implies that a large amount of sediment is trapped in the Channel reservoir despite the release of the considerable amount of flow through the reservoir. This can be attributed to the fact that the Channel reservoir is rather long (at present ~80 km) and is in a flat area. Therefore, the sediment settles in the reservoir due to the backwater effect even when the outflow discharge is almost equal to the inflow.
  - The peak flow volume is observed in July, whereas the peak sediment load is observed in May. This can be attributed to the catchment characteristics generating large volumes of sediments during the start of the high-flow period (which is May). This can be explored further in more detail as this is important for sediment management efforts.
  - The major volume of sediment loads is transported during the snowmelt period, i.e., from May to August (more than 70% of total annual loads).
- The variation of monthly-averaged sediment concentration at upstream and downstream of the Channel reservoir also shows a large difference revealing the outflow of significantly more clear water (Figure 2-16). This also demonstrates the effect of the reservoir on sedimentation. The peak concentration at the upstream is found to be in May(thus, the sediment load as mentioned above).

- Some previous studies show that the sediment load varies based on the hydrological feature of the year, e.g., the annual sediment load is found to be 30-40 million tons during low-flow year, whereas it is in the range of 150-170 million tons during high-flow year (the value we calculated above is valid for the average-flow year).

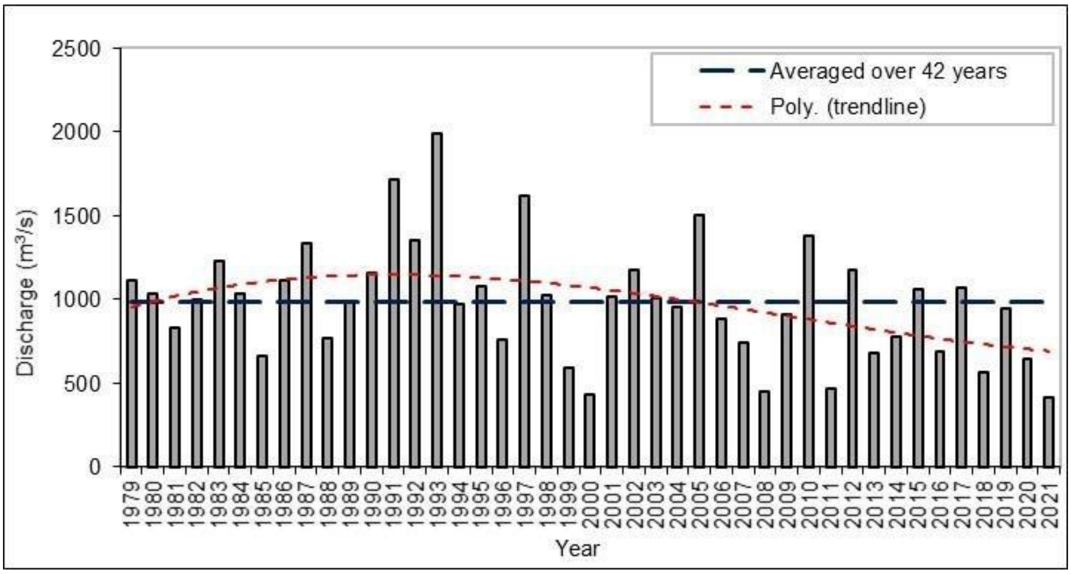


Figure 2-13 Variation of annual-averaged discharges (the reservoir inflow)

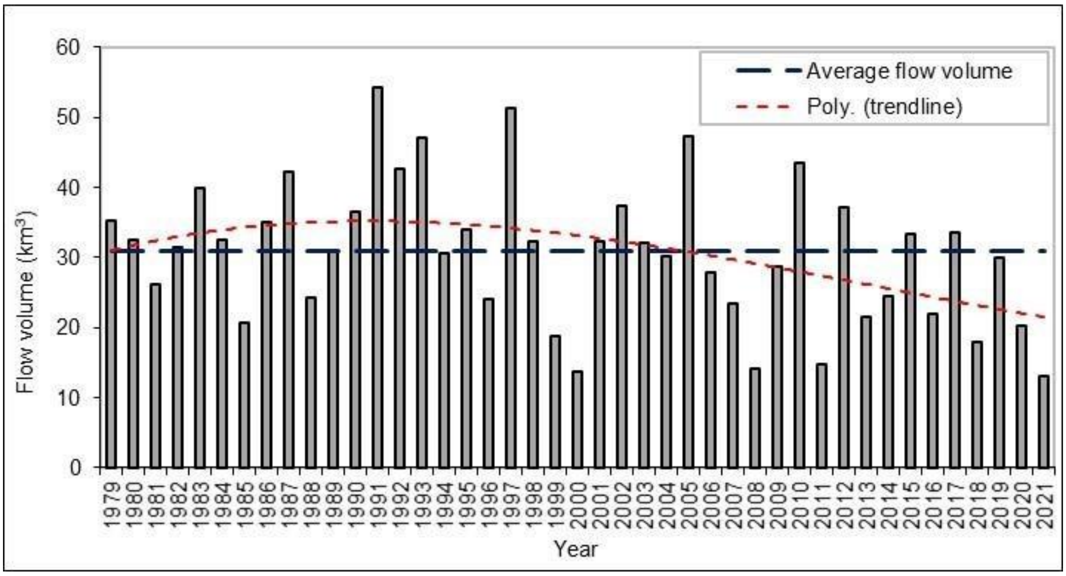


Figure 2-14 Variation of annual volumes of water inflow at the Channel reservoir

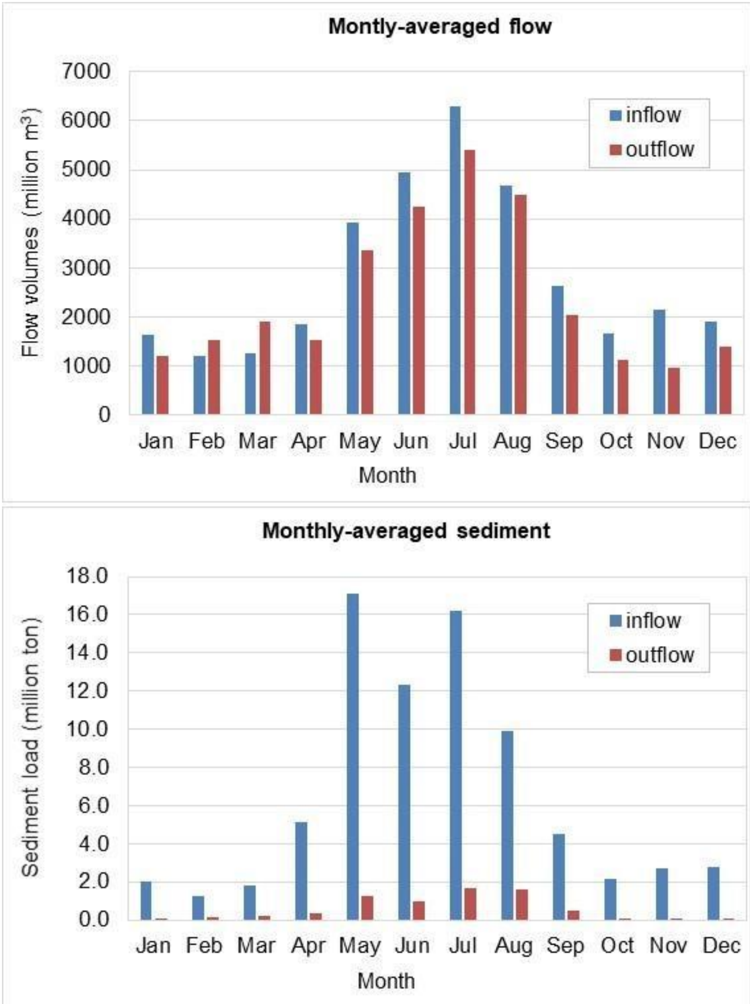


Figure 2-15 Monthly averaged variation of water discharges (upper plot) and sediment loads (lower plot) at the inflow and outflow locations of the Channel reservoir

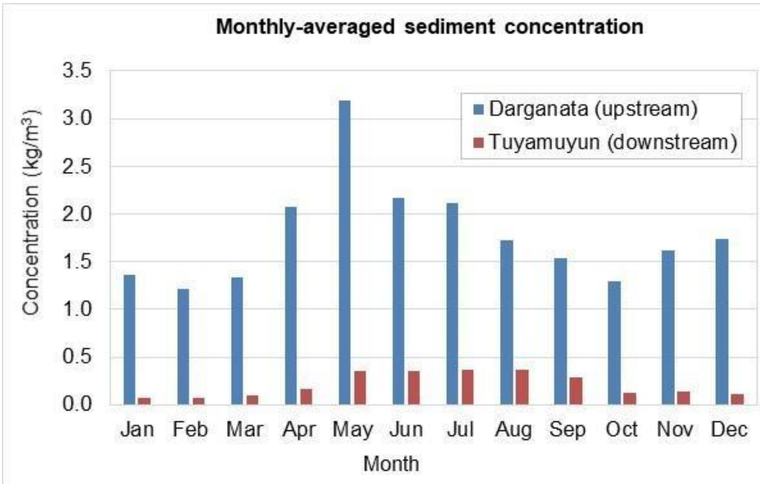


Figure 2-16 Monthly averaged sediment concentration at upstream and downstream of the Channel reservoir

2.2.2.3 Morphological changes at Channel reservoir

There are sporadic measurements of the Channel reservoir bathymetry (Ikramova M., 2021). The most recent measurement was carried out in 2021. Some characteristic features of morphological changes at the Channel reservoir based on the measurements are:

- The reservoir level-capacity curves for three (3) selected years (including initial and recent years), depicted in Figure 2-17, shows significant storage loss even at the FRL (130 m). The total storage loss is about 1.48 billion m^3, i.e., 63% of total initial storage volume (i.e., 2.34 billion m^3)
- The storage below the level 124 m is almost fully lost in 2021 (the design dead storage level is - 120 m). The storage loss at this level is about 31% of the total initial storage volume (including dead storage, which is about 11% of the total volume). The storage loss between the levels 124 m and 130 m (FRL) is about 32% of the total initial storage volume.
- The dead storage was fully lost already by 2008 (Ikramova M., 2021).
- Based on the available data, as depicted in Figure 2-18, it can be inferred that the larger amount of sediment was deposited at the upstream reach (≈ 720 million m^3) and rather less near the dam area (≈ 120 million m^3). However, the deposition near the dam area significantly increased in 2021 (≈ 812 million m^3). This implies that a large part of the upstream deposition (if not all) of 2008 was propagated to the dam area in 2021.
- About 200 million m^3 of sedimentation is deposited within the reach of 10 km upstream of the dam as revealed by the measurement of 2021.
- We also attempt to quantify the sedimentation area along the reach near the headworks (within 10-15 km) by using Aqua Monitor - an automated online tool, based on advanced satellite image processing, developed by Deltares, to quantify the changes in areas with water occurrence between any selected years. The tool can be used (with care) to quantify morphological changes (sedimentation and erosion) in large rivers and reservoirs. The morphological change between 2008 and 2022 along the Channel reservoir, particularly near the headworks, is depicted in Figure 2-19. It that shows a largeextent of sedimentation within the area. This appears to be consistent with the ground measurement. The tool cannot detect the changes below minimum water level since satellite images do not capture them. Nevertheless, such tool is useful for the rivers and reservoirs that become almost dry during low-flow period.
- A comparison between longitudinal profiles in 1981 and 2021 reveals large deposition along the Channel reservoir reaching almost 15 m of deposited layer near the dam leading to a significant change in the reservoir bed slope (as shown in Figure 2-20).
- The storage loss during 1981-2021 is consistent with the sediment balance between reservoir inflow and outflow (describe in section 2.2.2.2 above).

It is evident that the Channel reservoir has been suffering from sedimentation since the commissioning. The severity of the problem could have been avoided if the efforts were made at least in 2008, when a large amount of deposited sediment was still in the upstream reach (there appear to be earlier measurements as well). There could be some earlier efforts, but there is no information regarding any sediment management actions that were made earlier. It could be useful to know if there were any such efforts, and why they did not work and/or addressed. This information could be helpful in now moving forward.

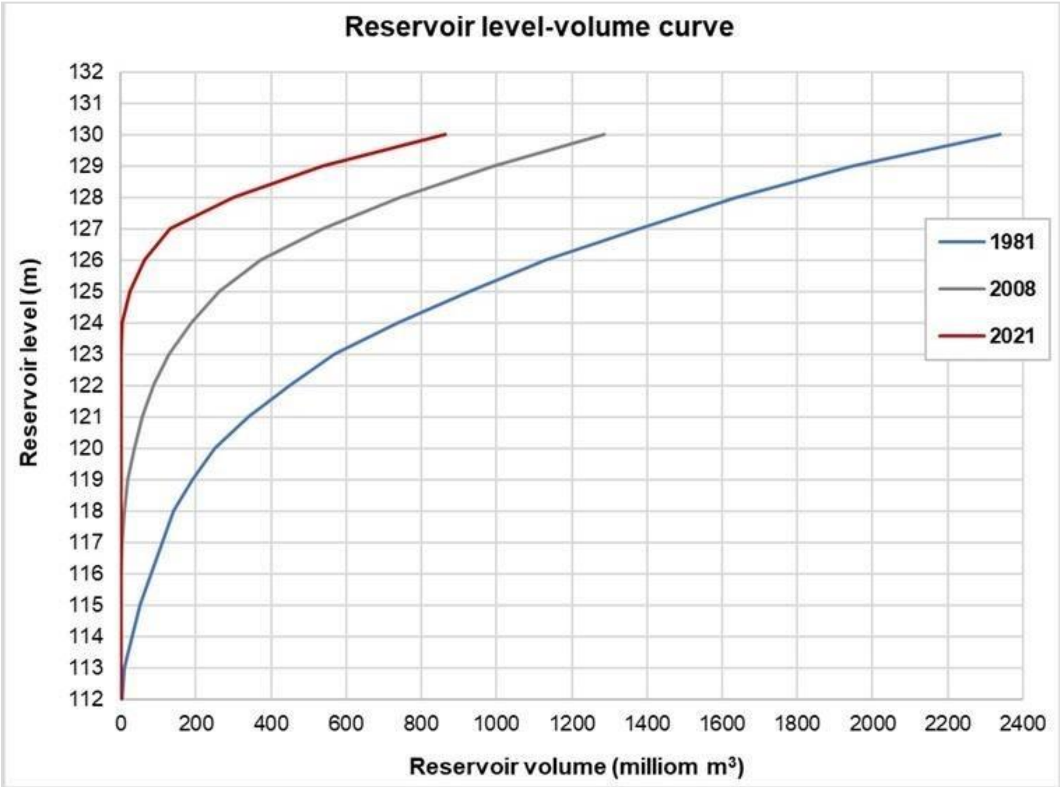


Figure 2-17 Reservoir level-capacity curve for three years (including initial year 1981)

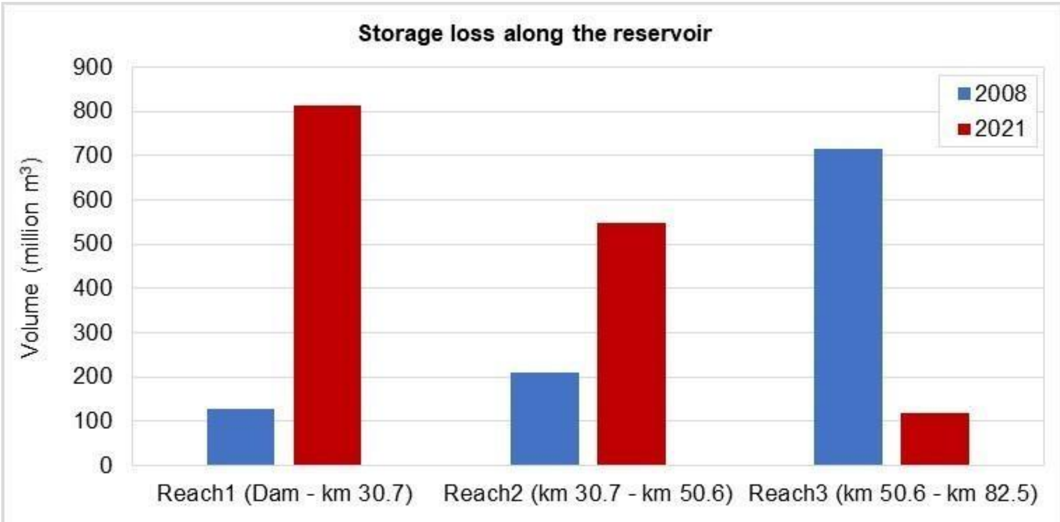


Figure 2-18 Comparing the storage loss along the Channel reservoir between 2008 and 2021

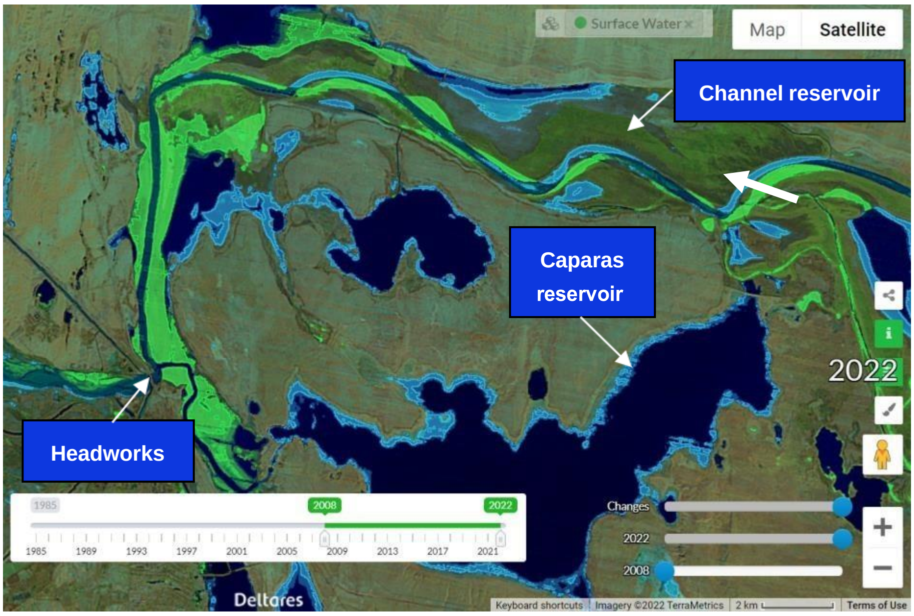


Figure 2-19 The area with sedimentation (in green), developed during 2008-2022 along the Channel reservoir nearby the headworks (quantified by Aqua Monitor based on satellite images, so there could be certain inaccuracies due to various reasons)

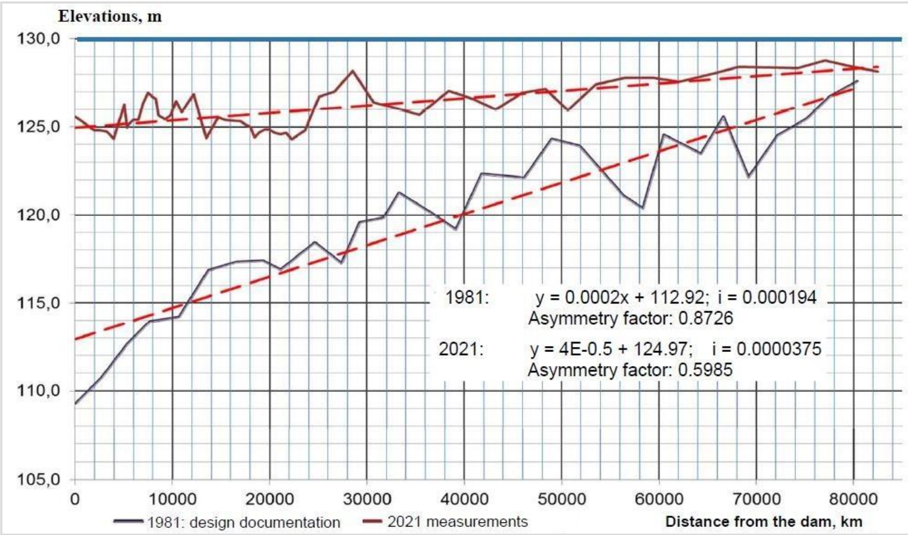


Figure 2-20 Comparing longitudinal profiles between the initial (1981) and recent (2021) bed levels along the Channel reservoir (Ikramova, 2021)

2.2.2.4 Sediment composition and beneficial reuse potential

Two different field campaigns were carried out during 14 to 24 June 2021 at the Turkmen side (the level near the dam was 126 m), and from 5 to 15 August at Uzbek side (the level near the dam was 125 m (Uzbek side) to measure the mechanical and chemical compositions of the sediment and water (Shirokova Y. I., 2022). The measurements were carried out in the laboratory based on the samples of the deposited sediment and water in selected locations along the Channel reservoir. Some facts and figures as well as some remarks are outlined based on a review and rapid analysis of the measured data:

- Sediment and water sampling locations are limited with the lower half of the reservoir (i.e., near the headworks and off-channel areas). However, there is no information aboutthe sample depth. It is also not clear which guidelines are considered for sediment sampling strategy. The mechanical and chemical compositions of sediment may differ inupstream area. It is important to consider them in future since the sediment from the upstream part of the reservoir could be removed (dredged) and beneficially reused as well.
- Based on the measurement data, we made a plot of the fraction content of all the taken samples of deposited sediment along the Channel reservoir (mostly at the lower reach) as depicted in Figure 2-21. Also, the grain-size distribution curves are prepared for some samples (Figure 2-22). The following aspects can be observed:
  - Most of the samples has a large content of the size fraction of 0.01-0.05 mm (more than 45% except three samples).
  - One sample shows the high content of coarser fraction, viz. about 39% of size fraction 0.1-0.25 mm and 37% of size fraction higher than 0.25 mm. Whereas, all other samples hardly contain the size fraction larger than 0.1 mm.
  - The median diameter (D_{50}) varies within the range of 0.003 mm to 0.2 mm. However, it is within the range of about 0.01 mm to 0.02 mm for most of the samples.
  - The clay content in the samples was measured separately from the sand fractions. It is found to be varying largely in the samples, i.e., from 2.4% to 82%. The minimum clay content (2.4%) is found in the sample with the coarsest fraction (with a D_{50} of about 0.2 mm). Whereas the maximum clay content (82%) is found in the sample with finer fractions (with a D_{50} of about 0.003 mm).
- There are 13 water samples taken from the reservoir to measure the sediment chemical concentration (mostly along the lower reach of the reservoir as sediment samples). The result is depicted in Figure 2-23, showing that the sediment concentration varies from 0.7 g/l to 3.85 g/l.
- Chemical analysis of the sediment and water samples reveals the following (some laboratory results are presented in Appendix 2 based on the report of Shirokova, 2022):
  - There are no harmful (toxic) and/or hazardous substances and contamination in any of sediment samples. Moreover, the samples contain useful trace elements such as iron, copper, boron, magnesium, zinc, manganese, cobalt, molybdenum.
  - The determination of humus and the total content of nutrients (NPK values) as per the accepted method in agrochemistry reveals that the sediment samples can be categorized as "poor" and "very poor".
  - The chemical composition of the water samples reveals that they have very good properties, e.g., pH 6.9 to 8.0; EC less than 1dS/m, TDS less than 1g/l (except for one sample). This implies that the water is suitable for drinking and other domestic, industrial and irrigation purposes and continue to be protected.
  - A comparison of MPC (Maximum Permissible Concentration) and the actual content of heavy metals in the sediment samples reveals that the presence of heavy metals does not pose any danger as per all the indicators in all the samples (except for one clay sample). The actual content of harmful elements is below the MPC, for some elements by 50-60 times.
  - Given the results of the chemical analysis, it can be concluded that the sediment is appropriate for all kind of beneficial reuse (biotic and abiotic).
- There was also some experimental investigation on potential beneficial reuse of sediment from the Channel reservoir (carried out by Central Asian Institute for Ecological Research in 2022). Some of the facts and figures about the investigation are presented:
  - The laboratory experiment is related to the applicability of the sediment from the reservoir for construction materials (bricks in this case).
  - Three different types of samples were taken from different regions and depth of the Channel reservoir, as reported (Figure 2-24).

- Chemical analysis was conducted for all three samples. The result is presented in Table 2-1. Some indicators differ significantly for three samples. All the indicators are under the allowable norm.
- Various experiments were carried out. The bricks were made without any additives and/or binders. (Figure 2-25).
- The recommendations are made for considering the sediments for other uses as well, e.g., for agricultural and animal husbandry use.
- The experimental outcomes require further rigorous investigation for large-scale commercial implementation and valorisation.

• The sediment samples were taken from the upper layer of the reservoir bed. Given that the deposited layer is significant (up to 15 m near the dam) and there appears to be underlayers with older deposition, only the compositions and quality of the upper or surficial layer may not be representative for all deposited sediment. Therefore, it is necessary to assess the samples from deeper layers. This must be considered in future endeavours and project designs.

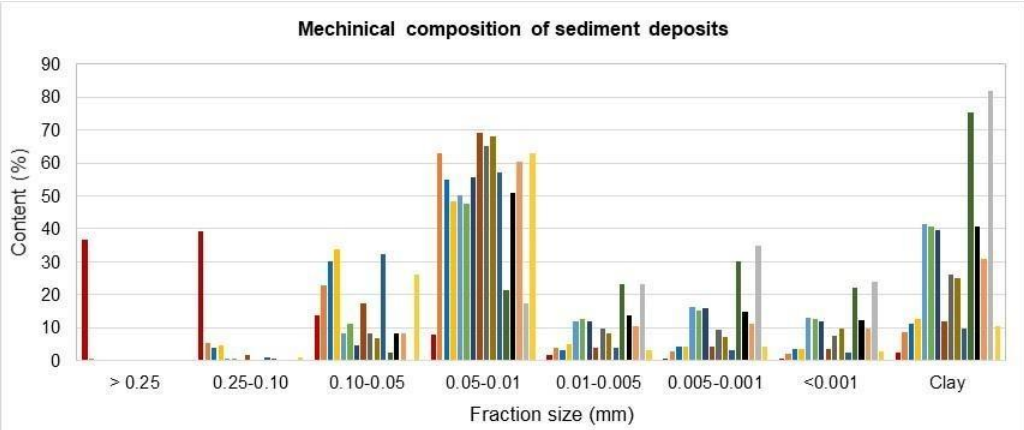


Figure 2-21 Sediment fraction content in different samples (the bars with the same color for all fraction sizes denote one sample – 16 sediment samples were taken along the reservoir)

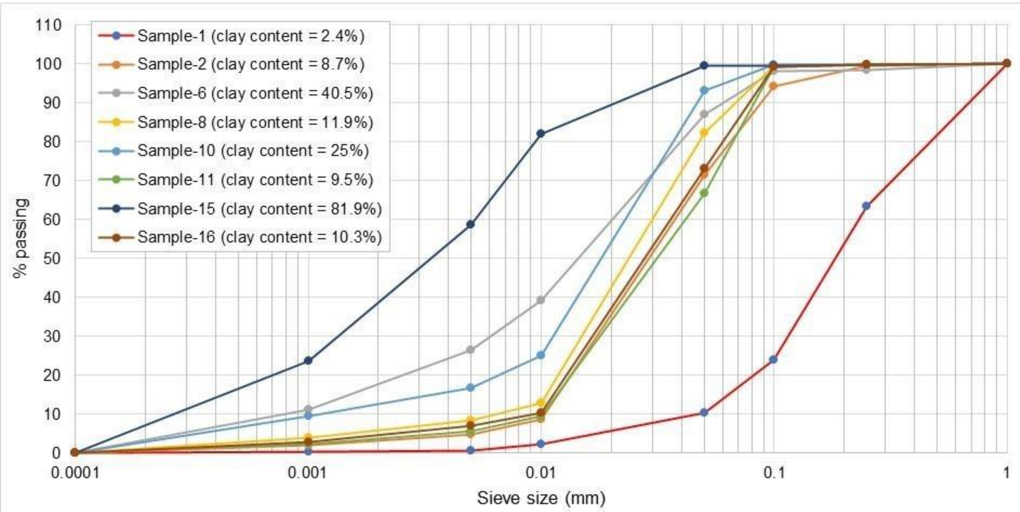


Figure 2-22 Grain-size distribution curves for some selected samples at the Channel reservoir

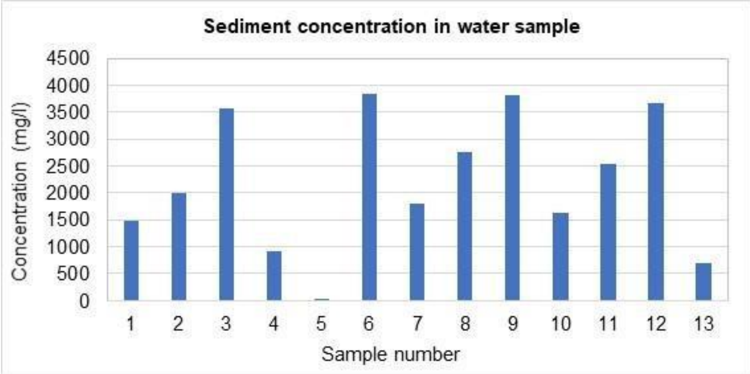


Figure 2-23 Sediment concentration (turbidity) in water samples (13 water samples were taken along the reservoir)

Figure 2-24 The samples, taken for the laboratory experiment (left - soil from the reservoir bottom; middle – sandy soil, right – clayey soil) (Central Asian Institute for Ecological Research, 2022)

Table 2-1 Chemical composition of three above-shown three samples (Central Asian Institute for Ecological Research, 2022) – the table alongside (right) shows the tested elements, translated in English

№	Определяемый показатель	Норма по НД	Результаты, мг/кг		
			Почва 1	Почва 2	Почва 3
1	pH, мСм/см		7,99	7,91	7,69
2	Нефтепродукты, мг/кг		< 5,0	< 5,0	< 5,0
3	Хлорид-ион, мг/кг		30,5	88,5	485,7
4	Нитрат-ион, мг/кг	130	8,66	12,8	< 3,0
5	Сульфат-ион, мг/кг		98,7	140,1	1573
6	Фторид-ион, мг/кг	2,8	3,1	14,6	< 1,0
7	Фосфат-ион, мг/кг		40,1	34,7	< 3,0
8	Аммоний, мг/кг		2,9	2,6	< 2,0
9	Калий, мг/кг		11,6	13,2	< 2,0
10	Натрий, мг/кг		73,05	136	862
11	Магний, мг/кг		24,5	32,6	237
12	Кальций, мг/кг		107	130	876
13	Алюминий, мг/кг		< 5,0	< 5,0	< 5,0
14	Марганец, мг/кг	100,0	2,535	2,510	2,485
15	Молибден, мг/кг		< 1,0	< 1,0	< 1,0
16	Кадмий, мг/кг	0,5	< 0,05	< 0,05	< 0,05
17	Свинец, мг/кг	6,0	< 0,5	< 0,5	< 0,5
18	Кобальт, мг/кг	5,0	< 0,5	< 0,5	< 0,5
19	Железо, мг/кг		< 0,5	< 0,5	< 0,5
20	Никель, мг/кг	4,0	< 0,5	< 0,5	< 0,5
21	Медь, мг/кг	3,0	< 0,5	< 0,5	< 0,5
22	Ртуть, мг/кг	2,1	< 0,005	< 0,005	< 0,005
23	Хром, мг/кг	6,0	< 0,5	< 0,5	< 0,5
24	Цинк, мг/кг	23,0	< 0,5	< 0,5	< 0,5
25	Плотный остаток, %		0,084	0,096	0,734

	Tested indicators
1	pH
2	Oil products [mg/kg]
3	Chloride [mg/kg]
4	Nitrate [mg/kg]
5	Sulphate [mg/kg]
6	Fluoride [mg/kg]
7	Phosphate [mg/kg]
8	Ammonia [mg/kg]
9	Potassium [mg/kg]
10	Sodium [mg/kg]
11	Magnum [mg/kg]
12	Calcium [mg/kg]
13	Aluminium [mg/kg]
14	Manganese [mg/kg]
15	Molybdenum [mg/kg]
16	Cadmium [mg/kg]
17	Lead [mg/kg]
18	Cobalt [mg/kg]
19	Iron [mg/kg]
20	Nickel [mg/kg]
21	Copper [mg/kg]
22	Mercury [mg/kg]
23	Chromium [mg/kg]
24	Zinc [mg/kg]
25	Solid residue [mg/kg]

Figure 2-25 The ready sample product (bricks), made using the samples of the Channel reservoir sediment (Central Asian Institute for Ecological Research, 2022)

2.2.2.5 Reservoir operation

Based on the available data on the reservoir level and volume variation at the Channel reservoir during 2015-2020, the following facts and figures can be outlined (see the report by M. Ikramova, 2021 for the details):

- The variation of reservoir levels, depicted in Figure 2-26, shows that the FRL is not reached during most of the period, particularly during drier years. As the analysis of the discharge data revealed (see above in Figure 2-13 and Figure 2-14), the last 15 years were relatively a lower-flow period showing decreasing trends.
- The FRL was never reached in 2020. This indicates towards even more of a serious problem regarding water availability given the fact that the reservoir has lost almost 60% of its total initial volume by 2020. This means that the reservoir should be filled up quicker and the FRL should be reached even with less inflow discharge.
- The variation of monthly-averaged flow volumes during 2015-2021 (partly) can be seen in Figure 2-27. It reflects the reservoir level variation. However, we can see that for the (same) FRL in 2015, 2017 and 2019, the volumes show a decreasing trend. This can be attributed to the storage loss due to the sedimentation.

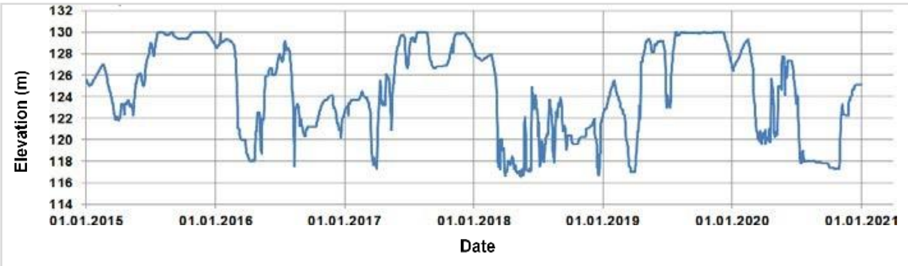


Figure 2-26 Variation of the Channel reservoir level during 2015-2020

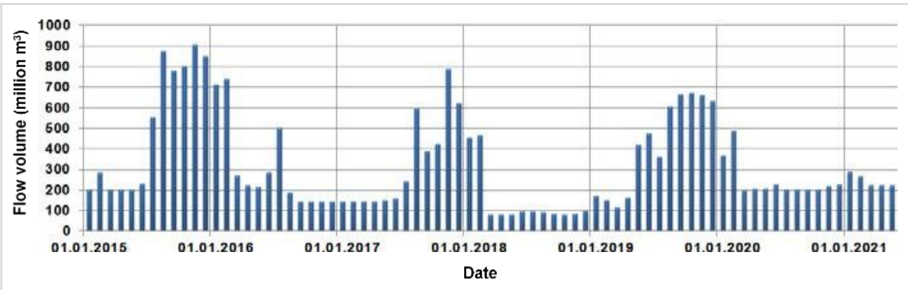


Figure 2-27 Variation of monthly-averaged flow volumes in the Channel reservoir during 2015-2021

2.2.2.6 Water losses

It is important to quantify the water losses from the reservoir due to other reasons. The water balance calculation, made by M. Ikramova (2021), reveals the following facts and figures:

- The water losses due to evaporation and transpiration at THC. Moreover, the impact of filtration was also quantified.
- The analysis showed that after commissioning the Channel reservoir, depending on the actual operation regime, the annual evaporation losses reached the value as much as 250 million m^3. The losses are found to be high for a long time during high-flow years due to the high reservoir level during longer periods. Whereas the losses are minimal during low-flow years due to large drawdown.
- The water losses due to the ffiltration is found to be significant during high-flow years. Whereas, in low-flow years, an influx of filtration flows was observed that can be attributed to the deep drawdown. The maximum observed annual inflow and outflow volumes, caused by the filtration in the Channel reservoir, are up to 130 million m^3 and 280 million m^3 respectively.
- The annual water losses appear to be significant and comparable to annual storage losses due to the sedimentation. This fact should be taken into account while consideringthe management of sediment-induced problems. More rigorous observation and analysis should be conducted to precisely quantify the water losses.

It should be noted that there is no data and information on water losses at the canals due to seepage and sedimentation.

2.2.3 Economic loss

A rapid calculation was carried out by M. Ikramova (2021) on the economic losses due to the decrease of agricultural and hydropower productions. The calculation shows an approximate annual loss of 37 million USD and 6-16 million USD due to the loss in agricultural and hydropower productions respectively. The agricultural and energy loss in 2021 was calculated as 59 million and 16 million USD respectively. The details of the calculation can befound in M. Ikramova (2021).

It should be noted that these are the financial losses apart from other losses and impacts that we have mentioned above, i.e. (i) loss of agricultural land, water supply leading to deterioration of livelihood of the people; (ii) environmental problems/impacts (deterioration of river ecology, water quality, habitats); and (iii) safety of the people and infrastructures (e.g., flood safety, malfunctioning and complete blocking of the intakes).

2.2.4 Data uncertainties and inaccuracies

All the reviews and rapid analysis is made based on available data, reports, and information provided. There could be uncertainties and inaccuracies in data and outcomes due to a variety of reasons. Some of them can be outlined as follows:

- Inaccuracies in reservoir volumes due to the coarse resolution of the measurement. For example, there is more than (1km) one-kilometer interval between the measured cross-sections that may lead to the missing sandbars or deep areas between the measured sections (depending on how they are selected).
- The measurement and sensitivity approaches and techniques that are used for different measurements during different periods (e.g., bathymetry measurements that are carried out initially and other years) may cause some inaccuracies.

- Other aspects such as consideration of insufficient number of samples along the reservoir and their frequencies, e.g., only surface sediment sample from the location where the deposition layer is large; one-point water sample for turbidity measurement as it may change significantly over the water depth; inappropriate period of measurement or difficulties in measurement during high-flow conditions etc. can also lead to imprecise quantification and interpretation. In general, not following clear international guidelines and standards for the sampling strategy, sample site selection, sample taking, sample homogenisation, sample preservation and accredited analytical methods introduce uncertainty in the quality of the chemical data.
- Measurement artefacts and errors can also lead to inaccurate assessment.

2.3 Characterization of the sediment-induced problems and impacts at the THC

THC is a multipurpose hydrocomplex being used for agriculture, energy, water supply, aquaculture, and flood management. Based on the review and analysis of the data and information, presented above, we can infer that the sediment-induced problems have created significant adverse impacts on various aspects and functions of the THC. Consequently, we can categorize the problems and impacts, as described hereafter, that can be of help to further categorize the measures and solutions accordingly.

2.3.1 1st-category problem: Functionality and safety of the structures at headworks

The measurement in 2021 shows that there is a significant sedimentation (≈12 m thick deposited layer as depicted in Figure 2-28) in front of the hydropower and the canal intakes. The problem has led to poor functioning of hydropower plant affecting the energy production and plant efficiency. The further deterioration by situation will lead to the malfunctioning of the hydropower plant. Furthermore, the large sedimentation front has propagated towards the intakes of the irrigation canals. The condition is rather severe particularly at the intake of the right-bank canal leading to malfunctioning of the canal. The situation will get worse given the fact that the intake is located at the inner bend of the river that is more prone to sedimentation. A sandbar is visible even in an image, depicted in Figure 2-29.

Such a large deposition in front of the headworks is also very risky for safe flood passage that may affect not only structures but also the area and the populace. Hence, the problem must be addressed urgently in a holistic engineering evaluative careful manner.

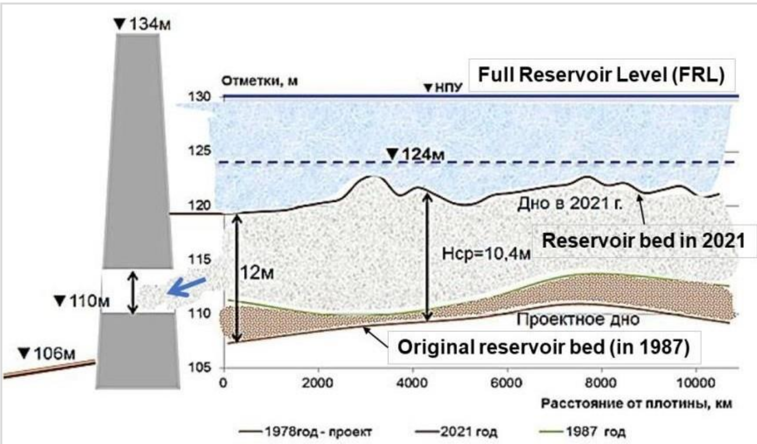


Figure 2-28 Schematic sketch of the deposition layer near the headworks (M. Ikramova, 2021)

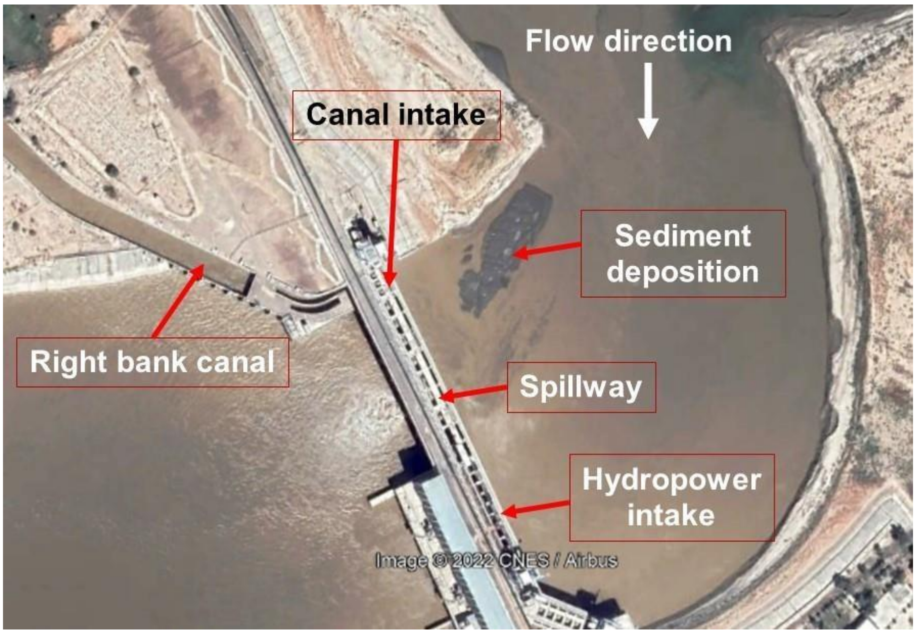


Figure 2-29 The hydropower and canal headworks (Google Earth image)

2.3.2 2nd-category problem: Reservoir storage loss

As it has been revealed from the measurement of 2021 (as shown in previous section), there is large depositional area along the Channel reservoir, particularly within 50 km upstream of the dam. This has resulted in the storage loss of about 1.5 billion m^3 at the Channel reservoir (this is about 63% of total storage). Apparently, the large sedimentation at the Channel reservoir has started to create the problems for other off-channel reservoirs as well. However,there is no data and information on the problems at the off-channel reservoirs.

The loss of storage implies less water supply for agricultural and drinking purposes. There is already a problem with abandonment of some agricultural lands. Moreover, the reservoir condition will deteriorate further if no measures are taken, thereby resulting in large social and economic (adverse) impacts for the area affecting the livelihood and economy of the people and region.

The significant loss of the reservoir volume is also quite risky in terms of flood safety since the flood regulation is almost impossible at present as there is much less storage to accommodate the design flood. This may lead to the hazard in case there is a large flood in the river that should not be excluded.

2.4 Concluding remarks

In this Chapter, a thorough review of the past and current state of the THC has been carried out. It is evident that THC has been suffering from severe problems induced by the sedimentation in the Channel reservoir already for a few decades. The problems have created various impacts in terms of functions and operation of the hydrocomplex. Based on the type and magnitude of the impacts, we have described the problems in two main categories to differentiate them in terms of required resources and urgency. The 1st-category problem requires urgent planning and action (as to not lose the resource which is the THC itself) as well as the short-term need to address critical infrastructure (deterioration and eventual replacement) including regularity that can be executed speedily within the limited investment and resources. The second problem requires proper scoping study, large-scale planning, feasibility study, basis of design, and execution with a long-term strategy (demanding large investment and resources).

This has been done to further categorize the measures and solutions that will help to prioritize them based on the possibility to acquire necessary financial and technical resources.

3 Management of sediment-induced problems at THC

3.1 Introduction

Based on our review and rapid assessment of the sediment-induced problems at THC (particularly in the Channel reservoir), we consider three main aspects while proposing the measures/solutions to deal with them, viz.:

1) Strengthening functionality and safety of the hydropower and canal headworks
2) Improving the situation with water storage and availability
3) Enhancing reservoir sustainability and adaptive approach(s)

The first aspect requires an urgent action plan due to the concerns related to the functionality and safety of the hydrocomplex. The measures to deal with this aspect are mainly related to regular maintenance, monitoring and adaptation. This would not require a large investment and technical resources (in fact, the maintenance measures should already be in place for the operational day to day activities for such a large complex).

The second aspect is associated with the longer-term large-scale measures and interventions. These measures have a good potential of being feasible and effective, particularly to deal with the storage loss problem at Channel reservoir. However, they requireproper project scoping studies in complement with careful and detailed feasibility and impact assessments given the requirement for large financial and technical resources endeavour.

The third aspect is related to no-regret measures and programs that are required to maintain and adapt the implemented measures as well as to enhance the long-term sustainability of the complex. All the measures and solutions should be in line with the sustainability criteria in parallel with the Nexus approach.

Herein, we have concisely outlined the possible measures based on a quick screening, and subsequently developed preliminary recommendations for the measures/solutions at THC considering the aspects, mentioned above.

3.2 Screening possible measures for THC

Based on the review of existing data and information as well as rapid analysis of the challenges and the conditions at THC, we have outlined some possible measures that can beapplicable to manage the sediment-induced problems. The measures are classified as recurrent, structural/soft structural and non-structural measures as shown in Figure 3-1.

There could be variable combinations (hybrid approaches) of proposed possible measures. The choices for the solutions should be based on: (i) type, magnitude and urgency of the problems to be addressed (e.g., safety of the structures and inhabitants, rehabilitation of the reservoir(s) for storage gain, sustainability of the hydrocomplex); (ii) availability of financial and technical resources (including engineering constraints); (iii) social, economic and environmental impacts and benefits; and (iv) regional specifics and constraints (legal, transboundary aspect) among others.

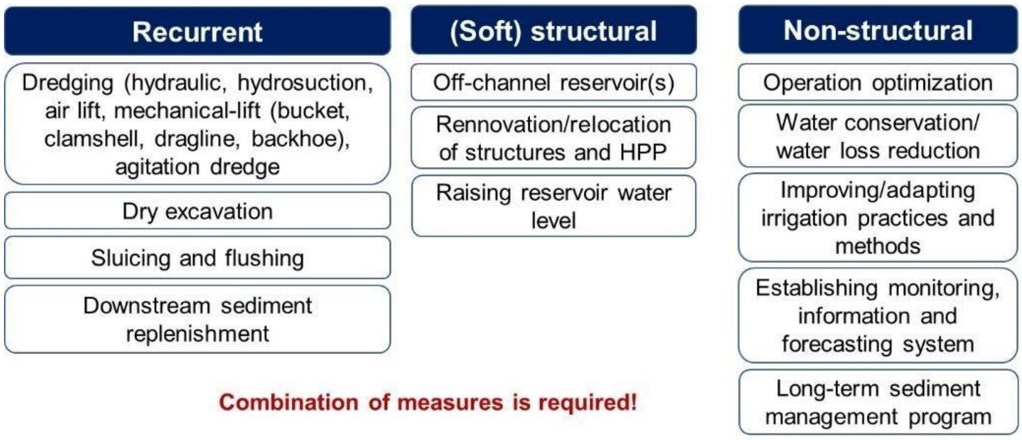


Figure 3-1 Possible measures to manage sediment-induced problems at THC

3.2.1 Recurrent measures

3.2.1.1 Sediment removal and disposal

One of the very important measures required to address the problems at Channel reservoir is sediment removal and disposal and/or placement. Given the problem, conditions and resources, the sediment removal measure can be categorized in two parts (i) maintenance dredging; and (ii) large-scale sediment removal (capital dredging) in complement with a sediment disposal and long-term management plan considering beneficial reuse (in both cases).

1) Maintenance dredging plan

Regular maintenance dredging as a part of a comprehensive sediment management program should be immediately considered. This is inevitable for the Channel reservoir so as not to deteriorate the existing function of the hydropower plant and off-channel reservoirs as well as to avoid endangering the civil/mechanical structures, thus, to restore the energy production capacity and the safety of the plant infrastructure itself. This measure should include following activities (but not limited to):

- Set-up a regular maintenance dredging program for removing the sediment deposition near the dams, hydropower and canal intakes in combination with a comprehensive sediment management program
- Acquiring equipment for excavation and dredging (with Operation & Maintenance (O&M)) long-term contract(s) and capacity building of local authorities)
- Piloting beneficial reuse alternatives preferably with commercial scale experience of dredged sediments that is appropriate in the region such as for engineering/geotechnical, agricultural, and ecological – habitat restoration use
- Implement a protocol to test if sediment is suitable for beneficial reuse.

2) Large-scale sediment removal and disposal plan

This measure is a major activity associated with capital dredging in conjunction with large-scale beneficial reuse of sediment. This measure may include following activities (but not limited to):

- Target and strategic removal of sediment up to 500 million m^3 in the shortest and most efficient (cost included) possible period. This is a multi-year capital program campaign.
- Conducting project scoping, stakeholder identification, financing (investments), high-level planning and proposal, pre-feasibility assessment

- High-level planning and proposition for large-scale beneficial reuse of removed sediment such as developing commercial productions units/industries, creation of ecological zones and green development in the nearby areas

3.2.1.2 Sluicing and flushing of Channel reservoir

Sluicing and flushing operations are a prerequisite to maintain and enhance the effectiveness of the sediment removal measures proposed above. A general example of possible flushing sequence is shown in Figure 3-2. A preliminary proposition on reservoir operation rule for the Channel reservoir was made in one of the previous investigations. An operation rule was proposed based on monthly-averaged reservoir level for high, medium, and low flow years as reported by M. Ikramova (2021). This should be studied in more detail in conjunction with maintenance measures as a part of a comprehensive sediment management program, which should also include proper social, economic, and environmental, and engineering impact assessments.

It should be noted that the sluicing and flushing operations require the release of considerable amount of water. Therefore, the optimal approach for the reservoir operations should be carefully studied so that the refilling of the reservoir can be done without losing thewater volume. This can be performed better in complement with some non-structural measures such as the establishment of a monitoring system in the catchment that enables reservoir inflow forecasting with sufficient lead time. Subsequently, it can be combined with the dam operation (that can be done using hydraulic computational models with dam operation).

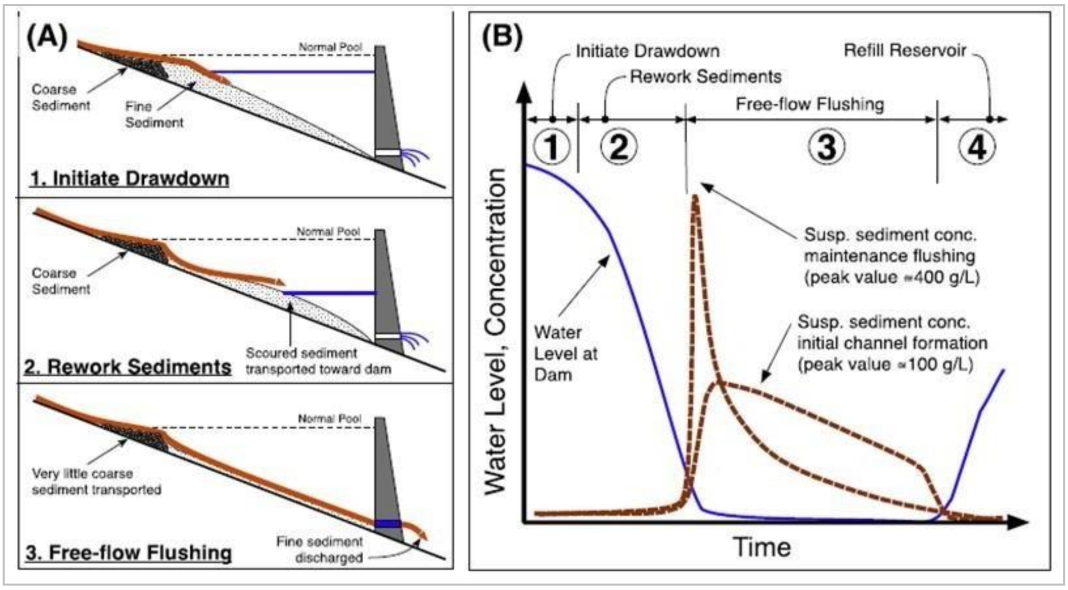


Figure 3-2 An example of flushing sequence (left) and corresponding variation of discharge and sediment concentration (Annandale et al., 2016)

3.2.1.3 Downstream sediment replenishment

This measure is related to the transport and disposal of removed sediment from the reservoir to the downstream area. The sediment is disposed of in a planned way on the part of the river where the sediment can be transported by the flow during a high-flow period. The measure can be a part of the comprehensive sediment management program, and could be useful, particularly given the fact that the riverbed along the downstream reach has been suffering from degradation after the construction of the reservoir (although we do not have data, but only a statement in the report by Ikramova M., 2021).

Also, the replenishment along the downstream reach can be used for creating ecological zones (a tentative proposition is depicted in Figure 3-3).

It should be noted that this measure may not be much of a benefit given the sediment characteristics (very fine materials) and the condition at the downstream reaches of the Amu Darya that might be adversely affected due to the transport of replenished materials creating high turbidity as there are canals and headworks in the downstream reach. Secondly, the replenished material might be consolidated quickly during dry season. This might not even be required in case proposed sluicing and flushing operations are effective. In any case, downstream sediment management when the transport is increased is crucial. Therefore, this requires very careful and detailed consideration.

Figure 3-3 A part of the downstream reach where removed sediment can be replenished and also the creation of ecological zone can be considered.

3.2.2 Structural (soft and hard) measures

3.2.2.1 Raising the full reservoir level (FRL)

As a soft-structural measure, it is proposed to consider the raising of FRL (without raising the dam height) as an option to increase the reservoir storage. It is proposed to raise the level by 2 m maximum. As per the design, the FRL is 130 m (Figure 3-4). Given that there is 4 m free board (as the crest level of the dams and embankment is 134 m), it is proposed to raise the FRL to 132 m (max). This is also given the fact that, 131.5 m is considered as a maximum level (the level, referred to as “forced level” that should be used in extreme situation and should not be maintained for the long period) as per the design. As an example, we found from the data (considering that the record is reliable) that the reservoir level had reached 132 m in August 2004 (as depicted in Figure 3-6).

The proposed increase in the reservoir level may result in a noticeable increase of storage in the Channel reservoir (as can be inferred from Figure 3-6 that shows the extrapolation of the level-volume curve, although this has to be investigated properly to estimate the gained storage precisely). Moreover, there could be potential to increase the storage in other off-channel reservoirs as well.

This is proposed to be considered as an alternative to the capital dredging program. However, this requires very careful analysis given the possible adverse impacts and risks. Some impact and risk could be minimized by implementing some structural strengthening.

For the consideration of this measure, following aspects shall be considered:

- Comprehensive dam stability and safety assessment
- Exploration and investigation on some structural strengthening to mitigate the risks related to structural stability
- Development of optimal flow operations and sediment management strategy and program
- Detailed assessment of the condition of other off-channel reservoirs
- Proper monitoring and maintenance (e.g., dredging, flushing) program

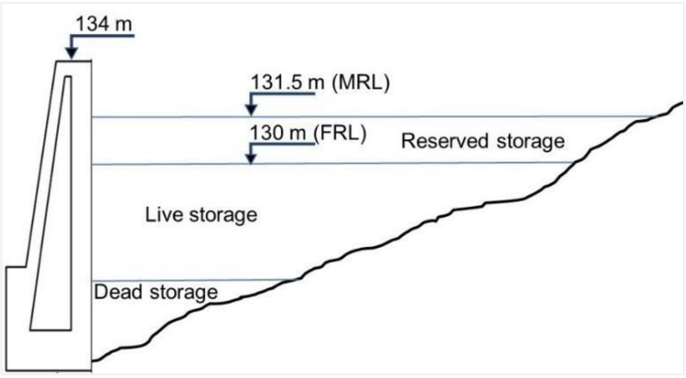


Figure 3-4 Schematic sketch of design levels in Channel reservoir

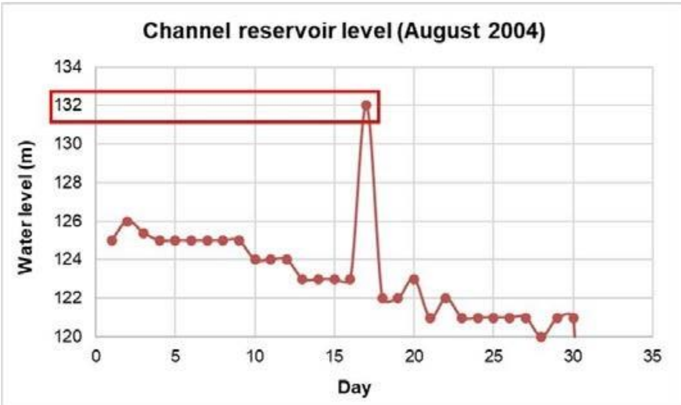


Figure 3-5 Observed reservoir level in August 2004 when the level reaches 132 m

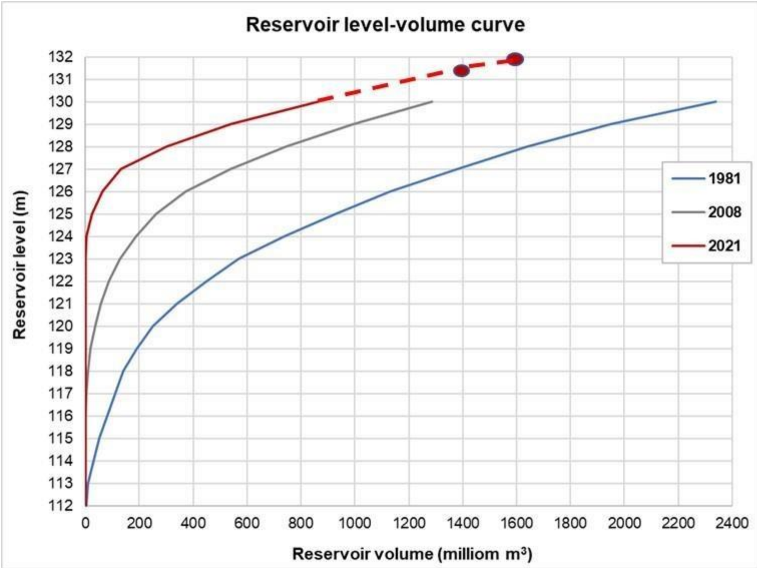


Figure 3-6 Reservoir level-volume curve

3.2.2.2 Additional off-channel reservoirs

This structural measure is another alternative to capital dredging that would compensate the loss of storage at Channel reservoir with additional off-channel reservoirs. Our rapid analysis based on freely available remote-sensing data (Figure 3-7) and images shows that there are areas where it could potentially be possible to build additional off-channel reservoir(s) at both sides of Channel reservoir (in Uzbekistan and Turkmenistan). There are some areas with significant depressions (Figure 3-8) that can be used for the water storage. However, this requires proper and detailed analysis and feasibility assessment considering technical (e.g., geotechnical, geological), environmental (including ecological) and social aspects.

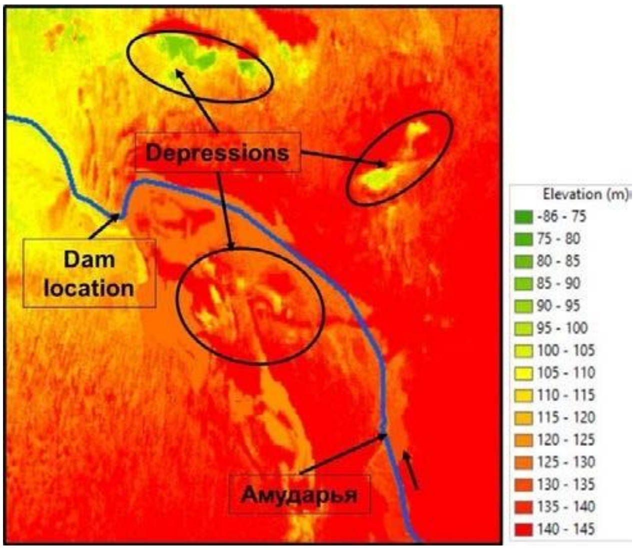


Figure 3-7 Topography based on SRTM data showing some depressions near the THC

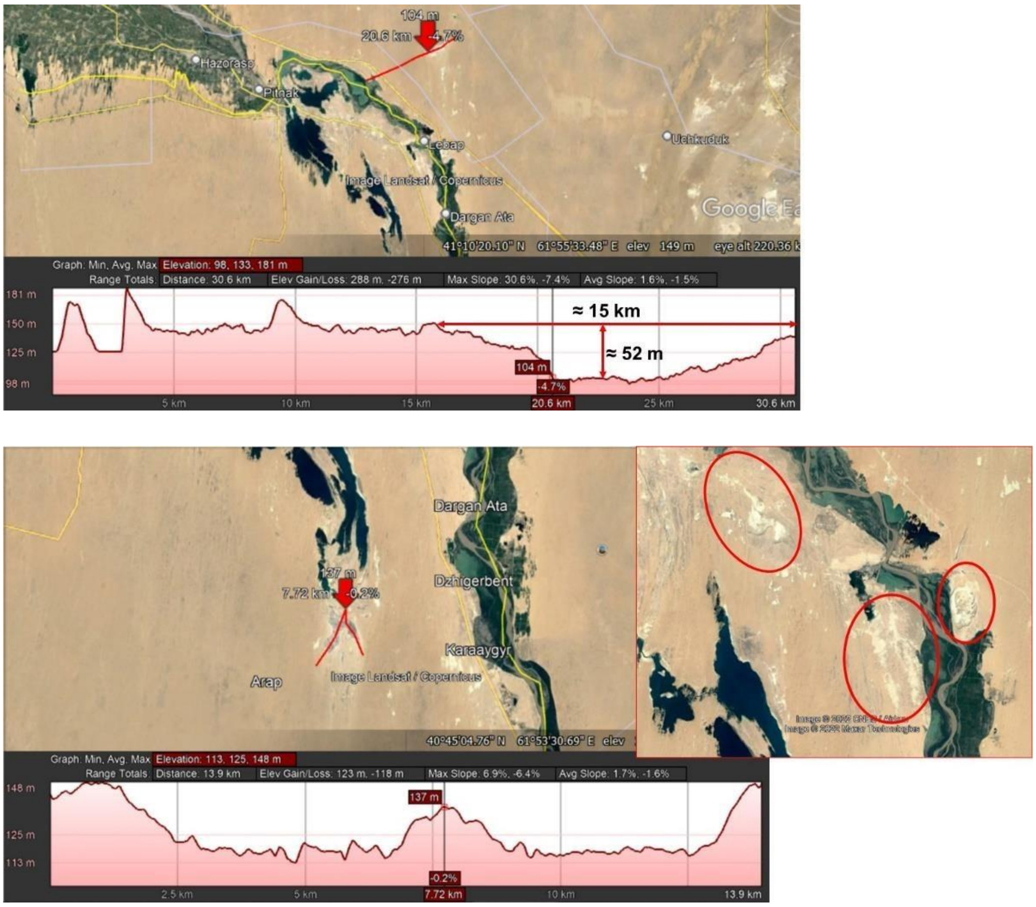


Figure 3-8 Bed profiles along some selected sections of the depressions (based on Google Earth) that could be used as off-channel reservoirs

3.2.2.3 Renovation and/or relocation of (hard) structures

Another option for the hard measure that is worth considering as an alternative to capital dredging or off-channel reservoir(s) is renovation or relocation of the hydro-structures. Two options can be considered for their technical, social, economic and environmental assessment, viz.: (i) relocation of headworks and the hydropower plant. This is a drastic and significant change that may be less preferable at this stage and more suitable for future consideration; and (ii) heightening of the dams/embankment (e.g., using smart fusegates), which can be a part of solution in combination with the proposed soft measure on increasing the FRL above design level (as described in section 3.2.2.1) as it may require structural strengthening. The implementation of the measure (particularly relocation) requires comprehensive project scoping, substantial financing, proper feasibility, and impact assessment. Nevertheless, there are global practices in the regions where water availability and flood safety are vital for the people and their livelihood. Some pictorial examples are depicted in Figure 3-9 and Figure 3-10.

There are global examples, briefly presented in section 5.3 (Chapter 5).

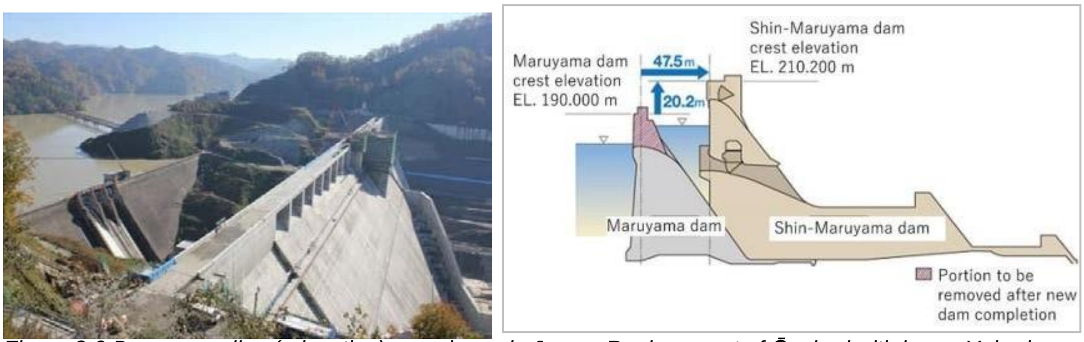


Figure 3-9 Dam upgrading (relocation) experience in Japan: Replacement of Ōyubari with larger Yubari Shuparo (left image – received from Y. Shimizu) and the Maruyama dam upgraded by Shin-Maruyama (right plot - https://doi.org/10.20965/jdr.2018.p0585)

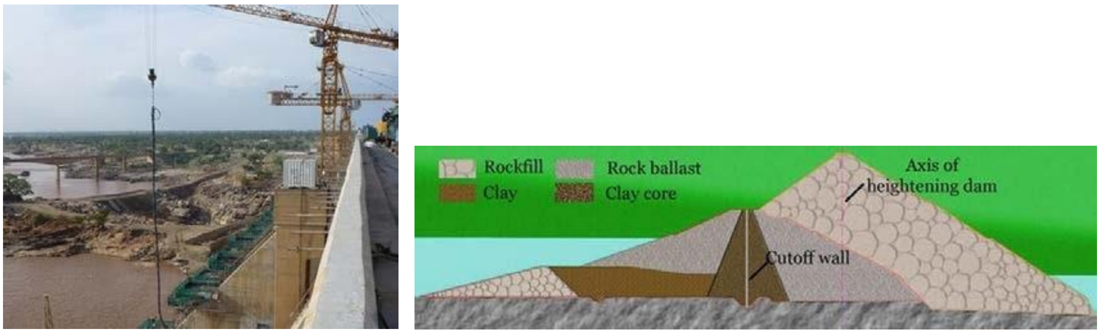


Figure 3-10 Heightening of Roseires dam in Sudan (left image- http://pf.bbrnetwork.com/Projects/Manager/media287A-INFOslider_medium.jpg) and a profile of Zhushou dam heightening in China (right plot - https://www.intechopen.com/Chapters/71980)

3.2.3 Non-structural and supplementary measures

Non-structural measures are important in combination with any recurrent and/or structural (soft and hard) measures for an effective management, adaptation, operation, and maintenance of the rehabilitation efforts. The measures are also necessary for the preventionand mitigation of adverse impacts in the future. We can categorize two types of non-structuralmeasures, viz. (i) improving reservoir operation considering sediment management, and (ii) improving technology, practices, monitoring, and management.

3.2.3.1 Improving reservoir operation considering sediment management

For all proposed measures above, it is necessary to analyse and optimize the reservoir operation strategy as an integral part of a comprehensive sediment management program. Optimization of the reservoir operation rules is required to deal with the changes due to the implementation of measures. Secondly, most of the proposed measures that are related to the increase of storage capacity will increase sediment-induced problems as well. Therefore, the optimal reservoir operation strategy must be developed to minimize the sediment-induced problems in complement with some recurrent measures (like maintenance dredging, sluicing and flushing, sediment replenishment) to maintain the effectiveness and sustainability of the measures.

3.2.3.2 Improving technology, practices, monitoring and management

Since most of the proposed large-scale measures (particularly related to gaining the storage) require significant technical and financial resources, there are other indirect measures that would help to partly address the problem associated with water stress and losses. By this way, it would be possible to optimize the efforts required for large-scale measures. Such indirect (non-structural) measures can be outlined as follows (but not limited to):

- Improving agricultural practices and methods that require and/or minimize less water resources
- Implementing technology(s) for minimizing water losses at the reservoirs and canals (due to sedimentation, seepage, evaporation)
- Establishing water/sediment monitoring, information and forecasting systems/sediment management program development to effectively deal with the water and sediment related challenges, thus, to improve the situation regarding water and structural safety
- Catchment and river management to reduce sediment generation and transport (as a part of a comprehensive sediment management program)
- Regular investment on Research and Development supporting local research and/or academic institutions as well as commercial pilot activities as they are an integral part of the measures to address the problems and adapt the solutions (i.e., knowledge- and information-based adaptive approach) – this also helps to create jobs, facilitate economic development (including regional investment) and revitalization and enhance capacity building.
- Establishing Integrated and Participatory Management (following Nexus approach) – this is important given that the THC is a transboundary complex with multipurpose water use, thus addressing the challenges that requires participation of all involved stakeholders, authorities and countries.

More description and examples are provided in section 3.5.6.

3.3 Screening of possible options for beneficial reuse of sediment at THC

Given the fact that the magnitude of the problem is rather large, i.e., significant volume of deposited materials in Channel reservoir, most of the large-scale measures would not be feasible without proper disposal methods, placement strategy and operational techniques. The solutions associated with sediment removal will only be effective in synergy with the options for disposal and placement opportunities including beneficial reuse from an economicpoint of view and as a social-economical driver for the region.

Based on our review and rapid analysis, the following potential options of beneficial reuse of removed sediment have been shortlisted for THC for further consideration:
Manufactured topsoil improvement and fertilizer production for agriculture and afforestation
Creation and restoration of ecological (habitat) zones that support livelihood functions
Establishment of commercial industries for producing building materials (including the addition of polymers), landscape (ecological) design, engineered fill (structural and non-structural) and environmental applications
River structures and training (bank protection, berms and engineered fill to raise surrounding area elevation, sand plugs, earthen dams, etc.) for flood management and resilience

All the proposed options require comprehensive impact and risk assessment (social, economic, environmental) in conjunction with appropriate recurrent and/or structural measures.

3.3.1 Manufactured topsoil improvement and fertilizer production for agriculture and afforestation

Application of sediment for top-soil improvement is a well-established practice in the case that the quality of the deposited materials allows for the same. This is also appropriate for thearea around THC as well given that it is a desert-arid region. Moreover, recent laboratory tests on the chemical and mechanical properties of the deposited material (shown above in section 2.2.2.4) shows that they can be appropriate for various value-added beneficial reuse.

This can also be inferred from some already developed green/agricultural lands along the Amu Darya river and Channel reservoir (Figure 3-11) that the top-soil improvement with amendments could be possible.

We also came to know that there was already some practice by local farmers to use the sediment from the reservoir and canals as fertilizer. Consequently, the deposited sediment can also be used as fertilizers in a large-scale and more systematic way for agriculture, afforestation, and green development (sustainability) efforts. Natural topsoil is a non-renewable resource. This option of beneficial reuse can also be useful to improve the situation with abandonment of agricultural areas (due to water stress situation) in complement with the measures to increase water availability.

Figure 3-11 Green agricultural land along Channel reservoir at Amu Darya river

3.3.2 Creation and restoration of ecological zones and livelihood

One of the advantages of the location is that there is availability of a large area within and around the THC (Figure 3-12) for creating confined and upland disposal and treatment (e.g., ripening) facilities. A large part of sediment disposal facilities can be converted and designed to facilitate ecological zones, creation of new habitats (and improving existing ones) and new landscape contours. Given the large desert area around THC, there is a potential for creation and restoration as ecological zones for nature and livelihood. A large volume of sediment could be reused in this way by dredging and side-casting the sediments to produce these ecological zones.

There are some good practices around the world that could be the examples to learn from (presented in section 5.4 (Chapter 5).

Figure 3-12 Large area around the THC (left image) and along Channel reservoir (right image) to be used for land improvement using removed sediment

Deltares

3.3.3 Establishment of industries for producing building/engineering materials

Sediments is a very useful resource for producing building materials. There are already some small-scale experiments on reuse of deposited sediment at Channel reservoir for producing bricks (briefly presented in 2.2.2.4). Therefore, there is a potential even to establish production units and commercial industries in the region. This requires more detailed assessment in the homogeneity of the sediments to keep producing large volumes of bricks. There are ample examples of such application of reusing removed sediment (although mostlyfrom rivers and coastal areas, and not much from the reservoirs). It is critical to understand the existing market needs/drivers and product forecasting to not over-saturate the existing market. The advantage of this brick making manufacturing is that it does not need an investment of a high temperature oven since the sediment characteristics form a hard clay product.
Some examples are presented in section 5.4 (Chapter 5).

3.3.4 River training and guiding structures

The measures and works related to sediment removal (e.g., dredging) from the Channel reservoir, as proposed in previous section, must be properly maintained, and managed to minimize the morphological impacts and risks. This may require additional work and earth structures for training and guiding of the river within the reservoir and upstream reaches. This is useful (and even required) for the purpose of flood and sediment management. Moreover, the disposal facilities may require some structures (like dikes, berms and embankments). For constructing such structures, the removed sediment can be used as well.

3.4 Development of preliminary recommendations for the solutions at THC

Based on the first screening of the possible measures, presented above, we propose a preliminary recommendation for a set of possible best-case implementable measures and solutions that could be considered for further analysis and assessment (cost-benefit analysis as well as social, environmental, and engineering impact assessment). We have attempted to distinguish the measures in two categories. The first category of the measures is urgent and essential that are supposed to be investigated, designed, and executed as soon as possible since the resource (THC) is being immediately affected. The second category of the measures are large-scale endeavours that require more careful assessment as well as large interdisciplinary technical and financial resources. The first category of the measures would require fewer technical and financial resources compared to the second category of the measures (large-scale). We have also tried to briefly outline the advantages and disadvantages of each proposed measure. They are described hereafter.

3.4.1 Urgent and essential sediment management and storage recovery program

The current state of the affair at THC reveals that the problem is rather acute and is affecting the THC and the water resources in real-time – it is happening now. Therefore, it requires an emergency action plan for the *development and execution of a sediment management and storage recovery program*.

It is proposed that the program includes a combination of measures and a pilot case, viz. (i) regular maintenance dredging; (ii) technical assessment of raising Full Reservoir Level (FRL); (iii) regular flushing and sluicing; (iv) a pilot case on beneficial reuse of removed sediment; and (v) non-structural measures.in the most impacted areas of the THC – including the impacts on the dam hydropower infrastructure affecting energy production.

3.4.1.1 Regular maintenance dredging

A well-planned regular maintenance dredging program is urgently required so as not to deteriorate the existing function of the hydropower plant and canal intakes. This is needed to restore the energy production (plant efficiency) and irrigation functions.

More importantly, this is required to ensure the safety of the structures and safe flood passage to avoid any possible hazards and downstream disasters. These measures should be in place as part of a holistic sediment management plan and executed regularly in perpetuity during the whole reservoir life in complement with other soft and recurrent measures.

The maintenance dredging should be carried out near the hydropower and canal intakes, spillways, and the intakes of the off-channel reservoirs. For this purpose, the following activities are proposed to be carried out:

- Planning of a first-tier sediment removal program aiming at removal of at least 1-2 million m^3 annually (that can be increased with time, experience, and production rate efficiency)
- Carrying out (i) comprehensive technical assessment for safe and efficient sediment removal; and (ii) social and environmental impact assessment
- Execution of the sediment removal plan by acquiring equipment for excavation and dredging in complement with 2-3 years (as required) of O&M agreements with the professional dredging firm(s) that includes capacity building of local peoplepower. This includes developing long-term, seamless, and efficient contract mechanisms.

Advantages

- The main advantage is rather obvious as the urgent measure related to maintenance dredging is inevitable for avoiding safety problems and proper functionality of the hydraulic and hydropower structures. What is the short and long-term costs to the resource and infrastructure of not performing this task in a timely manner?
- Creation of regional employment and capacity building opportunities related to reservoir sediment management and optimal and efficient sediment removal using various types of dredging technology (hybrid where applicable).
- The experience will be useful for evaluating the effectiveness and feasibility of larger-scale capital dredging (proposed as one of the possible measures for technical, economic, and environmental feasibilities)
- Relatively lower financial investment (comparing to the loss of the resource)

Disadvantages

- The reservoir bed may be in a quasi-equilibrium state. Any disturbance without a proper planning and engineering study may have adverse impacts on headworks, embankments (erosion, failure) and other off-channel reservoirs
- If a large layer (or depositional lens) of sediment deposition in front of the headworks (about 12 m) is not removed properly and gradually in a well-planned manner, it may trigger retrogressive erosion and/or slope instability/incision leading to collapse of a large layer and sediment volume blocking the intakes and creating more risk to the safety and functionality of the hydraulic structures, canals, and hydropower plant.
- Risk and impacts of sediment removal and dredging operation are described in next Chapter.

3.4.1.2 Regular flushing and sluicing of the reservoir

The Channel reservoir has facilities for the sluicing and flushing (there are undersluices/low crest spillways, designed for downstream transport of near-bed sediment). The regular flushing and sluicing plan of Channel reservoir should be prepared, executed, and adapted in complement with the maintenance dredging. Furthermore, controlled sediment replenishment along the river reach downstream of the dam that can be transported during higher flows should be considered as well. Following activities can be outlined (but not limited to):

- Carrying out (i) comprehensive technical assessment of sluicing and flushing operations for safe and efficient sediment removal and downstream transport; and (ii) social and environmental impact assessment (see next Chapter for detailed technical and impacts assessment)
- Establishment of an optimal reservoir operation rule considering regular flushing, sluicing and maintenance dredging operations based on their impact assessment and efficacy
- Assessment and establishment of non-structural measures to support the safety, efficacy, and adaptation as well as for mitigating the adverse impacts of the flushing and dredging operations
- Consideration of sediment traps in strategic areas to catch sediments that are mobilized
- Technical and environmental assessment of controlled sediment replenishment along the downstream reaches

Advantages
- Sluicing of a reservoir during sediment-laden high-flow period allows quasi-natural transport of sediment through the reservoir, and at the same time release of high-concentrated flow resulting in decrease of sedimentation in the reservoir (usually this should be a normal practice as a part of reservoir operation of any reservoir)
- Regular and planned flushing operation (with pressure or drawdown method) of the reservoir helps to maintain at least the area in the vicinity of the headworks (e.g., in front of the canal and hydropower intakes in case of the Channel reservoir)
- Regular sluicing and flushing are necessary in combination with required maintenance dredging (proposed above) for its effectiveness
- Controlled downstream replenishment has an advantage over the flushing (at least during initial period of maintenance), particularly considering the severe condition of the channel reservoir in which the deposited layer is rather large even near the spillways and intakes.
- Relatively lower financial investment

Disadvantages
- Due to the large deposition in front of the intakes/undersluices at Channel reservoir, it is most likely that the flushing operation will be difficult without proper maintenance dredging
- Flushing may not be much effective for a long and wide reservoir like Channel reservoir other than as a maintenance measure in combination with other measures (e.g., dredging)
- Flushing operation will not help to increase the storage for such a large reservoir with an existing problem like in Channel reservoir
- There will be a risk of unexpected hyper-concentrated sediment mass transport phenomenon due to large sediment deposition in the reservoir that may affect the hydropower plant as well as downstream canals and headworks that could be risky (there is an example)
- Downstream replenishment requires transportation of the sediments. The volumes cannot be too large to avoid any downstream impact (given that most of the deposited sediment is fine grained materials)
- There is also a risk of collapse (slope failure) of the sediment deposition layer during flushing/sluicing operation in front of the spillways leading to severe consequences such as blockage of hydropower and canal intakes
- Sluicing and flushing may need modification in reservoir operation rules (as it appears that there is no proper consideration of sluicing and flushing operation in channel reservoir)
- The effectiveness of the flushing depends on available time and flow volumes, sediment characteristics, dam facilities and condition (which is not that favorable at the current condition)

3.4.1.3 Raising Full Reservoir Level (FRL) above design value

It is proposed to carry out technical assessments of the impact of raising the FRL of Channel reservoir above the design value by 1.5 to 2 m, i.e., raising the FRL from current level of 130 m to 132 m (max) given the crest level of dams and embankments is 134 m (as there will still be a freeboard of 2 m). This measure may help to increase the reservoir storage to 500-700 million m^3 (a detailed study is required to estimate the volume above the FRL properly).

Following activities should be carried out to ascertain the pertinence of the proposed measure:

- Precise estimation of storage above the current FRL
- Detailed dam stability assessment given the fact that increasing the FRL higher than design value will affect the structural stability
- Detailed investigation of the requirement of additional structural interventions to strengthen and enhance the stability of the dam and embankments that could be requireddue to the reservoir level rise
- Optimization of reservoir operation rule as well as proper sediment management plan and measures given the fact that the increase in the reservoir level may lead to alteration of storage allocation as well as increase in sedimentation
- Proper investigation of the effect of the FRL raising on the condition of other off-stream reservoirs in conjunction with an assessment of the potential of their enhancement and storage increase

Advantages

- Likely gain of significant storage of Channel reservoir without major intervention(s)
- Possibility to gain storage of other off-channel reservoirs as well if the conditions are favorable/feasible (requires careful assessment)
- Relatively lower financial investment

Disadvantages

- There is a risk of a stability problem for the dams, spillway, and embankments due to additional hydraulic load (this requires careful study).
- The increase in reservoir level leads to the increase in inundation extent in upstream reach.
- The measure may require additional strengthening and reinforcement of the structures
- This may increase the sedimentation, thus requires additional sediment management measures.
- The increase in the Channel reservoir level may adversely affect the off-channel reservoirs and structures.
- This measure would require changes in reservoir operation strategy.
- The capacity for peak discharge buffering is partly lowered (only 1-1.5 m of free board remains).

3.4.1.4 Pilot cases on beneficial reuse of sediment

Since all afore-mentioned solutions/measures require sediment removal (e.g., maintenance dredging), with anticipated high dredging volumes we propose to consider a pilot campaign on beneficial reuse of removed sediment. This is also given the fact that the reuse of sediments at THC is one of the integral components. Already some efforts have been made so far that are related to laboratory testing of mechanical and chemical properties of the deposited materials at Channel reservoir as well as a first test on reuse of the sediment for construction materials (bricks).

For the pilot case, we propose to test a few options of beneficial reuse for their technical, environmental, and economic viabilities as follows:

- Production of construction materials (bricks, blocks, road construction, engineered fill)
- Manufactured top-soil improvement and fertilizer additions for agriculture
- Creation and restoration of ecological zones
- River training and sediment management measures within Channel reservoir, e.g., bank protection and river training using geobags filled with removed materials; flow and sediment management using sand plugs, and earth dikes for capturing sediment and diverting flow.

All these options require the following aspects (but not limited to) to be considered properly:

- Suitability/usability of the removed materials (also for the sediment from lower deposition layers as well as from different spatial locations along the reservoir)
- Assessment of demand and supply (regional and national market assessment and economic drivers)
- Estimation of required volumes
- Investigation of possibilities for industrial set up
- Dewatering, transport and storage methods and their impact assessment
- Sediment sustainability aspects of developing these products to off-set non-renewable resources

Advantages

- Beneficial reuse of removed sediment (focus on circular sediment management)
- Solution of the problems related to the disposal of a large amount of removed sediment volume
- Availability of enough space for disposal and processing for the reuse options
- Creation of regional industries and innovative business incubators, new jobs, employment, and skills
- Social, economic, and environmental development and restoration
- There is global experience in the production of these beneficial reuse products and engineering technologies (geotubes. The THC will not be the first and will benefit from what has been done globally – hence not needing long-term verification of proposed alternatives.

Disadvantages

- Adverse environmental impacts (e.g., during transportation and processing)
- Unknown quality and usability of the deposited sediments in the reservoirs, particularly in lower layers (that were deposited a few decades ago)
- Potential ecotoxicological (habitat restoration) and human toxicological risks (agricultural use) when chemical sediment quality is not meeting (international) standards
- Sourcing other additives for manufactured soil production
- Relatively larger technical and financial investment and efforts (depending on the magnitude of reuse)
- Availability of water, required to maintain top-soil enhancement and ecological restoration efforts
- Transboundary disputes and reluctance

3.4.1.5 Non-structural measures

Non-structural measures are important to consider together with all proposed recurrent and (soft) structural measures and solutions. This should start with an inventory of available non-structural measures and systems given the fact that some of the measures, efforts and initiations could be already in place.

We can categorize the non-structural measures as essential and desired measures that may help to prioritize in case there are limitations on their materialization/application.

i) Essential measures

The essential measures are outlined as follows:

- Establishment of water and sediment monitoring, information and forecasting systems
- Development of a sediment management program
- Optimization of reservoir operation rules considering all other measures and interventions
- Regular investment on Research and Development activities in cooperation with local and regional knowledge institutions/commercial pilot activities
- Community and public education with respect to understanding the resource and how to take care and nurture it for future generations. This included public involvement in monitoring and reporting systems.

The essential measures and programs are necessary for regular monitoring and assessment of the effectiveness and impacts of the recurrent and structural measures. Such regular monitoring and assessment also help to manage and adapt the measures to improve and optimize their effectiveness as well as to minimize the adverse impacts.

ii) Desired measures

The desired measures are outlined as follows:

- Improving agricultural practices and methods (also by improving proper coordination and synergy of other ongoing and/or envisaged efforts and programs related to these aspects)
- Implementing (innovative) real-time technology(s) for minimizing water losses at the reservoirs and canals (due to sedimentation, seepage, evaporation)
- Establishing Integrated and Participatory Management (following NEXUS approach in terms of both technical and governance aspects): *This is important given that THC is a transboundary complex with multipurpose water use, thus addressing the problems requires optimal use of water resources as well as participation of all involved stakeholders, authorities, and countries.*

The desired measures would help to minimize the challenges and impacts, particularly related to dealing with water-stress problems and find a way to compensate the storage lossby saving the water resources based on other measures and endeavors.

3.4.2 Large-scale measures and interventions

Besides regular (emergency) measures for maintenance and management of sediment-induced problems at Channel reservoir, described above, we also propose a few large-scale measures (including structural measures) for further consideration. We propose three options that can be weighed against each other in terms of their technical, social, environmental, engineering, and economic feasibilities and associated impacts. Since these measures require much more resources and investment, very careful and detailed planning, preparation, and studies must be carried out.

For such measures, a high-level analysis should be sufficient at this stage to trigger the discussions with the donors (national/international) regarding the potential investment strategy/program as well as exploring possibility for preparing project scoping statement and terms of reference. International interest and participation should be encouraged since there is a wealth of expertise and equipment in dredging/earthworks riverine construction.

A set of possible options is briefly described hereafter.

3.4.2.1 Option 1: Capital dredging in Channel reservoir with beneficial reuse of sediment

Capital/or new work dredging implies the removal of a large amount of sediment from the Channel reservoir (unlike the maintenance dredging) with an aim to gain some part of the storage in complement with utilization of a large volume of removed sediment for beneficialreuse. A first proposition for the measures is as follows:

- Removal of up to 500 million m^3 (but not limited to) of deposited sediment in Channel reservoir within the period of 5 years (the volume of sediment to be removed should be optimized in complement with the analysis of reservoir inflows based on historical data and future expected scenarios).
- Large-scale beneficial reuse of removed sediment, particularly for the development of ecological restoration project (like Desert Green Economy Pilot Initiative)

Advantages
- Noticeable storage gain
- Availability of a large amount of sediment for beneficial reuse, particularly for setting up regional development programs, industries, incubators, and enterprises (investments)
- Possibilities for the ecological restoration of the area, initiatives for desert development leading to social, economic, and environmental development and restoration
- Based on the large volume of sediments that need to be removed in this campaign, there would appear to be multi-national interest in working under a long-term contract scenario with internal corporate investment.

Disadvantages
- See also pilot cases on beneficial reuse of sediment
- Large financial investment
- Significant technical efforts and requirements
- Large intervention leading to adverse morphological impacts and risks
- Noticeable investment and efforts for pre-feasibility and impact assessment
- Significant efforts, human resources, and skills, institutional set up for monitoring, management, and adaptation
- New procurement and contract mechanisms that were never regionally done before
- Unfeasible without large-scale beneficial reuse and/or placement areas adjacent to the THC
- Transboundary dispute, hurdles, and reluctance due to large-scale initiatives

3.4.2.2 Option 2: Construction and/or extension of the off-channel reservoir(s)

There are some large depressions in nearby areas (revealed by our rapid and remote exploration of the area, shown above). Consequently, following structural measures are proposed for further investigation and assessment to create 0.5-1 billion m^3 additional water storage:

- Construction of additional off-channel water reservoirs near the THC (in Uzbekistan or/and Turkmenistan), considering the availability of depressions suitable for this (within the vicinity of 25-30 km).

- Enhancement/extension of existing off-channel reservoirs
- This measure should be considered as an alternative to capital dredging, but in complement with sediment management and maintenance
- Design of sediment traps as a part of holistic sediment management program

Advantages
- Significant storage gain
- No large morphological intervention in Channel reservoir

Disadvantage
- Large financial investment
- Significant technical efforts and requirements (although there are already off-channel reservoirs, hence the experience is there unlike capital dredging)
- Morphological and ecological impacts on the main river due to significant amount of flow diversion
- Problems related to geological/geotechnical conditions, e.g., seepage, safety and stability leading to ineffectiveness, hazards, and risks
- Transboundary dispute, hurdles, and reluctance due to large intervention and water use

3.4.2.3 Option 3: Renovation/relocation of structures

As a possible alternative to the capital dredging and off-channel reservoirs (that could be as costly as a new dam project), we propose to explore the structural measures such as enhancement or even relocation of the headworks and hydropower plant given that such practices do exist as shown in section 5.3 (Chapter 5). One of the following measures can be considered for a prefeasibility assessment:

- Heightening of the dams and embankments to raise the FRL (this measure shall be assessed in complement with the measure related to raising current level of FRL above design value, proposed in section 3.4.1.3)
- Relocation of the headworks and the hydropower plant

Advantages
- The heightening of the dams will increase the storage significantly (>500 million m^3)
- Relocation of the headworks might also resolve the problem related to storage loss as well as structural safety and sustainability (almost with the similar cost as required for capital dredging or construction of new off-channel reservoirs)
- The measures can still be combined with sediment management with beneficial reuse.

Disadvantages
- Large financial investment
- Significant technical efforts and requirement, particularly for relocation of the structures
- Morphological and ecological impacts of dam relocation
- Increase of inundation area at the upstream due to the increase in the reservoir level that may lead to some social and environmental problems
- Sedimentation problem due to dam heightening that requires additional sediment management and dam operation strategy
- Problems related to stability of the structures due to dam heightening and associated risks (due to increased hydraulic load)
- Transboundary dispute, hurdles, and reluctance due to large intervention, particularly for relocation of the structures

3.5 Development of a technical concept of sediment management with beneficial reuse at THC

3.5.1 Background

We have proposed various possible structural, recurrent, and non-structural measures to deal with sediment-induced challenges at THC. In this section, we focus on the development of a sediment management program that includes sediment removal and beneficial reuse. We consider here a 1st-category problem and corresponding measures as proposed in section above. The sediment removal from the Channel reservoir as a recurrent maintenance measure is inevitable due to the high risk associated with functionality and safety of the hydro-structures at headworks (e.g. hydropower and canal intakes). Therefore, we have attempted to prepare a preliminary technical concept for sediment management with beneficial reuse for THC. This proposition is merely a preliminary technical concept based on rapid analysis of limited data and information. Therefore, it will require further enhancement based on detailed investigation and studies including feasibility and impact assessment.

3.5.2 Technical concept

A schematic flowchart regarding a basic technical concept on a comprehensive sediment management program at THC is depicted in Figure 3-13. The concept includes four main components, viz. (1) sediment removal in the Channel reservoir and canals (major maintenance measures) in complement with sluicing and flushing (supplementary measures); (2) erosion and sediment inflow management in the Tuyamuyun catchment, the river, tributaries, and the Channel reservoir (mitigation measures); (3) pilot campaign for selected options of beneficial reuse of removed sediment, namely building materials, fertilizers, top-soil enhancement, river and reservoir training measures (as a part of scoping and prefeasibility assessment); and (4) establishment of monitoring, information, forecasting and early warning systems for water (quantity and quality), sediment (quality, quantity and reuse) and reservoir morphology that are required for regular revision and adaptation of the sediment management program (non-structural measures) .

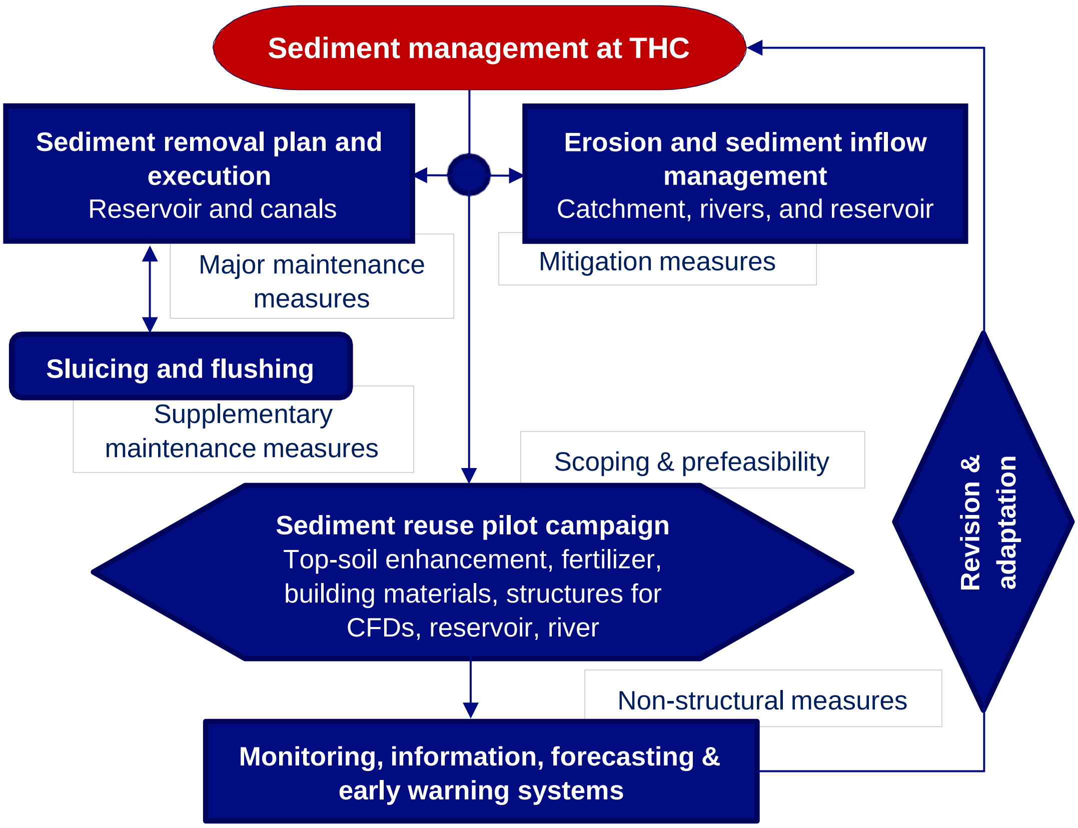


Figure 3-13 A basic technical concept of a comprehensive sediment management at THC with beneficial reuse

We briefly describe each component hereafter.

3.5.3 Sediment removal plan and execution

The sediment removal plan includes two main maintenance activities, viz. (i) sediment removal from the Channel reservoir and canals using appropriate dredging technology as a major maintenance measure (requires an urgent action and execution); and (ii) sluicing and flushing as a supplementary measure in conjunction with dredging.

3.5.3.1 Maintenance dredging plan and technology

Since the proposition is to address a 1st-category problem, the maintenance dredging should be carried out near the hydropower and canal intakes, spillways, and the intakes of the off-channel reservoirs. As a part of the sediment management effort to reduce the inflow from the upstream, some part of the upstream reservoir reach can also be dredged and partly used as a sediment trap with regular removal. A detailed design shall be made for this.

To start with a maintenance dredging plan, the tentative sediment volume to be removed (at least at the initial couple of years) as well as appropriate dredging technology should be defined. The first recommendation (describe in section 3.4.1.1) is to consider 1-2 million m^3 of annual dredging volume for first years. This t can be increased with time and gained experience. Since this should be permanent maintenance activities, the dredging technology (appropriate equipment) should be acquired by the THC authorities. This should be done in complement with 1-3 years of Operation & Maintenance (O&M) agreement with the technology developer(s) or professional dredging firm(s). This also implies developing long- term, seamless, and efficient contractual mechanisms with the professional dredging firm(s) including capacity building of local people.

Some of the options for dredging technology/equipment that could be appropriate for the sediment removal from a reservoir is depicted in Figure 3-14. The selection of the appropriate equipment depends on the hydraulic and morphological condition. The condition can be varying based on the season and with time in case a good amount of deposited sediment is removed regularly. At the Channel reservoir, a large part of the reservoir is rather shallow.
Moreover, it is most likely that there must be dry excavation (by mechanical means) as well, particularly during dry period (and upstream part). The reservoir area near the headworks (spillway, canal, and hydropower intakes), where the dredging should be carried out urgently, where the depth can vary from 2 to 4 m at the current condition. However, given that there could be up to 15 m of deposited layer, the depth will increase if the dredging is carried out properly in complement with upstream sediment management. Therefore, the equipment should be selected accordingly. It appears that there must be multiple types of technology(s) given the magnitude and severity of the problems (described in section 0). Some appropriate dredging equipment are depicted in Figure 3-15, Figure 3-16 and Figure 3-17. As it can be seen from the specifications of some of these technologies, the sediment removal production rate depends on the type and conditions of the deposited materials as well as pumping distance (there are some useful graphs showing these relationships, depicted in Figure 3-17 and Figure 3-18 for two different technology).

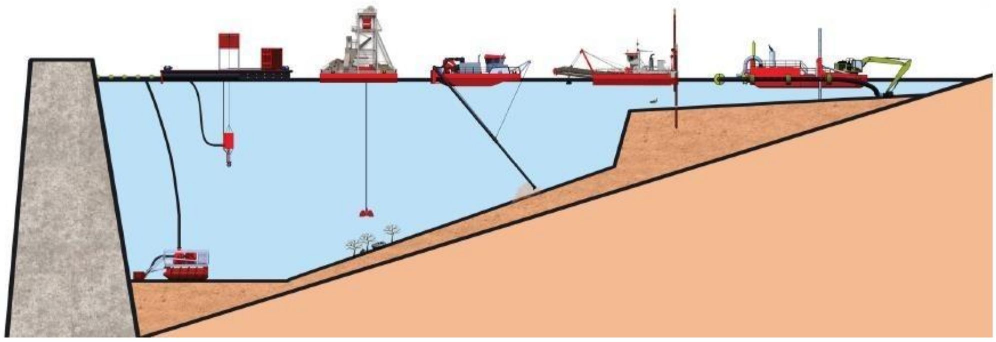


Figure 3-14 Various dredging technology for sediment removal from a reservoir based on hydraulic and morphological condition (provided by Royal IHC)

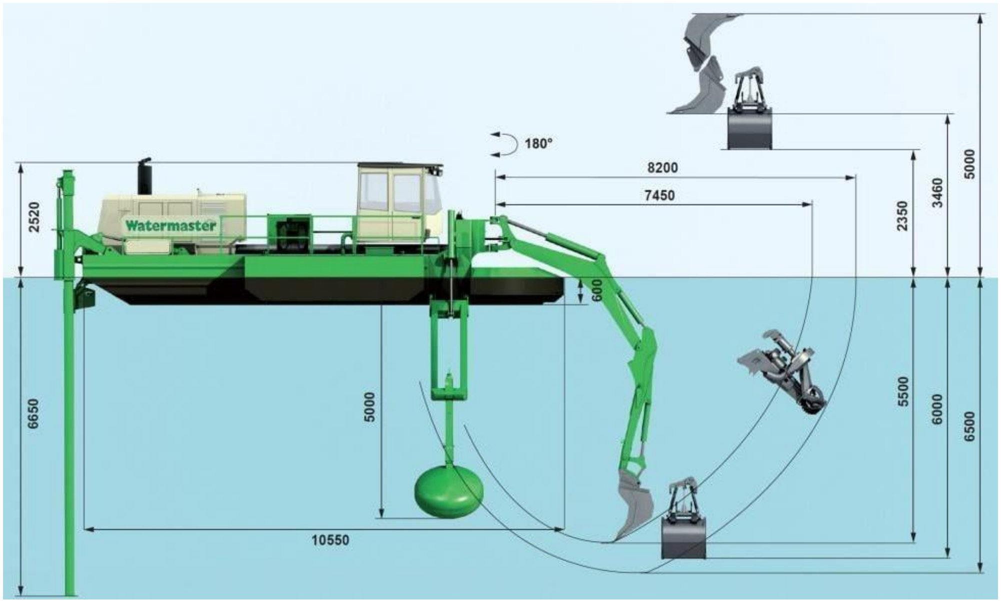
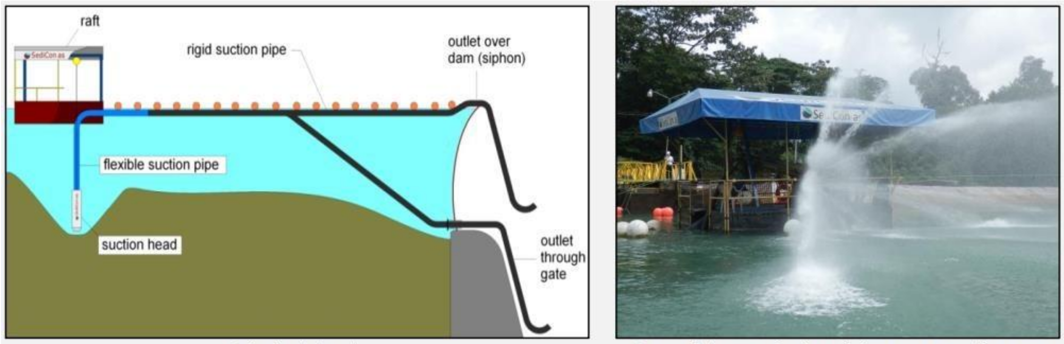


Figure 3-15 Amphibious multipurpose Watermaster – applicable for dry areas to the depth up to 6.5 m; the pumping rate is 600-900 m^3/hr (with 10-30% of solids) with max. pumping distance up to 1.5 km. The production rate is very much affected by various conditions, e.g. soil condition, pumping height and distance, presence of debris or stones, operators experience, etc. (https://watermaster.fi).

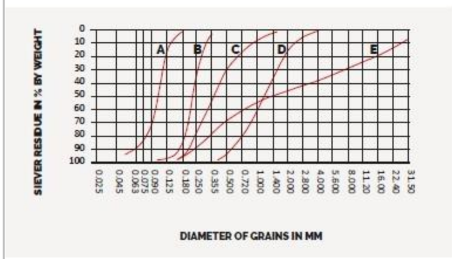


Principal sketch | Powerful water jetting disintegrates sediments

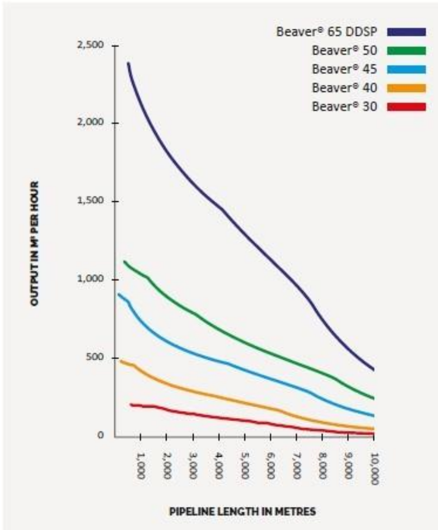
Figure 3-16 The SediCon Dredge is a hydrosuction system that uses the available water head between the reservoir and the outlet of the discharging pipe, for pumping out water and sediments (so, it does not require energy). Typical average capacity range from 50 m³ cohesive sediments per hour for 200 mm dredges and up to 1000 m³ per hour for sandy materials dredged with a 500 mm dredge (www.sedicon.no).

THE SAND TYPES AS INDICATED IN THE PRODUCTION GRAPHS ARE DEFINED AS FOLLOWS:

SAND TYPE	DECISIVE GRAIN SIZE	SITU DENSITY
A Fine sand	100µm	1,900kg/m³
B Medium fine sand	235µm	1,950kg/m³
C Coarse sand	440µm	2,000kg/m³
D Coarse sand and gravel	1.3mm	2,100kg/m³
E Gravel	7mm	2,200kg/m³



FINE SAND



TYPE OF DREDGER	AVAILABLE PUMP POWER	DISCHARGE DIAMETER	MAXIMUM DREDGING DEPTH	MAXIMUM VOLUMETRIC CONCENTRATION
Beaver® 30	250kW	300mm	6m	20%
Beaver® 40	409kW	400mm	8m	20%
Beaver® 45	764kW	450mm	10m	25%
Beaver® 50	1,258kW	500mm	14m	25%
Beaver® 65 DDSP	1,706kW	650mm	18m	30%

Figure 3-17 The production rates for various types of IHC Beaver cutter suction dredgers (provided by Royal IHC)

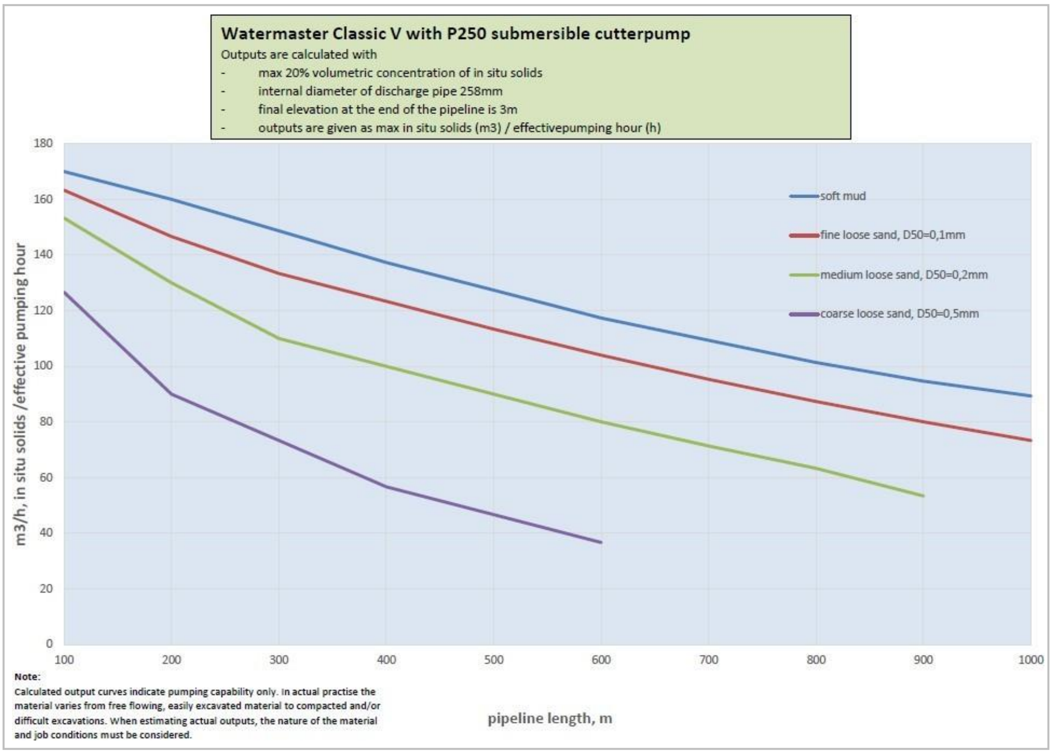
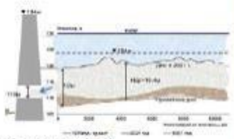


Figure 3-18 The production rates (assuming 20% of solid in total pumping volume) of Watermaster (Classic V) for various sediment type and pumping distance.

An example of selecting possible equipment and tentative estimation of the unit dredging cost for the Channel reservoir based on some parameters, assumptions, and possible requirements (volume(s) to be dredged, production target) is shown in Table 3-1. Note that this only includes the base dredging operation (with assumptions for costs of fuel/crewing/pipeline etc.) and does not include any other costs (such as costs incurred because of local law/legislation, mobilization / demobilization, overhead, local site preparation, further disposal/processing of dredged material, survey etc.). As this is only a quick scan and analysis, an in-depth analysis is advised to further investigate the data and project requirement to elaborate further on the dredging requirements and costs incurred.

Table 3-1 An example of a preliminary selection of the equipment and tentative estimation of the unit cost for the dredging at the Channel reservoir (provided by Royal IHC)



Project location :	Tuyamuyun Hydro-Complex Turkmenistan	
coordinates:	41.211768°, 61.405978°	
water depth in dry season [m]:	5	
water depth in wet season [m]:	10	
dredging layer {m]	12	
elevation up to {m}	4	Standard value, no details provided
max pumping distance [m]	500	Assuming disposal of material is possible onshore close to dredging area
material type	MEDIUM FINE SAND	
Volume to be dredged [m3]:		
Phase 1 volume to be dredge year 1:	2,000,000.00	Maintenance dredging close to the dam (length of channel to be dredged unknown)
Phase 2 volume to be dredge year 1:	20,000,000.00	Capital dredging to 10km upstream & downstream of the dam
Operational indicators:		
Operational hours per day [h]	24	Working 2 shifts of 12h each
Effective pumping hours per day [h]	16	Taking into account (minor) delays for crew change, cutter operation etc
days per week	7	
week per year	40	
operational factor	0.75	
ANNUAL PRODUCTION TARGET PHASE 1 [m3]	2,000,000.00	

	TTPump 30-250	**Beaver 45**	**Beaver 50**		**Beaver 65**
			standard version	extended ladder*	
estimated production according to given parameters [m3/oh]	350	700	1000	900	1500
annual production [m3]	1,176,000.0	2,352,000.0	3,360,000.0	3,024,000.0	5,040,000.0
time to close the project (2MLN m2 to be dredged) [year]	1.7	0.9	0.6	0.7	0.4
dredging depth [m]	10	10	14	17*	18
price per unit [Euro/m3]			1.81	1.98	1.66

* standard dredging depth extension is -2m, but can be further extended to reach -17.0m. Additional analysis is advised with regards to the pump performance and the material to be pumped

3.5.3.2 Sluicing and flushing operation

Some general descriptions on sluicing and flushing operations have been provided in section 3.2.1.2. Under the current condition of a large deposition near the undersluices and intakes, it is risky (and maybe even not possible) to carry out active sluicing and flushing operation. Consequently, before any flushing operation and planning, the sediment must be properly removed from the areas near the dams and intakes. The dredging should be carried out in a way that the exposed slope of the deposited layer should not be steep to prevent collapse of deposited layer (e.g., during sluicing or flushing, or even just under the hydraulic pressure during full reservoir level). There is a proposition for reservoir operation to facilitate the sluicing of the incoming sediment and flushing (as shown in Figure 3-19). However, this appears rather rough that requires proper analysis (e.g., using hydraulic and sediment modelling). The sluicing and flushing operation will be required and useful to improve the effectiveness of the sediment removal efforts and to maintain the functional requirement neardam areas in future as well. Nevertheless, these operations should be planned and studied properly before their execution. There are several examples about how to perform it. The operations should be carried out and monitored carefully to avoid any unforeseen impacts leading to hazards and risks for the intakes, hydropower plant and canals.

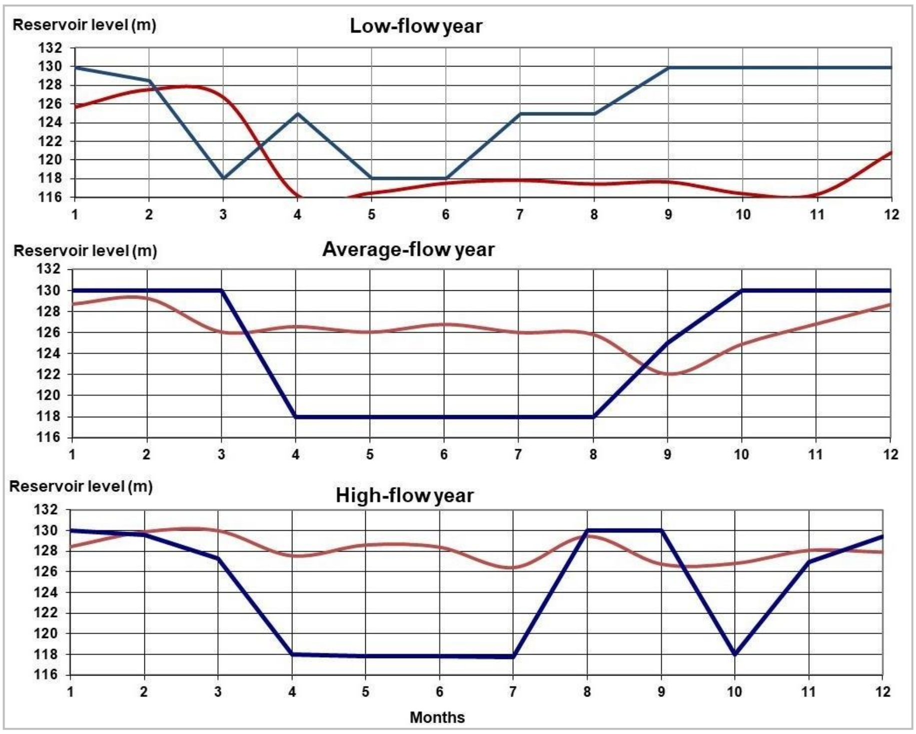


Figure 3-19 Proposed reservoir operation based on monthly-averaged reservoir level for high-, average- and low-flow years (M. Ikramova, 2021)

There are ill examples of sediment and ecological disasters due to flushing operations that were carried out without proper investigations on quantity, quality, and conditions of deposited sediment. For example, the flushing of a reservoir in India ended up with a huge sediment disaster. The deposited amount was large, thus the slurry during flushing got highly concentrated. It behaved like a fluidized sediment mass (or like hyper concentrated turbidity current). Moreover, there was an unforeseen trouble with the clogging of the undersluices (apparently due to the hindrance, induced by some debris), which led to the mass of sediment bursting towards the powerhouse (which is located on left side of the spillway similar to the t THC). The powerhouse area was covered with large volume of sediments, andthus the power generation had to be stopped for a considerable period.

Figure 3-20 gives some impression about the aftermath. There is another ill example of an ecological hazard caused by the flushing of a reservoir. The incident caused by the uncontrolled flushing of Kallarkutty reservoir in Kerala without proper assessment of sediment quantity and quality. The flushing operation resulted in an ecological disaster causing pollution of the downstream reach of the river Periyar, and thus obstructing the water supply for several months as well as affecting the aquatic life (Giri et al., 2019). Some other examples are presented in section 5.2 (Chapter 5).

Figure 3-20 Sediment deposited in (left) and around the powerhouse (right) as a result of a sediment hazard during flushing operation at Pillur reservoir in India (Giri et al., 2019)

3.5.4 Sediment reuse pilot campaign

Another important component of the proposed sediment management program is the development of a sediment reuse pilot campaign. The beneficial reuse of removed sediment will make the sediment removal option more efficient and sustainable. Since there is not yet much clarity about the feasibility of the reuse options, it is proposed to prepare a plan for a sediment reuse pilot campaign. There are some results of small-scale testing and experiments, but such a pilot campaign will help to determine the technical, economic and environmental feasibility of the beneficial reuse of removed sediment from the Channel reservoir and canals on a larger scale. The ability to commercially scale-up these beneficial use options is critical.

3.5.4.1 Sediment reuse options

For the pilot campaign, the following sediment reuse options shall be considered:

i) Manufactured top-soil enhancement (improving agricultural area and creating ecological zones)
ii) Fertilizer production
iii) Construction material (bricks, blocks, engineered fill) production
iv) Training/guiding earthen structures (e.g., embankments, dikes, sand plugs) for constructing disposal facilities, guiding flow and sediments in the reservoir and river

The options can further be prioritized based on additional information, conditions as well as technical and financial resources and convenience for the pilot campaign.

3.5.4.2 Transport, disposal, treatment, and processing

Confined or unconfined disposal facilities ((U)CFD) shall be built for the placement of removed sediments, their treatment and processing, e.g., dewatering and testing facilities depending on the selected reuse options.

At a first glance (exploring Google Earth), we see a couple of areas for the pilot campaign as shown in Figure 3-21. These areas are near to the headworks, i.e., and near the major maintenance dredging area in the reservoir. Consequently, the transport distance is less, thus enabling to use a slurry pipe and return flow after dewatering (an example is depicted Figure 3-22). The part of the (U)CFDs can be developed as agricultural and ecological zones. Part of the placement area can be used as a processing staging and production area (i.e., forfertilizer and construction materials).

Figure 3-21 Two possible areas (indicated by green polygons) for disposal, treatment and processing near the headworks (further detailed in-situ investigation is required)

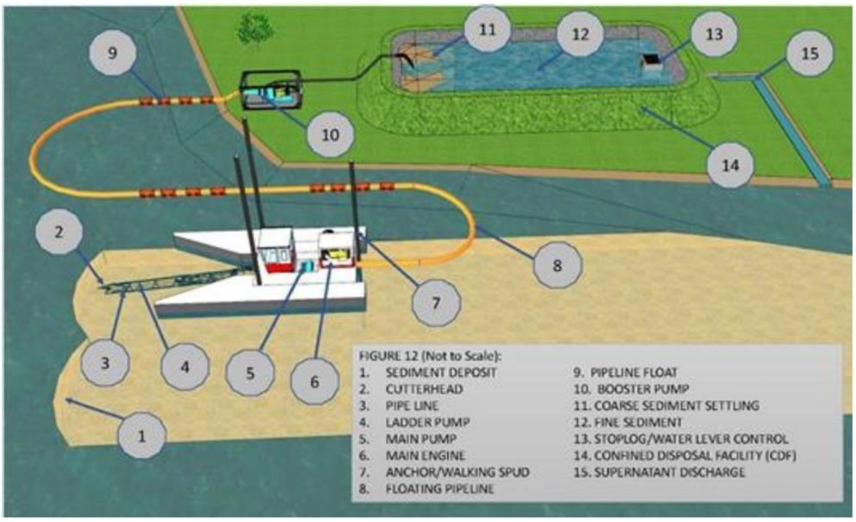


Figure 3-22 An example of dredging, transport, disposal (at CFD) and dewatering set-up (Source: J. F. Brennan)

The Pneumatic Flow Tube Mixing (PFTM) for sediment processing and reuse Stabilization of soft sediments similar to what is found in the THC to produce a structural and/or non-structural beneficial use product that has the consistency of a stiff clay engineeredfill material could be of value as part of a beneficial reuse program. The PFTM system is a rapid construction technique for stabilizing, transporting, and placing reclaimed dredged materials, soft soils, and mud, which allows for their beneficial use as structural and non- structural fills (Figure 3-23 and Figure 3-24).

It can be used on land or offshore (within rivers and canals) and is especially well suited for the reclamation and processing of contaminated (or non-contaminated) dredged materials from large scale navigational and remedial dredging projects. Prior to the development of this method, stabilization of dredged sediment and soils required special mixing plant vessels or cumbersome on-land processing plants. With the PFTM System, on-site pneumatic conveying capabilities, requiring ordinary equipment and facilities, can be used to simplify the mixing process within a small footprint. The process itself is enclosed in a tube to minimize spillage, and odors. It has also been shown to eliminate the expensive and environmentally problematic disposal of dredged sediments while simultaneously providing an economical and effective beneficial use application for engineered structural fill purposes.

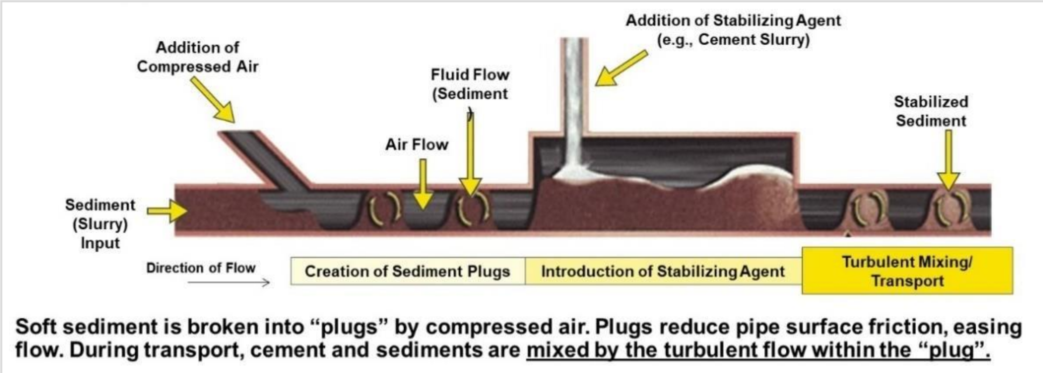


Figure 3-23 PFTM mechanism (Kitazume, 2002)

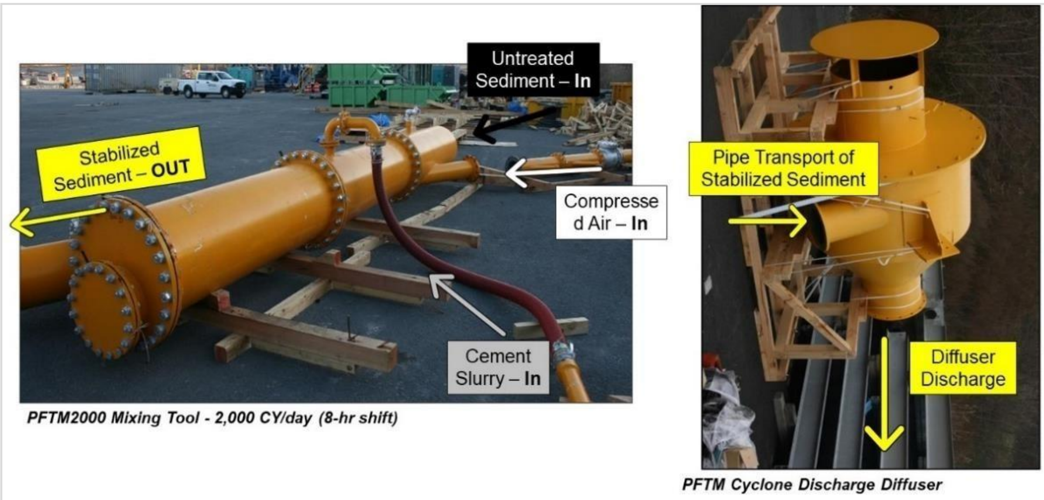
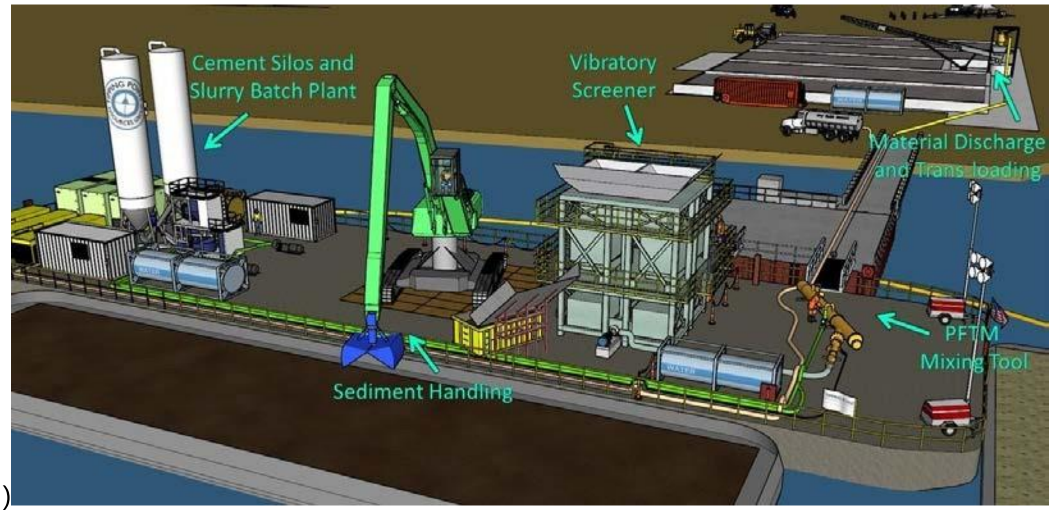


Figure 3-24 PFTM process equipment

Figure 3-25 Processed sediment using PFTM

The PFTM process produces a high-quality beneficial reuse fill (i.e., uniformly amended with Portland Cement or other binders like furnace slag or cement kiln dust)) that can be used for both environmental and structural purposes. Beneficial reuse or disposal/placement options are project specific and can include, brownfield development, bulkhead backfills, landfill covers, sub-base in roadway construction, coastal protection (berm construction) and shallow ground improvement as well as land reclamation. The PFTM system has processed over 20 million cubic yards (≈15.3 million m^3) of sediment in Japan for the construction of airports and land reclamation projects in the marine environment. This cement stabilization process can be operated on land or barge, with the ability to process and pump stabilized sediments up to3000 feet (or further with booster pumps) for structural and non-structural beneficial reuse. A schematic of a barge mounted PFTM mobile operating system is shown in Figure 3-26.



)

Figure 3-26 Barge-mounted PFTM Operations: Mobile Operating Sediment Engineering System (MOSES)

Developed in the early 2000’s in Japan, the method has been used extensively in projects of all sizes and scopes including offshore reclamation for the construction of the Tokyo Haneda International Airport Runway, Osaka International Airport, Nagoya International Airport, and within numerous harbors in Japan (Figure 3-27). The stabilization process is entirely enclosed from the time when it is loaded until the stabilized material is discharged from the system. The PFTM System received dredged materials similar to other stabilization systems; a scow containing dredged material is brought to the process location. The scow is unloaded via excavator and loaded into a grizzly and sediment size separator.

Due to the small size of the PFTM System (less screening is necessary for larger systems) the grizzly will require a 2-inch vibrating screen underneath in addition to the standard 6-inch bar screen.

The PFTM System mixes sediments with designated binders in a pipe via compressed air, during transportation from a source to the final placement site. The mixture of soft sediment and binder (cement) forms many separated mud-plugs in the pipe, and these are thoroughly mixed during transport via turbulent flow (short distance) generated within the plug. The soft sediment stabilized with binder has rapid increase in strength, and the strength of stabilized sediment can be easily controlled by changing the amount of binder and water content of the sediment through a real-time computer monitoring system. The sediment mixture deposited and cured at the site can gain relatively high strength rapidly so that no additional sediment/soil improvement is required. Transport of soft sediment in a pipe without any amount of air requires high pressure to compensate for friction generated along the inner surface of the pipe. When pulses of compressed air are injected into the pipe together with soft sediment and the binder, the mixture is separated into small plugs. The plugs are then pushed to an outlet. The formation of plugs reduces the friction along the pipe's inner surfaceand can considerably reduce the air pressure required for transport. The air pressure required for transporting sediment depends upon many factors such as sediment properties, injected air volume, pipe diameter and length. In the current practice, an inlet air pressure of 400 to 500 kPa is used. The plugs are transported at speeds exceeding 10 m/sec in the pipe resulting in turbulent flow within the plugs due to the friction along the inner pipe surface which mixes the sediment and binder. PFTM has been used for a variety of sediment types with varied effectiveness. It has been shown to work well for fluidized highly organic, silty claysediments with water content in the range from 50% to 200%.

Figure 3-27 Examples of artificial island in Japan (upper images), built using PTFM technique (lower image shows the workflow and features of dredged sediment recycling system (Giri et al., 2019, internet source)

3.5.4.3 The examples of dredged sediment placement facilities

One of the key requirements for the beneficial reuse pilot campaign is the preparation of the dredged sediment placement facilities, e.g., confined or non-confined disposal facilities (CDFs). The facilities may be an upland or in-water structure. We demonstrate here a couple of global examples and practices that could be useful to consider for the THC.

However, the design, execution, and monitoring of the pilot sediment placement facilities at the THC should be very specific based on detailed investigation of various local conditions and nuances (technical, economic, social, and environmental). Some other global examples are shown in 5.4 (Chapter 5).

1) Great Lakes dredged material placement facilities (USA)

The US Army Corps of Engineers has constructed several sediment disposal/placement facilities around the US Great Lakes since the late 60's for the disposal of contaminated and non-contaminated dredged materials from various navigation projects. They are located in several areas around the Great Lakes/harbors and ports. They are constructed at upland sites, in open water, near the shore and as CDF (Figure 3-28). A Fact Sheet for one of the CDFs at Toledo Harbor in Ohio is described. Hr - Island 18 (see the reports, prepared by Hull & Associates, provided with this report):

- Island 18 (also known as Grassy Island) is an in-water facility in Toledo, Ohio, located in Maumee Bay northwest of the mouth of the Maumee River.
- Local sponsor is the Toledo-Lucas County Port Authority.
- CDF area: 150 acres with a total capacity of 5,000,000 y^3 (3.8 million m^3)
- CDF constructed in 1961-62 as part of new work project (cost not available). Dikes subsequently raised for disposal of maintenance dredging. New dikes constructed in 1977 on top of existing fill at a cost of $5,000,000 USD.
- Dike design is an earthen dike using new work dredged material and previously maintenance dredged material
- Dredged material placed in CDF from hopper dredge by pipeline.
- CDF dewatered by discharge from overflow weir and dike seepage to Lake Erie.
- Effluent treatment by primary settling and filtration in dike core.
- Water quality impacts evaluated during pilot program (US Army Corps of Engineers Buffalo District 1969).
- Local sponsor plans to use site for recycling of dredged material.

It was extended in 1994 (Toledo Harbor Site 3 – Cell 2 CDF) as shown in Figure 3-29. Here are some facts about the extended CDF:

- Toledo Harbor Site 3 – Cell 2 CDF has an area of 155 acres, with a total capacity of 5,300,000 cubic yards (around 4 million m^3).
- Testing and analysis have indicated that the majority of the Maumee Channel sediment is suitable for open lake placement making the future need for CDF capacity very limited.
- Non-Federal interests may use this disposal facility if it is determined that the capacity to be used by the non-Federal interest will not reduce the availability of the disposal facility for Federal navigation project purposes, that the material is environmentally acceptable, and after payment of a tipping fee.
- Direct transportation access to the CDF is available via road and water.

There is a whole list of CDFs in the report. Some of them are listed in Table 3-2, which provides some features and tentative costs of the facilities. The full list is provided in the report.

A CDF can serve as a storage facility for large volumes of dredged sediments from the THC. It provides needed storage capacity for Capital and maintenance dredging to proceed. Dredged material that is placed in the CDF can also be mined out for beneficial use alternatives thus extending the longevity of the CDF.

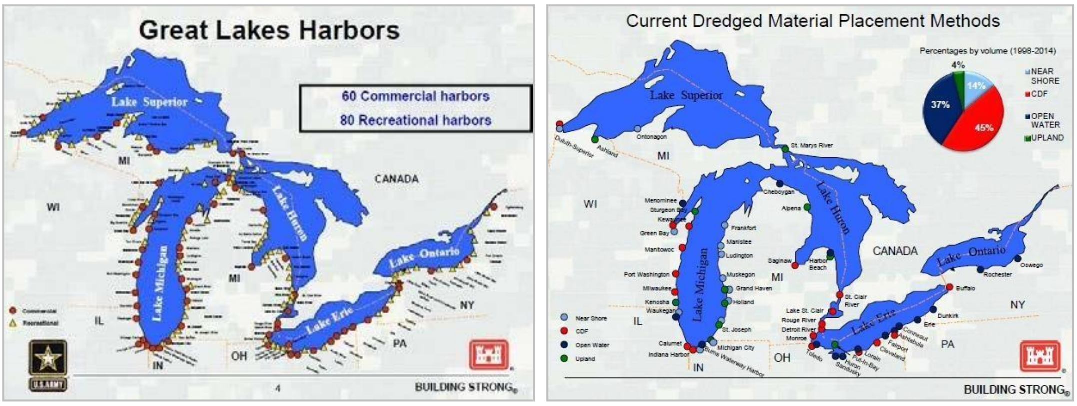


Figure 3-28 Great Lakes harbours (left) and the dredged material placement location and methods (courtesy: D. Romano, 2015)

Figure 3-29 One of the Great Lake CDFs (extended in 1994) at Toledo harbour - Island 18

Great Lakes Dredged Material Center for Innovation

This is an exemplary endeavor that can well be adapted for the THC as well. This specific program on piloting beneficial reuse of dredged sediment was started in 2016 by the Toledo-Lucas County Port Authority with the support of a 2.5 million USD grant provided by Ohio Healthy Lake Erie Fund including cooperative partnerships between the Ohio EPA, ODNR, Port Authority, City of Toledo and US Army Corps of Engineers. The impetus for this project stems from the fact that dredged material disposal in Lake Erie ceased in 2022 and upland placement was needed. Dredged sediments need to be considered as a resource and not as a waste.

The Port of Toledo dredges about 6 to 8 million m^3 of material dredged annually from the shipping channel. This is a research project that is supposed to help to explore the beneficial reuse of dredged materials (that otherwise simply disposed of at in-water sites). The program evaluated dredged material placement, materials handling, dewatering, the use of the dredged sediments as interim cover for crops, soil amendments, and other testing, operations and maintenance activities necessary to plan for the full-scale implementation of the beneficial use of dredged materials for agricultural and blended soil product purposes (Hull & Associates, 2018). This also demonstrate as an example of public-private partnership.

As per the report by Hull & Associates (2018 - see the report for the details), This grant was provided for design, permitting and construction of various cells (Figure 3-30) associated with following research activities and investigation:

- *Agricultural Technology Field Testing Area*: Four 2.5-acre cells to demonstrate and analyze the feasibility of enhancing agricultural fields with dredged material. The cells canbe used independently to evaluate various treatments or amendments, consolidation rates, plantings, etc.
- *Edge-of-Field Treatment System Research Area*: An underdrain tile system installed in the cells to drain water into an edge-of-field treatment system. This water management and treatment system can support future nutrient runoff reduction research.
- *Blended Soil Production Area*: Dredged materials can be blended with other materials, including leaf compost from the city of Toledo's composting facility. A Materials Certification Program is supposed to be established to ensure that appropriately prepareddredged material-based blended products are acceptable for unrestricted public and commercial uses.
- *Mooring Area*: Improvements may be made at the riverfront for a dredged material offloading area.
- *Site Access and Infrastructure*: Potential improvements include an access road upgrade/extension, water and sewer extensions, and security fencing and gates.

Some other facts are outlined as follows:

- Dredged material is supposed to be transported from barges to the cells by hydraulic means where the material will be consolidated and dewatered using the drainage system and edge-of-field treatment system.
- A mooring and bulkhead structure may be constructed to accommodate hydraulic or mechanical offloading.
- The facility is initially supposed to accommodate approximately 100,000 cut cubic yards (76,000 m^3) of dredged material.
- Ramped up production of blended soil product could facilitate a significant volume of material leaving the site once the Material Characterization Program is established and placed dredged materials are dry enough and ready for processing.
- Dredged materials were anticipated to be placed over the two years. Future site activities and analyses were anticipated to extend beyond the completion date of the Healthy Lake Erie Fund project.

Figure 3-30 Various cells for the placement of dredged materials

Table 3-2 Some of the CDFs at Great Lakes (Hull & Associates, 2018)

CDF Name[1]	Navigation Projects Served	State	Type[3]	Year Built	Size (acres)	Initial Design Capacity[4] (cu yd)	Percent filled[5]	Authority[6]	CDF Construction Cost[7]	Existing or Planned Uses After Filling	Status
Sebewaing Harbor	Sebewaing Harbor	MI	U	1979	9	84,000	100	Sec 123, PL 91-611	$1,300,000	airport expansion	last used in 1988
Sebewaing Harbor - Marina Site	Sebewaing Harbor	MI	U		11			Provided by sponsor			active
St, Clair River - Dickinson Island	St. Clair River and Channels in Lake St. Clair	MI	U	1975	174	2,000,000	71	Sec 123, PL 91-611	$5,072,000	wildlife area	active
St. Joseph Harbor - Malleable Site	St. Joseph Harbor	MI	U	1978	15	35,000	100		$173,474	private land	material removed from site
St. Joseph Harbor - Whirlpool Site	St. Joseph Harbor	MI	U	1978	14	25,000	100	Project specific O&M	$638,000	tranfer site	last used in 1999
Toledo Harbor - Island 18	Toledo Harbor	OH	I	1961	150	5,000,000	92	provided by sponsor	$5,000,000	wildlife area	last used in 1978, although capacity still remains
Toledo Harbor - Riverside Park	Toledo Harbor	OH	U	1961	150		100	Project specific O&M			last used in 1961
Toledo Harbor - Site 3	Toledo Harbor	OH	L	1976	242	11,100,000	98	Sec 123, PL 91-611	$18,400,000	wildlife area	active
Toledo Harbor - Site 3 Extension	Toledo Harbor	OH	L	1994	155	5,300,000	0	Project specific O&M	$4,800,000	wildlife area	active
									$297,796,474		
Legend											
1 - CDF name is that most commonly applied, not necessarily a formal title											
2 - Federal navigation project from which material was dredged											
3 - CDF types (L = in-lake site attached to land; I = in-lake island; U = upland site)											
4 - Planned capacity of CDF at time of construction											
5 - Percent filled, based on adjusted capacity estimates											
6 - Authority for CDF construction. Bayport CDF expanded by non-Federal sponsor with local funding and grant from EPA											
7 - Contract cost for CDF construction, not inflated to current value. Does not include planning and design costs. Some early CDFs were developed by non-Federal interests for limited or one-time use, and construction costs are unknown.											

2) Confined Disposal Facilities (CDF) in the Slufter (The Netherlands)

The Port of Rotterdam must conduct regular maintenance dredging with an annual volume removal of 12-15 million m^3. A large amount of the dredged sediment (mostly clay and silt) is contaminated that must be disposed in a CDF. De Slufter is a nearshore CDF close to the Port of Rotterdam (Figure 3-31). Started as a diked, subaquatic nearshore CDF 25 m below sea level in 1987, twenty years later it's been filled to sea level and in the future will be filled to 25 m above sea level. At present, sand separation and clay production for beneficial reuseare taking place. This could offset some costs (Pianc Working Group Envicom 5).

Some more facts and figures about the CDF De Slufter are outlined as follows:

- Operational since 1987
- Partnership between the Port of Rotterdam Authority & Ministry of Infrastructure and Environment. The CDF is managed by the international dredging company Boskalis.
- Area approx. 260 ha (2.6 km^2) and storage capacity is 150 million m^3
- Sediments are from two major rivers (Rhine and Meuse), placed into the CDF
- Contaminated sediment is also stored.
- Energy-producing windmills are installed on the dikes.
- Upon completion of the embankments, special grass was planted to prevent erosion. On the seaside of the facility a recreational area was created, compensating the loss of existing recreational facilities. On top of the embankments an inspection road (approx. 6 km long) was built with public viewing points into the pit area.
- South of De Slufter a nature reserve was created, which gradually became vegetated and attracted various species of birds.
- Dry parts of the facility are frequently used as breeding grounds by birds (seagulls, ducks, and other shore birds). This can sometimes impede operations on the site.
- A monitoring system was installed to check the mobility of the contamination.
- Dredged sediment from Belgium and Germany is also stored (interest from other countries, namely UK, Sweden, Denmark, Ireland)
- The total cost of constructing the facility was about 68 million €. Operating costs run at approx. 9 million € per year and are independent of the quantity of material that is disposed of. The costs of the discharging barges or dredgers are not included in this figure. The costs of keeping the equipment on site up-to-date, after treatment and the execution of several tests are also omitted. All included unit costs shall remain well below 4.5 €/m^3. The average cost of treating sandy materials by using the mechanical sieve was 11 €/tds. Use of the sedimentation basins added 2.7 €/m^3 to the total cost.

Figure 3-31 A top view of De Slufter (left GE image) and sedimentation basin and clay production fields (right image - Pianc Working Group Envicom 5)

3.5.5 Erosion and sediment inflow management

3.5.5.1 Catchment erosion and treatment

Catchment degradation is one of the main reasons for high sediment yield, transport, and deposition. As found in previous studies (Rakhmatullaev et al., 2013), in Amu Darya basin, the land degradation resulted in desertification, loss of biodiversity, land salinization and overgrazing of land. In Uzbekistan, the common forms of erosion are mainly wind and irrigation. As reported in Rakhmatullaev et al. (2013), wind erosion is particularly dominant in desert regions of Khorezm, Bukhara and Karakalpakstan. The erosion by water and irrigation has increased due to the improper irrigation methods and to the increase of irrigated areas onsteep slopes. In addition, the main contributing factors are deforestation and overgrazing (UNESCO, 2000). Nowadays, wind erosion has dramatically decreased by 50% against the 1980s due to preventive action plans by vegetation strips around irrigated areas but the specific losses of humus layer over a season due to erosion can still reach 80 t/ha (UNDP, 2007). Similarly, it was reported (UNEP, 2005) that about 75% of the total number of mudflows in the CA region occurred in Uzbekistan. Various mitigation measures have been used in Uzbekistan such as the implementation of vegetation strips, terracing on steep slopes, implementation of engineering erosion preventive structures and the application of conservation tillage techniques (Rakhmatullaev and Le Coustumer 2006; Rakhmatullaev et al. 2008b). Dust clouds in eastern Uzbekistan are largely loess related, but in the west dust material is raised from the drying Aral Sea bed; this is mainly composed of clay minerals agglomerated material and can carry on dangerous pollutants (Rakhmatullaev et al., 2013).

One of the options of beneficial reuse of removed sediment from the Channel reservoir can be used for desert greening, afforestation, and improvement along the reservoir (e.g., using low-water-demand trees and shrubs - Figure 3-32) will also help to reduce the wind erosion. Several erosion and sediment transport control methods and soft measures can be used for reducing the sediment yield from upper catchment and tributaries (Figure 3-33).

Figure 3-32 Desert greening for wind erosion control

Figure 3-33 Some examples of (soft-structural) catchment and river sediment management measures

3.5.5.2 Erosion and sedimentation management in river and reservoir

The transport of the sediment due to riverbed and bank erosion as well as propagation of deposited sediment at the upstream reach also appear to be the cause of sedimentation at the reservoir (particularly near the dam). For example, a large amount of sediment deposition was found at the upstream part of the reservoir in 2008 that eventually propagated towards the dam in 2021 (see section 0). This means that apart from the sedimentation due to the settlement of suspended particles, the transport of bedload from upstream reach of the reservoir towards downstream (towards headworks) is also a major problem. This can be minimized by trapping and/or diverting them at the upstream and removing on time so that they are not transported downstream towards the dam and intakes. The erosion and transport of sediment from upstream part can be managed by using some soft erosion control and trapping structures (e.g., using the deposited materials). This should be studied and designed in a proper way. Moreover, some baffles and guiding soft structures can be built along the reservoir to redirect, trap, and remove the sediment to reduce the downstream transport. Sediment traps can possibly also work in this environment.

After the maintenance dredging near the dam area is performed, it is necessary to prevent the transport of bedload towards the intakes. This can be done using various soft structures such as eco-friendly bottom screens and barriers. However, the effectiveness of such measures should properly be studied. An example is shown in Figure 3-34.

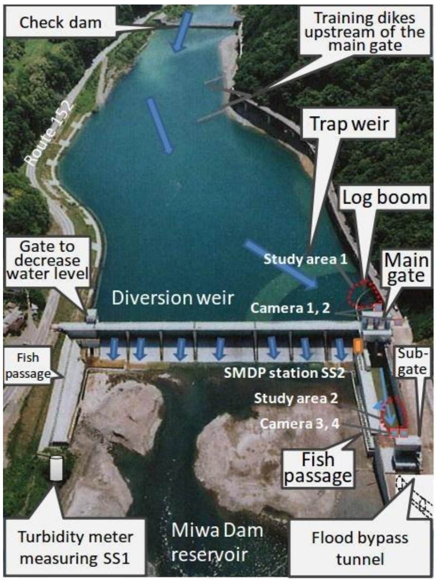


Figure 3-34 Sediment management and monitoring measures at Miwa dam in Japan (Kantoush et al., 2011)

3.5.6 Monitoring, information, forecasting and early warning systems

The regular and systematic monitoring in the catchment, river and reservoir reaches is an important component. The monitoring and measurement should be comprehensive that includes various processes and parameters in various spatial (from catchment to river and reservoir reaches) and temporal resolution and frequency (Figure 3-35). However, only monitoring and collection of data will not add much values if they are not properly managed, stored, analyzed and utilized for the purpose of improvement and adaptation of measures. Moreover, the data should be used to establish an information, forecasting and early warning systems in conjunction with some prediction methods, e.g., empirical, data-driven and/or physics-based computational models. Such real-time early warning systems can be used for not only dissemination of the information but also for decision-making processes during critical situations.

There are already some observation stations along the Amu Darya and at the THC for collecting regular data associated with rainfall, flow, reservoir level and sediment transport (concentration). Also, the reservoir bathymetry has been measured a few times. However, there is not much information on the spatial and temporal resolution of the observation, how automated the data collection and management systems are as well as the quality and frequency of their processing, analysis and utilization. This must be explored first. There are advanced measurement instruments for automated and real-time observation (e.g., for high-frequency observation of rainfall, water levels, discharge, sediment concentration). Also, there are several tools and information systems (open-source) that can be applied for not only management and dissemination of the data and information, but also to incorporate prediction methods., Models to be used as forecasting and early warning system such as Delft-FEWS (Forecasting and Early Warning System), developed by Deltares are also employed. The system Delft-FEWS can incorporate all kinds of data from various sources (e.g. freely available global data, ground data in real-time or standalone mode) in an automated way. The tool also includes various statistical analysis packages and tools, and the possibility to incorporate prediction methods and models (Figure 3-36). The Delft-FEWS are being widely used not only as an information and operational system but also as a forecasting and warning system in both standalone and real-time mode.

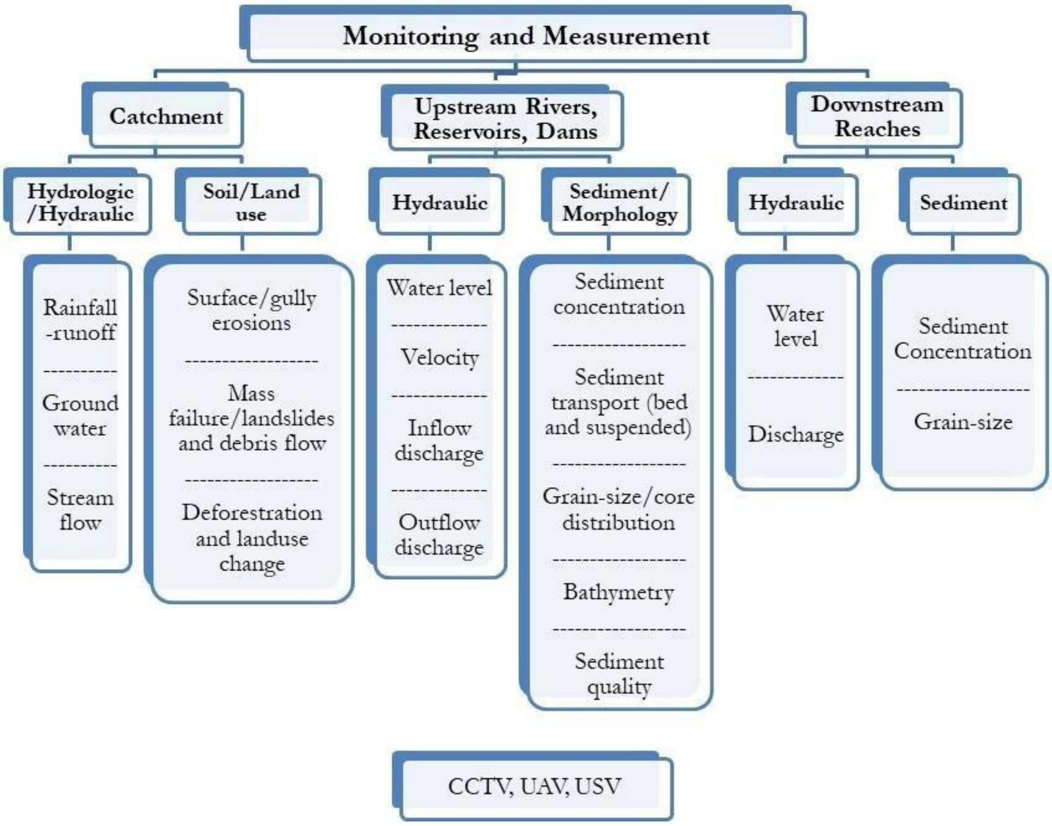


Figure 3-35 Some of the quantities that should be monitored and measured (Giri et al., 2019)

For the case of THC, such a system like Delft-FEWS can be adopted first to automatize the monitoring, data management and analysis part (e.g., for rainfall, water levels, discharges, sediment concentration data). Subsequently, the catchment hydrology and overland erosion models (conceptual and/or physics-based), the river flow and sediment transport models as well as a reservoir operation and morphological model for the Channel reservoir can be developed and incorporated in the system. This is to be used for operational and prediction purposes that will be very helpful for adaptation of the sediment management measures as well as for decision-making processes. A few examples are shown in Figure 3-37 and Figure 3-38.

Similarly, in a sediment management handbook (Giri et al., 2019), an approach has been described that includes procedure and required reporting and documentation related to development of a Reservoir Morphology Information System (RMIS). This is based on good practices and the longstanding experience of US 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 US Geological Survey on setting up Reservoir Sedimentation Survey Information System (RESIS) (Ackerman et al, 2009).

Having such a system is required and very useful for the THC regardless of what kind of measures (maintenance or/and large-scale) are implemented. This is an important non-structural and adaptation measures that will help to deal with the problems related to flow (flood and drought) and sediment management at the THC.

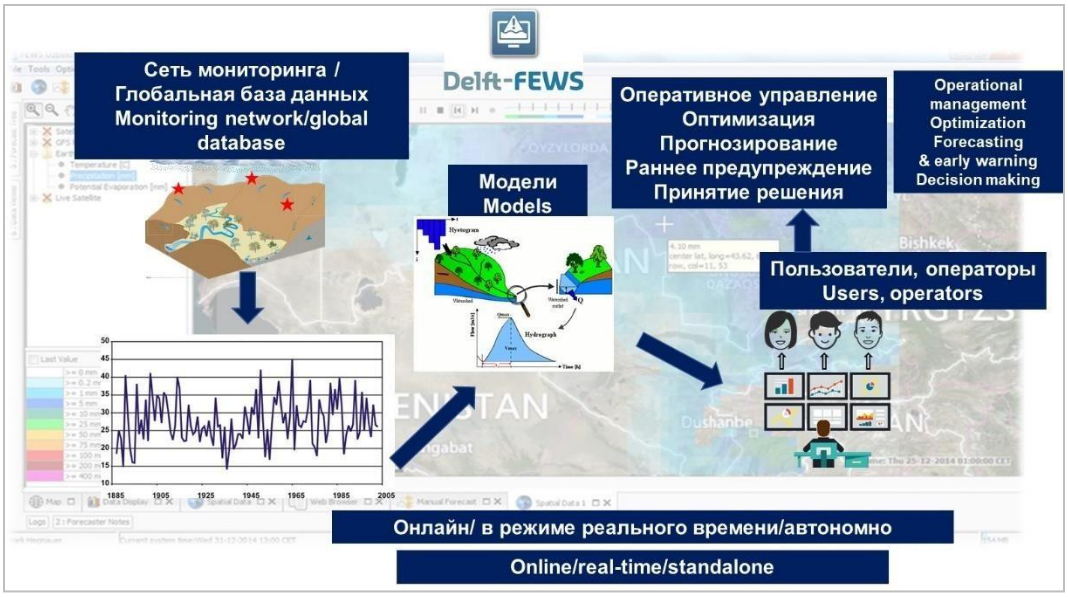


Figure 3-36 Basic principle and components of Delft-FEWS

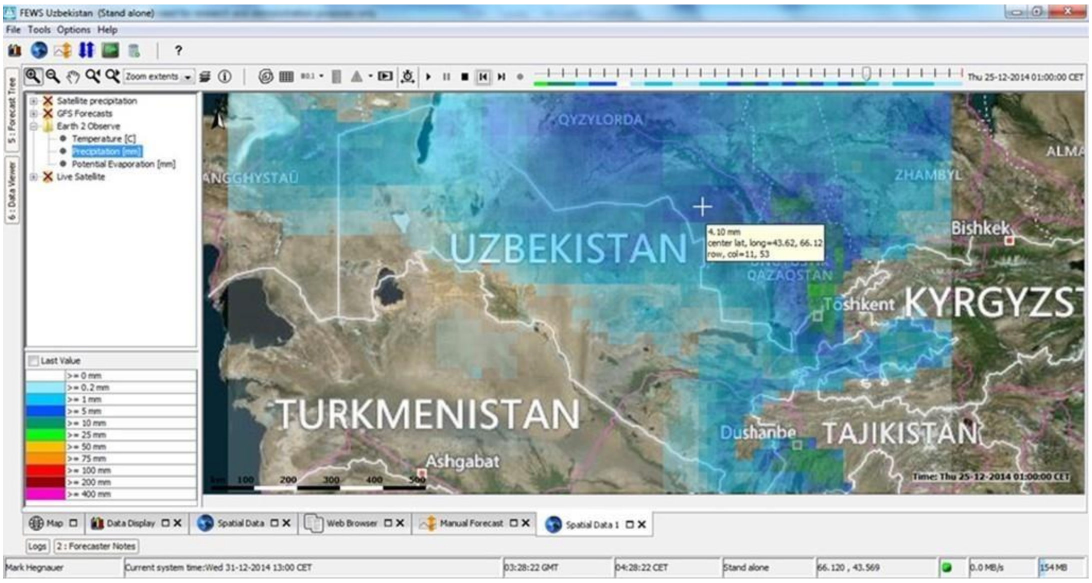


Figure 3-37 An example of adaptation of Delft-FEWS as water information system for Central Asia

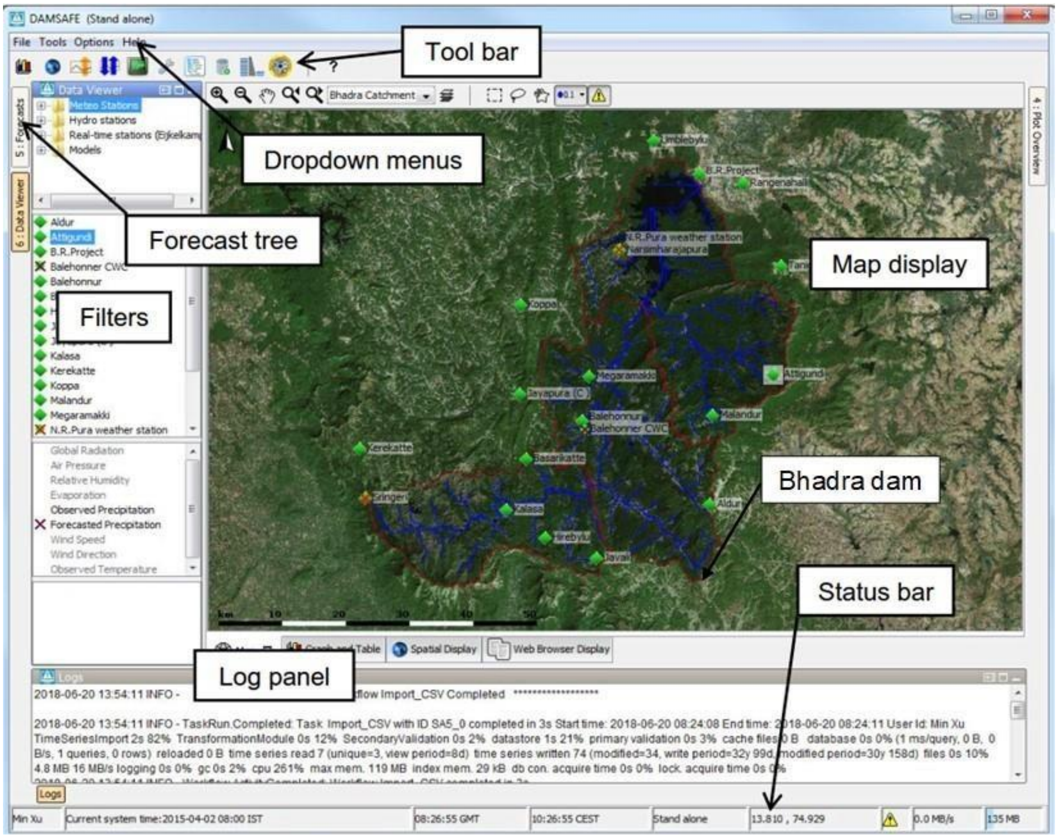


Figure 3-38 An example of Delft-FEWS application for hydrological, reservoir inflow and dam stability monitoring and prediction in Bhadra catchment and reservoir (India)

3.6 Concluding remarks

Based on a rapid screening of measures and reservoir management of sediment-induced problems, we have proposed two categories of the measures/solutions to address the sediment-induced problems at THC, namely (i) urgent and essential sediment management and storage recovery program; and (ii) large-scale measures and interventions. All these proposed categories of the measures have been practiced in different parts of the world (although the problems were not always related to sediment-induced problems in the reservoir) – most of them are related to large-scale earthworks, sediment removal capital projects. Nevertheless, given the specifics of the problem and the region, the measures and solutions that will be suggested upon should be THC specific. With that said, there should be an understanding that there are large scale examples that could be implemented and thus “not reinventing the wheel”. There are global dredging and marine contractors that have this type of experience.

The first category of the measures is very important and crucial to address the problems associated with not only storage loss, but also safety of the complex and the people/community. Therefore, most of these measures are no-regret measures and do not even require detailed cost-benefit analysis. However, proper assessment of technical, social, engineering, and environmental impacts is required for proper planning, design, and execution of the measures so as to avoid/manage any risk involved.

The second category of the measures cannot be considered quickly as they require project scoping as well as proper feasibility and impact assessment considering technical, financial, engineering, and environmental aspects. The proposed measures require large investment, thus more exploration, negotiations, and proper planning.

These activities can be carried out in conjunction with the execution of the first category of the measures that can eventually be adapted in case the second category of the measures are implemented.

We have eventually proposed a technical concept on a comprehensive sediment management program that includes sediment removal and beneficial reuse. The technical concept has been prepared for a 1st-category problem and corresponding measures. We have presented some technical solutions and examples related to sediment removal (dredging) and sediment reuse (mainly focus on their placement and disposal). This proposition is merely a preliminary technical concept based on rapid analysis of limited data, information, and global practices. Therefore, it will require further enhancement and specific refinement based on detailed investigations and studies including feasibility and impact assessments.

A combination of recurrent, soft, and hard measures in complement with non-structural adaptive measures will be the best choice. The non-structural adaptive measures are very important to monitor and maintain the effectiveness and sustainability of the rehabilitation work with an adaptive management approach. Besides, supplementary measures such as catchment and river management and treatment to reduce sediment generation and transport should be an integral part of the comprehensive sediment management program.

4 Feasibilities, impacts, benefits, and constraints

4.1 Introduction

It is evident that the sediment-induced problems at THC are rather acute. We have categorized the problems and possible measures and solutions in previous Chapters. The measures and solutions are rather complex technically and economically. Moreover, they might cause various adverse impacts as well. Consequently, it is important to carry out feasibility and impact studies considering social, economic, and environmental aspects. It is also important to assess the benefits and constraints for an optimal selection of the measure (or combination of the measures). It is also possible that during preliminary screening and high-level project scoping, a rapid pre-feasibility and impact assessment is made. In the caseof the Channel reservoir, the 1st-category problem must be addressed urgently, thus the feasibility of the measures is obvious. The importance is to assess the impacts and safety issues to plan, design and execute the measures in a proper way. Regarding the 2nd- category problems and the measures, there must be a high-level scoping study at first basedon a preliminary exploration and discussions on the possibilities to acquire financial and technical resources. It will require a comprehensive feasibility and impact assessment in laterstages.

4.2 Technical, economic, environmental, and social feasibilities and impacts

4.2.1 Approach and methods

It is useful to have a rapid pre-feasibility and impact analysis during screening of the measures and solutions. This may not always be possible due to lack of enough data and information. Some general aspects related to the approach and methods for feasibility and impact assessment can be outlined as follows:

- Generally, when there are information and data to some extent, it is possible to carry out a tailored analysis for a particular reservoir to have sufficient ideas about the pre- feasibility and impacts of the possible measures and solutions. This is the case with THCas the problem is clear. Moreover, a part of the measures is obvious and inevitable.
- Comprehensive feasibility and impact assessment are not always a simple task as it requires complex investigations, such as rigorous field measurements, complex analysis using advanced tools and methods such as process-based hydraulic and morphological modelling, economic analysis and modelling, environmental and social impact assessment.
- As a part of pre-feasibility assessment, outline of all associated impacts can be considered as a first approximation (usually the impacts are obvious, but only their quantification and associated risks are not fully known). Some experience of ill and good practices and incidents can be useful to consider, particularly when the impacts are not that obviously foreseen.
- There must be a tailored approach despite some common aspects that can be borrowed from global experience since the feasibility of a solution is based on regional and societal factors and importance that cannot always be evaluated in a generic term.
- There are also legal constraints related to the measures and solutions that must be investigated and analysed.
- There are also options and considerations to mitigate or minimize the adverse impacts. This may require comprehensive and integrated studies.

In regard to the economic feasibility, there are various approaches and previous experiences that can be taken into account. For example, there is a recently published paper (Harrington et al., 2022) that presents development of a regionally downscaled economic model to assess the impacts of the management of dredged sediments on Gross Domestic Product (GDP) and jobs created. The model is validated and applied using real project data from sediment management projects in Ireland and Scotland. The model allows the quantification and comparison of the direct, indirect and induced benefits of a range of sediment management options and projects yielding key information for project planning and decision- making purposes. The model user can economically assess and compare various potential sediment management options. The model can be used for impact analysis considering the economic aspect of sediment management projects with the potential to facilitate and inform stakeholders across the sediment management sector. (Harrington et al., 2022). A flow chart, presented in the paper, showing the model structure with inputs and outputs are shown in Figure 4-1. The further details can be found in the paper.
Please note that the economic analysis is beyond the scope of this assignment.

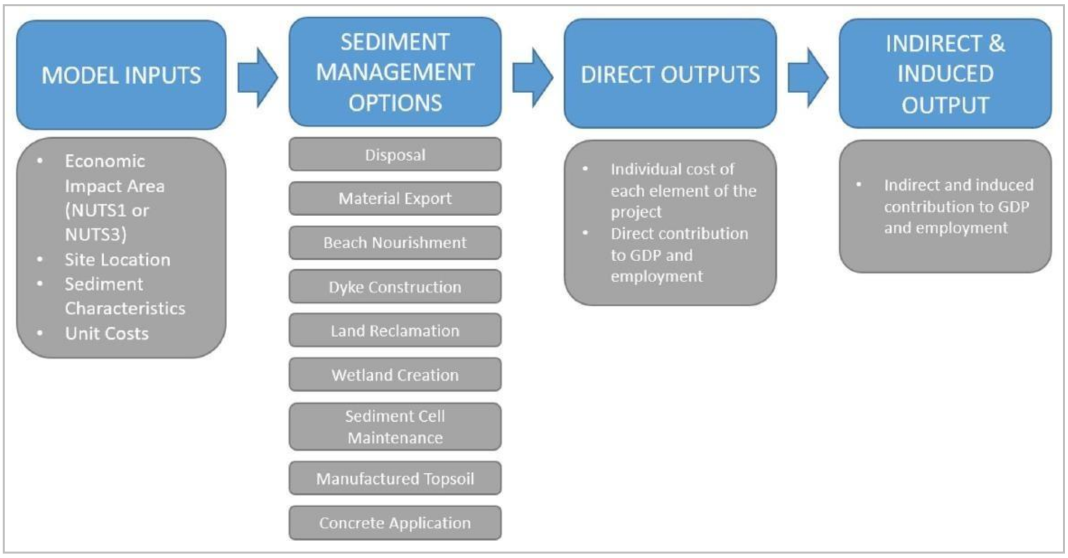


Figure 4-1 The economic model structure with inputs and outputs related to the management of dredged sediment (Harrington et al., 2022)

4.2.2 Rapid assessment of proposed measures

The main objective of this assignment is to propose some possible measures and solutions to the sediment-induced problems at THC based on available (similar) global practices. The comprehensive feasibility and impact assessment are beyond the scope of this assignment. Therefore, we only briefly outline the positive and negative impacts of each measure that can also provide an idea about the feasibility. This can also be of help for a first cost-benefit analysis, particularly for the solutions of the 1st-category problem.

Some of the apparent impacts (positive and negative) of the proposed measures to deal with sediment-induced problems at THC are outlined in Table 4-1. Based on this, a rapid pre-feasibility assessment is made by indicating '*High*', '*Medium*' and '*Low*' feasibility of each measure (as shown in Table 4-2). It is to be noted that we have considered beneficial reuse of reservoir deposits as a part of the measures for impact and pre-feasibility assessment.

Table 4-1 Possible negative and positive impacts of the proposed measures

Measures	Impacts: Negative (-) / Positive (+)		
	Social/Safety	**Environmental**	**Economic**
Maintenance dredging/ excavation	1) Vulnerability and risks (retrogressive erosion, bed and bank slope stability etc. during execution and transport) (-) 2) Hydropower functionality (+) 3) Flood safety (+) 4) Safety of structures 5) Employment and capacity building (+)	1) Air (dust), water (turbidity), noise pollutions (-) 2) Disturbing aquatic life and wildlife (-) 3) Green energy (+) 4) Large dredging volumes to handle (-)	1) Temporary loss of water and energy (-) 2) Moderate investment (+) 3) Beneficial reuse of sediment (+) 4) Hydropower gain (+)
Capital dredging	1) Vulnerability and risks (retrogressive erosion, bed/ bank slope collapse etc.) (-) 2) Water availability (+/-) 3) Hydropower functionality (+) 4) Flood safety (+) 5) Safety of structures (+) 6) Employment and capacity building (+)	1) Air (dust), water (turbidity), noise pollutions (-) 2) Disturbing aquatic life and wildlife (-) 3) Sediment reuse for ecological restoration (+) 4) Green energy (+) 5) Large dredging volumes to handle (-)	1) High investment (-) 2) Temporary loss of water and energy (-) 3) Beneficial reuse of sediment (+) 4) Irrigation and water supply benefits (+) 5) Hydropower gain (+)
Flushing, sluicing, sediment replenishment	1) Water loss (-) 2) Downstream flood and sediment hazard (-) 3) Water availability (+) 4) Hydropower functionality (+)	1) Altered downstream flow, erosion, sedimentation, and turbidity (-) 2) Downstream sediment transport continuity (+)	1) Temporary loss of energy (-) 2) Water loss (-) 3) Low investment (+) 4) Hydropower gain (+)
Raising FRL	1) Stability of structures (-) 2) Upstream inundation (-) 3) Water availability (+) 4) Flood safety (+)	1) Upstream and downstream hydraulic and morphological impacts (-) 2) Sedimentation (-) 3) Green energy (+)	1) Low investment (+) 2) Irrigation and water supply benefits (+) 3) Hydropower gain (+) 4) Beneficial reuse of sediment (+)
Additional off-channel reservoir(s)	1) Landscape intervention (-) 2) Vulnerability and risk (geotechnical, flood etc.) (-) 3) Flood safety (+) 4) Water availability (+) 5) Employment (+)	1) Hydraulic and morphological impacts (-) 2) Land-use change (-) 3) Aqua life and ecological restoration in desert (+) 4) Green energy (+)	1) High investment (-) 2) Irrigation and water supply benefits (+) 3) Hydropower gain (+) 4) Beneficial reuse of sediment (+)
Dam heightening	1) Stability of structures (-) 2) Upstream inundation (-) 3) Water availability (+) 4) Flood safety (+)	1) Upstream and downstream hydraulic and morphological impacts (-) 2) Sedimentation (-) 3) Green energy (+)	1) Moderate investment (+/-) 2) Irrigation and water supply benefits (+) 3) Hydropower gain (+) 4) Beneficial reuse of sediment (+)
Dam relocation	1) Upstream inundation (-) 2) Vulnerability and risk (-) 3) Water availability (+) 4) Hydropower (+) 5) Flood safety (+) 6) Employment (+)	1) Upstream and downstream hydraulic and morphological impacts (-) 2) Ecological impact (-) 3) Green energy (+)	1) High investment (-) 2) Irrigation and water supply benefits (+) 3) Hydropower gain (+) 4) Beneficial reuse of sediment (+)
Beneficial reuse of sediment	1) Vulnerability and risks (e.g., contamination, sediment consolidation, quality) (-) 2) Employment and capacity building (+) 3) Societal development (+) 4) Agricultural development (+)	1) Air (dust), noise pollutions (-) 2) Industrial effluent (-) 3) Land-use change (-/+) 4) Desert green restoration (+)	1) High investment (-) 2) Water loss (-) 3) Economic development (+) 4) Direct economic gain (+)

Table 4-2 A rapid pre-feasibility assessment of the proposed measures

Measures	Feasibility			Overall assessment and remarks
	Technical	Environmental	Economic	
Maintenance dredging/ excavation	High	High	High	High feasibility (proper design and impact assessment is required)
Capital dredging	Medium	Medium	Low	Moderate feasibility (additional investigation is required)
Flushing, sluicing, sediment replenishment	High	Medium	High	High feasibility (proper design and impact assessment is required)
Raising FRL	Medium	Medium	High	Moderate feasibility (additional investigation is required)
Additional off-channel reservoir(s)	Medium	Medium	Medium	Moderate feasibility (additional investigation is required)
Dam heightening	Medium	Low	Medium	Moderate feasibility (additional investigation is required)
Dam relocation	Low	Low	Medium	Low feasibility
Beneficial reuse of sediment	High	Medium	High	High feasibility (proper design and impact assessment is required)

4.2.3 Possible preventing measures and conditions

Proposed non-structural and supplementary measures and conditions should be considered and implemented to minimize the negative impacts of the solutions to the sediment-induced problems at THC. Some of the possible impacts and corresponding preventive measures and conditions are presented in Table 4-3. These impacts are related to all proposed measures (described in previous section). All non-structural measures, outlined in section 0, must also be considered as preventive measures against all possible impacts and risks.

Table 4-3 Possible preventive measures and conditions against negative impacts

Possible negative impacts	Preventive measures and conditions
Upstream and downstream sediment transport and morphological impacts (due to all proposed measures)	1) Comprehensive study and analysis for quantification of the impacts before the executions (e.g., using morphological models, analytical methods, satellite imagery, supported by expert judgement – valid for all the measures) 2) Regular measurement and monitoring during and after the executions of the measures, e.g., monitoring of upstream sedimentation, bathymetry changes (at key locations), bank and toe conditions, downstream turbidity (e.g., during flushing and replenishment), downstream morphological changes 3) Proper morphological analysis and maintenance dredging near the dam before carrying out flushing 4) Investigations on existence of upstream and downstream infrastructures such as water supply systems, irrigation intakes, dams and barrages, recreational spots, settlements for consideration of measures for their safety 5) Regular (or real-time) measurement of turbidity to control the environmentally hazardous quantity, make use of balance between sediment and flow release during flushing, for example additional flow release from the spillway or other outlets during flushing operation to dilute the downstream flow and reduce the sediment concentration and hazards 6) Proper measurement of sediment quality (also in deeper layers of sediment deposits) 7) Hazard and risk analysis (e.g., sediment hazards) including Emergency Action Plan 8) Development and execution of a comprehensive sediment management program (including catchment treatment and river management plan and measures to minimize sediment inflow)

Possible negative impacts	Preventive measures and conditions
Retrogressive erosion, collapse of the deposited layer (due to sediment removal/dredging)	1) Proper planning and design of sediment removal activities 2) Quantification of upstream retrogressive erosion (computation, expert judgment) – this is particularly important if there are river and reservoir infrastructures nearby like bridge, embankments, earthen dams) 3) The effect of sediment removal near the dam and intakes should be properly studied, designed, and executed in a proper way so that there is no slope failure/collapse (e.g., removal sediment from the layer maintaining milder slope) 4) Bed and bank stability analysis 5) Hazard and risk analysis (e.g., blockage of the intakes) including Emergency Action Plan 6) Regular measurement and monitoring
Increase in upstream inundation and sedimentation (due to raising of reservoir level and dam heightening)	1) Quantification/computation of the inundation extent 2) Thorough investigation of social and environmental impacts and preventive measures (compensation, relocation, restoration) 3) Quantification/computation of reservoir sedimentation 4) Study and development of operation rules and scenarios 5) Hazard and risk analysis (e.g., dam break impacts) including Emergency Action Plan 6) Development and execution of a comprehensive sediment management program (including catchment treatment and river management plan and measures to minimize sediment inflow)
Environmental and social impacts, pollutions, hurdles and disturbances (during dry/hydraulic dredging, trucking, slurry transport, disposal as well as due to some other measures)	1) Dredging and disposal activities should not disturb water supply and irrigation, otherwise proper arrangements for alternative options shall be made. 2) The operation must be carried out in systematic manner with regular cleaning, water sprinkling and repairing of the site and the transport route. 3) Site clearance and tidiness is strictly required to have less of a visual impact of dredging and disposal activities. 4) Equipment and vehicles used for transportation of dredged materials must meet prescribed emission norms, e.g., they shall have Pollution Under Control (PUC) Certificates. 5) Noise impact (due to equipment as well as transportation) must be avoided. Also, environmentally friendly equipment should be used. 6) Trucking should not disturb regular transportation (clean operations) 7) Protection of aquatic life shall be ensured. 8) Specific plan with eco-restoration should be in place. 9) Health and safety of workers should be taken care of.(health and safety program) 10) Effect of reservoir depletion must be assessed properly, such as effects on wildlife. 11) Regular monitoring of the dredging and disposal activities to ensure effective regulatory compliance of all stipulated conditions. 12) Comprehensive social and environmental impact assessment and action plan
Threatening safety and stability of structures (due to raising of reservoir level and dam heightening)	1) Detailed stability analysis (computations) of dams and embankment under the changed hydraulic loads 2) Opting for safer techniques, like.g., Fusegates for dam heightening 3) Hazard and risk analysis (e.g., dam break impacts) including Emergency Action Plan
Hydraulic, geotechnical, and geological safety and impacts (due to additional off-channel reservoirs)	1) Comprehensive study and analysis of hazards and risks due to additional water bodies, flow diversion and losses 2) Comprehensive geotechnical and geological investigations to assess the suitability of the measure 3) Hazard and risk analysis (e.g., dam break impacts) including Emergency Action Plan
Sediment quality and quantity, water losses, disposal (related to beneficial reuse of sediment)	1) Proper and more comprehensive investigations given the unknown sediment quality and condition, particularly in deeper levesl of reservoir deposits as they can be contaminated and/or consolidated 2) Proper estimation of usable sediment volumes including regular availability in future as well (i.e., proper study of sustainability of sediment reuse options)

Possible negative impacts	Preventive measures and conditions
	3) Comprehensive analysis and estimation of required water for the reuse options (e.g., for ecological restoration, top-soil improvement, building materials) 4) Comprehensive studies and investigations assisting proper planning, design and execution of transport, disposal, and processing of removed sediment 5) Hazard and risk analysis including Emergency Action Plan

4.3 Contribution to the principles of Nexus and Sustainable Development Goals (SDGs)

The functions of THC are explicitly associated with water, food, and energy security. The functions are linked with the ecosystem services in a basin scale and must consider the social and environmental aspects as well. Consequently, the Nexus Water-Food-Energy + Environment (WFEE) shall be considered as an integral part of the sustainable management of a hydrocomplex.

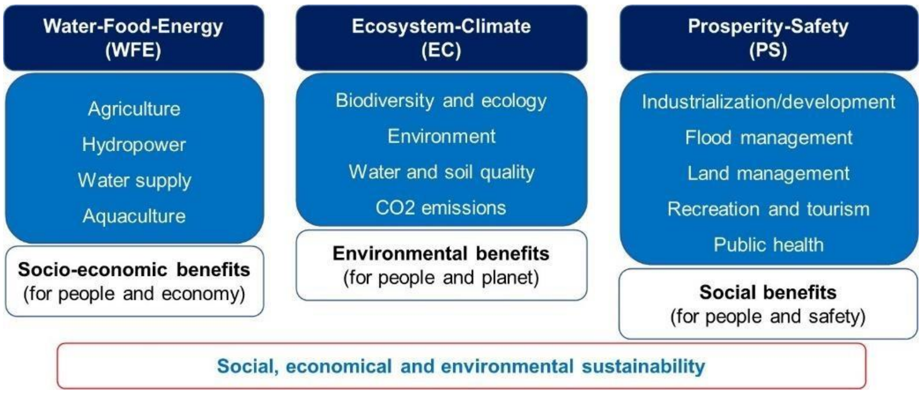


Figure 4-2 The Nexus WFEE with a broader consideration for the reservoir sustainability

All the proposed measures and interventions to improve the situation of THC explicitly or implicitly contribute to the Sustainable Development Goals (SDGs). This should be taken into account while conducting the feasibility and impact assessments. We have attempted to describe the interlinkage between Nexus and SDGs through the measures associated with sustainable management of THC in a form of a chart, depicted in Figure 4-3. Another important aspect related to the sustainable management of THC is the governance on a basin scale. There must be a proper connection between the technical part of the Nexus with the governance part as an essential sustainability criterion. This implies that the sustainable management is linked with the Integrated and Participatory River Basin Management (IPRBM). This is succinctly presented in Figure 4-4.

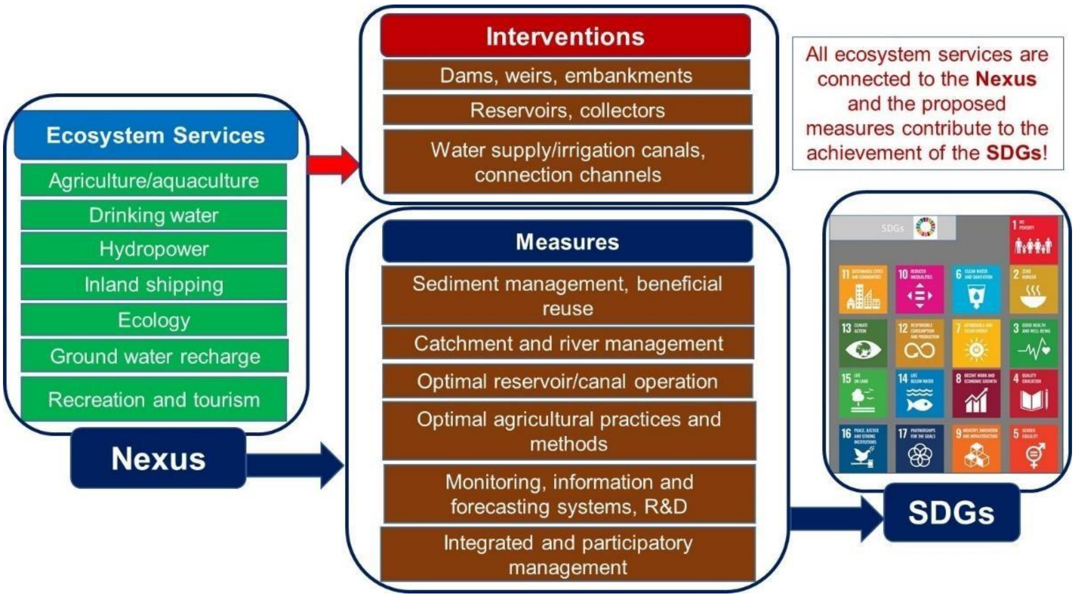


Figure 4-3 Linking Nexus and SDGs through the measures and interventions: Applicable to the sustainable management of THC

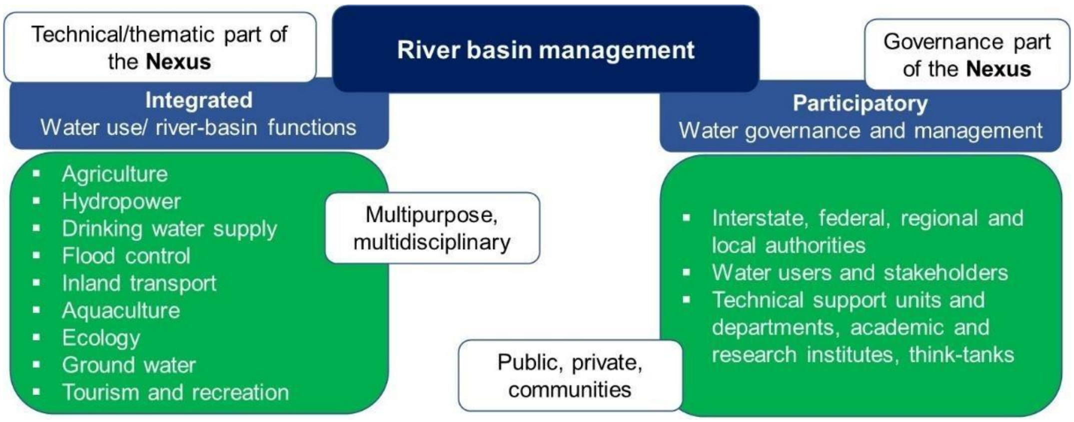


Figure 4-4 Integrated and Participatory River Basin Management (IPRBM): An essential sustainability criterion (relevant to THC)

4.4 Constraints and challenges

There are several challenges, constraints, and limitations with respect to the handling of sediment-induced problems as well as beneficial reuse of removed sediment. Like every hydro-complex, the THC may have its distinctive constraints and challenges. These aspects are important to explore already in the preliminary phase of project scoping. In general, the constraints and challenges can be categorized as: (i) physical; (ii) social and environmental; (iii) economic; and (iv) legal and others.

4.4.1 Physical constraints and challenges

Some possible physical constraints and challenges are outlined as follows:

- Magnitude and severity of the problems (e.g., volume of the sediment, scale of the deposition, quality of the deposited materials)
- Condition of the deposited materials (e.g., strongly consolidated materials are difficult to remove)
- Duration, permitting windows, regularity timeframe
- Availability of space and advanced technology for disposal facilities and recycling

- Lack of commercial industries for processing, treatment, and beneficial uses (particularly in nearby areas)
- Inappropriate size and feature of the structures and the reservoir to implement some measures (e.g., dam heightening)
- Inappropriate hydrological, geological and geotechnical conditions to implement some measures (e.g., off-channel reservoirs)
- Accessibility (transportation, infrastructures) and project logistics
- Lack of market and/or oversaturation for products as secondary raw material (e.g., building materials)
- Limitations for beneficial reuse due to standards for the products – public and industry perception
- Future degradation and unfavourable changes (e.g., decreasing inflow or increasing erosion due to upstream catchment degradation and interventions)

4.4.2 Social and environmental constraints and challenges

Some possible social and environmental constraints and challenges are outlined as follows:

- Social (safety, functionality) and ecological impacts and risks due to the large interventions and changes (e.g., for farmers, fishermen and other inhabitants)
- Social resistance and unwillingness for new things and interventions
- Pollutions (air, water, noise)
- Contaminated or poor quality of deposited materials

4.4.3 Economic constraints and challenges

Some possible economic constraints and challenges are outlined as follows:

- Availability of the investment and willingness of the investors (e.g., private and corporate investors, donors)
- Budget limitation (e.g., for the state authorities)
- Ambiguous economic viability and justification
- Financial risks (loss or reduction of benefits, e.g., due to possible extremes, hazards, failures, economic instability)
- Innovative contracting mechanisms and multiple and integrated procurements

4.4.4 Legal and other constraints and challenges

Some possible legal and other kind of constraints and challenges are outlined as follows:

- Legal aspects and regulations in specific countries, particularly related to sediment removal and beneficial reuse (they may be considered as mining activities and interventions)
- Stakeholders' priorities and interests (hydropower, irrigation, water supply, flood management)
- Strict regulations, e.g., reservoir operation rule
- Lack of acceptance to innovative approach and technology
- Transboundary disputes
- Political will
- Differences in perception of urgency i.e. "I got this" = "Do nothing"

4.5 Concluding remarks

In this Chapter, we have concisely described about the aspects related to feasibility and impacts of the proposed measures to deal with sediment-induced problems at THC. We have attempted to outline the outcomes of the rapid assessment of feasibility impacts.

This could be a starting point towards a comprehensive assessment, particularly when there will be further clarity and preference on the proposed measures. We have also outlined the possible preventive measures and conditions that should be followed to mitigate/minimize the adverse impacts of the interventions. Furthermore, we have attempted to interlink the Nexus (associated with the functions of the THC) and the Sustainable Development Goals through the proposed measures and interventions to demonstrate their contribution to the sustainability criteria. Additionally, we have also touched upon the necessity of integrated and participatory basin management as a sustainability criterion applicable to THC as well.

Finally, we have briefly described several constraints and challenges that must be considered and properly addressed during the selection and further assessment of the measures.

5 Global practices and examples

5.1 Introduction

The presentation of global practices is not the scope of this assignment. Nevertheless, we present here some of the practices and references that could be relevant to the management of sediment-induced problems at the THC.

Reservoir sediment management is a complex process, particularly for large reservoirs and their watersheds due to technical, economic, environmental and safety requirements as well as legal constraints in some cases (particularly related to sediment removal and beneficial reuse). Sediment depositions in reservoirs are of global concern. Many years and decades of non-action and/or assessment has exacerbated the situation whereas large volumes have impacted either the structural integrity and/or operations of dams, reservoirs (including storage loss), or hydroelectric plants. We have included some of the examples of sediment removal not only from reservoirs but also from rivers/canals to demonstrate the technical possibility of sediment removal, e.g., dredging that could be relevant for the THC due to largevolumes that need to be dredged.

We have also included some examples of beneficial reuse of sediments. Since not all reservoir sediment management cases include sediment treatment and beneficial reuse (due to various conditions and constraints including safety and legal aspects in some countries), we have considered for the cases with sediment treatment and beneficial reuse regardless of whether it is sediment from the reservoir or from rivers, lakes, and coastal areas. There are experiences around the world regarding sediment treatment, processing and beneficial reuse.The global experience and practices reveal that beneficial reuse of sediments (particularly soft and/or contaminated) often requires some treatability studies (specifically for geotechnical beneficial use applications) and pilot applications before it can proceed to actual implementation. Therefore, some existing experience and practices of such pilot cases could be useful.

Although global practices and experience provide very useful information and ideas that can be adapted, it should be emphasized that the management of sediment-induced problems and potential for beneficial reuse of sediment should have a tailored-made modified approachthat is technically, socially, economically and environmentally appropriate for the THC conditions.

5.2 Management of sediment-induced problems in reservoirs

There are several guidelines and manuals that describe the approaches and methods related to managing sediment-induced problems in reservoirs. One of the recent guidelines include the handbook, prepared by Deltares (Giri et al., 2019) under the Dam Rehabilitation and Improvement Program (DRIP) in India. A schematic chart with the actions, procedures, and tools to deal with sediment-induced problems is depicted in Figure 5-1. The chart also shows the relevant Chapters and sections in the Handbook (freely accessible). More specifically, Figure 5-2 provides an impression about the sediment management options and strategies. Brief descriptions of some global examples of reservoir sediment management is provided hereafter (most of them are adapted from the handbook). The handbook (Giri et al., 2019) includes more cases and examples.

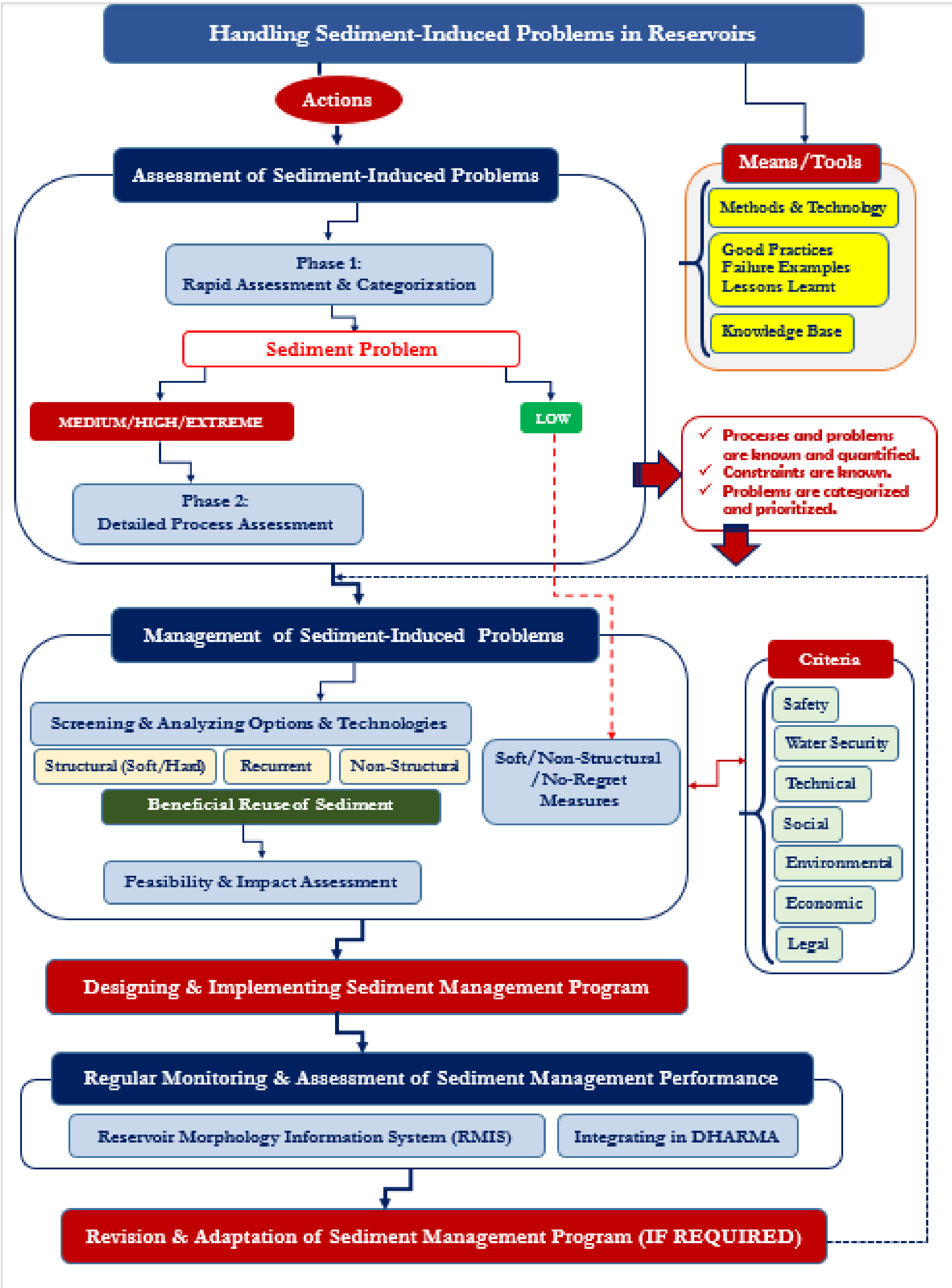


Figure 5-1 A schematic chart with the actions and tools to deal with sediment-induced problems in a reservoir (Giri et al., 2019)

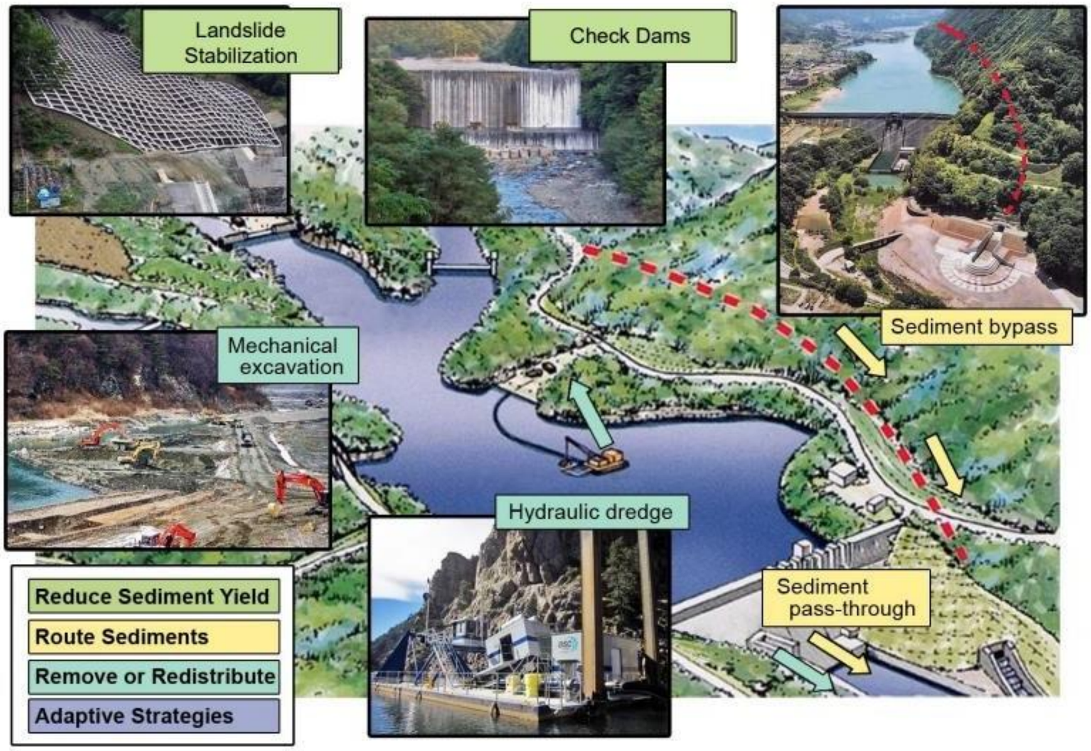


Figure 5-2 Reservoir sediment management options and strategies (Randle et al., 2019)

5.2.1 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 capacity of about 252 million m^3. The length of the reservoir is 16.5 km long 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 and recreational use. Most of the presented information, facts and figures are based on a recent publication by Lai and Wu (2018). This case shows how the dam structures can be modified in conjunction with several sediment management options to deal with the sedimentation problem.

a) 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 a larger number of landslides and surface erosion as an effect of the 1999 earthquake.
- There were more than 100 check dams in the 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 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, formed 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.

b) 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 the powerhouse intake, the permanent channel outlet and the Shihmen intake (as shown in Figure 5-3).
- Several modifications and rehabilitation of the facilities have been carried out since 2006 for increasing sediment release capacity, such as rehabilitation of the permanent channel outlet as it was clogged, modification of the powerhouse intake to use one of the two penstock pipes exclusively for sediment sluicing (which allows increasing the sluicing capacity from 137 to 380 m^3/s) as shown in Figure 5-4
- 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 5-5 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. 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 Giri et al. (2019).
- Catchment management, forecasting and decision support systems, that are very useful for sustainable reservoir management, are in place as well..
- Figure 5-6 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).

Figure 5-3 Location of existing outlets that may be used for sediment release (Google Earth image)

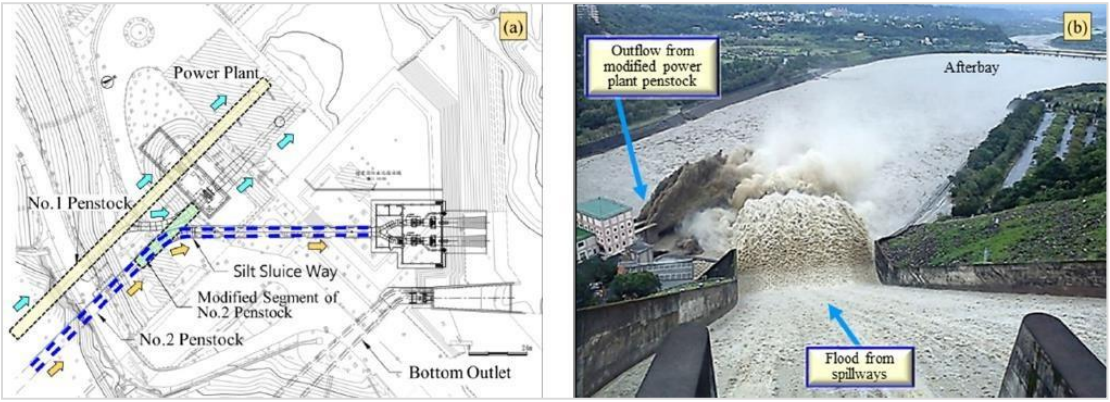


Figure 5-4 Modified segment of second penstock being used for sluicing and flushing (left drawing) and sediment sluicing through modified penstock and spillway (right image) during the first operation in 2013 Typhoon event (Lee et al., 2022)

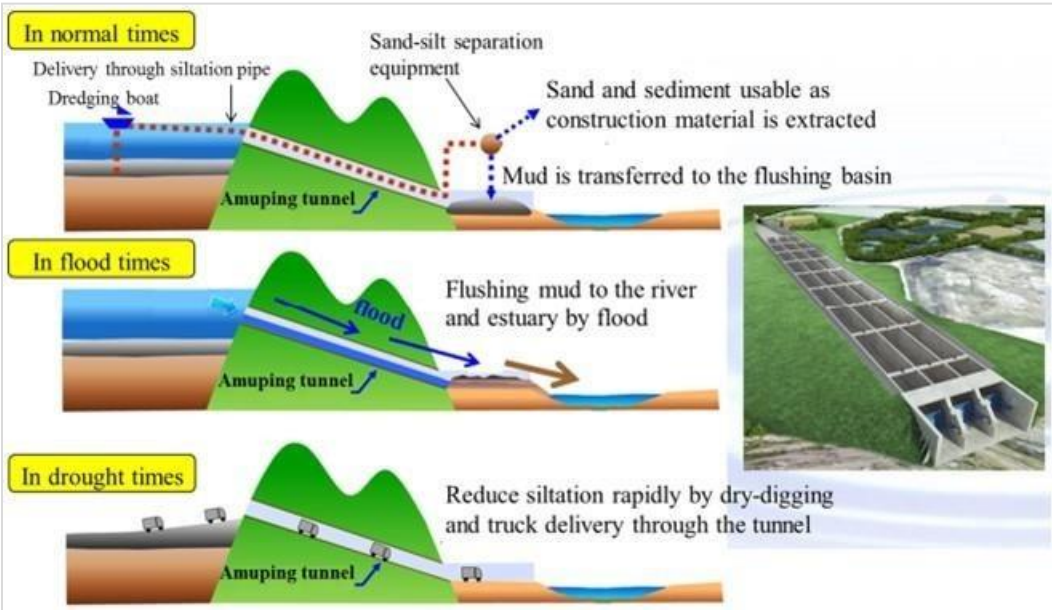
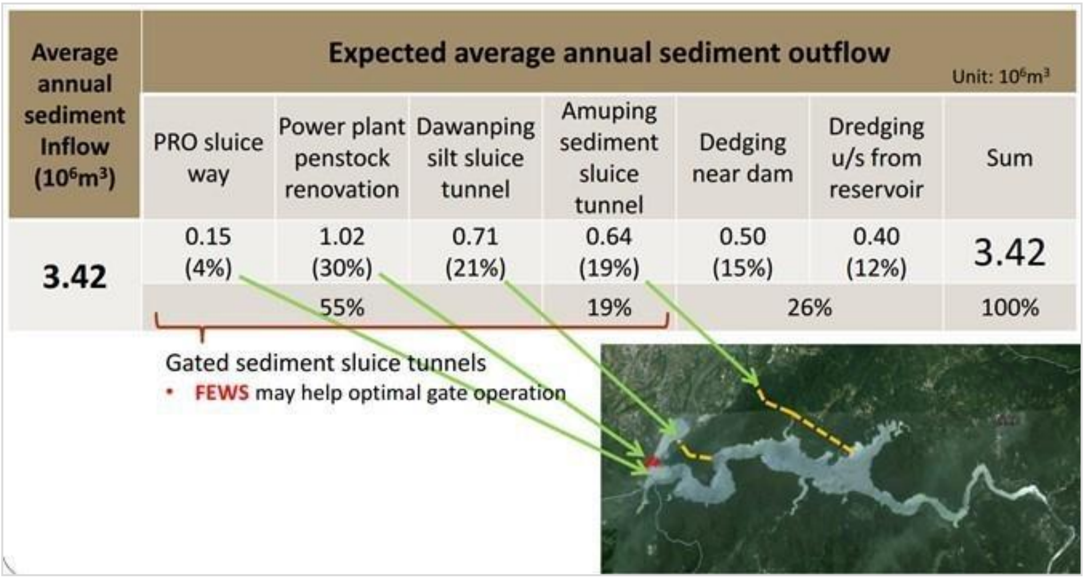


Figure 5-5 Functions and operation of designed bypass tunnel (Lai, 2017)



Average annual sediment Inflow (10^6m^3)	Expected average annual sediment outflow (Unit: 10^6m^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 5-6 Existing and proposed sediment management measures in Shihmen reservoir and expected results of their implementation (Courtesy: Jinn Chuang Yang)

5.2.2 Sediment management in Sakuma reservoir (Japan)

Sakuma dam is one of the dams in a cascade system in the 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 dam 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 5-7):

1) Flow-induced sediment 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 the upper reaches to facilitate 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, 000 m^3 (denoted by a yellow arrow in Figure 5-7). This is implemented by EPDC.
2) Intra-reservoir transport: This is realized by dredging and disposal of the sediment from the middle reach to the tail reach within the limit of the effective volume. The target annual volume is 400,000 m^3 (denoted by a green arrow in Figure 5-7). As an additionalmeasure to accelerate the realization of the plan, the dredging operation is started to becarried out at the upstream reach as well with the target annual volume of 300,000 m^3 (denoted by red arrow in Figure 5-7). This is also implemented by EPDC.
3) Sediment 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 the right to use dredged sand andgravels as construction material and for other purposes, such as making concrete, asphalt, as well as using sand for golf course preparation and others. The dredging and removal arrangement is depicted in Figure 5-8.

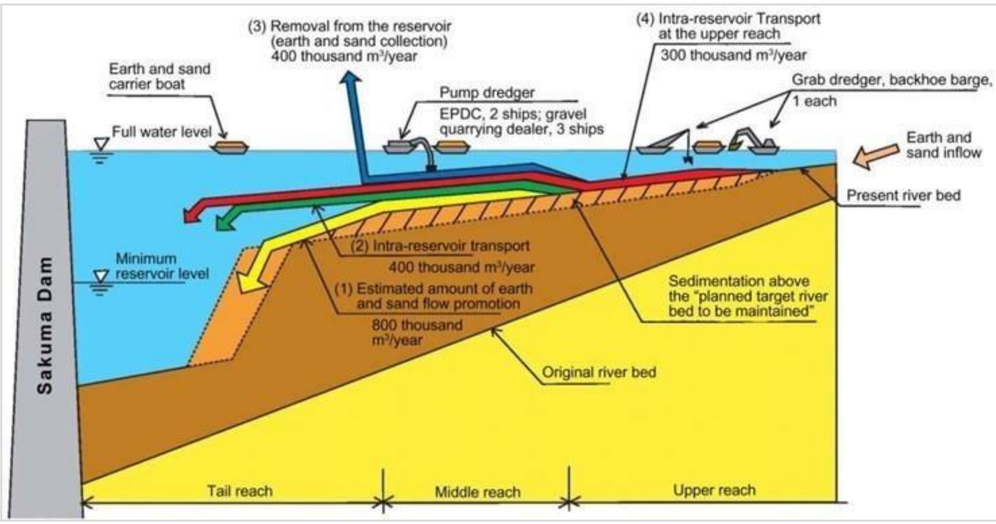


Figure 5-7 Sediment management at the Sakuma Dam (provided by J-Power)

Figure 5-8 Sediment dredging and removal arrangement (provided by J-Power)

5.2.3 Sediment sluicing and flushing in Chamera-I and Chamera-II (India)

National Hydroelectric Power Corporation (NHPC) carried out sediment management of two reservoirs. Both reservoirs are located on the Ravi River - a tributary of the Indus River in North part of India. Chamera - I is a medium size reservoir with a gross storage of 412.8 million m^3 and submergence area of 9.5 km^2 and reservoir length is about 15 km. Total catchment area is 4725 km^2. Chamera-II is a small size reservoir with a gross storage of 2.25million m^3 and length of the reservoir is about 3.6 km. A schematic layout of both reservoirs isdepicted in Figure 5-9.

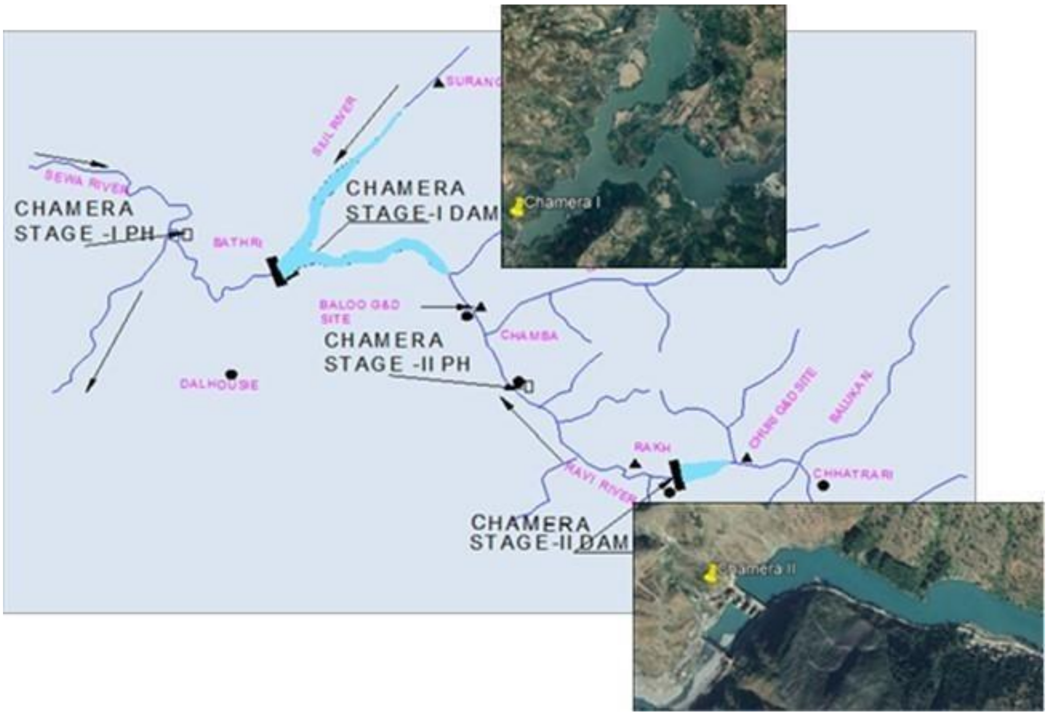


Figure 5-9 Schematic layout of Chamera-I and Chamera-II (Dayal et al., 2016; Google Earth)

The data reveals that the gross storage has been reduced in both reservoirs, although losses in live storage capacity are still insignificant so far. This may be owing to regular sediment management as mentioned hereafter.

a) Sediment flushing at 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 a 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 as follows:

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

- 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.
- 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 favourable 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.

b) Sediment Management in Chamera - II

- Given the 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.
- A free flow flushing is carried out in Chamera-II. The flushing operation is carried out when excess discharge is available during the monsoon season.
- The minimum discharges during 1 June to 31 August and 1 September to 30 September are 350 m^3/s and 250 m^3/s respectively. In the former case, even if the 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 the 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 this case, there is a 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 low as possible to get a 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 season (i.e., after flushing operations) at specified locations.
- The powerhouse must be shut down during the flushing operation. The power generation restarts after closing all the gates and attaining the desired reservoir level.
- The results of flushing operations that were carried out since 2008 are presented in Table 5-1.
- Also, numerical, and physical modelling studies were carried out on sediment flushing in Chamera-II reservoir, which can serve as an example how such studies are taken place (Isaac et al., 2014).

Table 5-1 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

5.2.4 Managing water availability problem due to sedimentation at Khashm el-Girba dam (Sudan)

Some useful facts and figures from various sources are outlined as follows:

- The Khashm el-Girba dam is a gravity and embankment composite dam on the Atbarah river in Eastern Sudan (Figure 5-10).
- The dam was commissioned in 1964. The total design storage is 1.3 billion m^3.
- The primary purpose of the dam is irrigation to provide locals with water supply for about 2000 km^2.
- The main portion of the dam is an earthen embankment; the spillway and irrigation headworks sections are concrete gravity.
- In 2002, a small hydropower power station was developed in the dam with 10 MW (in the river) and 6 MW (in the canal).
- The reservoir lost ~60 % of its capacity (based on the measurement of 2009). About 25% of the storage was lost in the first 6 years due to sedimentation. This was not recognized before that.

- Regular flushing operation was considered after the problem was recognized to (partly) mitigate the storage loss. The time record of time-varying storage loss (depicted in Figure 5-11) shows that the storage loss rate was less after the regular flushing operation. However, it did not solve the problem fully.
- Studies were conducted in early 70s to solve the water deficit problem. The studies suggested two locations that are most suitable for developing two new connected reservoirs, at the upper main two tributaries of the Atbara River (Figure 5-12).
- Each reservoir is expected to ensure the water availability for around 30 years.
- In 2010, the government of Sudan decided to build these two reservoirs together as a twin dam. The new dam was called the Dam Complex of Upper Atbara (Figure 5-12).
- The new dam has two spillways since it crosses two rivers and a powerplant. The combined reservoir has a capacity of 3.68 billion m^3.
- The new reservoir benefits about 160,000 farmers who rely on irrigated agriculture.
- The Upper Atbara was commission in 2018.
- Proper sedimentation management and operation studies were conducted for this twin reservoir to mitigate sedimentation problem (considering a lesson from previous problem). Deltares was involved in this study. The study considered: (i) initial filling; (ii) time of filling; (iii) hydrological year; (iv) proper reservoir sluicing approach; (v) proper reservoir flushing approach (full and half flushing); and (vi) combination of measures.
- The maintenance dredging near the dam and intakes is carried out regularly. The reservoir is equipped for this.
- Total project cost was about 1.5 billion USD, financed by following institutions:
  - OPEC Fund (loan administrator)
  - Saudi Fund for development (SFD)
  - Islamic Development Bank (ISDB)
  - Kuwait Fund for Arab Economic Development (KFAED)
  - Abu Dhabi Fund for Development (ADFD)
  - Government of China
  - Government of Algeria
  - Government of Sudan
- The funding was used for the following activities
  - Construction of a dam complex consisting of two main dams - Rumela and Burdana on the Upper Atbara and Settit rivers respectively
  - Construction of a 13 km long dike system to form a common water storage reservoir (capacity of 3.68 billion m^3), which connects the two dams
  - Construction of spillways equipped with radial hydraulic gates
  - Construction of a 320 MW hydro power station on the Rumela dam
  - Installation of a 28 km-long, 220 kV transmission line to the Shuwak substation that was joined to the national grid
  - Land acquisition and resettlement
  - Construction and consultancy services

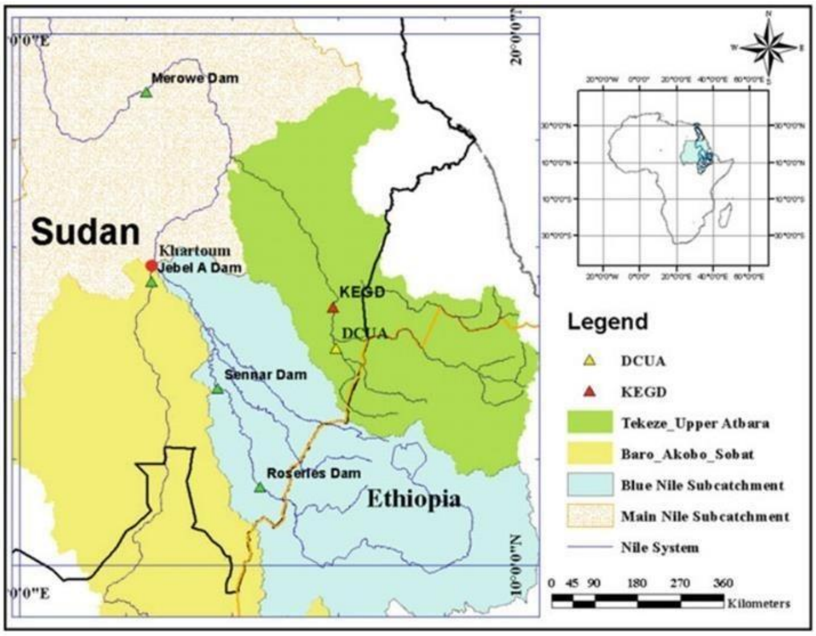


Figure 5-10 Location of the dam

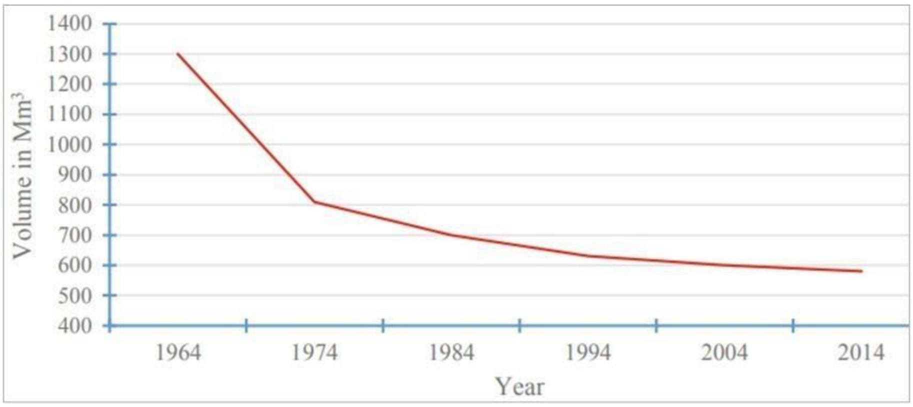


Figure 5-11 Time-variation of the at Khashm el-Girba reservoir storage loss

Figure 5-12 Location of the new twin reservoirs (Upper Atbara Dam Complex) extended to two tributaries

5.3 Examples of dam upgrading

There are already a few decades of global practices on dam upgrading as a structural measure. This is related to various measures such as an additional (larger) dam as a replacement to the old one, dam heightening, enhancement/reconstruction of part of the dam (e.g. spillways, intakes, outlets, pipes, tunnels etc.). Japan is one of the countries, where the upgrading of the dams has been carried out actively for a number of dams since the last few decades (Figure 5-13).
There are also many other countries where dam upgrading has been practiced during the last couple of decades.

5.3.1 Dam upgrading in Japan

5.3.1.1 General aspects and examples

The "Investigative Committee on Effective Use of Existing Dams" (2007–2008), which was established within the Japan Commission on Large Dams, compiled 240 cases of dam upgrading (effective use of existing dams) projects, and investigated their nationwide status (Sasaki and Kondo, 2018). A paper by Sasaki and Kondo (2018) gives a good overview of the trends in dam upgrading in Japan. The paper is useful as it is focused on dam heightening and strengthening the functions of the intake and discharge facilities in the dambody, as there are many cases among upgrading projects involving dam body retrofitting.
Some of the general and specific facets and experience that have been mentioned in the report are as follows:

- To effectively carry out the required dam upgrading, it is necessary to address technological issues specific to targeted dams, such as advanced dam gate control, taking into account weather forecasts, or the design and construction methods required for modifying existing dams, such as dam heightening.
- Examples of improving the discharge facilities in Japan include the addition of a tunnel discharge facility in natural ground, in projects of such as the Amagase dam (concrete arch dam, completed in 1964, dam height 73 m, upgrading project currently in progress) and the Kanogawa dam (concrete gravity dam, completed in 1958, dam height 61 m, upgrading project currently in progress). As effective use is made of existing dams, dam upgrading makes it possible to strengthen dam functions and efficiently extend service life.
- There are certain aspects that are more difficult than in the construction of a new dam. For example, when the existing dam targeted for upgrading is old, information on the existing dam and its foundation, which is necessary in upgrading, is often insufficient. In such cases, it is necessary to conduct surveys, such as boring of the dam foundation or dam body, however, the maintaining of the existing dam function could be a constrained condition for those surveys. Furthermore, when the dam body is to be drilled for installing additional conduits, it is necessary to prevent any side-effects that the existing dam body cannot tolerate.
- The "Investigative Committee on the Effective Use of Existing Dams" within the Japan Commission on Large Dams has pointed out technical issues based on the collected cases of effective use obtained in a survey. Its successor, the Dam Refresh Committee, has been investigating specific technical issues and directions towards their solutions with respect to dam heightening, modification of intake and discharge facilities, and sedimentation measures for upgrading projects.
- The addition of sediment control measures to manage the sediment-induced problems in the dams and reservoir has started to be undertaken mostly since 2000 onwards.

- Figure 5-14 shows an example of dam heightening in a concrete gravity dam – the , Shin Maruyama dam. The original dam was commissioned in 1955. The dam height was raised from 98.2 m to 118.4 m resulting in an increase of total reservoir capacity from 7,952 m^3 to 13,135 m^3.
- Figure 5-15 shows an example of retrofitting the selective intake and discharge facility at Nagayasuguchi dam. This is a concrete gravity dam, commissioned in 1955. The dam height is 85.5 m.

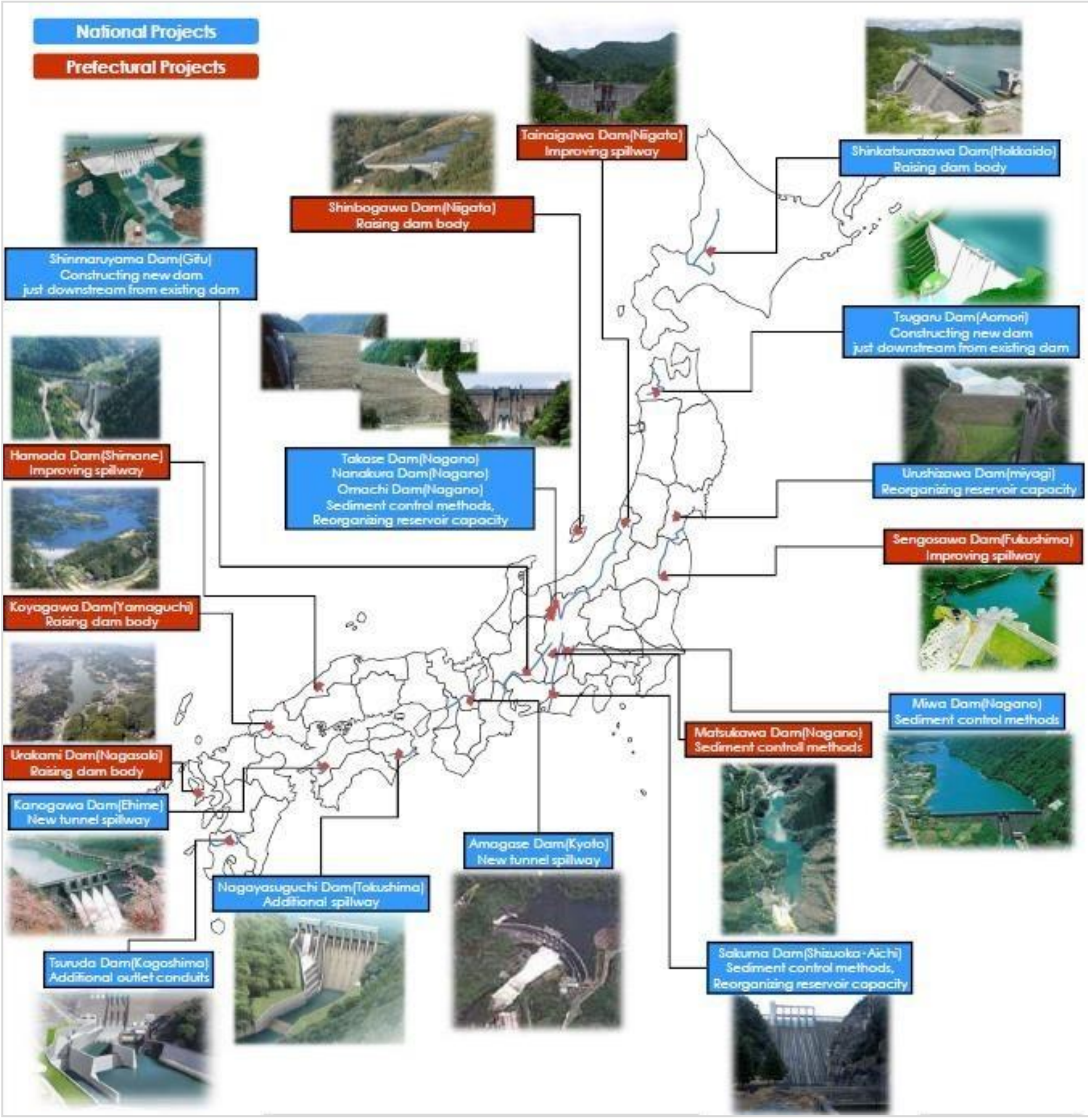


Figure 5-13 Upgrading of various dams in Japan (Courtesy of Water and Disaster Management Bureau, Ministry of Land, Infrastructure, Transport and Tourism, Japan)

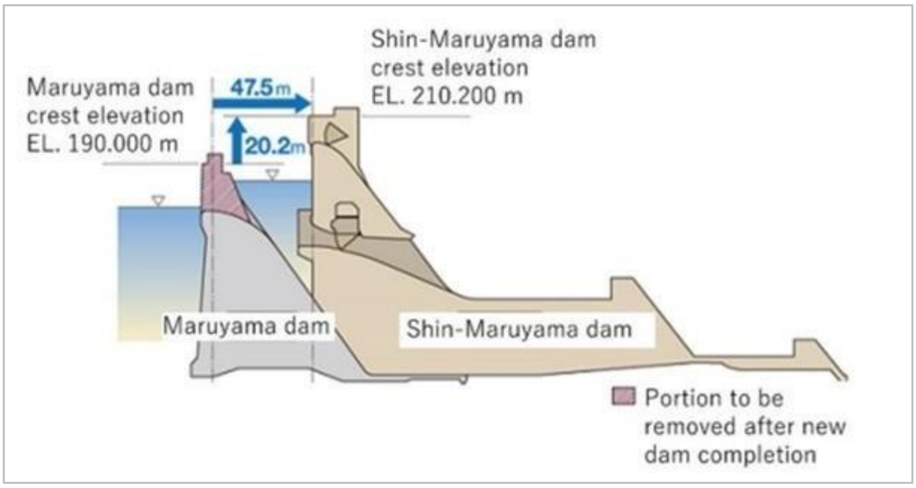


Figure 5-14 Upgrading (heightening) the Maruyama dam

Figure 5-15 Example of intake and discharge facilities modification at Nagayasuguchi dam (Sasaki and Kondo, 2018)

5.3.1.2 Additional outlet facilities at the Tsuruda dam

A note by Kazunori et al. (2019) provides a good set of information on construction of additional outlet facilities at the Tsuruda dam. Some of the facts and figures that are includedin the paper are outlined here as follows:

- The Tsuruda dam (Kagoshima Prefecture), situated in the middle of the Sendai River, is a multipurpose dam with an effective reservoir capacity of 77.50 million m^3. It was constructed for the purposes of flood control and power generation) and was completed in 1966.
- In July 2006, there was significant damage in the watershed area of the Tsuruda dam by a catastrophic flood caused by the record torrential rains. Consequently, the Tsuruda dam redevelopment project was planned. Specifically, it was planned to increase the maximum flood control capacity from 75.00 million m^3 to 98.00 million m^3 to increase the flood management capacity.
- The plan included the installation of additional outlet facilities, which involved the construction of five tunnels through the dam. Outlet gates were also constructed in the dam. From this perspective, this project was the largest in scale among the dam redevelopment projects in Japan. The project faced several challenges. Figure 5-16 gives a good impression of the upgrading of the dam.

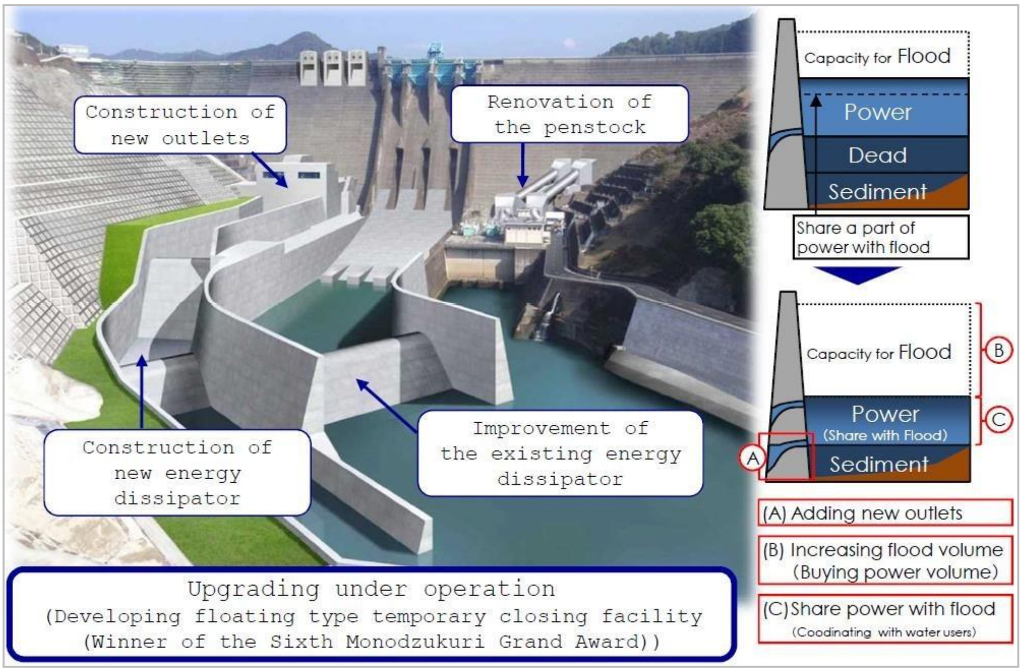


Figure 5-16 Upgrading of Tsuruda dam (Courtesy of Water and Disaster Management Bureau, Ministry of Land, Infrastructure, Transport and Tourism, Japan)

5.3.1.3 Replacement of Oyubari dam

Some facts and figures are as follows:

- As part of the Hokkaido Comprehensive Development Plan, the Ōyubari dam was constructed in 1953 as part of the state-run Ōyubari Land Improvement Project. The purpose of the dam is irrigation and hydropower.
- In 1981, Typhoon No. 12 struck Hokkaido, and the Ishikari River basin was hit by a flood damage unprecedented in the history of observation. In response to this, the Hokkaido Development Bureau revised the "Ishikari River Basin Construction Implementation Basic Plan" and planned to construct a flood control dam as a replacement of Oyubari dam. In addition, due to the increase in water demand and the population growth of Sapporo and other cities, it was considered to be developed as a multi-purpose dam project. As a result, a new dam (Yubari Shuparo dam) replacing the older one (Oyubari dam) was built.The new dam was built 155 m downstream of the old one (Figure 5-17 and Figure 5-18).
- The dam height was raised from 67.5 m to 110.6 m.
- Details are available at the official website of Hokkaido Development Bureau (in Japanese): https://www.hkd.mlit.go.jp/sp/yuubari_damu/index.html

Figure 5-17 Comparing the Google Earth image showing before (left) and after (right) removal of Oyubari dam

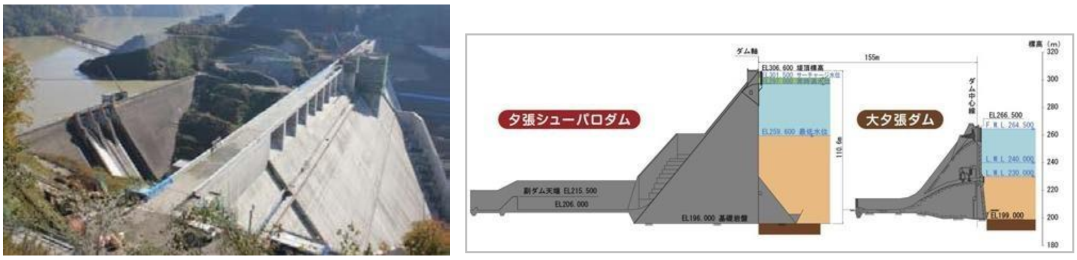


Figure 5-18 Oyubari and Yubari Shuparo dams next to each other (Provided by Y. Shimizu)

5.3.2 Heightening of Zhushou dam (China)

The details are presented in the paper by Yumeng et al. (2020). Some facts and figures from the paper are outlined as follows:

- The Zhushou dam is located in the Liangshan prefecture, Sichuan province, and is a medium-sized reservoir. Its crest elevation is 2416.1 m, the dam length is 190 m, the top elevation of the wave-proof wall is 2417.1 m, the dam height is 63.4 m, and the width of the dam top is 6.0 m.
- According to the water supply project planning, to meet the production and domestic water demand of the resettlement area, the Zhushou dam had to be expanded and matched to the corresponding water diversion project.
- The older Zhushou dam was a clay core rock-debris dam with a maximum height of 63.4 m. After heightening, the new dam is a concrete-faced rockfill dam with a maximum height of 98.1 m.
- When the dam was heightened, the impervious body of the original dam had to be strengthened.
- The design was to make use of the water-retaining capacity of the original core wall dam to produce rockfill heightening on the top and downstream slope of the old dam so that the original dam body becomes a part of the heightened dam. At the same time, a core wall and foundation anti-seepage system of the original dam was strengthened, a concrete cutoff wall was added, and the foundation anti-seepage curtain grouting was strengthened.
- The construction period of dam heightening is 31 months.

Details can be found in Yumeng et al. (2020).

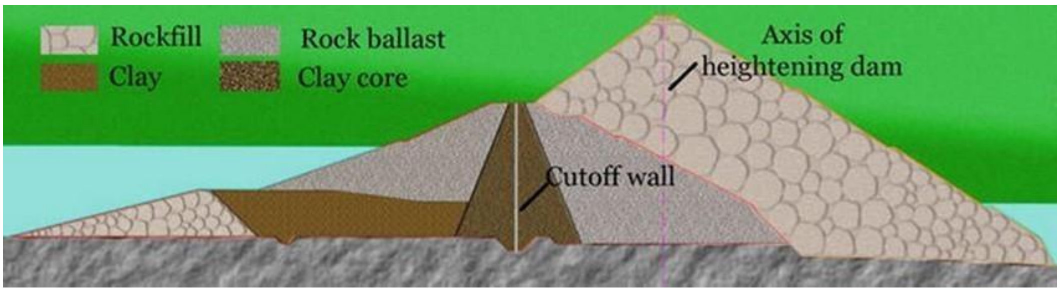


Figure 5-19 The profile of the heightened dam (Yumeng et al., 2020)

5.3.3 Heightening of the Roseires dam (Sudan)

Some of the facts and figures are as follows:

- The Roseires dam was built on the Blue Nile at Ad Damazin in Sudan in 1966, initially for irrigation purpose. A hydropower plant of 280 MW was added in 1971.

- The Roseires dam scheme consists of a main dam and two secondary embankment dams. Over the year, siltation reduced storage capacity. Consequently, the project had to be enhanced to improve water management of the Blue Nile.
- Consequently, following enhancement to the existing dam was made: (i) raising the height of the main concrete dam by 11 m to increase storage capacity from 3 billion m^3 to 7.3 billion m^3; (ii) raising the embankments by 10 m; (iii) construction of an access bridge; (iv) rehabilitation of the power station to enable it to generate an additional 566 GWH of power; (v) relocation of about 7,400 families to new settlements fully provided with social infrastructure.
- The project was approved in 2008 and completed in 2013.
- Total project cost was about 476 million USD.

https://opecfund.org/operations/list/heightening-of-the-roseires-dam-rehabilitation-project

Figure 5-20 Heightening of Roseires dam (http://pf.bbrnetwork.com/)

5.4 Global practices on processing, treatment, and beneficial reuse of sediment

Some of the useful technology(s) and practices, particularly related to the dredging and placement of removed sediment (e.g., CDFs) that could be relevant to the THC is presented in section 3.5 as well. Here we have briefly shown a few more projects related to sediment removal and beneficial reuse of sediment (e.g., ecological restoration and desert green initiatives). Some of these practices are not necessarily related to dams and reservoir, and not explicitly relevant. Nevertheless, some of their components and experience could be of use to consider for the THC given the similar requirement and magnitude.

Some national strategy and practices related to the management of dredged sediments in some developed countries are presented in Appendix 3: Summary of national strategy and practices for management of dredged materials in some countries. See also Appendix 4: Applicability of dredged sediments for beneficial use based on type and quality and Appendix 5: Treatment options for dredged sediments, practiced in Ireland.

5.4.1 The Kubuqi Ecological Restoration Project (China)

Some useful aspects, facts and figures have been synthesized from the report by UNEP (2015) and presented here. We refer to the report for more detailed information.

5.4.1.1 General overview

As early as 1988, the Elion Resources Group began restoration of part of the Kubuqi Desert, located in Inner Mongolia Autonomous Region, China (Figure 5-21), in an initiative that developed into an example of Desert Green Economy.

Almost three decades later, one third of Kubuqi has been greened. Through an innovative model of private-public-community investments an area of more than 5,000 km^2 has been afforested through planting trees, shrubs, and grasses (Elion 2014).

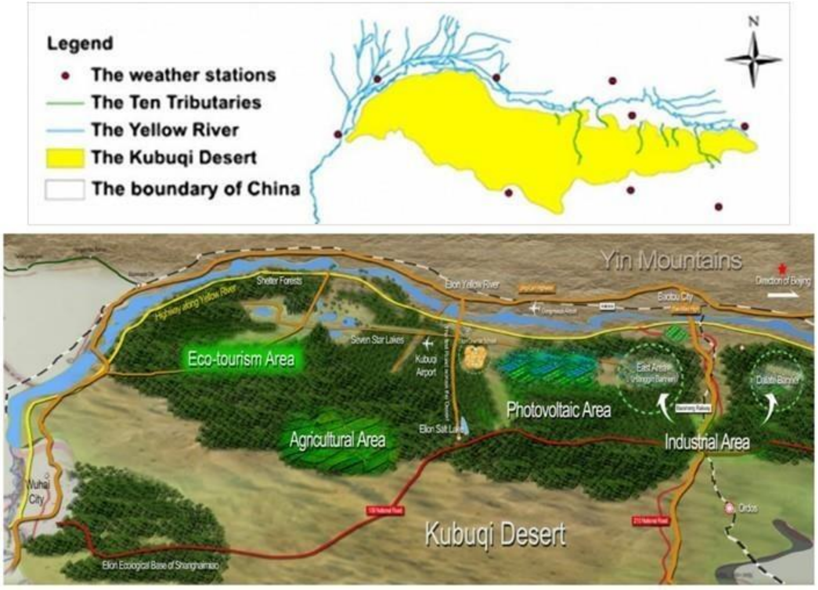


Figure 5-21 The Kubuqi restoration project location (UNEP, 2015)

There are three main aspects that are briefly described as follows (Elion, 2014):
1) **Economic development** includes infrastructure development, eco-industries and green agriculture, manufacturing of new building materials from sand, eco-tourism, and renewable energy sources such as solar power. Planting of high value herbs, such as liquorice, is now supporting a large scale, natural pharmaceutical industry.
2) **Social development** includes building of new homes and schools, and development of cultural programmes.
3) **Ecological restoration** has resulted in reduced dust storms and sandification, and restoration of the degree and extent of biodiversity.

Over 100,000 farmers and pastoralists, through various means, became one of the largest beneficiaries of the project's green economy such as:

- renting desert land to the enterprise and becoming shareholders;
- developing desert national tourism and becoming tourist property owners;
- planting trees, grass, and herbs to provide small businesses or employment;
- farming activities, such as planting vegetables and fruits, or raising cattle and sheep.

Farm produce supplies meat, eggs, poultry, milk, and green organic food to enterprises and tourism. A chart, shown in Figure 5-22, provides an idea about the various enterprises associated with the project.

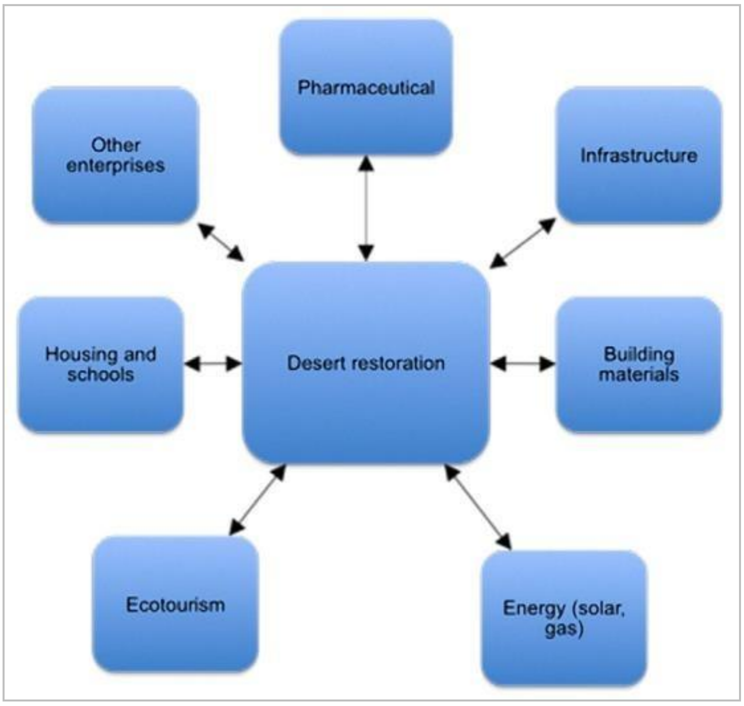


Figure 5-22 Various Elion enterprises associated with the project UNEP, 2015)

5.4.1.2 Public-private partnership

Elion Resources Group and the government built a comprehensive partnership with the following features:

- **Financing.** The central and local governments provided the necessary policy tools and established a cooperative framework between banks or financial companies and Elion. This included coordination with the National Development Bank, Agricultural Bank of China, Industrial and Commercial Bank of China, China Construction Bank, and other policy or commercial banks. The framework provided a financial guarantee for Elion's self-development and desert restoration activities.
- **Investment arrangements**. The central and local governments opened project opportunities to private enterprise, such as public projects for combating desertification, ecological restoration projects and vegetation rehabilitation projects. The Elion group could be a service provider or contractor of the national projects. This brought a new source of profit to Elion. For example, Elion won the bid to build an ecological restoration project for the venue of the Beijing Olympic Winter Games.
- **Technological innovation and services.** The government took the responsibility to provide technical services for the Enterprise in the 1990s. However, from 2005 Elion became a major participant in technology research and development of desertification prevention, and actively introduced advanced international technology for irrigation water use and management. In 2014, Elion established the Desert Research Institute.
- **Policies and projects.** Elion became a lead stakeholder, participating in all levels of government reforms of anti-desertification policy, institutional innovation, and governance

The report by UNEP (2015) also includes a detailed cost-benefit analysis.

5.4.2 Reservoir dredging and sediment reuse projects by the Great Lakes Dredge & Dock Company (USA)

5.4.2.1 John Redmond Reservoir dredging

Some facts and figures are outlined as follows:

- The John Redmond Dredging Project was a design/construct dredging contract that included the hydraulic dredging of 3 2,293,664 cubic meters of sediments from the John Redmond Reservoir near Burlington, Kansas. It was the first contract in the United States for a State Government to dredge on federal property.
- Dredged material was excavated and pumped through 9.7 km of pipeline. Placed over three existing gas pipelines, with one river and five road crossings to the contractor-provided Confined Disposal Facilities ("CDFs").
- The CDFs included the design and construction of 41,350 lineal feet of dike, using 592,530 cubic meters of compacted fill. The CDFs will eventually be returned to agricultural use.
- The John Redmond Dredge Project was named the winner of the Western Dredging Association's (WEDA) 2017 Annual Safety Excellence Award for a Dredging Project.

Figure 5-23 John Redmond reservoir (left) and the project details (Great Lakes Dredge & Dock Company)

5.4.2.2 Lake Decatur (Phase 2) dredging

Some facts and figures are outlined as follows:

- Dredging included both maintenance and deepening work in Basins 1-4 and removal of silts from sediment traps in Basins 1 & 6 (Figure 5-24). The work also involved the Rehabilitation of the Oakley Confined Sediment Basin by raising the existing berm by 10 feet, which required over 587,942 cubic meters of earthwork.
- Dredged material was excavated and pumped through 14.5 to 16.1 km of discharge pipeline, placed to the Oakley Confined Sediment Basin.
- To save the city money, improve efficiency and better manage environmental concerns, the entire dredge and booster pump stations were electric.
- This project will increase the water storage capacity for the City of Decatur by 30 percent, while also meeting future demands and improving tourism with greater recreational opportunities.

Figure 5-24 Lake Decatur (left) and the project details (Great Lakes Dredge & Dock Company)

5.4.2.3 Pass A'Loutre dredging

Some facts and figures are as follows:

- This project involved maintenance navigational dredging in the Mississippi River Ship Channel from the Gulf of Mexico to Baton Rouge, Louisiana (Figure 5-25).
- The scope of the project entailed deepening the draft navigation entrance channel from 12.2 meters to -13.7 meters deep and 750 feet wide, improving travel through the New Orleans and Baton Rouge reaches of the Mississippi River.
- In total, approximately 6.1 million cubic meters of sediments were dredged from the Head of Passes Hopper Dredge Disposal Area (HDDA).
- The California, Florida, and Terrapin Island deposited the material in the Wetland Creation Area for beneficial reuse.

Figure 5-25 Dredging operation at Pass A'Loutre (left) and the project details (Great Lakes Dredge & Dock Company)

5.4.2.4 Mosaic dredging

Within the scope of this project, rivers and lakes dredged 12.2M cubic meters of clay tailings and pumped it 8 km to a final disposal and restoration area. Mosaic has tens of thousands of acres of strip-mines in the Florida area.

Figure 5-26 Dredging operation at Mosaic (left) and the project details (Great Lakes Dredge & Dock Company)

5.4.3 Restoration projects in The Netherlands (Ecoshape)

EcoShape – Building with Nature is a network of organizations and individuals, working together to advance the application of Building with Nature in water and sediment related societal issues. The organization stimulates knowledge development via pilot projects, to demonstrate and monitor Building with Nature in practice (Nature-Based Solutions). To carry out projects and related applied knowledge development, EcoShape has concluded a consortium agreement with 15 parties (engineering consultants, knowledge institutes, contractors, and NGO's) being Deltares one of them. Furthermore, EcoShape regularly collaborates with parties outside the signatories to the consortium agreement, e.g., with public parties and universities.
Based on the monitoring results, guidelines for replication and scaling up are developed and disseminated through the website of EcoShape (www.ecoshape.org/en).

We have synthesized some selected pilot projects under the Ecoshape. The details of presented and other projects can be found in the website.

5.4.3.1 Nature restoration project Marker Wadden

The project is related to creating about 6,000 to 10,000 hectares of man-made islands leading to more wildlife. Some facts and figures are outlined as follows:

- The group of islands has an overall size of 4.5 km by 2.3 km (Figure 5-27).
- The lay-out of Marker Wadden is subdivided in the main dam, secondary dams, compartments, sheltered marshland, recreational elements, a sandpit, and sedimentation channel.
- The construction of the first phase commenced in 2016 and finished in 2020.
- The construction included placement of cohesive and non-cohesive sediments that originate from the Lake Marker ecosystem, construction of harbour jetties, creation of beaches, dunes and marsh area.
- Volumes of used materials (Boskalis, 2019)
  - Armour rock =100,000 ton
  - Sand = 12,500,000 m^3
  - Clay, silt, peat = 15,500,000 m^3
- Finance, stakeholders, public-private partnership:
  - The design and construction of the Maker Wadden (first phase) is financed by Natuurmonumenten – a Dutch nature conservation NGO via a charity fund from a national lottery the Postcodeloterij (30.5 million EUR), Ministry of Infrastructures and Water Management (18.5 million EUR), Ministry of Economic Affair (18.5 million EUR) and Province Flevoland (6.5 million EUR).
  - The respective contributions were deposited on an external account of the Dutch national fund for green investments.
  - Monitoring activities and knowledge development were separately financed.

– Twelve stakeholders were especially involved: Municipality of Lelystad, Natuurmonumenten, Boskalis, Ministry of Economic Affairs, Ministry of Agriculture, Ministry of Infrastructure and Water, Province Flevoland, Nationaal Groeifonds, RWS Midden-Nederland and KIMA associates.

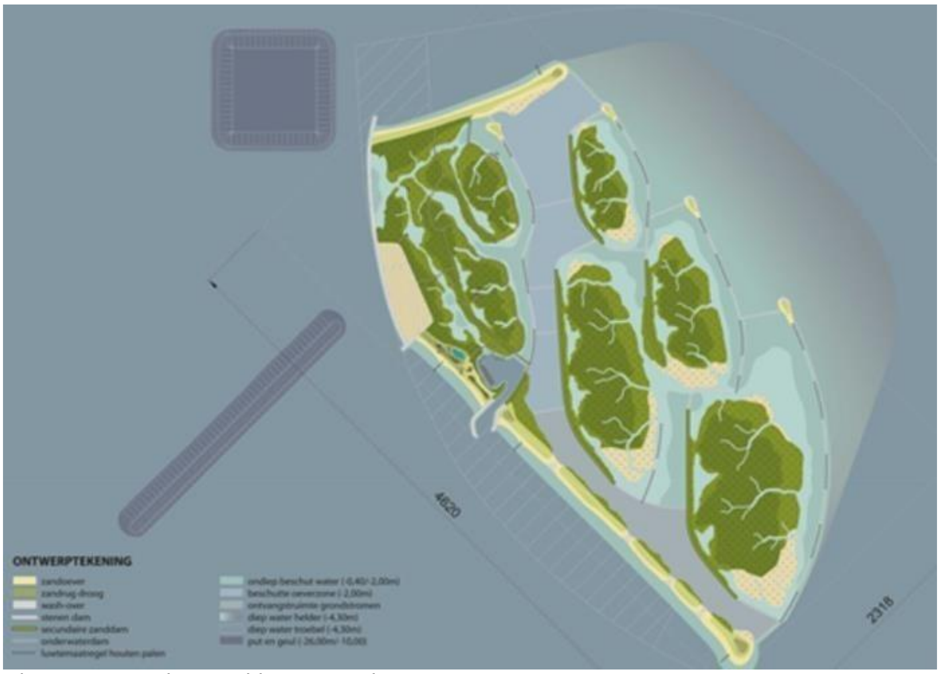


Figure 5-27 Marker Wadden restoration area

5.4.3.2 Clay ripening pilot

The goal of one of the Ecoshape pilot projects was to find out with which innovative methods of the placement of sludge on land can be converted into clay in a useful and cost-effective way. In the pilot project, multiple stakeholder objectives are merged effectively. As part of the project a business case for a scenario of large-scale implementation of the concept is evaluated.

The pilot is based on collecting silty sediments from the Eems-Dollard estuary and converting it into clay soil creating a double win situation: the water and ecosystem quality in the estuary improves, and more clay soil is available for reinforcing sea dikes along the Eems-Dollard estuary. The material may also be used for raising agricultural land to compensate soil subsidence.

Rijkswaterstaat (part of the Dutch Ministry of Infrastructure and Water Management), the Province of Groningen, Groningen Seaports, Water Authority Hunze en Aa's, nature conservation organization Het Groninger Landschap and EcoShape teamed up in the Clay Ripening pilot to look at different ways of transforming dredged fine sediment into clay soil, applicable in dike reinforcement operations. EcoShape researchers are engaged in practical experiments to investigate which approaches to clay ripening performs best.

This pilot forms a good example of how intensive and constructive stakeholder involvement can lead to a unique project, in which multiple stakeholder objectives, gathered around the reduction of freely moving silts in the estuary, can be merged effectively.

The aim of the pilot is to convert 290,000 m^3 of silty estuary sediment into roughly 105,000 m^3 of clay which meets the requirements of clay for dikes. “Water Authority Hunze en Aa’s” will be using 70,000 m^3 of the produced clay to transform/strengthen one kilometer of dike into a Wide Green Dike, in a subsequent pilot project. This is a dike with a shallow slope covered bygrass. If the produced clay proves to be successful in this test section, the remaining section (about 11.5 kilometers) of the flood defense structure it forms part of may also be strengthened with this method. In addition, the ripened sediment may be suitable as a raw material for the brick industry and for raising agricultural land.

The pilot will generate knowledge about transforming dredged material into clay soil and the usefulness of this process. This knowledge could also be very valuable elsewhere, where building materials are scarce and intensive flows of fine sediment led to high dredging costs and/or loss of ecological value, such as in Singapore or the Western Scheldt estuary (NL).

Figure 5-28 Clay Ripening location Delfzijl (left) with location of source of the sediment (right) (picture: Satelliet data portaal, 2018)

- Location: Eems-Dollard estuary, Delfzijl (The Netherlands)
- Expected project duration: January 2018 to January 2022
- Involved parties: Rijkswaterstaat, Province of Groningen, Groningen Seaports, Water Authority Hunze en Aa’s , Het Groninger Landschap and EcoShape. The project is financially supported by the Waddenfonds and the Dutch national flood protection program HWBP.
- Technology Readiness Level (TRL): 3 (i.e., experimental proof of concept)
- Environment: Muddy coasts, rivers and estuaries, ports

The more details about the project can be found here: www.ecoshape.org/en/cases/clay-ripening-pilot-project-delfzijl-nl/

5.4.4 New Suez Canal project: An iconic dredging project

Some facts and figures about this iconic project (Van Bemmelen et al., 2016):

- Involvement of six major dredging contractors: The Challenge Consortium comprised of Royal Boskalis and Van Oord from The Netherlands; National Marine Dredging Company (NMDC) from Abu Dhabi; Jan De Nul NV from Belgium. The total contract value amounted to US $1.5 billion. The second consortium, Dredging International NV (an operating company of DEME Group) from Belgium and Great Lakes Dredge & Dock Company (GLDD) from USA received the assignment to deepen and widen the western branch of the Suez Canal, worth US $540 million.
- Largest number of dredgers ever deployed on a single project – 28 units and over 40 pieces of auxiliary equipment.
- About 245 million m^3 of sand was dredged in 9 months.
- Most of funding for the project came from the Egyptian public who were invited to participate in the purchase of interest-bearing investment certificates. The US $8.4 billion goal was achieved in 8 days.

Figure 5-29 A satellite image of different dredging equipment for the Challenge Consortium at the work site (upper image) and picture of vessels (lower image)

5.5 Concluding remarks

Various global examples on management of sediment-induced problems were briefly presented. Furthermore, some examples were shown that could be of use while considering beneficial reuse of sediment at the THC. There is hardly any example related to the management of large sediment volumes at the reservoirs (as in the Channel reservoir), particularly their removal and reuse. Generally, most of the cases have much smaller volumes.

There were intensive capital dredging projects and equipment though that moved considerable sediment volumes that are on par with what would be expected within the THC.However, those experiences could be useful to consider for urgent maintenance work at the THC as well as for the pilot campaign on the beneficial reuse of sediment.

We also suggest looking at our presentation slides which briefly includes some global experiences as well. We have also included a list of various relevant literature and publication sources list that could be useful (see References).

6 Conclusions and recommendations

6.1 General conclusions

Our in-depth review and assessment of the previous available studies and a rapid analysis of the sediment-induced problems at the THC have revealed that the situation is rather severe in terms of not only storage loss of the THC resource but also for the safety of the populace, effect on the local economy and the dam structures. Furthermore, the further loss of resources without action (do nothing - wait) is also a realistic threat. The problem has alreadyresulted in decreasing flood safety as well as malfunctioning of the hydropower and irrigationstructures and facilities. There is a significant amount of storage loss (almost 1.5 billion m^3) leading to a water stress situation severely affecting the livelihood of more than 5 million people in the region. Consequently, it is the opinion undertaken in this review that the problems and associated challenges must be addressed urgently.

Several examples of global practices and references have been provided. They can be useful to consider and pursue in greater detail while considering and designing the possible mitigation measures. However, there is no generic method and technique alone. Thus proposed solution(s) and measure(s) should be site specific as per the local/regional situations associated with social, technical, environmental, economic, and integrated with the engineering feasibility of the solutions. It should be emphasized that all the measures and interventions should be properly assessed for their adverse impacts and feasibility. For example, the measures related to the sediment removal (by excavating, dredging as well as flushing and sluicing) should be properly studied to avoid any adverse impacts leading to hazards and risks such as collapse of the sediment layer leading to blockage of the intakes, transport of high sediment load leading to sediment hazards and damages in the reservoirs and downstream infrastructure and habitants.

There are still knowledge gaps globally, particularly related to the beneficial reuse of fine, clay-silt soft sediment, which appears to be the case for most of the sediment in the Channel reservoir. Fine grained soft sediments can be applied for beneficial reuse on a large scale but other processing conditioning steps that include both mechanical and other additions to produce a high-quality manufactured soils and stabilized sediments such as for engineered structural (non-structural fill) are usually undertaken. These manufactured products do have a high value and take the place of unrenewable resources. Most of the application are related to coarse sediment fractions that are easier to process via liquid -well established liquid-solid separation technologies and can even be directly used for a number of purposes also having a high monetary value as sand. For the fine sediment, the sediment placement and/or disposal, sediment processing for the beneficial reuse should be properly assessed based on a commercial-scale pilot campaign (as suggested). The intent is to develop large commercial-scale sediment manufacturing incubators/facilities that can spur economic growth. Many of these described processes can be scaled-up. As mentioned before, beneficial reuse of sediments is a resource – not a waste.

6.2 On managing sediment-induced problems with beneficial reuse of sediment at THC

The problems and the corresponding measures have been categorized as per the urgency and scale. These challenges of the 1st-category require immediate attention and action.

Whereas the 2nd-category will require more detailed impact and feasibility assessments. Also, the experiences that could be gained from the implementation and execution of the measures to address the 1st-category problems would be useful for the assessment of the measures to address the 2nd-category problems. These are summarized below in Table 6-1.

Table 6-1 The categorization of the problems at the THC and the proposed measures

	Problem description	Proposed measures	Remarks
1st-category	-Functionality and safety of the hydropower and irrigation structures -Flood passage (due to partial blockage of spillways)	A comprehensive sediment management program with beneficial reuse of the sediment is proposed: -Major maintenance measure (sediment removal plan and execution for the Channel reservoir and canal intakes) -Supplementary maintenance measure (sluicing and flushing of the Channel reservoir) -Mitigation measure (erosion and sediment inflow management in the catchment, the river and the reservoir) -Non-structural adaptive measures (monitoring, information, forecasting & early warning systems; water loss reduction) -Pilot campaign on beneficial reuse of sediment from the Channel reservoir (Top-soil enhancement, fertilizer, building materials, structures for CFDs, reservoir, river)	- Urgent action - A cost-benefit and feasibility analysis (particularly for beneficial reuse of the sediment - should be a part of the pilot campaign) - Detailed impact assessment (particularly for the sediment removal) - Market analysis for sediment products (volume, value, potential customer segments, demand patterns in the region, oversaturation of the market, other products and competition, other local and important factors).
2nd-category	-Storage loss leading to water stress for irrigation, drinking water affecting the livelihood of the people -Decrease in volume of the Channel reservoir affecting safe passage of (design) floods	-There options are proposed for the comparative feasibility and impact assessment: Option-1: Capital dredging in the Channel reservoir with beneficial reuse of sediment Option-2: Construction and/or extension of the off-channel reservoir(s) Option-3: Renovation/relocation of the structures (e.g., dam heightening or strengthening to increase the operation level of the reservoir) -Mitigation measures -Non-structural adaptive measures -Beneficial reuse of sediment (large-scale application that should be based on the outcomes of the pilot campaign)	-Large-scale interventions, thus detailed feasibility and impact assessment is required. -Experience, gained from the application and pilot campaign as a part of category 1 (urgent) measures, should be considered. -This may require more time for the feasibility and impact assessments as well as for the decision making processes

Based on our review of previous studies and laboratory tests, we have shortlisted some potential options of beneficial reuse of removed sediment for the THC for further consideration as follows:

- Manufactured topsoil improvement and fertilizer production for agriculture and afforestation
- Creation and restoration of ecological (habitat) zones that support livelihood functions

- Establishment of commercial industries for producing building materials (including the addition of polymers), landscape (ecological) design, engineered fill (structural and non-structural) and environmental applications
- River and reservoir training structures (bank protection, berms, sand plugs, earthen dams, etc.) for flow and sediment management

Each one of these proposed beneficial use options are directly linked to a processing operation to facilitate the manufacturing and/or placement of the removed sediments.

We have suggested to carry out a commercial-scale pilot campaign (as a part of comprehensive sediment management program) to assess the technical feasibility for their real-world application. This should also include market drivers and cost-benefit analysis as well as the detailed impact and risk assessment (social, economic, and environmental).

6.3 On sustainable management of THC

The functions of the THC are explicitly associated with water, food, and energy security for the region that supports a population of more than 5 million people. The functions are linked with the ecosystem services in a basin scale and must consider the social and environmental aspects as well. Consequently, the Nexus Water-Food-Energy + Environment (WFEE) shall be considered as an integral part of the sustainable management of the THC.

All the proposed measures and interventions to improve the situation of the THC should eventually contribute to the Sustainable Development Goals (SDGs). This should be considered while conducting the feasibility and impact assessment of the proposed measures. We have attempted to describe the interlinkage between Nexus and SDGs through the measures associated with sustainable management of the THC. Another important aspect related to the sustainable management of the THC is the governance perspective that should be in a basin scale as there are various interventions and influence atthe upstream catchment. Moreover, the THC is a transboundary complex that makes the cooperation and understanding between the two countries more important for improving the situation at the THC. There must be proper connection between technical part of the Nexus with the governance part as an essential sustainability criterion. This implies that the sustainable management is linked with the Integrated and Participatory River Basin Management (IPRBM), which appears to have partly been already considered within the scope of the Amu Darya basin management.

6.4 On constraints and challenges

There are several challenges, constraints, and limitations with respect to the handling of sediment-induced problems as well as beneficial reuse of removed sediment at the THC.
In general, the constraints and challenges, that could be relevant to the THC have been categorized as follows:
(i) Physical constraints: Magnitude, severity and conditions of the problems and the facilities; timeframe; space and advanced technology; accessibility and project logistics; market drivers and limitations for the products (related to sediment reuse); unfavourable changes in the future (e.g. decreasing inflow or increasing erosion due to upstream catchment degradation and interventions).
(ii) Social and environmental constraints: Safety concerns, ecological impacts and risks due to the large interventions and changes (e.g., for farmers, fishermen and other inhabitants); social resistance and unwillingness; pollutions (air, water, noise); contaminated or poor quality of deposited materials

(iii) Economic constraints: Availability of the investment and willingness; budget limitation (e.g., for the state authorities); ambiguous economic viability and justification; financial risks (loss or reduction of benefits, e.g., due to possible extremes, hazards, failures, economic and political instability)
(iv) Legal and other constraints: Rules and regulations, stakeholders' priorities and interests; acceptance to innovative approaches and technologies- (do what we always do); transboundary disputes; political will; differences in perception of urgency.
(v) Contracting and financing: Innovative contract and procurement packages that entice long-term investments that balance risk.

All the relevant constraints and nuances must be properly explored and addressed already in a preliminary phase of the scoping studies and prefeasibility assessment. Whereas the conclusions of this study may appear to be daunting – and they are based on the magnitude of these integrated challenges, the will to move forward knowing that there is precedence from mega-scale projects that have been conducted globally exist. The decision is left to deciding how long can the THC hold and sustain before collapse.

6.5 Acknowledgement

We are very grateful to Prof. Dr. Malika Ikramova for her regular help with providing data, information, and valuable suggestions throughout. We also acknowledge the experts from CAREC and the THC authority for their regular help, insight and fruitful discussions.

References

Guidelines, books, manuals, and reports

1) Ackerman et al. (2009): RESIS–II: An Updated Version of the Original Reservoir Sedimentation Survey Information System (RESIS) Database. Data Series 434, U.S. Geological Survey.
2) Annandale et al. (2016): Extending the Life of Reservoirs: Sustainable Sediment Management for Damsand Run-of-River Hydropower. World Bank publication.
3) Atkinson E. (1996): The Feasibility of Flushing Sediment from Reservoirs. Report OD 137. HR Wallingford.
4) Battisacco E. (2016): Replenishment of sediment downstream of dams: Erosion and transport processes. Communication 67, Laboratory of Hydraulic Construction, Swiss Federal Institute of Technology (EPFL).
5) Blanton J. O. (1982): Procedures for Monitoring Reservoir Sedimentation. Technical Guideline for Bureau of Reclamation. Sedimentation and River Hydraulics Section, Engineering and Research Center, Colorado.
6) Carvalho et al. (2000): Reservoir Sedimentation Assessment Guideline. Brazilian Electricity Regulatory Agency - Aneel Hydrological Studies and Information Department – SIH
7) Carvalho et al. (2000): Sedimentometric Practices Guide. Brazilian Electricity Regulatory Agency - Aneel Hydrological Studies and Information Department – SIH
8) CWC (2015): Compendium on Silting of Reservoirs in India. Watershed & Reservoir Sedimentation Directorate. Central Water Commission.
9) CWC (2018): National Register of Large Dam (NRLD). Internet Source: http://www.cwc.nic.in/main/downloads/NRLD_06042018.pdf
10) DB Sediment (2013): Sediment Management of John Compton Dam. Feasibility Study. Final Report, June 24th 2013.
11) Dennis et al. (2004): Restoration and management of Lakes and Reservoirs. ISBN 0-7484-0772-3. Taylor & Francis Group Publication.
12) **Giri et al. (2019): Handbook for Assessing and Managing Reservoir Sedimentation, Doc. No. CDSO_GUD_DS_04_v1.0. A handbook prepared under Dam Rehabilitation and Improvement Project in India – available online**.
13) Giri S. (2015): Reservoir Sedimentation and Desiltation: Sediment Management Plan for Selected Reservoirs. Mission Report. Engineering and Management Consultancy Services for Central Project Management Unit under Dam Rehabilitation and Improvement Project.
14) Halcrow Water (2001): Sedimentation in Storage Reservoirs. Final Report. Department of the Environment, Transport and the Regions.
15) Hydrology Project (2003): Sediment Transport Measurement – Design Manual. Volume 5.
16) http://nhp.mowr.gov.in/docs/HP1/MANUALS/Surface%20Water/5014/SW%20Design%20Manual%20Volume%205%20Sediment.pdf).
17) IAEA (2005). Fluvial sediment transport: Analytical techniques for measuring sediment load. IAEA-TECDOC-1461. International Atomic Energy Agency (IAEA).
18) ICOLD (2011): Reservoir and Seismicity. Bulletin 137.
19) ICOLD (2010): Icold Bulletin on Environmental Hydraulics. The Interaction of Hydraulic Processes and Reservoirs Management of the Impacts Through Construction and Operation. Downstream Impacts of Large Dams. Bulletin 162.
20) ICOLD (2009): Sedimentation and Sustainable Use of Reservoirs and River Systems. Draft Bulletin 147.

21) ICOLD (2007): Mathematical Modelling of Sediment Transport and Deposition in Reservoirs. Guidelines and case studies. Bulletin 140.
22) ICOLD (2000): Reservoir Landslides: Investigation and Management. Guidelines and case studies. Bulletin 124.
23) ICOLD (1996): Dealing with Reservoir Sedimentation. Guidelines and case studies. Bulletin 115.
24) ICOLD (1989): Sedimentation Control of Reservoirs. Guidelines. Bulletin 67.
25) ISI (2011): Sediment Issues & Sediment Management in Large River Basins. Interim Case Study Synthesis Report. International Sediment Initiative Technical Documents in Hydrology. CN/2011/SC/IHP/PI/2
26) Julien P. Y. (2010) : Erosion and Sedimentation. 2nd Edition. ISBN-13 978-0-511-71294-4, Cambridge University Press. The Edinburgh Building, Cambridge CB2 8RU, UK.
27) K-State Research and Extension publication (2008): Sedimentation in Our Reservoirs: Causes and Solutions. Edited and designed by the Department of Communications at Kansas State University.
28) Kawashima et al. (2003): Reservoir Conservation, Volume 2. RESCON Model and User Manual. Economic and engineering evaluation of alternative strategies for managing sedimentation in storage reservoirs. The International Bank for Reconstruction and Development/THE WORLD BANK.
29) Kimbrel et al. (2015): Formulating Guidelines for Reservoir Sustainability Plans. U.S. Department of Agriculture, Bureau of Reclamation (internet source).
30) Klik et al. (2010). Soil erosion and sediment transport measurement and assessment. Department of Irrigation, Drainage and Landscape Engineering Faculty of Civil Engineering, CTU Prague.
31) Levec and Skinner (2004): Manual Instructions: Bathymetric Surveys. Ministry of Natural Resources, Ontario.
32) Lysne et al. (2003): Hydraulic Design. Hydropower Development, Volume 8, Department of Hydraulic and Environmental Engineering Norwegian University of Science and Technology N 7491 Trondheim, Norway.
33) Ministry of Environment, Forest and Climate Change (2016): Sustainable Sand Mining Guidelines. www.moef.in
34) Ministry of Mines (2018): Sand Mining Recommendations. A draft report: https://mines.gov.in/writereaddata/UploadFile/sandmining16022018.pdf
35) Morris and Fan (2010): Design and Management of Dams, Reservoirs and Watersheds for Sustainable Use. Reservoir Sedimentation Handbook. McGraw-Hill.
36) Mekong River Commission (MRC) (2017): Guidelines for hydropower environmental impact mitigation and risk management in the Lower Mekong mainstream and tributaries (ISH0306). Volume 1 to 4. 2017. Info: www.mrcmekong.org/assets/Publications/leaflet/ISH-0306-brochur-update-2016.pdf
37) Palmieri et al. (2003) : Reservoir Conservation, Volume 1. The RESCON Approach. Economic and engineering evaluation of alternative strategies for managing sedimentation in storage reservoirs. The International Bank for Reconstruction and Development / THE WORLD BANK.
38) Randle et al. (2013): Dam Removal Analysis Guidelines for Sediment Draft Report, September 10, 2013. Prepared for Subcommittee on Sedimentation, U.S. Department of Agriculture, Bureau of Reclamation.
39) Rasmussen et al. (2011). Guidelines and Procedures for Computing Time-Series Suspended-Sediment Concentrations and Loads from In-Stream Turbidity-Sensor and Streamflow Data. Techniques and Methods 3–C4. U.S. Department of the Interior. U.S. Geological Survey.
40) USBR (2006): Erosion and Sedimentation Manual, U.S. Department of the Interior Bureau of Reclamation, Technical Service Center Sedimentation and River Hydraulics Group, Denver, Colorado, USA.

41) UNEP/MAP Athens (2006): Methods for Sediment Sampling and Analysis. UNEP (DEC)/MED WG.282/Inf.5/Rev.1.
42) USACE (1989): Sedimentation Investigations of Rivers and Reservoirs. EM 1110-2-4000. U.S. Army Corps of Engineers, Washington, DC 20314-1000.
43) Utah State Water Plan (2010): Managing Sediment in Utah's Reservoirs. A report by Utah Division of Water Resources of USWP.
44) Wischmeier, W.H. and Smith D.D. (1978): Predicting Rainfall Erosion Losses: A Guide to Conservation Planning. Agriculture Handbook No. 537. USDA/Science and Education Administration, US. Govt. Printing Office, Washington, DC. 58pp.
45) WMO (2009): Guide to Hydrological Practices. Volume I: Hydrology – From Measurement to Hydrological Information WMO-No. 168.
46) WMO (2008): Guide to Hydrological Practices. Volume II: Management of Water Resources and Application of Hydrological Practices WMO-No. 168.
47) WMO (2003): Manual on Sediment Management and Measurement. World Meteorological Organization. Operational Hydrology Report No. 47. WMO-No. 948.

Publications related to case studies on management of reservoir sedimentation

1) Aras T. (2009): Cost Production of Sediment Removal from Reservoir. Master's Thesis, Middle East Technical University
2) Arbat-Bofill et al. (2014): Suspended sediment dynamics of Ribarroja Reservoir (Ebro River, Spain). Reservoir Sedimentation – Schleiss et al. (Eds), Taylor & Francis Group, London, ISBN 978-1-138-02675-9.
3) Bel et al. (2014): Debris flow monitoring in the French Alps. Reservoir Sedimentation – Schleiss et al. (Eds), Taylor & Francis Group, London, ISBN 978-1-138-02675-9.
4) Bollaert et al. (2014): Sequential flushing of Verbois and Chancy-Pougny reservoirs (Geneva, Switzerland). Reservoir Sedimentation – Schleiss et al. (Eds), Taylor & Francis Group, London, ISBN 978-1-138-02675-9.
5) Bonviller et al. (2017): Sedimentation in the Ruzizi 1 and 2 reservoirs: Means of response and forecasting. Proceedings of International Conference Hydro-2017, Morocco.
6) Boroujeni H. S.: Sediment Management in Hydropower Dam (Case Study – Dez Dam Project). Shahrekord University, Iran. Internet Source.
7) Brandt S. A. (1999): Reservoir Desiltation by Means of Hydraulic Flushing: Sedimentological and Geomorphological Effects in Reservoirs and Downstream Reaches as Illustrated by the Cachi Reservoir and the Reventazon River, Costa Rica. PhD Thesis. University of Copenhagen, ISSN 0908-6625.
8) Dysarz et al. (2014): Two approaches to forecasting of sedimentation in the Stare Miasto reservoir, Poland. Reservoir Sedimentation – Schleiss et al. (Eds), Taylor & Francis Group, London, ISBN 978-1-138-02675-9.
9) Harb G.: Sediment management and reservoir flushing in Austria. Graz University of Technology. Internet Source.
10) Emamgholizadeh and Samadi (2008): Desilting of Deposited Sediment at the Upstream of the Dez Reservoir in Iran. Journal of Applied Science and Environmental Sanitation, Volume 3, Number 1: 25-35.
11) Fruchart and Camenen (2012): Reservoir Sedimentation Different Type of Flushing - Friendly Flushing Example of Genissiat Dam Flushing. International Symposium on Dam for a Changing World, Kyoto, Japan.
12) Ghomari and Khalid (2017): Mitigation of reservoir sedimentation: A new life for the Timi N'Outine dam. Proceedings of International Conference Hydro-2017, Morocco.
13) Hasnaoui M. D. (2017): Impact of siltation on the use of surface water resources in the Moulouya watershed and upstream storage method as a countermeasure: The Case of Mohamed V dam. Proceedings of International Conference Hydro-2017, Morocco.
14) Hasnaoui et al. (2017): Upstream storage method and RUSLE model to assess and rationalize erosion and siltation for efficient watershed planning and management. Proceedings of International Conference Hydro-2017, Morocco.

15) Lai and Wu (2018): A numerical modeling study of sediment bypass tunnels at Shihmen Reservoir, Taiwan. International Journal of Hydrology, Volume 2, Issue I.
16) Lai C. H. (2017): Hydraulic desilting of reservoir in Taiwan. 2nd International Workshop on Sediment Bypass Tunnels. Kyoto, Japan.
17) Lee et al. (2016): Downstream Impact Investigation of Released Sediment from Reservoir Desilting Operation. 12th International Conference on Hydroscience & Engineering Hydro-Science & Engineering for Environmental Resilience November 6-10, Tainan, Taiwan.
18) Lewis et al. (2013): Calculating sediment trapping efficiencies for reservoirs in tropical settings: A case study from the Burdekin Falls Dam, NE Australia. Water Resources Research, Vol.49,1017–1029,doi:10.1002/wrcr.20117
19) Maricar and Hashimoto (2014). A comparison of wood-sediment-water mixture flows at a closed type and an open type of check dams in mountain rivers. Reservoir Sedimentation – Schleiss et al. (Eds), Taylor & Francis Group, London, ISBN 978-1-138-02675-9.
20) Mathieu et al. (2014): Storage Capacity of the Fena Valley Reservoir, Guam, Mariana Islands, 2014, Scientific Investigations Report 2015–5128, U.S. Department of the Interior, U.S. Geological Survey.
21) Meile et al. (2014): Reservoir sedimentation management at Gebidem Dam (Switzerland). Reservoir Sedimentation – Schleiss et al. (Eds), Taylor & Francis Group, London, ISBN 978-1-138-02675-9.
22) Morris G. L. (2011): Preliminary Sediment Management Recommendations Aimores Reservoir, Rio Doce, Brazil. Report, Gregory L Morris Engineering, and CEMIG.
23) Peteuil et al. (2013): Sustainable management of sediment fluxes in reservoir by environmentally friendly flushing: the case study of the Genissiat dam on the upper Rhone River (France). www.researchgate.net/publication/259272333
24) Sabir et al. (2013): The Impact of Suspended Sediment Load on Reservoir Siltation and Energy Production: A Case Study of Indus River and Its Tributaries. Pol. J. Environ. Stud., Vol. 12, No. 1.
25) Sawagashira et al. (2017): Sedimentation control effect and environmental impact of sediment bypass in Miwa Dam Redevelopment Project. 2nd International Workshop on Sediment Bypass Tunnels, Kyoto, Japan.
26) Shreshtha H. (2012): Sedimentation and Sediment Handling In Himalayan Reservoirs. PhD Thesis, Norwegian University of Science and Technology.
27) Sloff et al. (2018): Applying New Guidelines for Sediment Mitigation in Hydropower Projects In The Mekong Basin. Submitted to ICOLD-2018, Vienna, Austria.
28) Sloff et al. (2015): Design and modelling of reservoir operation strategies for sediment management, RCEM2015 - River and Coastal and Estuarine Morphodynamics, Peru, August.
29) Sumi T.: Evaluation of Efficiency of Reservoir Sediment Flushing in Kurobe River. Internet Source.
30) Taveira-Pinto et al. (2014): Global analysis of the sedimentation volume on Portuguese reservoirs. . Reservoir Sedimentation – Schleiss et al. (Eds), Taylor & Francis Group, London, ISBN 978-1-138-02675-9.
31) Tsai et al. (2012): Modeling the sediment yield from landslides in the Shihmen Reservoir watershed, Taiwan. Earth Surf. Process. Landforms. DOI:10.1002/esp.3309.
32) Van der Vat, M. (2015): Optimizing reservoir operation for flood storage, hydropower and irrigation using a hydro-economic model for the Citarum River, West-Java, Indonesia. Dissertation for fulfilment of degree of Msc. International Program at University of London.
33) Weirich F. (2014): The impact of flow transformations and reservoir floor topography on reservoir deposition patterns in high energy environments. Reservoir Sedimentation – Schleiss et al. (Eds), Taylor & Francis Group, London, ISBN 978-1-138-02675-9.
34) Wu B. (2007): Reservoir Sedimentation – with the Sanmenxia Reservoir as a Case Study. Tsinghua University, Incheon, South Korea. Internet Source.

35) Zamora and Jacobsen (2018): Sediment handling at the Indrawati III intake, Nepal. Seventh International Conference and Exhibition on Water Resource and Renewable Energy Development in Asia" organized by The international journal on Hydropower and dams, 13-15 March in Vietnam.

Note: Most guidelines (mentioned in the reference list above) also include a number of case studies.

Publications related to modelling studies (case studies and research)

1) Ahn J. (2011): Numerical Modeling of Reservoir Sedimentation and Flushing Processes. In partial fulfilment of the requirements For the Degree of Doctor of Philosophy Colorado State University Fort Collins, Colorado.
2) Amini et al. (2014): Comprehensive Numerical Simulations of Sediment Transport and Flushing of a Peruvian Reservoir. Reservoir Sedimentation – Schleiss et al. (Eds), Taylor & Francis Group, London, ISBN 978-1-138-02675-9.
3) Antoine et al. (2014): Numerical modeling of suspended sediment transport during dam flushing: From reservoir dynamic to downstream propagation. Reservoir Sedimentation – Schleiss et al. (Eds), Taylor & Francis Group, London, ISBN 978-1-138-02675-9.
4) Cajot et al. (2012): Reservoir Sediment Management Using Replenishment: A Numerical Study of Nunome Dam. International Symposium on Dams for a Changing World. Kyoto, Japan.
5) Castillo et al. (2015): Complementary Methods for Determining the Sedimentation and Flushing in a Reservoir. Journal of Hydraulic Engineering, ASCE, ISSN0733-9429/05015004 (10).
6) Commandeur A. S. (2015): Turbidity Currents in Reservoirs. Master's Thesis. Delft University of Technology. The Netherlands.
7) Esmaeili et al. (2017): Three-Dimensional Numerical Study of Free-Flow Sediment Flushing to Increase the Flushing Efficiency: A Case-Study Reservoir in Japan. Water, 9, 900, doi:10.3390/w9110900.
8) Esmaeili et al. (2014): Three-dimensional numerical modeling of flow field in rectangular shallow reservoirs. Reservoir Sedimentation – Schleiss et al. (Eds), Taylor & Francis Group, London, ISBN 978-1-138-02675-9.
9) Fukuda et al. (2012): Study on Flushing Mechanism of Dam Reservoir Sedimentation and Recovery of Riffle-Pool in Downstream Reach by a Flushing Bypass Tunnel. International Symposium on Dams for A Changing World. Kyoto, Japan.
10) Gibson and Boyd (2014) : Modeling long term alternatives for sustainable sediment management using operational sediment transport rules. Reservoir Sedimentation – Schleiss et al. (Eds), Taylor & Francis Group, London, ISBN 978-1-138-02675-9.
11) Giri et al. (2016): Reservoir sedimentation issues in India as a part of Dam Rehabilitation and Improvement Project (DRIP): Field reconnaissance and modelling. Accepted paper for International Symposium on River Sedimentation, Stuttgart, Germany.
12) Giri et al. (2016): Reservoir sedimentation issue in Pillur reservoir in Nilgiris basin (India): Field reconnaissance and numerical modelling using Delft3D. Accepted paper for River Flow 2016, St. Louis, USA.
13) Harb et al. (2014): Numerical analysis of sediment transport processes during a flushing event of an Alpine reservoir. Reservoir Sedimentation – Schleiss et al. (Eds), Taylor & Francis Group, London, ISBN 978-1-138-02675-9.
14) Hosseinzadeh et al. (2014): The numerical investigation of the effect of subsequent check dams on flood peaks and the time of concentration using the MIKE 11 modeling system (Case study: Golabdareh catchment, Iran). Reservoir Sedimentation – Schleiss etal. (Eds), Taylor & Francis Group, London, ISBN 978-1-138-02675-9.
15) Huffaker et al. (2010): Stability and Bifurcation Analysis of Reservoir Sedimentation Management. The Open Hydrology Journal, 2010, 4, 102-112.

16) Jodeau et al. (2014): Innovative in-situ measurements, analysis and modeling of sediment dynamics in Chambon reservoir, France. Reservoir Sedimentation – Schleiss etal. (Eds), Taylor & Francis Group, London, ISBN 978-1-138-02675-9.
17) Kostic S. (2014): Advances in numerical modeling of reservoir sedimentation. Reservoir Sedimentation – Schleiss et al. (Eds), Taylor & Francis Group, London, ISBN 978-1-138-02675-9.
18) Lai et al. (2015): Reservoir Turbidity Current Modelling with a Two-Dimensional Layer-Averaged Model. Journal of Hydraulic Engineering, ASCE, ISSN0733-9429/04015029 (15)
19) Luis et al. (2014): Simulation of the flushing into the dam-reservoir Paute-Cardenillo.
20) Maskey S. L. (2016): Sediment yield of the upper Koshi River basin: scenarios with and without reservoirs. Master Thesis. UNESCO-Institute of Hydraulic Engineering, The Netherlands.
21) Me et al. (2015): Effects of hydrologic conditions on SWAT model performance and parameter sensitivity for a small, mixed land use catchment in New Zealand. Hydrology and Earth System Sciences. 19: 4127-4147. Doi: 10.5194/hess-19-4127.
22) Mehshakti et al. (2012): Experimental Investigation of Pressure Flushing Technique in Reservoir Storages. Water and Geoscience. ISBN: 978-960-474-160-1. Reservoir Sedimentation – Schleiss et al. (Eds), Taylor & Francis Group, London, ISBN 978-1-138-02675-9.
23) Memarian et al. (2013): Application of SWAT for impact assessment of land use/cover change and best management practices: A review. International Journal of Advancement in Earth and Environmental Sciences. 1(1): 35-40.
24) Mool et al. (2017): Delft3D morphological modeling of sediment management in daily peaking run-of-the-river hydropower (PROR) reservoirs in Nepal. 85th Annual Meeting of ICOLD, July 3-7, Prague.
25) Omer et al. (2017): The effect of different gate opening patterns on reservoir flushing and morphological changes downstream a dam. Proceedings of International Conference Hydro-2017, Morocco.
26) Pandra et al. (2018): 3D flow simulation study for flushing at the intake of the Masang hydro plant, Indonesia. Seventh International Conference and Exhibition on Water Resource and Renewable Energy Development in Asia” organized by The international journal on Hydropower and dams, 13-15 March in Vietnam.
27) Shen et al. (2009): A comparison of WEPP and SWAT for modeling soil erosion of the Zhangjiachong Watershed in the Three Gorges Reservoir Area. Agricultural Water ManagementVolume 96, Issue 10.
28) Shrestha, N.K., P.C. Shakti and P. Gurung (2010): Calibration and validation of SWAT model for low lying watersheds: A case study on the Kliene Nete Watershed, Belgium. Hydro Nepal: Journal of Water, Energy and Environment. 6: 47-51. Doi: 10.3126/hn.v6i0.4194.
29) Sloff et al. (2016): New modelling approach for impact assessment of hydropower development and reservoir sediment management in the Mekong. Proc. ASIA 2016 conference (Hydropower and Dams), Vientiane, Laos, March 2016.
30) Sloff, C.J. (1994): Modelling turbidity currents in reservoirs. Comm. on hydr. and geotechn. engrg., Report No. 94-5, Delft Univ. of Technology, The Netherlands, 142 pp.
31) Tarekegn et al. (2014): Modelling suspended sediment wave dynamics of reservoir flushing. Reservoir Sedimentation – Schleiss et al. (Eds), Taylor & Francis Group, London, ISBN 978-1-138-02675-9.
32) Pringle et al. (2014): Numerical study of flushing half-cone formation due to pressurized sediment flushing. Reservoir Sedimentation – Schleiss et al. (Eds), Taylor & Francis Group, London, ISBN 978-1-138-02675-9.
33) Rai N. N. (2016): Optimization and Simulation of Reservoir Operation for Sediment Control. Second National Dam Safety Conference 12-13 January 2016, Bengaluru.

34) Rehman et al. (2015): Application of a 1d Numerical Model For Sediment Management in Dasu Hydropower Project. Proceedings of the 14th International Conference on Environmental Science and Technology Rhodes, Greece, 3-5 September 2015.
35) Singh A. (2009): Characterizing runoff generation mechanism for modelling runoff and soil erosion, in small watershed of Himalayan region. Master thesis submitted to the International Institute for Geo-information Science and Earth Observation.
36) Toniolo and Parker (2003). 1D numerical modelling of reservoir sedimentation. Proceedings, IAHR Symposium on River, Coastal and Estuarine Morphodynamics, Barcelona, Spain.
37) Valette et al. (2014): St-Egrève reservoir—modelling of flushing and evolution of the channel bed. Reservoir Sedimentation – Schleiss et al. (Eds), Taylor & Francis Group, London, ISBN 978-1-138-02675-9.
38) Wei et al. (2014): Combination of 2D shallow water and full 3D numerical modeling for sediment transport in reservoirs and basins. Reservoir Sedimentation – Schleiss et al. (Eds), Taylor & Francis Group, London, ISBN 978-1-138-02675-9.

Note: Most guidelines (mentioned in the reference list above) also include descriptions and details about numerical modelling.

Publications related to dredging and sediment reuse

1) Dukhovniy et al. (2018): Future use of the Amu Darya in the face of climate change. USAID report. Scientific Information Center of the Interstate Water Coordinating Commission of Central Asia
2) Agricultural Reuse of Polluted Dredged Sediments. Published on Eco-Innovation (https://ec.europa.eu/environment/eco-innovation/projects)
3) CIT (2013): Guidance on the Beneficial Use of Dredge Material in Ireland. Dr. Joseph Harrington & Gary Smith School of Building & Civil Engineering Cork Institute of Technology.
4) Dutch-German Exchange on Dredged Material (DGEDM) (2002): Treatment and Confined Disposal of Dredged Material (Part 2).
5) Dutch-German Exchange on Dredged Material (DGEDM) (2003): Dredged Material and Legislation (Part 1).
6) Englis and Hunter: A Description of Sediment Dewatering Methods. Internet source
7) Great Lakes Commission (2013): Beneficial Use of Dredged Material in the Great Lakes. www.seagrant.wisc.edu/home/Portals/0/BeneficialUse_online_FINAL.pdf
8) Honders et al.: Sediment Reuse, Treatment and Disposal in Netherlands: An Overview of Options.
9) https://rwsenvironment.eu/publish/pages/126603/sediment_treatment_24_310101.pdf
10) Hull, J. H. (2016): Reuse of Dredged Sediments. Lake Erie Waterkeeper Conference, W.W. Knight Nature Preserve, Perrysburg, Ohio.
11) Laboyrie, H. P.: Handling of Dredged Material in The Netherlands.
12) www.htg- baggergut.de/Downloads/Sprechtag03Laboyrie.pdf
13) Marcus O.P. (2018): Multifunctional small dredging solution for the maintenance of deep irrigation reservoirs and hydropower dams. Seventh International Conference and Exhibition on Water Resource and Renewable Energy Development in Asia" organized by The International Journal on Hydropower and Dams, 13-15 March in Vietnam.
14) OSPAR Commission: Revised OSPAR Guidelines for the Management of Dredged Material. Reference number: 2004-08.
15) Plummer et al. (2005): Dredging vs. New Reservoirs. Report, Texas Water Development Board (TWDB Contract #2004-483-534)
16) Sheehan, C. (2012): An analysis of dredge material reuse techniques for Ireland, PhD Dissertation, Cork Institute of Technology.
17) Sheehan et al. (2009): An Overview of Dredging and Dredge Material Beneficial Use in Ireland." Terra et Aqua, June Issue 2009, No. 115, pp. 3-14, The Hague, Netherlands.

18) Studds and Millar (2010): Sustainable material reuse solutions for dredged sediments. International Journal of Sustainable Engineering, Volume 3 - Issue 1: Materials and Sustainable Engineering
19) Sumi et al. (2017): Experimental study on the siphon dredging system at the Wonogiri multipurpose dam. Proceedings of International Conference Hydro-2017, Morocco.

Miscellaneous publications

1) Harrington et al. (2022): A downscaled economic model validated and applied to sediment management projects in Ireland and Scotland. Journal of Soils and Sediments, https://doi.org/10.1007/s11368-022-03267-z
2) Lee, F.-Z.; Lai, J.-S.; Sumi, T. (2022): Reservoir Sediment Management and Downstream River Impacts for Sustainable Water Resources—Case Study of Shihmen Reservoir. Water, 14, 479. https://doi.org/10.3390/w14030479.
3) Shirokova Y. I. (2022): ОТЧЕТ по проекту «Проведение комплексного биохимического анализа состава ила руслового водохранилища Туямуюнского гидроузла» Контракт № EMP-2022-C-026. Министерство водного хозяйства Республики Узбекистан (МВХ РУз). Научно- исследовательский институт Ирригации и водных проблем (НИИИВП)
4) Ikramova M. (2021): Technical recommendations: Ruslovoye reservoir sedimentation management at the Tuyamuyun hydrocomplex on the amu river and sediment control. Central Asia Nexus Dialogue Project: Fostering Water, Energy and Food Security Nexus and Multi-Sector Investment (Phase II). Ministry of Water Resources of the Republic of Uzbekistan Research Institute of Irrigation and Water Problems.
5) Allen and Dunbar (2005): Dredging vs. New Reservoirs. Texas Water Development Board. Austin, Texas.
6) American Society of Civil Engineers, ed. (1995): Guidelines for Design of Intakes for Hydroelectric Plants. American Society of Civil Engineers: New York.
7) Annandale et al. (2016): RESCON 2: Rapid identification of optimal strategies to mitigate reservoir sedimentation and climate change impacts on water supply reliability. Proceedings of International Conference Hydro-2017, Morocco.
8) Annandale, G.W. (1987): Reservoir Sedimentation. Elsevier Science Publishers, New York.
9) Annandale, G.W. (2008): Engineering and Hydrosystems Report: Tarbela Dam Fifth Periodic Inspection: Reservoir Sedimentation Management, Submitted to WAPDA, Islamabad, Pakistan.
10) Annandale, G.W. (2015): Policy Considerations for Sustainable Hydropower – Reliability, Climate Change and Sedimentation, HYDRO 2105, Bordeaux, France.
11) Ansari and Athar (2012): Design parameters of vortex settling basin. Water Management 166:262-271. Issue WM5.
12) Anselmetti et al. (2007): Effects of Alpine hydropower dams on particle transport and lacustrine sedimentation. Aquatic Sciences 69(2), DOI: 10.1007/s00027-007-0875-4
13) Arrow et al. (2013): Determining Benefits and Costs for Future Generations. Science 341.
14) Asselman, N.E.M. (2000): Fitting and interpretation of sediment rating curves. Jour. of Hydrology 234(2000):224-248.
15) Asselman et al. (2003): The impact of changes in climate and land use on soil erosion, transport and deposition on suspended sediment in the River Rhine. Hydrological Processes 17(6):3225-3244.
16) Athar et al. (2002): Sediment Removal Efficiency of Vortex Chamber Type Sediment Extractor. J. Hyd Eng 128(12):1051-1059.
17) Atkinson, E. (1996) The Feasibility of Flushing Sediment from Reservoirs. Report OD-137. HR Wallingford, Wallingford.
18) Auel et al. (2010): Sediment management in the Solis Reservoir using a bypass tunnel. Proc. of the 8th ICOLD European Club Symposium, 22-23 Sept. Innsbruck.

19) Auel et al. (2011): Design and Construction of the Sediment Bypass Tunnel at Solis. Hydropower and Dams 3: 62–66.
20) Auel and Boes (2011): Sediment bypass tunnel design – hydraulic model tests. Downloaded from ResearchGate: www.researchgate.net/publication/266420740.
21) Basson and Rooseboom (1997): Dealing with Reservoir Sedimentation. South African Water Research Commission Publication No. TT91/97, ISBN 1 8684G 2557.
22) Basson and Rooseboom (1999): Dealing with Reservoir Sedimentation: Guidelines and Case Studies. ICOLD Bulletin 115. Paris.
23) Bhatia et al. (2008): Indirect Economic Impacts of Dams: Case Studies from India, Egypt and Brazil. The World Bank: Washington D.C.
24) Bouvard, M. (1992): Mobile Barrages and Intakes on Sediment Transporting Rivers. Rotterdam; Brookfield: A.A. Balkema.
25) Boes, R.W. (2015): Proc. First Intl. Workshop on Sediment Bypass Tunnels. Laboratory of Hydraulics, Hydrology and Glaciology, ETH, Zurich, Switzerland. ISSN 0574-0056.
26) Boyce, R. C. (1975): Sediment Routing with Sediment-Delivery Ratios. In Present and Prospective Technology for Predicting Sediment Yields and Sources. ARS-S-40. USDA Sedimentation Lab., Oxford. Miss.
27) Brune, G.M. (1953): Trap Efficiency of Reservoirs. Transactions of the American Geophysical Union 34(3): 407-418.
28) Bagnold, R.A. (1956): The Flow of Cohesionless Grains in Fluids. Proc. Royal Soc. Philos.Trans., London, Vol. 249.
29) Bagnold, R.A. (1966): An Approach to the Sediment Transport Problem from General Physics. Geological Survey Prof. Paper 422-I, Washington.
30) Borland, W.M. and Miller, C.R. (1960): Distribution of sediment in large reservoirs. Paper No. 3019, ASCE, Transactions, Vol. 125, p. 166-180
31) Bronsvoort K. (2013): Sedimentation in Reservoirs. Investigating Reservoir Preservation Options and the possibility of Implementing Water Injection Dredging in Reservoirs. MSc Thesis, TU Delft.
32) Cost and Williams (1984): Debris-flow Dynamics. USGS Open-file Report 84/606.
33) Crosato, A. (2015), Morphological Response at the Reach Scale. River Morphodynamics Lecture Notes LN0381, UNESCO-Institute of Hydraulic Engineering.
34) Chaudhry and Rehman (2012): Worldwide Experience of Sediment Flushing Through Reservoirs. Mehran University Research Journal of Engineering & Technology, Volume 31, No. 3.
35) David et al.: Calculating Revised Universal Soil Loss Equation (RUSLE) Estimates on Department of Defense Lands: A Review of RUSLE Factors and U.S. Army Land Condition-Trend Analysis (LCTA) Data Gaps. Center for Ecological Management of Military Lands Department of Forest Science, Colorado State University Fort Collins, CO 80523 (internet source)
36) Dehgani et al. (internet). Evolution of Developing Flushing Cone during the Pressurized Flushing in Reservoir Storage.
37) De Vries, M. (1975): A morphological time scale for rivers. In Proc. 16th Congr. IAHR, São Paulo, Vol. 2, Paper B3, pp. 17-23.
38) Desta and Adugna (2012): A Field Guide on Gully Prevention and Control. Nile Basin Initiative. http://www.bebuffered.com/downloads/ManualonGullyTreatment_TOTFinal_ENTRO_TBIWRDP.pdf
39) Doyle et al. (2003): Channel adjustments following two dam removals in Wisconsin. Water Resources Research, Vol.39, No.1, 1011, doi:10.1029/2002WR001714.
40) Efthymiou et al. (2017): Rapid Assessment Tool for Sustainable Sediment Management, RESCON 2 User Manual, the World Bank, Washington DC.
41) Efthimiou et al. (2017): Comparative analysis of sediment yield estimations using different empirical soil erosion models. Hydrological Sciences Journal, DOI: 10.1080/02626667.2017.1404068

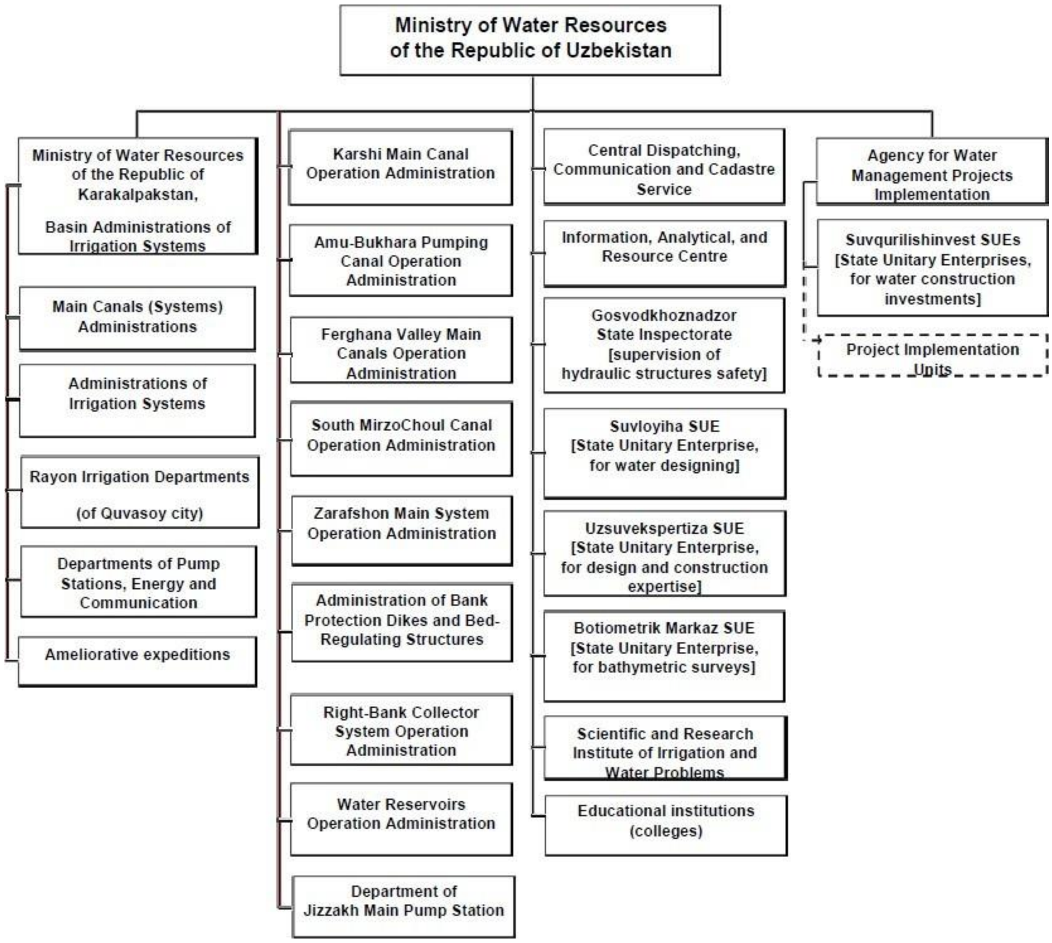
42) Einstein, H.A., 1950. The Bed-Load Function for Sediment Transportation in Open Channel Flow. Technical Bulletin No. 1026, U.S. Dep. of Agriculture, Washington, D.C.
43) Engelund, F. & Hansen, E. (1967): A monograph on sediment transport in alluvial streams. Copenhagen, Danish Technical Press.
44) Engelund, F. and Hansen, E., 1967. A Monograph on Sediment Transport in Alluvial Streams. Teknisk Forlag, Copenhagen, Denmark.
45) Espa et al. (2014): Downstream ecological impacts of controlled sediment flushing in an alpine valley river: a case study. River Research and Applications.
46) Ferrari, R.L. (2006) : Reconnaissance technique for reservoir surveys. U.S. Bureau of Reclamation: Denver.
47) Ffolliott, Peter F., Kenneth N. Brooks, Daniel G. Neary, Roberto Pizarro Tapia, and Pablo Garcia Chevesich. 2013. Soil Erosion and Sediment Production on Watershed Landscapes: Processes, Prevention , and Control. UNESCO.
48) Florsheim et al. (2011): From Deposition to Erosion: Spatial and Temporal Variability of Sediment Sources, Storage, and Transport in a Small Agricultural Watershed. Geomorphology 132 (3-4): 272–86.
49) Freeman et al. (2013): Declining discount rates and the Fisher effect: Inflated past, discounted future. Centre for Climate Change Economics and Policy Working Paper No. 129, Grantham Research Institute on Climate Change and the Environment, Working paper No. 109, London School of Economics, London.
50) Gao, B.C. (1996): NDWI - A normalized difference water index for remote sensing of vegetation liquid water from space. Remote Sensing of Environment, Vol. 58: 257-266.
51) Gellis et al. (1995): Assessment of Gully-Control Structures in the Rio Nutria Watershed, Zuni Reservation, New Mexico. AWRA Water Resources Bull. 31(4): 633-46.
52) Geyik, M.P. (1986): FAO Watershed Management Field Manual: Gully Control. Rome:FAO. http://www.fao.org/docrep/006/AD082E/AD082e00.htm.
53) Giovanni et al. (2001): Impact of Turbidity Currents on Reservoir Sedimentation. ASCE J. Hyd. Engineeri.ng 127(1): 6-16.
54) Głowacka et al. (2018): Photo system II Subunit S overexpression increases the efficiency of water use in a field-grown crop. Nature communications. DOI: 10.1038/s41467-018-03231-x
55) Glysson, G.D. (1987): Sediment Transport Curves. USGS Open-file Report 87-218, Reston.
56) Hotchkiss R. H. (2018): Financing reservoir sediment management for sustainability. Seventh International Conference and Exhibition on Water Resource and Renewable Energy Development in Asia" organized by The international journal on Hydropower and dams, 13-15 March in Vietnam.
57) Jansen et al. (1979): Principles of River Engineering; The non-tidal alluvial river. Pitman, London, Heruitgave Delftse Uitgevers Maatschappij, 1994, ISBN 90 6562 1466.
58) Jacobsen and Gupta (2016): Sedicon Sluicers as Effective Method of Sediment Removal from Desilting Tanks and Chambers. Compendium of Second Dam Safety Conference, Bengaluru, India.
59) Kantoush and Schleiss (2014): Influence of geometry shape factor on trapping and flushing efficiencies. Reservoir Sedimentation – Schleiss et al. (Eds), Taylor & Francis Group, London, ISBN 978-1-138-02675-9
60) Kantoush et al. (2011): Lighten the load. International Water Power & Dam Construction.
61) Kantoush and Sumi (2010): River Morphology and Sediment Management Strategies for Sustainable Reservoir in Japan and European Alps. Anuuals of DPRI Kyoto University, No. 53.
62) Kondwani et al. (2011): Reservoir Sedimentation and Flood Control: Using a Geographical Information System to Estimate Sediment Yield of the Songwe River Watershed in Malawi. Sustainability 2011, 3, 254-269; doi:10.3390/su3010254 .

63) Kovacs, A. and Parker, G. (1994): A new vectorial bedloadformulation and its application to the time evolution of straight river channels, J. Fluid Mech., 267, 153–183.
64) McFeeters S. K. (1996): The use of the Normalized Difference Water Index (NDWI) in the delineation of open water features. International Journal of Remote Sensing Volume 17, Issue 7.
65) Meshkati et al. (2009): Evolution of Developing Flushing Cone during the Pressurized Flushing in Reservoir Storage. World Academy of Science, Engineering and Technology International Journal of Environmental and Ecological Engineering Vol 3, No. 10.
66) Meyer-Peter, E. and Mueller, R., 1948. Formulas for Bed-Load Transport. Sec. Int. IAHR congress, Stockholm, Sweden.
67) Munk, W.H. and Anderson, E.R., 1948. Notes on the theory of the thermocline. Journal of Marine Research, Vol. 3, p 276-295.
68) Morris, G.L. (2015a): Collection and Interpretation of Reservoir Data to Support Sustainable Use. SEDHYD 2015, 10th Federal Interagency Sedimentation Conference, Reno.
69) Morris, G.L. (2015b): Management Alternatives to Combat Reservoir Sedimentation. Proceedings of International Workshop on Sediment Bypass Tunnels. Zurich.
70) Morris, G.L. (2010): Offstream reservoirs for sustainable water supply in Puerto Rico. Am. Water Resource Assn., Summer Specialty Conf. Aug 30 – Sept 1, San Juan.
71) Moun et al. (2013): Assessment of potential suspended sediment yield in Japan in the 21st century with reference to the general circulation model climate change scenarios, Global and Planetary Change, Vol. 102, pp. 1-9.
72) Okumura and Sumi (2012): Reservoir Sedimentation Management in Hydropower Plant Regarding Flood Risk and Loss of Power Generation, Proc. Of the International Symposium on Dams for a Changing World, 80th Annual Meeting of ICOLD.
73) Okumura and Sumi (2013): Influence of Reservoir Sedimentation on Power Generation, Proc. Of the12th International Symposium on River Sedimentation. Advances in River Sediment Research, pp. 1157-1163.
74) Parker, G. (1990): Surface-based bedload transport relation for gravel rivers, Journal of Hydraulic Research, 28(4): 417-436.
75) Pilton and Recking (2015a): Design of Sediment Traps with Open Check Dams. I: Hydraulic and Deposition Processes. Journal of Hydraulic Engineering, ASCE, ISSN0733-9429/04015045 (16).
76) Pilton and Recking (2015b): Design of Sediment Traps with Open Check Dams. II: Woody Debris. Journal of Hydraulic Engineering, ASCE, ISSN0733-9429/04015046 (13).
77) Randle and Bountry (2015). How to deal with sediment in dam removal. Sedimentation and River Hydraulics Group, USBR.
78) Shen H. W. (1999): Flushing sediment through reservoirs. Journal Of Hydraulic Research. Vol. 37, 1999. No. 6.
79) Shrestha et al. (2013): Impact of climate change on sediment yield in the Mekong River basin: A case study of the Nam Ou basin, Lao PDR. Hydrology and Earth System Sciences. 01/2013; 17(1):1-20. DOI: 10.5194/hess-17-1-2013.
80) Shrestha, H.S. (2012): Sedimentation and Sediment Handling in Himalayan Reservoirs. PhD Thesis. Trondheim, Norway: Norwegian Univ. of Science & Technology.
81) Simons et al. (1965): Bedload equation for ripples and dunes. U.S. Geological Survey Professional Paper 462-H, 9 p.
82) Sloff, C. J. (1997) Sedimentation in Reservoirs. Doctoral Thesis, Delft University of Technology, 270 pp.
83) Sumi, T. (2003): Approaches to Reservoir Sedimentation Management in Japan, Reservoir Sedimentation Management Symposium, Third World Water Forum, Kyoto, Japan.
84) Sumi et al. (2004): Reservoir sedimentation management with bypass tunnels in Japan. Proc. 9th Intl. Symp. on River Sedimentation, Oct 18-21, Yichang, China.

85) Sumi et al. (2010): Integrated management of reservoir sediment routing by flushing, replenishing, and bypassing sediments in Japanese river basins. Intl. Syp on Ecohydrology, Kyoto. pp.831-838
86) Syvitski, J.P.M. and Milliman, J.D (2007): Geology, Geography, and Human Battle for Dominance over the Delivery of Fluvial Sediment to the Coastal Ocean, The Journal of Geology, Vol. 115, pp. 1-19.
87) Swart R. (2015): Autonomous dredging of mud. Master thesis, Delft University of Technology.
88) Temmuyu et al. (2013): Sediment relocation trial by Ejector Pump Dredger System (EPDS) in a dam reservoir. Advances in River Sediment Research – Fukuoka et al. (eds),Taylor & Francis Group, London, ISBN 978-1-138-00062-9.
89) Van den Berg, J.H. (1987): Bedform migration and bed-load transport in some rivers and tidal environments. Sedimentology, Vol. 34, pp. 681-698.
90) Van Rhee (2003): The Breaching Process, Lecture notes Dredging Processes. Delft: Delft University of Technology.
91) Van Rijn L. (2013): Sedimentation of Sand and Mud in in Reservoirs in Rivers. Internet Source: www.leovanrijn-sediment.com
92) Van Rijn, L.C. (2012) : Principles of sediment transport in rivers, estuaries and coastal seas. Aqua Publications, Amsterdam, The Netherlands (WWW.AQUAPUBLICATIONS.NL)
93) Van Rijn, L.C. (2007): Unified view of sediment transport by currents and waves, I: Initiation of motion, bed roughness, and bed-load transport. Journal of Hydraulic Engineering, 133(6), p 649-667.
94) Van Rijn, L.C. (2007): Unified view of sediment transport by currents and waves, II: Suspended transport. Journal of Hydraulic Engineering, 133(6), p 668-389.
95) Van Rijn, L.C. (1984a): Sediment Transport, Part I: Bedload Transport. Journal of Hydraulic Engineering, ASCE, Vol. 110, No. 10.
96) Van Rijn, L.C. (1984b): Sediment Transport, Part II: Suspended Load Transport. Journal of Hydraulic Engineering, ASCE, Vol. 110, No. 11.
97) Van Rijn, L.C. (1984c): Sediment Transport, Part III: Bed Forms and Alluvial Roughness. Journal of Hydraulic Engineering, ASCE, Vol. 110, No. 12.
98) Walling, D.E. (2008): The Changing Sediment Load of the Mekong River, Ambio, Vol. 37, No. 3, pp. 150 – 157.
99) Wang Z. Y. and Wu B.: Management of impounded rivers (Internet source)
100) Wehrmann et al. (2006): Classification of dams in torrential watersheds. Proc. INTERPRAEVENT Conf., Universal Academy Press, Tokyo.
101) Wilcock & Crowe (2003): Surface-based Transport Model for Mixed-Size Sediment. J. Hydraul. Eng., 10.1061/(ASCE)0733-9429(2003)129:2(120), 120-128.
102) World Bank (2013): Toward a Sustainable Energy Future for All: Directions for the World Bank Group’s Energy Sector. Report No 79597. http://www.worldbank.org/content/dam/Worldbank/document/SDN/energy-2013-0281-2.pdf
103) World Bank (2015): Climate & Disaster Risk Screening Tools. http://climatescreeningtools.worldbank.org.
104) Xie et al. (2013): Rapid Reservoir Storage-Based Benefit Calculations. Journal of Water Res Planning and Management 139(6): 712-722.
105) Xu H. (2006): Modification of Normalized Difference Water Index (NDWI) to Enhance Open Water Features in Remotely Sensed Imagery. International Journal of Remote Sensing 27 (14).
106) Yang et al. (2003): Global potential soil erosion with reference to land use and climate change. Hydrological Processes 17: 2913-2928.

Appendix 1: Water resources and reservoir sedimentation in Uzbekistan – some facts and figures

Institutional structure of water resources governance in Uzbekistan



UzNCID (2020)

Actual and prospective water consumption by sectors in Uzbekistan (million m³/year)

Water consumers (by priority)	Total water requirement	including by source		
		Surface Water	Underground Water	Return Water
2018				
Domestic utilities	5320	2200	3120	0
Industry	1885	855	1030	0
Rural water supply	485	415	70	0
Fisheries	640	460	0	180
Energy	770	770	0	0
Irrigated Agriculture	55100	50000	1100	4000
Total	**64200**	**54700**	**5320**	**4180**
2030				
Domestic utilities	6200	2450	3750	0
Industry	3500	1580	1920	0
Rural water supply	950	810	140	0
Fisheries	640	460	0	180
Energy	780	780	0	0
Irrigated Agriculture	48000	46800	700	500
Total	**60070**	**52880**	**6510**	**680**

Dynamics of actual water withdrawal from rivers (million m³)

1960		1980		1990		2000		2010		2018	
Total	Irrigation	Total	Irrigation	Total	Irrigation	Total	Irrigation	Total	Irrigation	Total	Irrigation
30780	27900	64910	55510	56611	58156	53265	35687	56611	44718	54700	50000

Reservoir sedimentation records in Uzbekistan (Bathymetric Centre of the Ministry of Agriculture and Water Resources of Uzbekistan, 2013)

Reservoir	Initial Volume (Mm^3)	Silted volume (%)	Initial Volume (Mm^3)	Silted Volume (%)	Started to operate (Year)
	Total Volume Capacity		Dead Volume Capacity		
Tashkent	250	16.9	26	76.3	1962
Talimarjan	1525	3.9	125	2.23	1985
Janubiy Surkhandarya	800	37	100	78.7	1967
Kuyimazar	310	11.2	47	6.7	1958
Tudakul	1200	13.7	600	9.6	1983
Akhangaran	198	4.8	13	27.7	1969
Andijan	1900	13.4	150	39.2	1970
Jizzak	100	19.9	4	96.2	1966
Kattakurgan	900	22.5	24	87	1953
Tupalang	100	16.6	8.79	88.4	1992
Khissarak	170	13.2	8.4	100	1985
Chimkurgan	500	22.7	50	31.8	1963
Pachkamar	260	25.9	10	99.8	1967
Akdarya	112.5	17.2	2.5	41.6	1984
Ruslovoy	2340	44.9	270	86.5	1980
Kaparas	960	1.9	410	1.65	1983
Average		**17.8**		**54.6**	

Rakhmatullaev et al. (2013): Water reservoirs, irrigation and sedimentation in Central Asia: a first cut assessment for Uzbekistan. Environmental Earth Sciences, Springer, 68 (4)

Appendix 2: Chemical and agrochemical compositions of sediment samples

Table 0-1 Chemical properties of the sediment samples, taken from various location of the Channel reservoir (Shirokova Y. I., 2022)

Код Проб Sample code (№)	pH	ECe, dS/m	TDS Плотный остаток, %	Содержание растворимых ионов Content of soluble ions												
				%							в милиграммэквивалентах. 100 грамм in milligram equivalents. 100g					
				HCO_3'	Cl'	SO_4''	Ca¨	Mg¨	Na'+K'	S ионов, %	HCO_3''	Cl'	SO_4''	Ca¨	Mg¨	Na'+K'
1	8,9	0,60	0,068	0,026	0,005	0,024	0,008	0,002	0,011	0,063	0,420	0,148	0,499	0,400	0,197	0,471
2	8,8	1,08	0,112	0,018	0,011	0,048	0,012	0,002	0,018	0,100	0,300	0,296	0,998	0,600	0,197	0,800
3	8,9	0,68	0,074	0,026	0,007	0,026	0,008	0,002	0,013	0,069	0,420	0,197	0,541	0,400	0,197	0,562
4	8,9	0,64	0,072	0,027	0,007	0,024	0,008	0,002	0,012	0,067	0,440	0,197	0,499	0,400	0,197	0,541
5	8,7	1,04	0,106	0,028	0,007	0,045	0,012	0,005	0,014	0,097	0,460	0,197	0,936	0,600	0,395	0,601
6	8,6	1,04	0,108	0,034	0,011	0,039	0,013	0,004	0,017	0,100	0,560	0,296	0,811	0,650	0,296	0,724
7	8,7	1,76	0,168	0,033	0,014	0,060	0,014	0,002	0,030	0,137	0,540	0,395	1,248	0,700	0,197	1,289
8	8,7	1,08	0,110	0,020	0,014	0,045	0,01	0,004	0,020	0,102	0,320	0,395	0,936	0,500	0,296	0,857
9	8,7	1,12	0,112	0,021	0,011	0,048	0,012	0,004	0,017	0,102	0,340	0,296	0,998	0,600	0,296	0,741
10	8,8	0,72	0,078	0,028	0,007	0,028	0,008	0,004	0,013	0,073	0,460	0,197	0,582	0,400	0,296	0,545

11	8,9	0,64	0,076	0,027	0,009	0,024	0,008	0,002	0,014	0,070	0,440	0,247	0,499	0,400	0,197	0,590
12	8,7	1,96	0,184	0,035	0,011	0,092	0,02	0,007	0,028	0,175	0,580	0,296	1,914	1,000	0,592	1,202
13	8,5	1,32	0,132	0,033	0,007	0,060	0,016	0,005	0,018	0,123	0,540	0,197	1,248	0,800	0,395	0,794
14	8,5	1,84	0,174	0,027	0,018	0,076	0,018	0,004	0,030	0,159	0,440	0,494	1,581	0,900	0,296	1,323
15	8,6	6,96	0,502	0,035	0,179	0,088	0,024	0,012	0,121	0,441	0,580	5,034	1,830	1,200	0,986	5,264
16	8,9	0,92	0,094	0,024	0,011	0,036	0,01	0,002	0,017	0,088	0,400	0,296	0,749	0,500	0,197	0,750

Table 0-2 Agrochemical properties of the sediment samples (Shirokova Y. I., 2022)

Sample code	Sampling location	Humus, %	General assessment	Humus carbon, (Cg, %)	Content of gross forms						C/N	Nitrogen enrichment, C/N
					Nitrogen, %	General assessment	Phosphorus, %	very rich	Potassium, %	General assessment		
1	PK-23 "Uz"	0.19	Very poor	0.11	0.021	Very poor	0.155	Medium	0.20	Very poor	5.3	High
2	TMGU Ave. coast of Uzb	0.51	Poor	0.29	0.038	Very poor	0.195	Medium	0.72	Very poor	7.7	High
3	№130®515 m Ave. Bank Ruslovaya ST-1	0.30	Very poor	0.17	0.024	Very poor	0.200	Medium	0.42	Very poor	7.1	High
4	№130®515 m Ave. Bank Ruslovaya ST-1	0.34	Very poor	0.20	0.025	Very poor	0.180	Medium	0.66	Very poor	7.9	High
5	PK-25 "Uz"	0.74	Poor	0.43	0.052	Poor	0.160	Medium	0.90	Very poor	8.3	Medium
6	Military unit of TMGU Uzbek	0.68	Poor	0.39	0.048	Poor	0.150	Poor	0.69	Very poor	8.2	Medium
7	ST 22 Uzb	0.80	Poor	0.47	0.061	Poor	0.132	Poor	0.72	Very poor	7.6	High

Sample code	Sampling location	Humus, %	General assessment	Humus carbon, (Cg, %)	Content of gross forms						C/N	Nitrogen enrichment, C/N
					Nitrogen, %	General assessment	Phosphorus, %	very rich	Potassium, %	General assessment		
8	TMGU Ave. beregTMGU	0.32	Very poor	0.18	0.024	Very poor	0.165	Medium	0.49	Very poor	7.7	High
9	Etc. Bank No. 130 Run-of-river dam	0.57	Poor	0.33	0.042	Very poor	0.145	Poor	0.60	Very poor	7.9	High
10	Etc. Ruslovaya bank №130	0.53	Poor	0.31	0.039	Very poor	0.132	Poor	0.63	Very poor	7.9	High
11	ST 2® 436m Pr Bank Ruslova	0.27	Very poor	0.16	0.024	Very poor	0.141	Poor	0.37	Very poor	6.6	High
12	Sulton Sanzhar Ave. Ruslovaya bank	0.78	Poor	0.45	0.056	Poor	0.112	Poor	1.02	Poor	8.1	High
13	Military unit of TMGU Uzbek	0.84	Poor	0.49	0.064	Poor	0.136	Poor	0.72	Very poor	7.7	Medium
14	ST 2® 237m Pr	0.38	Very poor	0.22	0.027	Very poor	0.141	Poor	0.40	Very poor	8.2	High

Sample code	Sampling location	Humus, %	General assessment	Humus carbon, (Cg, %)	Content of gross forms						C/N	Nitrogen enrichment, C/N
					Nitrogen, %	General assessment	Phosphorus, %	very rich	Potassium, %	General assessment		
	Bank Ruslova											
15	Pr shore® 65 Run-of-river ST 5	0.95	Medium	0.55	0.068	Poor	0.108	Poor	1.46	Poor	8.1	High
16	ST 2® 436m Pr Bank Ruslova	0.36	Very poor	0.21	0.025	Very poor	0.145	Poor	0.54	Very poor	8.3	High

Appendix 3: Summary of national strategy and practices for management of dredged materials in some countries

CIT (2013), Giri et al. (2019)

Country	Dredged material (DM) management strategy and practices
The Netherlands	Annual DM production of 25-30 million m³, 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 m³, 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 m³ 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

Country	Dredged material (DM) management strategy and practices
	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 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.

Country	Dredged material (DM) management strategy and practices
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 framework 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).

Appendix 4: Applicability of dredged sediments for beneficial use based on type and quality

Sheehan (2012), Giri et al. (2019)

Category of Beneficial Use	Type of Beneficial Use	Dredged material 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	√	√	√	√	√	×	√	√	×	×

Appendix 5: Treatment options for dredged sediments, practiced in Ireland

CIT (2013), Giri et al. (2019)

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-overCDMS[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.	×	√	+	√	√	√	√	√	√	√
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 cementmatrix. 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 subsequently removing contaminants from DM.	×	√	×	√	√	√	√	√	×	√
Electro-osmotic Dewatering*	A small electric potential is applied across the DM inducing rapid flow of wateras 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, toxicand 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)

Deltares is an independent institute for applied research in the field of water and subsurface. Throughout the world, we work on smart solutions for people, environment and society.

Deltares

www.deltares.nl