Reservoir Sedimentation:  
Impacts on Water Management and Sustainability

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Preface

This extended abstract is a summary of a larger paper currently in technical review.

Introduction

Sedimentation in a reservoir created by a dam occurs due to changes in the characteristics of flow and the transport and resulting deposition. The accumulation of sediment in reservoirs is reducing storage capacity and is a significant problem facing dam managers globally. A 1987 World Bank study (McCully 1996) concluded that nearly one percent of global water supply is found in reservoirs. The study went on to state that of the global reservoir storage, it is estimated that approximately one-fifth or 20 percent of that storage has already been lost due to sedimentation. As sediments build up in reservoirs and water storage is replaced by sediments, operational options may be reduced and compromised leading to an increased risk of dam safety.

Reservoirs provide a valuable water source that supports agriculture and cities, protects people and lands from floods, provide sources for the generation of power, provides cooling water for power plants, support river levels for inland navigation, and provide locations for recreation and enjoyment (Hogeboom et al. 2018). Protection of reservoir storage capacity is important however limited resources have been allocated to determine the extent reservoir management is being impacted by sediment accumulation. Federal and state policy needs to be developed and aligned to address the concerns in a timely and cost-effective manner.

This paper was developed to assist water policy experts in identifying the challenges facing water and dam managers. Infrastructure and asset management of the Nation's dams, turbines, and reservoirs requires appropriate identification of the risk and the development of appropriate legislative direction and agency policy.

Identifying the Sedimentation Problem in Reservoirs

Reservoirs fill with sediment resulting in storage loss which leads to reduced water supply reliability, impacts to infrastructure including outlet works, turbines, spillways, river bypasses, water intakes, recreational boat ramps, marinas and water quality. Sediment deposition in the reservoir inflow areas often change the river base level causing deposition that often lead to flooding, channel migration and access to upstream riverine areas. Reservoir sedimentation rates are watershed and site specific and vary across
river basins, ranging from an average annual storage loss of capacity of 2.3 percent in China to 0.2 percent in North America (USBR 2015). Sediment inflow rates will likely increase as climate change brings about more extreme and variable runoff events. Sediment is mobilized more during the rising hydrograph during high flow events with deposition occurring during the descending hydrograph.

In most cases the impact of sediment depositing in reservoirs was not the first concern identified when dams were authorized for construction, designed, built and put into operation. According to the International ICOLD Register of Dams (2019) there is approximately 7,000km3 of reservoir water storage capacity of which approximately 3,000 km3 is classified as dead storage below the outlet works. This dead storage is typically where sediment accumulation occurs in reservoirs.

Including all dams (hydro and non-hydro dams) in 2006, 33% of the available reservoir capacity was filled with sediment. It is estimated that by 2050 this proportion of current total reservoir sediment capacity will have risen to 62% (IWPDC 2010). The annual combined global sediment load is estimated to be between 24-30 billion tons for a water inflow of 40,000 km3. Whether this loss of storage capacity is at hydropower, flood control or water supply reservoirs, the potential economic impact will increase due to loss of total reservoir capacity, impacts to dam and hydropower infrastructure, and ultimately increasing the cost of operations and maintenance. In addition, unless dam and reservoir operation manuals and operating procedures recognize the loss of storage capacity, risk in release and storage operations can increase resulting in loss of flexibility in management decisions.

All reservoirs that capture water are impacted by rising sediment levels. Depending on upstream watershed erosion and hydrology, sediments may be impacting storage capacity. Each river system is different in respect to what level of flows will mobilize and transport sediment downstream. Watershed condition and the physical structure and slope of the river channel may help to retard or accelerate sediment transport towards a reservoir. Once the sediment reaches the reservoir, limnological and geomorphic characteristics of the water body will determine how and where the sediment is distributed under the water surface. Typically, the reservoir inflow area and delta will build and shift because of the dynamics between inflow conditions, reservoir elevation, and the composition of the sediment load of the incoming flows.

Hydropower reservoirs can be filled slightly fuller with sediments since their use is dictated by the amount of water above the intakes. However, once reservoir sedimentation reaches 80% operational impacts due to the entrainment of sediment into flow of water driving the turbines occurs. Conversely, flood control and water supply reservoirs are dependent upon maintaining more storage capacity to meet their design functions. Their operational capacity will be hindered once the sedimentation reaches 70% (IWPDC 2010).

Many run-of-river hydropower plants built in sediment-loaded rivers are directly affected by sediment, both by a reduction in the amount of water available for daily peaking power production and by the rapid wear rates of turbines and other mechanical equipment, such
as gates and valves. The erosion rates on the infrastructure assets is directly proportional to the flow velocity. Brekke et al (2002) identified that sediment-induced turbine wear problems cannot be overcome by hydraulic design alone. The extent of damage can be reduced however through careful operational design avoiding rapid accelerations and reducing of turbine velocities. The extent of infrastructure erosion is a function of turbine design, type of surface coating, velocity of flow, reservoir head and sediment characteristics (Bishwakarma 2007)

Global regions and countries experiencing negative issues related to sedimentation in reservoirs by 2050 include:

- Middle East – Afghanistan, Iran, Oman, Pakistan, Saudi Arabia,
- Europe – Albania, France, Macedonia
- Africa – Algeria, Botswana, Kenya, Morocco, Namibia, Sudan, Tanzania, Tunisia
- South American – Bolivia, Columbia
- Central America – Ecuador, Mexico,
- Asia – China, Malaysia, Singapore, Sri Lanka, Uzbekistan
- South Pacific – Fiji, New Zealand
- Caribbean – Jamaica, Puerto Rico

In the United States small to large reservoirs are being impacted by sedimentation. For multiple reasons a large percentage of reservoirs across the United States have not been surveyed to determine the amount of capacity lost due to sedimentation. Sediment deposition in reservoirs is causing dam and river managers to modify their traditional operational parameters and evaluating ways to mitigate the impact of reservoir sedimentation. Two examples of the types of problems being experienced are the Conowingo Dam on the Susquehanna River in Maryland and Paonia Reservoir in Colorado.

**Susquehanna River, Maryland.** On the Susquehanna River in Maryland, the Conowingo reservoir is over 90% full of sediment, effectively reducing its ability to capture flood flows or serve as a river regulating facility. Conowingo Dam and reservoir are managed in coordination with two other dams and reservoirs on the lower Susquehanna River, Safe harbor Dam (Lake Clarke) and Holtwood Dam (Lake Aldred). The three reservoirs collectively cover 32 miles of the Susquehanna River and had a combined design water storage capacity of 510,000 acre-feet (acre-ft) at normal pool elevations. The Susquehanna River is the largest tributary to Chesapeake Bay and transports approximately one-half of the total freshwater input and substantial amounts of sediment, nitrogen and phosphorus to the bay (USGS 2015).
The three reservoirs began filling with sediments as soon as they were constructed. Conowingo Dam was completed in 1929 and 2011 estimates indicate that approximately 8 percent remained of the original 146,000 acre-ft of the reservoir storage capacity. As storage capacity in the reservoir is reached, a dynamic-equilibrium condition will exist between incoming and outgoing sediment and nutrient loads discharged downstream to Chesapeake Bay. This has led to increasing nutrient and sediment loading to Chesapeake Bay with subsequent challenges to meeting the established Total Maximum Daily Load mandates for sediment and nutrients (Nitrogen and Phosphorus). Estimates for nutrient and sediment loading are approximately 153 million pounds of nitrogen and 9.1 million pounds of phosphorus carried along with 6,600 million pounds of sediment (USGS 1997).

**Paonia Reservoir, Colorado.** Paonia Dam was completed in 1962 by the Bureau of Reclamation. The purpose of the dam is to provide water primarily for irrigation with additional benefits accrued to flood control and recreation. Due to upstream erosion, caused by land disturbance and logging, sediment moved into the reservoir basin and accumulated to levels that have reduced the storage capacity and limited the management of the reservoir to basically run-of-river operations. It is estimated that more than 8 million cubic yards of sand, silt, and other particles have accumulated behind the dam (HCN 2017).

The issues of sediment accumulation in reservoirs was not unanticipated by dam engineers and builders. Engineers design reservoirs to function for 50 to 100 years. Many western dams constructed by the federal government are now 60 years or older and nearing the end of their sediment and construction design life. This is requiring federal, state, tribal and water district dam managers to evaluate what alternatives exist to reservoirs that are filling or are filled with sediments.

**Managing the Sediment in Reservoirs**

Multiple options exist for dam and reservoir managers – none of them are easy or without substantial cost. Regulatory permitting of dam operations often requires the attainment of federal and state approval, adding considerable time to the implementation of operational changes. Traditional approaches have explored flushing, dredging and physical removal of sediments by drawing down the reservoirs and moving the sediments with heavy equipment. Alternative approaches have included physical construction of sediment sluicing gates in dams, retrofitting dams to move intakes above the sediment levels and upstream watershed control of sediment sources. Each of these alternatives are costly and generally need appropriation of funds and appropriate policy and agency support.

Of interest globally is the study of the high sediment loads in many Asian rivers, especially the Yangtze and Yellow rivers in China and the Mekong River in southeast Asia. These
rivers, whose watersheds include the highly erosive loess soils of the Tibetan Plateau, have historically exhibited large seasonal flow and sediment transport events that have tested infrastructure and public safety. Chinese hydrologic engineers and academic experts have developed intricate assessments of sediment loading. Chinese river managers have employed multiple approaches to managing sediment on the Yangtze and Yellow rivers including upstream watershed stabilization, constructing sediment capturing dams on tributaries and construction dams so that large suspended sediment load flows can be routed through reservoirs and through mainstem dams (Yang et al. 2006).

Planning and design considerations when either designing and constructing dams in high sediment yield catchments requires a vision about the possible changes in upstream watershed management and land use. Often not considering potential upstream development will lead to reduced operational flexibility and impacts to infrastructure. Important elements for consideration include:

- Site selection – location, watershed characteristics, and rainfall/runoff patterns
- Data collection – gathering of reliable sediment data that takes into account sampling locations, techniques, frequency, technology and skill of personnel.
- Design of project including efficient sediment flushing options, trapping efficiency of the reservoir, estimated impact of sediment on the infrastructure, and costs associated with flushing or shut down during high sediment transport periods.
- Turbine design – dependent upon sediment load characteristics and anticipated turbine wear, and appropriate turbine design, construction and operation.
- Optimization of sediment exclusion – sediment control and removal of sediments should be identified and addressed during the planning and operational phases of the project.
- Real time sediment monitoring – to provide early warning system regarding sediment concentration and asset management of the physical equipment.

**Tasks for Maintaining Sustainable Water Supplies**

Sediment accumulation in reservoirs is diminishing their useful life span and operational flexibility. During the dam development era in the United States (1940-1970’s) limited thought was given to plan for reservoirs filling up sediment. It was assumed the dead pool area would suffice. That assumption did not consider changing hydrology and upstream land practices and their impact on erosion and sediment transport. Authorizing legislation and subsequent policy and development of operations manuals did not take into consideration the impact of sediment loading into reservoirs, its impact of infrastructure nor a systems perspective on upstream and downstream development.
Research and Risk Assessment. A need exists now, while we have time on the planning horizon, to assess what the impact of reservoir sedimentation will be on river management and dam operations as more extreme weather and resulting hydrologic events lead to increased sediment mobilization and transport to and in reservoirs. Coordinated research and assessment focused on determining the extent of the potential risk at dam assets and to prioritize and assess remediation and mitigation strategies will be value added to protection of our water assets.

System Water Resource Planning. Significant advances in water resource planning have occurred with the advent and adoption of adaptive management, watershed management and integrated water resources management. The foundations for these approaches evolved from early watershed and river basin management. The building of dams has been justified based on dam’s ability to provide a constant supply of water for agriculture, municipal, industrial, hydropower, power plant cooling, navigation, downstream flood control, and in some cases for water quality purposes. Justification, design and operation of these reservoirs is predicated on the assumption that the original design capacity of the reservoir will be available to provide project benefits.

To assist water managers and decision-makers in achieving project goals and objectives, significant investments have been made developing and implementing technology to gather data and information to allow for the characterization of the hydrology and other operationally important parameters to populate dam and river management models and operational options. The resulting dam and operation supporting infrastructure provide significant and expected economic and social benefits.

Assessment of Sediment Removal Techniques. One of the largest challenges in sediment management is to have a plan on how to handle deposited sediments from the reservoir basins or settling areas. The removal of the accumulated sediments and their ultimate disposal in an environmentally friendly way need to be considered. Current methods currently include sediment flushing, sediment sluicing systems, removal by pipeline and routing of sediments through reservoir basins.

Limited Monitoring. Unfortunately, most of the large and small reservoirs in the world are not monitored in respect to sediment capture and the resulting build up and lost water storage capacity. Many reservoirs around the globe are experiencing increased sediment build up due to upstream watershed erosion driven by development and variable rainfall and runoff events.

Climate Change. Climate change is significantly increasing watershed-sediment erosion rates and as a result sediment transport rates in rivers and an increase in the rates of reservoir storage capacity loss.

Historically there was generally enough capacity in reservoirs to meet the authorized goals and objectives of dam and river managers. However, with the increase in larger and more frequent extreme weather and hydrology driven events, dam and river managers are faced with challenges in maintaining public safety and water supply.
New Tools. Developing new technology is critical to efficient collection of reservoir sedimentation data. This data needs to be integrated into improved reservoir management models that can assist in sediment management. The U.S. Army Corp of Engineers and others are assessing the use of LIDAR to measure sedimentation in reservoirs (USACOE 2016).

Technical Coordination. Multiple federal, state and academic institutions dialogue on the reservoir sedimentation. The National Reservoir Sedimentation and Sustainability Team provides a forum for the scientific and engineering discussion on sedimentation in reservoirs. Additional support to ensure the information is fed back to policy and decision-makers is critical to ensure that the information is formulated into appropriate policy and action. A National focused forum should be established to ensure that the information generated is carried into the appropriate policy forums.

Policy Support. Providing direction to agencies and groups to initiate data collection, model development and risk assessment often requires direction and support from agencies and appropriators. It is important that appropriate direction and funding is allocated to the agencies to adequately assess the reservoir sedimentation problem and formulate appropriate actions to address.

Recommendations

Under the existing operation and management regimes of the reservoir management community the impact of sedimentation will continue to increase. Not accounting for the reduction in storage capacity in reservoirs due to sediment is already impacting operational efficiency. Sustainable reservoir and water management requires that an improved and coordinated approach to understanding and managing the sediment loads in reservoirs be developed.

While it may be desired to calculate sediment deposition rates and loss of storage capacity for every reservoir it is not cost effective or likely to occur. What is possible however is to develop a risk assessment approach to reservoirs located within specific watersheds/river basins to help prioritize activities. Actions to be taken should include:

1. Develop federal policy to work with the states to aggressively address the issue and develop a set of recommendations for consideration by Congress.
2. Establish a National level Water Commission to help coordinate agency actions and approaches to defining the risk, build linkages between agencies, and to formulate cooperative watershed-based approaches.
3. Charge the Bureau of Reclamation, the U.S. Army Corps of Engineers, Department of Energy and the Federal Emergency Management Administration to evaluate the current state of the knowledge on sediment management in reservoirs including the identification of best practices, research needs, and policy priorities.
4. Establish river basin forums to identify and prioritize reservoirs to be assessed as to loss of reservoir storage capacity due to sedimentation (USBR 2015).
   - Determine the magnitude of the sediment problem
   - Define sediment management options
   - Define stakeholders and constraints
5. Prioritize the identified reservoirs based on their potential impact to public safety, water supply, flood control, access and energy production.
6. Assess the desired level of quality of data that is needed to address the initial assessments
   - Design and implement a sediment management monitoring program
   - Facilitate and invest in remote sensing technology to assess the level of deposition in high risk reservoirs or watersheds.
7. Develop new technologies to gather data
   - Developing new technologies for collecting reservoir sedimentation data
   - Implement data collection and analysis programs to develop quality data sets
   - Design and coordinate pilot studies to test assumptions
   - Integrate data into Geographic Information System for watersheds/river basins
8. Refine and or develop new models.
   - Models to address operational impacts associated with identified reservoirs.
   - Integrate real time data streams into modeling applications
   - Verify and validate the models
9. Update and Refine Operations Manuals
   - Integrate data and reservoir modeling information into operational manuals
   - Develop and implement a sediment management plan
10. Adaptation, Mitigation and Remediation Strategies
    - Develop useful adaptation, mitigation and remediation mitigation strategies
    - Identify methods to both reduce sediment loading to the reservoirs and the potential and cost-effectiveness of sediment removal to improve operational flexibility

References


High Country News. 2017. As sediment builds, one dam faces its comeuppance: Officials at a Colorado reservoir are reckoning with decades of accumulation.


