FORMULATING GUIDELINES FOR RESERVOIR SUSTAINABILITY PLANS

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INTRODUCTION

As time passes, reservoirs storing water also continue to fill with sediment, causing storage loss, reducing water supply reliability, and impacting infrastructure, particularly marinas, boat ramps, outlet works, turbines, and water intakes. In addition, reservoir deltas may extend upstream from the full reservoir pool and increase the frequency of flooding. The release of clear water downstream from the dam can lead to channel degradation. Sedimentation will also reduce the surface area available for recreation. The rate of reservoir sedimentation varies across the world and is very site specific, ranging from an average annual storage loss of 2.3 percent in China to 0.2 percent in North America (Garcia et al., 2008). The traditional approach in the design of federal dams in the United States was to construct the outlet works intake structure to be above the predicted reservoir sediment level at the dam during the first 50 to 100 years of operation, thereby allocating space in the bottom of the reservoir for sediment. However, reservoir sediment accumulation affects all levels of the reservoir (Utah Division of Water Resources, 2010), affecting all storage allocations by use (e.g. Conservation, Multi-Use, or Flood Pool). Under traditional dam building approaches, future generations will have to take some action after the sediment design life is reached, which could include dredging, sediment flushing, or dam decommissioning. However, the cost or feasibility of these measures was not determined.

In the field of natural resources management in the United States, there is recently more attention on reservoir sedimentation by managers, engineers, and scientists. For example, there is the recent resolution proposed by the Subcommittee on Sedimentation (SOS) to the Advisory Committee on Water Information (ACWI), who represents the interests of water-information users and professionals in advising the Federal Government on Federal water-information programs and their effectiveness in meeting the Nation's water-information needs (www.acwi.org):

> "Continued sedimentation threatens the project benefits for many of the Nation's reservoirs. The SOS encourages all Federal agencies to develop long-term reservoir sediment-management plans for the reservoirs that they own or manage by 2030. These management plans should include either the implementation of sustainable sediment-management practices or eventual retirement of the reservoir. Sustainable reservoir sediment-management practices are practices that enable continued reservoir function by reducing reservoir sedimentation and/or removing sediments through mechanisms that are functionally, environmentally, and economically feasible. The costs for implementing either sustainable sediment management practices or retirement plans are likely to be substantial, and sustainable methods to pay for these activities should also be identified.
>
> Federal agencies are encouraged to start developing sustainable reservoir sediment-management plans now for one or two reservoirs per year on a pilot basis. From this experience, interagency technical guidelines will be developed for preparing sustainable reservoir-sedimentation plans."

This technical report provides information beginning the development of guidelines for the formulation of reservoir sustainability plans for the effective management of inflowing sediment loads and in-situ deposits.

METHODS

This technical document summarizes key information from a Reclamation Science and Technology (S&T) Program research report (Reclamation, 2015), which provides addition details in the development of guidelines for the formulation of reservoir sustainability plans. Two key questions were set at the beginning of the research process, along with further pertinent information as the research progressed:

1. What is the process for developing a plan and strategy for the managing sediment inflow and deposition in Reclamation reservoirs? Sedimentation occurs at all reservoirs at various rates and sedimentation eventually impacts reservoir facilities and storage capacity. Taking a proactive approach to managing reservoir sediment provides the best chance for extending the useful life of any reservoir.

A sediment management plan must address the social, environmental, technical, economic, and legal challenges. With guidance adapted from Utah Division of Water Resources (2010) and Garcia et al. (2008), the following broad and general steps are provided to develop a reservoir sustainability plan. Not all steps are mandatory and some steps can occur concurrently:

   a. Determine the magnitude of the sediment problem
   b. Define preliminary sediment management options
   c. Define stakeholders and constraints
   d. Assess feasibility and economic viability of options
   e. Develop and implement a sediment management plan
   f. Monitor and revise plan if necessary

2. What is the best method for identifying which Reclamation reservoirs present the highest risk for experiencing adverse operational impacts and pose the greatest need for implementing an appropriate sustainability plan? Many Reclamation reservoirs in multiple Regions have experienced operational challenges due to sedimentation. Early identification of sediment related problems and proactive implementation of a customized sustainability plan are vital components in the preservation of a dam or reservoir's ability to meet Reclamation's mission.

The best way to determine the rate and extent of the reservoir sedimentation begin with direct surveys. However, the vast majority of Reclamation's reservoirs haven't even been surveyed since dam closure. Other indirect methods are available to estimate the amount of storage loss and determine which reservoirs have the greatest sedimentation problems.

Further guidance on the steps in developing a reservoir sustainability (or any other sediment sustainability) management plan and methods on quantifying reservoir impacts are detailed in further sections. This document details the preliminary steps in terms of what sustainable reservoir sediment management options are available in formulating a reservoir sustainability plan.

There is a wealth of knowledge giving detailed options available in addressing the problems of reservoir sedimentation. Garcia et al (2008) provides a good general discussion on reservoir sedimentation and sediment management options. Morris and Fan (1998) and Basson and Rooseboom (1997) both provide the most comprehensive information on sediment management in reservoirs. This research is intended to only reference the options as part of the guidelines for formulating reservoir sustainability plans.

a. <u>Determine the Magnitude of the Problem:</u>

The second question asked in the research effort was: what is the best method for identifying which Reclamation reservoirs present the highest risk for experiencing adverse operational impacts and pose the greatest need for implementing an appropriate sustainability plan?

As the saying goes, "one cannot manage what they cannot measure." The best method, or in this case methods, of determining the magnitude of the problem are direct measurements. As mentioned in the summary, there are two direct ways to measure storage loss and the potential of sediment problems in a reservoir:

1. Performing a repeat hydrographic survey of the reservoir, and;
2. Sediment flux measurements upstream and downstream of the reservoir.

Chapter 9 in Reclamation's Erosion and Sedimentation Manual (Reclamation, 2006) provides guidance on the performance of reservoir surveys. Prior to the development of modern measurement techniques with Global Positioning System (GPS) and acoustic depth sounding equipment, early reservoir surveys were performed along range lines (cross sections), where the station and depth were directly measured from a boat. With modern techniques, the entire reservoir can be surveyed and contour maps can be developed. The comparison of reservoir

survey data collected using entirely different methods can result in high uncertainty. Therefore, to reduce uncertainty in the estimate and distribution of reservoir storage loss, more frequent reservoir surveys are needed to accurately measure the rate of reservoir sedimentation.

Sediment flux measurements entail the continuous or repeated measurement of suspended sediment loads and bed load sediments both upstream and downstream of a reservoir, where then by conservation of mass, the amount of sediment depositing in the reservoir, or the storage lost, is estimated. Flux measurements, however, give only a storage loss estimate, and do not provide a measurement of sedimentation near important features (e.g. marinas, boat ramps, outlet works and water intakes).

Sediment flux measurements generally require more continuous monitoring and therefore more resources than periodic reservoir surveys. However, in combination, both provide a robust estimation of the timing and rate of reservoir sedimentation, including the properties of incoming and outgoing sediments (e.g. particle size).

Chapter 9 in Reclamation (2006) notes that the frequency of reservoir surveys should depend on the estimated rate of reservoir sediment accumulation, along with the current operation and maintenance plan.

Generally, the availability of funding limits the performance of direct measurements by reservoir survey and/or sediment flux measurements. At a lesser cost, the potential impacts of reservoir sediment to important features (e.g. outlet works, water intakes, boat ramps) can be evaluated with a reconnaissance survey, where a profile of the reservoir is rapidly surveyed to determine priorities.

At lesser cost but with greater uncertainty, there are several indirect methods are available to estimate the amount of storage loss and determine which reservoirs pose the greatest of impacts. Prior to the implementation of using indirect methods to determine sedimentation rate, one can define reservoirs that are offstream and possibly those in a series that have may have reduced sedimentation rates. These reservoirs generally have a low likelihood of impacts due to reservoir sedimentation.

On the other end of the spectrum, according to Basson and Rooseboom (1997) and Dendy et al. (1973), reservoirs with small storage/runoff ratios in relatively small catchments in semi-arid areas with high sediment yield ratios are highly vulnerable to reservoir sedimentation.

As far as indirect computations, the simplest method to determine reservoir storage loss and potential impacts at a given reservoir is to extrapolate storage loss or sediment yield rates from other nearby surveyed reservoirs in RESSED which are in similar hydrologic/geologic areas.

Next, a more detailed and process intensive way to estimate reservoir storage loss rates is the use of Geographic Information System (GIS) analyses. Several methods are listed, from least to most detailed:

1. Compute the regional rate of storage loss, for example by applying a regional regression equation. For example, extrapolate from other nearby reservoirs or by Hydrologic Unit Code (HUC). Another example is the 3W Model (Minear and Kondolf, 2009), which is a reservoir sedimentation prediction model that accounts for regional sediment yields, changing trap efficiencies over time in reservoirs, and the passing of sediment between a series of reservoirs.
2. Perform detailed watershed sediment yield estimates with GIS information. Several models/methods are available, such as the Watershed Erosion Prediction Project (WEPP) model (http://www.ars.usda.gov/News/docs.htm?docid=10621)

Additional Site Specific Data:
For a given site, once preliminary information is gained and there are potential sediment impacts that confirm the need for development of a sustainable sediment management plan, additional site-specific data should be collected. A reservoir survey should be performed if one was not recently collected. Next, a study should be performed of the composition of sediments that are flowing into and possibly out of the reservoir, and of sediments that may have already deposited in the reservoir. This study would include fluvial sediment sampling of the river above and below the reservoir, and in-situ sediment sampling of reservoir deposits.

In some cases, the presence of any contaminants above background concentrations will need to be determined prior to the implementation of any sediment management options. An inventory of upstream and downstream infrastructure in and near the reservoir which may be impacted by sediments and/or any changes to the reservoir and dam is necessary.

Depending on the availability of data, a more detailed hydrologic study may be necessary to better understand the timing and volume of inflows into the reservoir as part of developing any further sediment management options. In addition, data describing the operations of the reservoir is necessary.

Once preliminary information and rates of sedimentation are identified for a reservoir, the next step is to determine when sedimentation will impact key features.

Estimating Reservoir Life:
Once storage loss rates are calculated, various methods are available to determine the amount of time until reservoir sedimentation affects the design function of a reservoir. One traditional way is estimating the reservoir life, or the time until the usable storage pool completely fills with sediment, presumably followed by the abandonment of the structure (Garcia et al., 2008). However, sediment problems will arise well before the reservoir completely fills with sediment (Garcia et al, 2008) and reservoir life should not be viewed in such a manner. Some reservoirs experience problems with storage loss as little as 6% (Loehlein, 1999; Garcia et al.,2008). Reservoir sedimentation will become a serious problem when an important structure or key feature (e.g. outlet works, water intake, and boat marina) are buried, clogged, or abraded by sediments. An empirical method to estimate when sediment levels reach key features is to spatially estimate the sediment distribution in a reservoir based on methods from Reclamation (1982) and Reclamation (1962). Without direct measurement of sedimentation patterns, the spatial distribution of sediment may have high uncertainty.

According to Garcia et al. (2008), the "life" of a reservoir is better described based on the three distinct stages:

1. Continuous Sediment Trapping
2. Partial Sediment Balance
3. Full Sediment Balance

Most large reservoirs worldwide are operated in Stage 1, continuously trapping sediment. Only a few reservoirs worldwide have been designed to achieve Stage 3, which is the ultimate goal in formulating a sediment management plan for a reservoir. By achieving a Full Sediment Balance between upstream and downstream points of the reservoir, additional reservoir storage is no longer lost.

The time when sediment will reach key structures can be estimated by extrapolation from measurements, numerical modeling, or physical modeling. In addition, GIS analyses can be used to evaluate the complex bathymetry of reservoirs (e.g. Reclamation, 2012). Generally, analyzing profiles of repeat surveys, and estimating either the rate of delta progression for an upstream feature, such as a marina, or estimating the rate of bottomset delta growth near dam intakes are means to estimating when sediment problems will affect these particular facilities.

One useful way to determine the relative impact of the arrival of sediments to infrastructure at a dam is comparing the hydrologic size (Reservoir Capacity/Mean Annual Runoff), K_w, and the reservoir capacity to sediment inflow (Reservoir Capacity/Mean Annual Sediment Yield), K_t, of a particular facility to other facilities in an inventory.

Figure 1 presents this empirical diagram, derived from Basson and Rooseboom (1997), which is also a means to understand ways to manage reservoir sedimentation. The larger the hydrologic size (K_w) of the reservoir, the more important carry over storage into multiple years becomes for the facility. Data needs for this method are:

1. Total Reservoir Capacity
2. Mean Annual Sediment Yield
3. Mean Annual Runoff

In general, the farther a particular reservoir is toward the bottom left quadrant of Figure 1, the sooner that reservoir sediments will impact infrastructure located near the dam. For example, in Reclamation's inventory of dams, Black

Canyon, Guernsey, Paonia, and Lake Sumner are reservoirs near the bottom and left of the diagram. Currently, all these facilities pass measurable amounts of sediment through their respective outlet works facilities. The former Lake McMillan was nearly filled with sediment and replaced with the larger Brantley Dam, inundating the structure. An important feature to Figure 1 is that as time passes and reservoirs fill with sediment (decrease in storage), their plotting position moves toward the bottom left quadrant.

Figure 1 also presents three potential sediment management options: flushing, sluicing, and storage/dredging. The ranges of these preliminary options are taken from Basson and Rooseboom (1997), and are based on empirical data from Chinese and South African reservoirs. At the most bottom-left, flushing, is defined as drawing down the water level to re-entrain previously deposited sediments and to remove these sediments from the reservoir through bottom outlets. In the middle, sluicing, is defined as an operation technique whereby sediment-laden inflows are passed through the reservoir before the sediment particles can settle, thereby reducing the sediment trap efficiency of the reservoir, and maintaining reservoir storage capacity. The storage or "dredging" option is defined as inflowing sediment is stored in the reservoir and mechanical means are necessary to maintain or possibly regain storage, with the exception that the venting of turbid density currents is a possible sediment management option for reservoirs in this category. The majority of Reclamation reservoirs in RESSED fall into the "dredging" category. These potential sediment management options, along with several others, are presented in more detail in the following section.

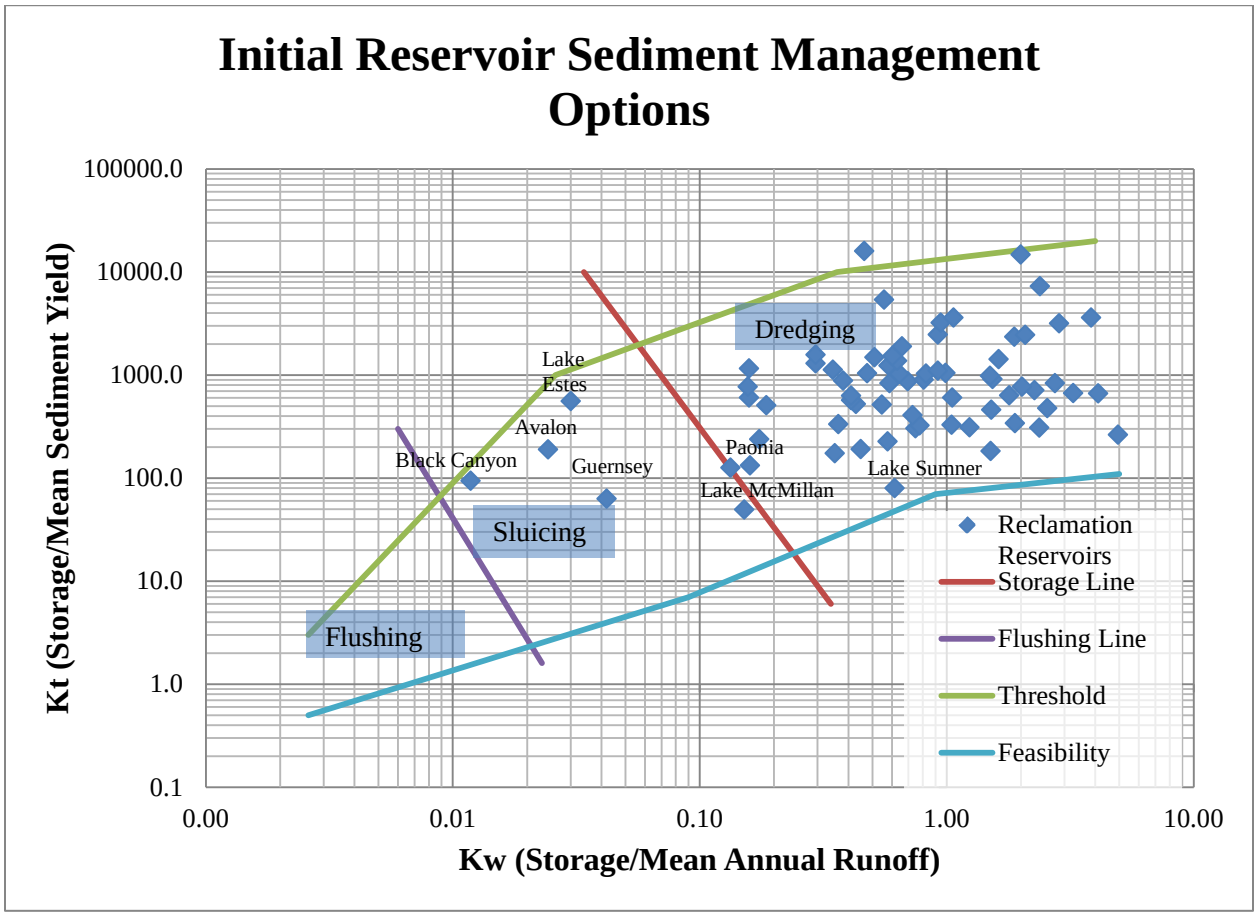

Figure 1. Diagram Adapted from Basson and Rooseboom (1997) for Determining Relative Reservoir Impact and Preliminary Reservoir Sediment Management Options

Necessity of a Sediment Management Plan:
Sediment management plans for achieving reservoir sustainability at Reclamation facilities are currently developed on a reactive basis for reservoirs which are already experiencing impacts from reservoir sedimentation. Currently, no programmatic-level allocation of resources is in place at Reclamation for proactive, comprehensive, sustainable sediment management of facilities. However, in addition to the SOS resolution promoting the development of sediment management plans, there is the push within other organizations at International (e.g. China and South Africa), Federal (e.g. U.S. Army Corps of Engineers), and State (e.g. California, Utah, Kansas, and Texas) levels that are in the process of systematically developing and implementing reservoir sustainability plans for reservoirs.

Whether sediment management planning of reservoirs is performed programmatically or at an ad-hoc basis, in the likeliest case of limited funding, prioritization is necessary to determine the reservoirs that may need to implement a sustainable sediment management plan.

Basson and Rooseboom (1997) provided general guidance for South African reservoirs relative to other reservoirs quantified using the index presented in Figure 1. According to their guidance, if the relative storage loss rate, K_t is less than 50, the reservoir sedimentation problem is considered serious, meaning sediment management actions need to be taken.

Comparing Reclamation's surveyed inventory, only the former Lake McMillan falls below a K_t value of 50. It is important to note that this inventory does not include any reservoirs which have not been surveyed. If the criterion were set to a value K_t less than 300, this would encompass most reservoirs with already known sediment issues, which are 13 of the 83 surveyed Reclamation reservoirs (16%) in RESSED. These facilities would have initial priority in following the guidelines developed in this document to formulate a sustainable sediment management plan. Other prioritization schemes to determine the necessity of a sediment management plan or dam decommissioning may involve the quantification of the time until sediments reach key features, and the quantification of the loss of benefits as a result of plugging, burial, and/or abrasion of pertinent features which provide benefits.

Eventually, all reservoirs need to be managed sustainably to provide benefits for future generations or decommissioned. The process is envisioned that a continued development of sustainable sediment management plans would occur for most Reclamation reservoirs that have inflowing sediments or a decommissioning plan would be put in place.

b. <u>Define Preliminary Sediment Management Options:</u>
With the development of relative reservoir impact and the unveiling of preliminary potential sediment management options presented in Figure 1, this section provides more detail of potential sustainable reservoir sediment management options/methods that have been applied to other reservoirs worldwide. All reservoir sediment management methods can be put into three different categories (Garcia et al, 2008; Kondolf et al, 2014):

1. Reduce Sediment Delivery (Watershed Management)
2. Prevent Sediment Deposition (Route Sediments through or around Storage)
3. Increase or Recover Volume (Removal of Deposited Sediments)

Figure 2 shows a variety of sediment management techniques placed into the three above categories by Kondolf et al. (2014). The exception within the three categories is raising a dam to increase storage, which does not fully deal with the management of incoming sediments, but extends the reservoir life by the creation of more storage.
There can be instances where a combination of methods from the above categories is necessary to maintain reservoir capacity and achieve reservoir sustainability.

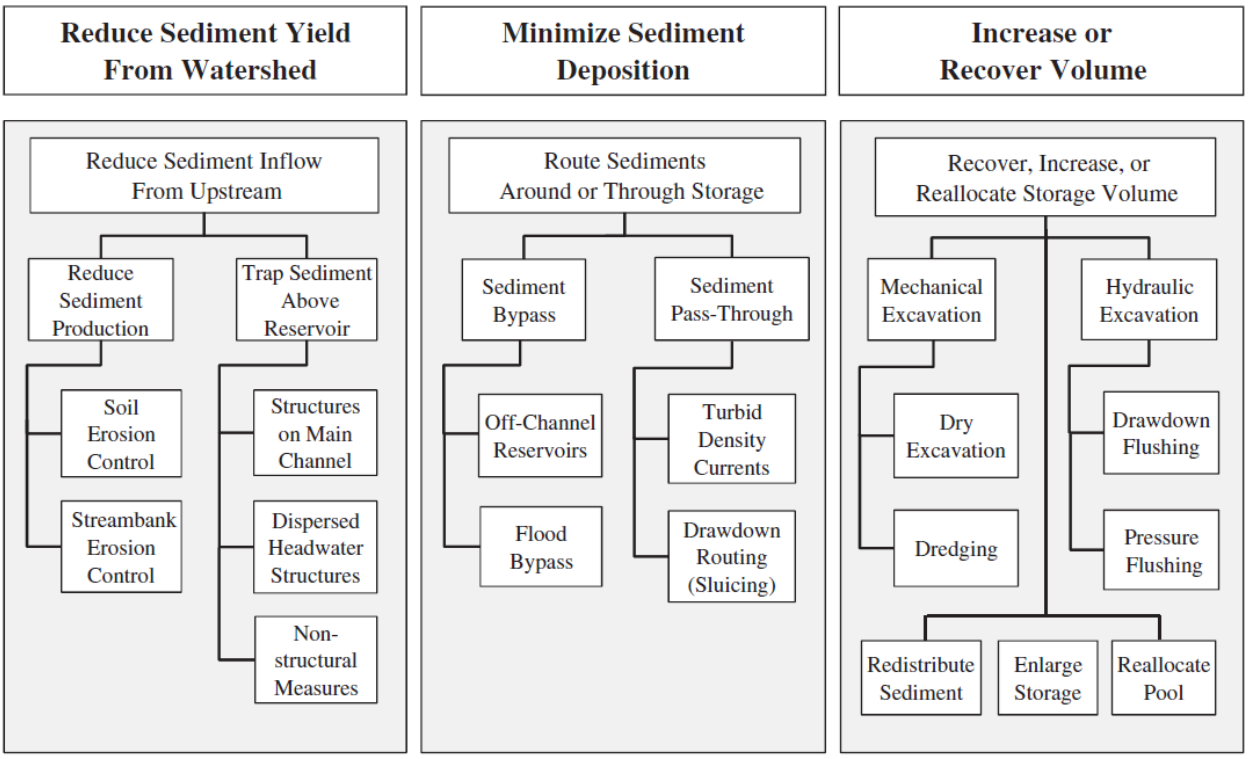

Figure 2. Diagram of Sediment Management Options for Reservoir Sustainability (taken from Kondolf et al. 2014)

The majority of sustainable sediment management options which are applicable to Reclamation's Mission are focused within the second and third categories presented in Figure 2. The first category, watershed management, is to reduce the amount of sediments entering there reservoir (thereby reducing sediment yield) would require involvement with other federal agencies, such as the U.S. Forest Service, Bureau of Land Management, State, County, and City resource managers, and private landowners.

Watershed management options include the control of land use practices; such as grazing, mining, logging, and land development. Other structural options include the development of land terracing, check dams, erosion control structures, and sediment basins in tributaries. A unique method is warping, which is the release of sediment laden flows on agricultural land to filter out sediments and return clearer flows back to the river.

The second category involves reducing sediment deposition of sediments flowing into a reservoir. This would either entail designing features to bypass sediment either through or around the reservoir. Included is the construction of bypass features in the reservoir, which may be an open channel, tunnel, or pipeline to divert sediment-laden flows from upstream end of the reservoir and discharge the flows downstream of the dam. Other means of reducing sediment deposition is to allow sediment-laden flows to pass-through the reservoir, either by allowing turbid density currents to pass through outlet works structures while the reservoir is full, or by drawing down the reservoir before the arrival of sediment-laden flows to keep flow velocities high enough through the reservoir and outlet works to pass sediment. Another option is this category includes the development of offstream reservoirs, where sediment-laden flows pass downstream, and clear water flows are diverted from the river to the reservoir.

The third category involves methods to remove deposited sediments. The first subcategory is hydraulic removal, where either the reservoir is drawn down, allowing flow velocities to increase near outlet works structures in order to erode previously deposited sediments (drawdown flushing), or by opening the outlet works gates and to not allow the reservoir to completely draw down, but rely on velocities near the structure to flush sediments through the gates (pressure flushing). The second subcategory is mechanical removal of sediments, which is by either dredging deposited sediments while storage remains near full in the reservoir or by dry excavation with construction equipment when the reservoir is drawn down.

Dredging is the most common sediment management method for reservoirs located in regions where carry over storage through multi-year droughts is paramount, and the reservoir cannot be drawn down. Dredging is typically more expensive than operational sediment management techniques (flushing or sluicing) to pass sediment downstream of the dam, and typically only occurs locally around structures due to the expense. Basson and Rooseboom (1997) noted that dredging is generally more expensive than creating new storage (e.g. dam raise), but that technology has narrowed the gap in cost. The most typical type of dredgers are cutter-suction and bucket-wheel types for reservoir depths less than 30 meters. If the reservoir is short enough in distance (e.g. less than 4km), a hydrosuction type of dredge is the most economical dredging option. Electric powered dredging is cheaper than diesel-powered when electricity is readily available nearby. The disposal cost of sediment is a major factor when estimating the cost of dredging as a sediment management option for reservoir sustainability. The dredging of reservoirs to maintain storage capacity is less expensive than dredging for navigation because the shape of the excavation area is not nearly as important and there is less movement and downtime with reservoir dredging.

Basson and Rooseboom (1997) and Morris and Fan (1998) both provide comprehensive information on the dredging of reservoirs for sediment management.

Timing of Methods:
Recovering decades of storage lost to sedimentation may be cost prohibitive. However, long-term dredging of the average annual sediment load may be economically viable, especially when compared to the long-term costs of no action and reservoir retirement.

The timing of reservoir sediment management methods is generally determined on a site-specific basis. For example, the method of sluicing requires drawdown of the reservoir before the arrival of the snowmelt or flood season in order to pass the initial sediment-laden flows and then capture the clear water flows at the end of the flood season for storage and use during drier periods of the year. Dredging may need to occur while the reservoir is or nearly at full pool for the dredger to access and remove deposited sediments. Nonetheless, dredging could occur at different locations depending on the reservoir level, where depths ranging from 30 to 50 feet are targeted. Over the longer term, sediment management methods may occur annually or periodically (e.g. biennial, decadal), depending on the rate of inflowing sediments and other site constraints.

c. <u>Define Stakeholders and Constraints:</u>

The majority of dams and reservoirs will have a unique combination of site specific constraints. Critical to the identification of site constraints is the involvement of all stakeholders that benefit or may be impacted by the implementation of sediment management methods for reservoir sustainability. The determination of unique and potentially conflicting requirements on a given reservoir or set of reservoirs is necessary prior to further development and implementation of any reservoir sediment management methods within a plan. The general types of constraints to identify as part of developing a sustainable reservoir sediment management plan are:

a. Physical Constraints
    a. Dam Height
    b. Storage Volume
    c. Reservoir Length and Width
    d. Hydrology
    e. Geology
    f. Spatial sediment distribution
    g. Sediment grain size
b. Operational Constraints
    a. Allocation of Use
    b. Carryover Storage
c. Economic Constraints
    a. Loss of Revenue
    b. Reduction of Benefits

c. Costs of retirement under the no action alternative

d. Environmental Constraints

i. Downstream Impacts

1. Infrastructure
2. Water Quality
3. Reversal of channel degradation
4. Permitting
5. Other reservoirs

ii. Upstream Impacts

1. Reversal of channel aggradation

iii. Contaminants

e. Other Constraints

In most cases, the implementation of a reservoir sustainability plan will cause a reduction in benefits in the short-term, with the tradeoff that the reduced benefits will be available on a sustainable basis. Some stakeholders will potentially lose some short term benefits in order to sustainably manage a reservoir. Ultimately, however, all benefits would be lost to all stakeholders if the reservoir fills with sediment and the dam must be decommissioned at great expense to future generations.

d. <u>Assess Feasibility and Economic Viability of Options:</u>

The economics, or in other words, the associated costs relative to the associated benefits over the life of the reservoir, ultimately drive whether to finance sediment management methods to manage a reservoir sustainably. Traditional design and economic analyses do not appropriately take into account the long-term costs or benefits to achieve reservoir sustainability (Garcia et al., 2008). The long-term loss of benefits for agricultural, municipal, industrial, recreational, and other uses due to the loss in reservoir storage due to reservoir sedimentation must be accounted for in comparison to the long-term costs of maintaining the associated benefits the facility provides, in addition to the cost of decommissioning the dam or the creation of additional storage once reservoir sedimentation problems have become too severe.

The goal of making a resource, in this case the water storage a reservoir provides, sustainable or renewable requires a change from the traditional economic concept of time discounting a reservoir's value, which ignores the potential loss of benefits to future generations. A life cycle approach must be developed, where either the reservoir is managed as an exhaustible resource with a sinking fund to pay for the decommissioning of the dam and the development of new storage, or to manage the resource sustainably, such as using the RESCON (REServoir CONServation) approach (Palmieri et al, 2003).

As best stated in Garcia et al. (2008), the RESCON methodology proceeds in three stages:

1. Determine which methods of sediment management are technically feasible;
2. Determine which alternatives are more desirable based on an economic analysis;
3. Incorporate environmental and social factors to select the best course of action for sediment management.

The RESCON approach is applicable to proposed or existing dams and reservoirs to develop a preliminary assessment of sustainable sediment management alternatives, and to compare the alternatives to the alternative of allowing the reservoir to fill up with sediment and the ensuing course of dam decommissioning (Garcia et al., 2008). The RESCON approach accounts for major benefits and costs over the complete project life-cycle and, in particular, acknowledges the concept of *intergenerational equity*, which is the concept of taking into account the economic, social, and environmental cost and benefits of all future generations. Making a reservoir a sustainable, rather than an exhaustible resource, promotes intergenerational equity (Annandale, 2013). Additional information regarding the performance of the RESCON approach as part of determining sustainable sediment management options for a reservoir can be referenced in Palmieri et al (2003).

Environmental Considerations:
In order to achieve reservoir sustainability, a change in the operation and maintenance of the reservoir may be required. It is then necessary to consider the environmental consequences, and to minimize any impacts that are potentially detrimental. For example, some sediment management methods require the passing of sediments downstream of the reservoir. The release of high sediment concentrations from a reservoir can pose serious impacts to downstream aquatic environments, infrastructure, and recreation (Utah Division of Water Resources, 2010). However, high sediment concentrations could be of benefit to fisheries and geomorphic features reliant on higher sediment concentrations (e.g. cover and sandbar development), such as the case in many Southwestern United States Rivers (e.g. Colorado River in the Grand Canyon). Federal laws and agencies are in place to enforce the law of the land where, in the case of the United States, relatively strict water quality standards are in place to protect environmental resources. Determination of water quality impacts from reservoir sediments and any potential contaminants must be analyzed to minimize adverse environmental impacts and to comply with various laws, such as the National Environmental Protection Act, Clean Water Act, and the Endangered Species Act (Utah Division of Water Resources, 2010). Sources providing more information on sediment impacts and regulatory requirements include Sedimentation Engineering (Garcia et al., 2008) and Managing Sediment in Utah's Reservoirs (Utah Division of Water Resources, 2010).

e. <u>Develop and Implement a Sediment Management Plan:</u>

Based on the potential feasible sustainable sediment management methods that are determined in combination with the RESCON approach, water quality requirements, and any other unique site-specific constraints, a detailed consensus-based reservoir sustainability plan can be developed and implemented for the reservoir. The reservoir sustainability plan itself would detail any changes involving the dam and reservoir, which would include a combination of a monitoring plan of incoming, depositing, and passing sediments, the change in operational and maintenance procedures, the design and construction of new infrastructure to pass sediments, a periodic dredging plan, agreements of funding, and coordination with other stakeholders public and private.

f. <u>Monitor and Revise Plan if Necessary:</u>

As with the management of any resource, continued monitoring of reservoir sediments is necessary to track whether the implemented sediment management options are performing as predicted or not. If a particular sediment management method is not sustainably maintaining the storage of a reservoir, the plan may need to be revised to meet the criteria of sustainability. This revision of the plan may require one or more of the previous steps outlined in this document.

CONCLUSION AND SUMMARY

This technical paper details the general steps and guidance that could be followed in developing a reservoir sustainability plan (Reclamation, 2015). The dam owner and investigator(s) should not only follow these general guidelines, but should refer to other guidelines and case studies that are widely available and referenced throughout this document, such as Utah Division of Water Resources (2010), Garcia et al. (2008), Morris and Fan (1998), and Basson and Rooseboom (1997). Development of reservoir sustainability plans for reservoirs will be no less site-specific and unique as the site conditions and operations that each dam and reservoir inherently encompasses. The reservoir sustainability guidelines outlined in this document are:

a. Determine the magnitude of the sediment problem
b. Define preliminary sediment management options
c. Define stakeholders and constraints
d. Assess feasibility and economic viability of options
e. Develop and implement a sediment management plan
f. Monitor and revise plan if necessary

Findings from the research in Reclamation (2015), pertinent to Reclamation's inventory of dams and reservoirs, recommends the development of additional Geographic Information System (GIS) data that includes the storage capacity, drainage area, mean annual inflow, and mean annual sediment yield for all Reclamation reservoirs. This data would be valuable in further determining the relative impact of reservoir sedimentation in all Reclamation reservoirs, short of a comprehensive reservoir survey program for all Reclamation reservoirs. Additional reservoir sedimentation distribution tools can be refined and developed to estimate the spatial and temporal impacts of reservoir sedimentation to important features. Other prioritization schemes to determine the necessity of a sediment management plan or dam decommissioning may be necessary. These decision-making schemes may involve the quantification of the time until sediments reach key features, and the quantification of the loss of benefits as a result of plugging, burial, and/or abrasion of pertinent features which provide benefits.

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