ICOLD Reservoir Sedimentation Bulletins: Case Studies and Bypass Systems

Martin J. Teal, Principal Engineer, WEST Consultants, Inc., San Diego, California, USA, mteal@westconsultants.com

Abstract

The International Commission on Large Dams (ICOLD) consists of member agencies from over 100 countries and has more than 25 technical committees dedicated to all facets of dam planning, design, maintenance, and safety. The ICOLD Technical Committee on Sedimentation of Reservoirs has actively contributed to the global state of knowledge on this subject by developing ICOLD bulletins on estimating, modeling, and managing sediment in and around reservoirs going back at least 30 years.

This paper describes the latest two bulletins produced by this committee that should be of interest to those involved in reservoir sediment management and design. The first is Bulletin 182 “Sediment Management in Reservoirs: National Regulations and Case Studies” which was completed in December 2019. This bulletin provides a concise summary of environmental regulations associated with sediment management activities in different countries and a series of case studies which compare sediment management techniques from various projects around the world. The second presented, Bulletin 193, deals with the subjects of sediment bypassing and transfer. This bulletin deals with methods for sediment bypassing to route sediment arriving at a reservoir either through or around the lake by structures such as channels and tunnels, and sediment transfer to remove already deposited sediments. The intent is that this bulletin will be a resource for practitioners seeking guidance for design and implementation of these methods for either existing projects or those in design.

Introduction

ICOLD and USSD

The International Commission on Large Dams (ICOLD) consists of member agencies from over 100 countries and has more than 25 technical committees dedicated to all facets of dam planning, design, maintenance, and safety. The United States National Committee of ICOLD is the United States Society on Dams (USSD). USSD also has technical committees which roughly parallel those of ICOLD. USSD has the opportunity to appoint U.S. members to the ICOLD technical committees.

The ICOLD governing board approves each ICOLD technical committee’s Terms of Reference (TOR), normally for a three-year period. The TOR functions as a charter and outlines the work activities and goals of the committee for that period. Normally the committee will produce an ICOLD bulletin and accompanying workshop as part of the TOR.

ICOLD Technical Committee J, Sedimentation of Reservoirs

The ICOLD Technical Committee on Sedimentation of Reservoirs (Committee J, as all ICOLD committees are designated by a letter) has actively contributed to the global state of knowledge on this subject by developing ICOLD bulletins on estimating, modeling, and managing sediment in and around reservoirs going back over 30 years. Past ICOLD bulletins developed by the committee touch on subjects such as mathematical modeling of sediment, sediment control measures, guidelines and case studies for dealing with sediment, sediment and sustainable use of reservoirs, and others.

The current and previous TOR of Committee J resulted in two bulletins developed by the committee members under the leadership of this paper's author serving as committee Chair. This paper describes these bulletins that should be of interest to and serve as a resource for practitioners involved in reservoir sediment management and design. The first is ICOLD Bulletin 182 "Sediment Management in Reservoirs: National Regulations and Case Studies" completed by the committee in December 2019. This bulletin provides a concise summary of environmental regulations associated with sediment management activities in different countries and a series of case studies which compare sediment management techniques from various projects around the world. This is available from the ICOLD website although it is labeled as a "preprint" and is only available to members while ICOLD finalizes the formatting and formal issuance and sale through its publisher.

The second, Bulletin 193, is also available in preprint and deals with the subjects of sediment bypassing and transfer. This bulletin covers methods for sediment bypassing to route sediment arriving at a reservoir either through or around the lake by structures such as channels and tunnels, and sediment transfer to remove already deposited sediments. The intent is that this bulletin will be a resource for practitioners seeking guidance for design and implementation of these methods for either existing projects or those still in design.

ICOLD Bulletin 182, Case Studies

Overview

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

The second part discusses classification of sediment management methods before presenting seventeen case studies of sediment management experiences from ten countries. A common framework is used to compare the various projects. Committee members and other interested volunteers provided case studies that give some insight as to current management practices around the world. The particular case studies included are just a sampling of activities world-wide but shed some light for those dealing with sedimentation issues as to what has been done elsewhere, whether successful or not.

National Regulations

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

Jurisdictions: The first jurisdiction reviewed is the European Union (EU). Initially, the bulletin describes regulations affecting all member countries, followed by more detailed country-specific regulations for Germany, Austria, Italy, France, Holland, Spain, the Czech Republic, and Slovakia. Afterwards sections describe the regulatory environment in Switzerland, the United States, Japan, and Korea.

Specific Regulations: While available space precludes summarizing the regulations from each of the jurisdictions, some key points can be briefly mentioned. For example, the European Union Water Framework Directive (EU-WFD) established a framework for community action in the field of water policy as a binding act for all EU member countries. The WFD recognizes the important role of rivers, lakes, and groundwater for the ecosystem, aiming to safeguard and improve the aquatic environment as a primary resource for life. The EU-WFD defines general minimum standards for water. Despite being a binding document, for applicable legislation each of the twenty-eight member countries has had to transfer the EU-WFD into national law. Though the general standards remain the same, the special focus on details such as riparian obligations vary.

In Switzerland, laws vary from canton to canton, but national law does state that sediment transport balance must be maintained and that any flushing or drawdown activities must avoid negative impacts on flora and fauna. The regulatory environment in the U.S. is complex and governed by local, state, and federal regulations, potentially including regulation by several federal agencies. In general, the National Environmental Policy Act (NEPA) requires agencies or other owners to address the impacts of their actions on the environment. In Japan, agencies updated regulations in 1997 based on a comprehensive (watershed based) sediment management concept balancing sediment transport from the source to the coast. Regulations exist in Korea to encourage sediment continuity and prevent ecological damage although specifics differ from project to project.

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

Case Studies

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

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

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

The ratio CAP/MAS defines the reservoir life, while the water turnover rate is defined as ratio of CAP/MAF. Following the work of previous ICOLD bulletins (1999 and 2009), Sumi (2005), and Annandale (2013), each project is displayed in a figure which suggests which type of sediment management actions may result in sustainable or non-sustainable futures (Figure 1).

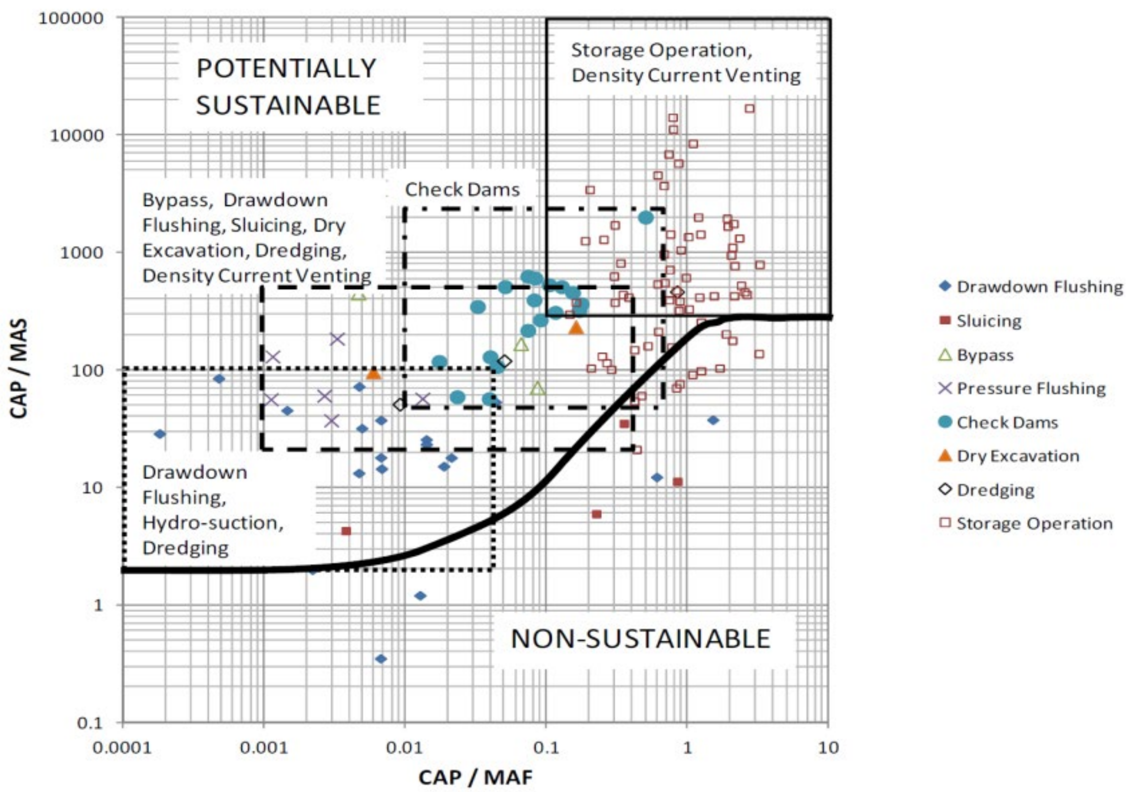

Figure 1. Sediment Management Activities (Annandale, 2013)

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

1. Regulatory constraints (including environmental, sediment or fish continuity)
2. Special items, such as
   - Density currents
   - Sediment bypasses
   - Reservoirs filled with sediment (management methods and success of methods)
3. Hydrology
4. Basic dam/reservoir data
5. Sediment data (if available)
   - Transport, grain sizes, etc.
   - Annual inflow versus capacity to store sediment and water
6. Economics/sustainability
   - Rehabilitation
   - Cost comparisons
7. New dam versus retrofit of existing dam
8. Owners
9. Political issues, if any
10. Classification of sediment management, using Dr. Sumi's chart if possible
11. Plot of capacity versus mean annual flow

These key items were also requested so that the case studies could prove more useful to readers who are researching alternatives for their particular project. In order to be included in this bulletin, submitted case studies were required to include as much of this data as possible. Table 1 below presents a list of the projects chosen for inclusion. The Karnali (Nepal) and Bunji (Pakistan) projects were either under study or in construction, but the others had already entered into operation.

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

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

Table 1. Sediment Management Case Studies

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

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

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

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

The case studies show that the dam community is facing the challenge of dealing with progressing sedimentation in different ways, and that there is room and demand for further innovative approaches.

ICOLD Bulletin 193, Sediment Bypassing and Transfer

Overview

As proposed in the Terms of Reference for the committee, this bulletin deals with methods for **sediment bypassing** to route sediment arriving at a reservoir either through or around the lake by structures such as channels and tunnels and **sediment transfer** to remove already deposited sediments. The intent is that this bulletin will be a resource for practitioners seeking guidance for design and implementation of these methods for either existing projects or those still in design, as such guidance is scarce in the literature.

Following the introduction and a brief review of sediment yield, the bulletin first focuses on sediment connectivity, defined as the connected transfer of sediment from upstream to downstream within a watershed. The bulletin then presents sediment bypass design, especially design of channels and tunnels. Major subsections deal with issues such as tunnel hydraulics, sediment transport, and abrasion, as well as operational aspects and monitoring. Case studies are also provided. A section then deals with transfer systems via hydrosuction or continuous sediment transfer and provides design guidance and case studies for those methods of sediment management. The bulletin also provides a summary of its themes and an extensive bibliography. In this paper we focus on the two major topics of sediment bypass design and sediment transfer systems.

Sediment Bypass Design

Operators commonly bypass sediment around a reservoir via a tunnel. However, depending on the topography, open channels may also be used. A sediment bypass tunnel (SBT) has the advantage that only newly entrained sediment is diverted from the upstream to the downstream reach. Previously accumulated sediments in the reservoir are normally not mobilized. The sediment pulse is therefore of natural character, and sediment connectivity is re-established during floods, improving the downstream ecological system (Auel, 2018).

In Japan, investigators have studied SBTs for a long time. Although this technique involves a high cost due to tunnel construction, there are many advantages when applied to existing dams: it typically does not involve drawdown of the reservoir level and therefore does not cause storage capacity loss; and it has no negative impact on the environment because sediment is discharged during natural flood events (as compared to sediment flushing which discharges accumulated sediment in a short period) (Sumi, 2015).

SBTs are located mainly in mountainous regions at small- to medium-sized reservoirs (Boes et al., 2019). River bed slopes are normally steep, so that a considerable amount of coarse material may be transported. SBTs normally transport all sediment sizes up to design flood flow, although primarily coarser material for higher flows. SBTs can be used with other methods that are more appropriate for finer material (e.g., bottom outlet sluicing).

The bulletin describes in detail the approach to accurately design an SBT. This paper will provide an overview only.

The committee on reservoir sediment management of the Water Resources Research Center (WEC) in Japan studied several aspects of reservoir sedimentation management including sediment bypassing. This committee summarized several topics for design and operational considerations for sediment bypass systems as presented in Sumi (2015). Major considerations include:

- Facilities for trapping gravel and woody debris
- Determination of the diversion rule (in case of multipurpose dams)
- Construction of the diversion weir and sediment trap weir
- Measurement of inflow discharge
- Design and construction of the tunnel inlet section
- Abrasion countermeasures in the inlet and the tunnel
- Design discharge of the tunnel
- Horizontal and vertical tunnel alignment
- Volume and grain size of sediment to be transported
- Tunnel cross section shape, hydraulics, and sediment transport
- Inspection and repair methods
- Design and construction of the tunnel outlet
- Sediment loading of downstream river and monitoring

The bulletin discusses each of these items in detail. Figure 2 shows sketches of two typical SBT systems. It should be noted that construction of the tunnel from a geological and geotechnical point of view is an important design factor but is outside the scope of the bulletin.

Abrasion: Abrasion prediction and countermeasure design is one of the topics treated in detail within the bulletin (Figure 3 shows an example of SBT abrasion). A section on abrasion resistant invert materials describes the performance of various types of materials on projects around the world, including concrete, natural bedrock, pavers, steel, and epoxy resin. For the selection of adequate material, not only the initial investment, but also the total life-cycle cost including maintenance and repair should be considered and weighed. For this purpose, equations are provided to predict abrasion depths and thus service life of different materials.

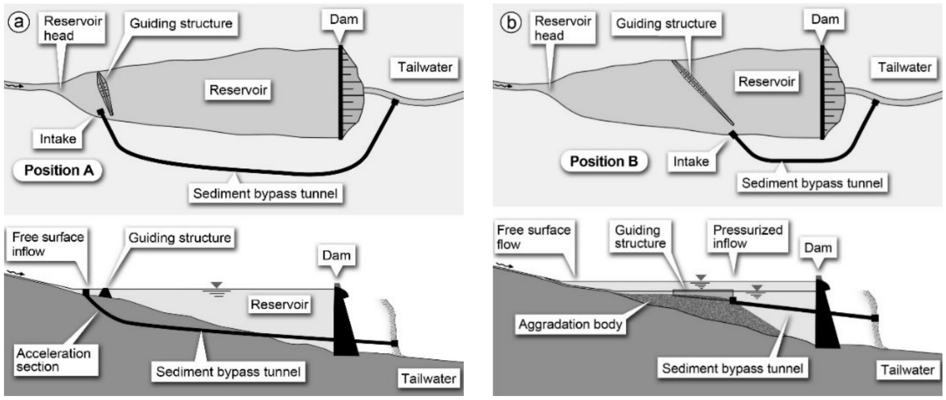

Figure 2. Sketches of two SBT systems. a) Location of the tunnel intake at the reservoir head. Inflow under free surface conditions. b) Location of the tunnel intake downstream of the reservoir head. Inflow in pressurized conditions (Auel and Boes 2011).

Figure 3. Invert damage in Palagnedra SBT, Switzerland. Horseshoe tunnel cross section with deep abrasion channel (courtesy C. Auel).

Real Time Operation: Depending on the tunnel intake location, the reservoir operation during sediment bypassing varies. If the intake is located at the reservoir head, operators open the gate during floods and the incoming sediment-laden flow is routed in free-surface flow conditions through the tunnel. Operation is relatively simple as a partial reservoir level drawdown is not required.

Operation is more challenging if the intake is located between the reservoir head and dam. The reservoir level must be lowered prior to an incoming flood to an extent that depends on the distance of the reservoir head from the tunnel intake and the height of sediment aggradation in that reach. The reservoir reach upstream of the intake must have free-surface flow to ensure high transport capacity so that incoming sediment is transported towards the intake. The reservoir should be kept at a lower level during bypass operation to avoid interruption of the sediment transport (Figure 2b, lower water surface in profile view).

A reliable rainfall and runoff forecast combined with a decision support system is crucial for a successful operation. The bulletin provides an example showing reservoir operation at Solis, Switzerland (Oertli and Auel, 2015). A flood forecast of about 16 hours is needed to draw down the reservoir to the desired level. This is done via both the turbines and - if needed - the bottom outlets. Operators open the bypass tunnel for 15 hours, diverting the flood and its incoming sediments, before closing the gates smoothly over three hours. Energy production continues if the reservoir level permits.

Case Studies: The bulletin provides a table with all SBTs/channels known to the committee and an appendix gives details on many of the projects listed in the table. Although most projects are in Japan and Switzerland, there are others in Indonesia, Pakistan, South Africa, Taiwan, and the United States.

Sediment Transfer

The previous section dealt with preventing sediment from entering the main reservoir via bypassing. However, even with the best bypass systems, a part of the sediment will still enter the main reservoir which is especially true for fine particles. Sediments that enter the reservoir will, depending on the reservoirs trap efficiency, deposit in the reservoir and reduce the storage volume. Although many well-known methods can be classified as transfer, including conventional dredging, sluicing, flushing, and venting, the bulletin concentrates on two lesser-known methods: Hydrosuction and Continuous Sediment Transfer.

Both techniques remobilize and suck accumulated sediments into a pipe and transfer sediments through the pipe in such a way that they end up downstream of the dam (Figure 4). This can be done either through the power station, directly downstream, or across an opening within the dam structure. Hydrosuction dredging or discharge into the powerplant intake does normally not require plant outages, not even during installation.

Hydrosuction: Hydrosuction is a system that uses available water head between the reservoir and the outlet of the discharging pipe for pumping out water and sediments. The outlet can either be through the dam body or over the dam. The available head difference and water is utilized to dredge sediment from the reservoir and pass it to the downstream river without use of additional power. A water jetting system loosens cohesive sediments. Hydrosuction dredging is an old principle, but the technology was refined and studied further by Jacobsen (1997) and is now commercialized and used in over twenty countries.

During operation, no pump is required to transfer the sediments to the downstream side of the dam. The jetting pump is operated if the sediments are too cohesive and need to be disintegrated to be sucked into the suction head. Hydrosuction is normally limited to 300-400 m into the reservoir if the outlet pipe passes over the dam. If the outlet of the suction pipe is through the dam body the range depends on the level of the outlet. An outlet at 20 m depth will typically allow a range of up to 1 km; with deeper outlets the transfer length may be increased further.

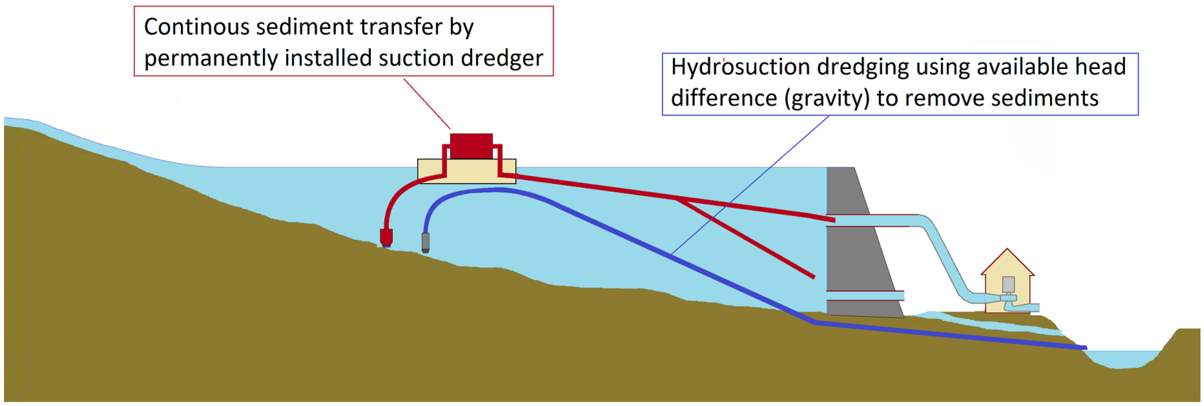

Figure 4. Sediment Transfer Options

Hydrosuction theoretically allows sediment removal without pumps, although pumps are normally used for the jetting system and for creating the suction pipe vacuum upon start up. The entire flowline is completely unrestricted so any particles that pass the (slightly smaller) suction head will also pass the suction hose and the outlet pipe without causing blocking. There is a minimum of movable parts that can fail, and the suction head can be designed for automatic balancing of sediment concentration. It is therefore suitable for remote or automatic operation or a combination of both, requiring a minimum of personnel and allowing continuous operation. For hydrosuction it is essential to utilize the available head and water efficiently, yet one must avoid overly high concentrations and blocking of the pipe.

Continuous Sediment Transfer: Continuous Sediment Transfer has been developed to imitate natural sediment transfer on a permanent basis. Manual operation of a moored vessel is possible, but typically the operation is fully automated on a 24/7 basis. This allows maintaining sediment continuity and an effective use of the installed equipment, i.e., continuous operation allows for more transfer or significantly smaller components. The actual transfer rate may be adjusted according to the corresponding downstream river's receiving capacity.

Sediment can be dredged by different suction devices such as jet rings or cutter heads, depending on sediment characteristics. Maximum dredging depth is typically 160 m. An on-board pump combined with sediment measuring devices allows for adjustment of the actual sediment transfer, while a GPS unit is used for transfer documentation. Usually, the pump allows for a transfer length of around 1.6 km / 1 mile. Further extension is possible by additional booster pumps, in principle to an unlimited range.

Depending on site characteristics, sediment can be transferred across turbines or over the dam. However, particles larger than sand are usually not recommended for turbine passage. For fine particle transfer, an economic assessment leads to a recommendation to either utilize sediment transfer with power generation equipment or to use available water for discharge through other outlets.

The bulletin handles the topics of sediment water mixture transport in pipes and design recommendations, including economic considerations and operation and maintenance. These discussions are then followed by two case studies, one from Europe and the other from Central America.

Summary

The two latest ICOLD bulletins developed by the ICOLD technical committee on Sedimentation of Reservoirs should be of great interest to the sedimentation community. The first of these, Bulletin 182 completed in 2019, is available as a preprint from ICOLD although final publication and dissemination is expected in 2023. This bulletin provides a summary of national regulations regarding sediment management from several countries and presents numerous case studies of sediment management activities and strategies from around the world. The second, Bulletin 193, which is also available as a preprint from ICOLD, focuses on informing professionals about the concept and design of sediment bypassing and sediment transfer systems.

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