Formulating Guidelines for Reservoir Sustainability

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Introduction

As time passes, a reservoir storing water will continue to fill with sediment, causing storage loss, reducing water supply reliability, and impacting infrastructure, particularly to marinas, outlet works, and turbine intakes. 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 dams in Reclamation is to size a dead pool to account for 100 years of 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, after the “design life” is reached, the dam and reservoir would be taken out of service, with future generations to deal with the decommissioning and sediment problems.

Referencing the number of Reclamation reservoirs in Reclamation’s DataSpace Console (Reclamation, 2006-11) and the Statistical Compilation of Engineering Features on Bureau of Reclamation Projects (Reclamation, 1992), Figure 1 shows the age distribution of Reclamation Reservoirs. Half of Reclamation’s reservoirs are over 60 years old. Nearly 20 percent are at least 80 years old, 7 percent are already over the “design life” of 100 years.

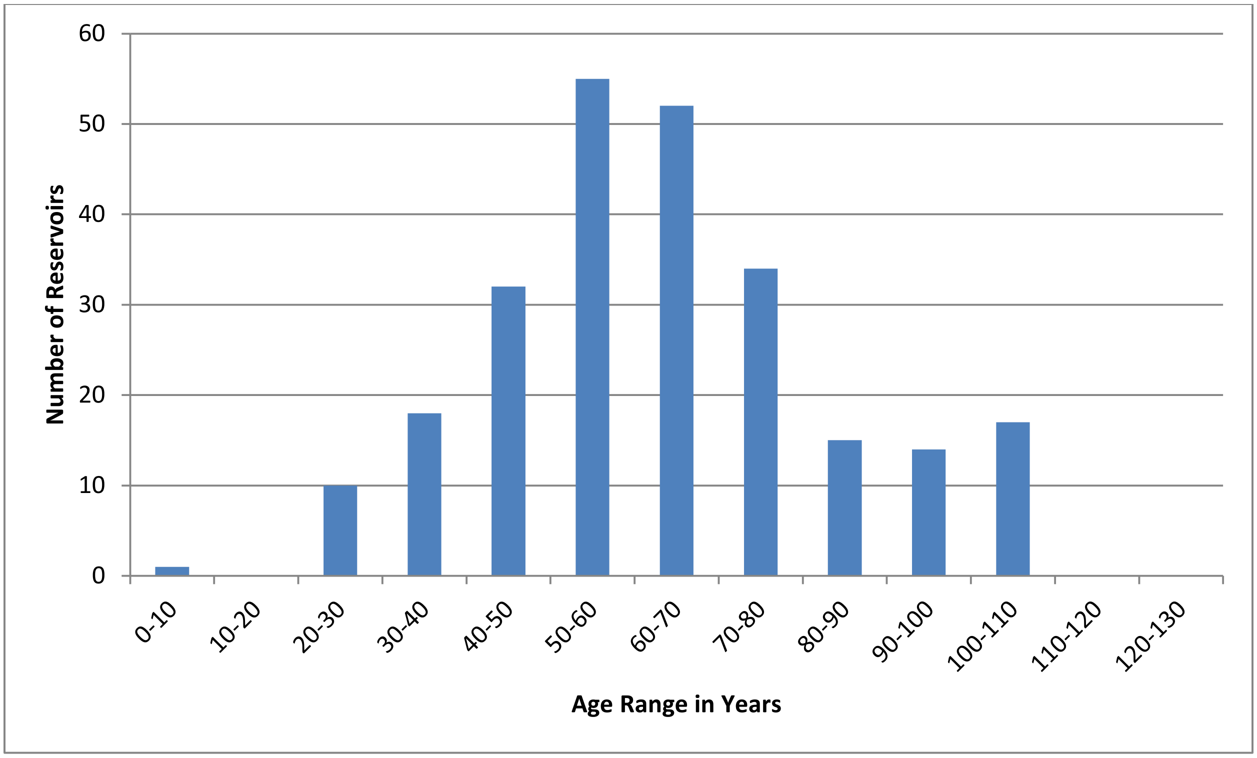

Figure 1. Age Distribution of Reclamation Reservoirs as of 2014

Within the next several decades, many Reclamation facilities will be nearing or are past their original design life of 100 years and will still serve critical water related needs. The importance of water storage is likely to increase in the future as the human population increases and with climate change. These aging facilities likely have no plan or other site available to replace the facility, so periodic retrofitting and upkeep are necessary for continued deliveries of water supply. Even if additional reservoir sites are available, they are likely more expensive to develop than the existing reservoir (Annandale, 2013).

As a means of defining the rate of storage loss in Reclamation reservoirs, the United States Geological Survey (USGS) REServoir SEDimentation (RESSED; Gray et al., 2010) database lists 83 Reclamation reservoirs with repeat hydrographic surveys. The repeat hydrographic surveys provide a measure of the storage loss and the rate of reservoir sedimentation in each respective reservoir. The 83 surveyed reservoirs encompass approximately one-third of the 248 reservoirs owned by Reclamation that are listed in Reclamation DataSpace which have a storage capacity listed in the 1992 Reclamation Statistical Compilation.

The total storage loss in Reclamation reservoirs reported in RESSED is 5.2 million acre-feet, based on the last average survey date being 8/31/1990, which is a 3.7% storage loss in all measured reservoirs.

The average annual percent storage loss of all Reclamation reservoirs listed in RESSED is 0.19, which is comparable to the loss rate of 0.2 for North American reservoirs (Garcia et al., 2008), and 0.22 in Utah reservoirs (Utah Division of Water Resources, 2010).

As an estimate of the reservoir storage loss over time in Reclamation reservoirs, Figure 2 presents the change in total storage capacity in all Reclamation reservoirs over time. Storage capacity and date of closure values are referenced from the 1992 Statistical Compilation for all reservoirs, noting which reservoirs are offstream, and extrapolating the annual average storage loss of 0.19 to all reservoirs. The figure shows the increase in total storage as dams were constructed and reservoirs entered into service. The figure also shows the decrease in storage as a result of reservoir sedimentation.

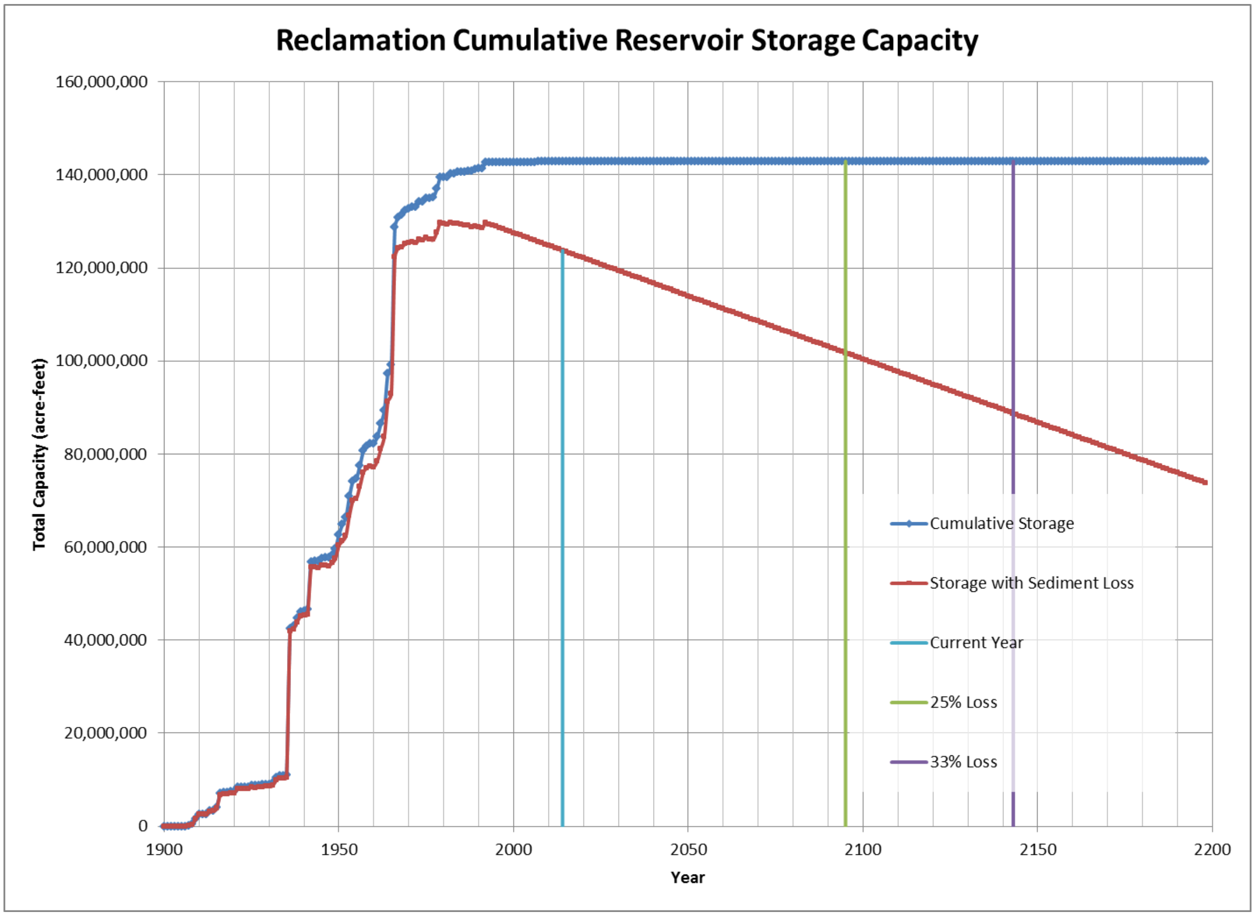

Figure 2. Total Capacity of All Reclamation Reservoirs over Time

Based on the time-average constant rate of storage loss (0.19), as of 2014, an estimate of 19 million acre-feet of storage is now lost to reservoir sedimentation (13% loss). The storage loss due to sediment puts the total storage capacity in Reclamation's inventory back to the total storage in year 1965. If an average value of water at $2,000 per acre-foot (Brown, 2006) is applied, the value of storage lost is $38 Billion in 2003 dollars. Assuming no new Reclamation dams are constructed in the future, by 2081, 25% of storage will be lost, and 33% of storage will be lost by 2123.

To gain an idea of Reclamation's total storage capacity affected by large reservoirs, the two largest reservoirs, Lake Mead and Lake Powell, have a combined storage capacity of 56.75 million acre-feet. This combined capacity is nearly 40 percent of a total storage capacity of 142.9 million acre-feet, assuming no loss to reservoir sedimentation. These reservoirs have an average annual storage loss of 0.12 and 0.128, respectively. Removing these two reservoirs from the analysis does little to change the average annual storage loss rate (0.195) or the percent total loss over time.

In general, with storage loss due to reservoir sedimentation, increasing demands for water supply, aging infrastructure, and the limited number of feasible and economical sites available for the construction of new dams and reservoirs (Annandale, 2013), these factors show the impetus that current and new Reclamation facilities need to be designed, re-operated, and/or retrofitted for sustainable use in terms of limiting the loss of reservoir capacity due to sedimentation.

The first step is that a sustainable sediment management plan must be developed for a reservoir prior to investing in the greater expense of designing, retrofitting, and/or re-operating a given dam and reservoir sustainably.

This research report provides the guidelines for the formulation of reservoir sustainability plans for the effective management of inflowing sediment loads and in-situ deposits. Two key questions set at the beginning of this research are answered in the research process, along with further questions 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 sediments provides the best chance for extending the useful life of any reservoir.

From the outset, a sediment management plan must address the social, environmental, and technical options with a goal of avoiding legal and political pressures in making important decisions (Reclamation, 2006).

With guidance adapted from Utah Division of Water Resources (2010) and Garcia et al. (2008), the following steps and guidance are provided in developing a reservoir sustainability plan. Not all are mandatory and some steps can occur simultaneously:

   a. Determine the magnitude of the sediment problem: gather information
   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

or are experiencing operational challenges due to a variety of sediment deposition issues. 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 methods have been and are direct measurements. There are two direct ways to measure storage loss and the risk of sediment problems in a reservoir:

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

However, the vast majority of Reclamation's reservoirs haven't been surveyed since dam closure. Other indirect methods are available to estimate the amount of storage loss and determine which reservoirs pose the greatest risk.

Further guidance on the steps in developing a reservoir sustainability (or any other sediment sustainability) management plan and methods on quantifying reservoir risk 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.

This document is intended for the use by Engineers, Scientists, and Natural Resource Managers as guidance in formulating sediment management plans for reservoirs, in order to achieve the goal of making a reservoir a sustainable and therefore renewable resource.

Determine the Magnitude of the Sediment Problem: Gather Information

The second question asked in this research study 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, are direct measurements. There are two direct ways to measure storage loss and risk 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) (http://www.usbr.gov/pmts/sediment/kb/ErosionAndSedimentation/chapters/Chapter9.pdf) provides a wealth of 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 a set group of range lines, 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.

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.

Sediment flux measurements generally require more continuous monitoring and therefore more resources than periodic reservoir surveys. However, in combination, both provide a more 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. The vast majority of Reclamation's reservoirs have not been re-surveyed since dam closure.

Therefore, there are several indirect methods are available to estimate the amount of storage loss and determine which reservoirs pose the greatest risk. 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 risk 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 way to determine reservoir storage loss risk 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.
2. Estimate a regional sediment yield calculation. For example, extrapolate from other nearby reservoirs or by Hydrologic Unit Code (HUC).
   a. The 3W Model (Minear and Kondolf, 2009) is a good reservoir sediment 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.

3. Perform detailed watershed sediment yield estimates with GIS information. Several models/methods are available:
   a. PLoad version 3.0: http://water.epa.gov/scitech/datait/models/basins/upload/2002_05_10_BASINS_b3docs_PLOAD_v3.pdf
   b. Watershed Erosion Prediction Project (WEPP) model: http://www.ars.usda.gov/News/docs.htm?docid=10621

Additional Site-Specific Data

Once preliminary information is gained and there is the recognition of the need for development of a sustainable sediment management plan, additional site-specific data should be collected. Primarily, 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 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 determination of the presence of contaminants or other nutrients in reservoir sediments is necessary prior to the implementation of any sediment management options. An inventory of upstream and downstream infrastructure 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 question is, if has not already happened, when will sedimentation 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). Generally sediment problems will arise well before the reservoir completely fills with sediment (Garcia et al, 2008). In most reservoirs, sediment will seriously interfere with design functions by the time half the storage pool is lost (Dendy et al. 1973; Murthy 1977). *Reservoir half-life,* the time required to lose half the original capacity to sedimentation, is thus a much better approximation of when sedimentation problems will become truly serious. Some reservoirs experience problems with storage loss as little as 6% (Loehlein, 1999; Garcia et al.,2008). Without direct measurement of sedimentation patterns, the spatial distribution of sediment is not easily estimated.

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 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, reservoir storage is no longer lost.

Estimating when sediment will reach key features (e.g. Marina, Intakes, Outlet Works, etc.) is hard to define. All reservoirs have spatial and temporal variations, and averaging issues make this estimate hard to define. 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.

There are few practical, repeatable ways with indirect measurements to estimate sediment arrival to a particular upstream structure in the reservoir, other than using storage loss as the primary indicator and applying a "life" or "half-life" estimation.

One useful way to determine the relative risk 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. Figure 3 presents this empirical diagram, derived from Basson and Rooseboom (1997), as a means to understand ways to deal with 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. 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 3, the sooner that reservoir sediments will impact infrastructure located at the dam. For example, Black Canyon, Guernsey, Paonia, and Lake Sumner are reservoirs near the bottom and left of the diagram. Currently, all 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. As time passes and reservoirs fill with sediment (decreasing in storage), their location on Figure 3 moves toward the bottom left quadrant.

Figure 3 also presents three potential sediment management options: flushing, sluicing, and storage. 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 option is defined as inflowing sediment is stored in the reservoir and mechanical means are necessary to regain storage.

These potential sediment management options, along with several others, are presented in more detail in the following section.

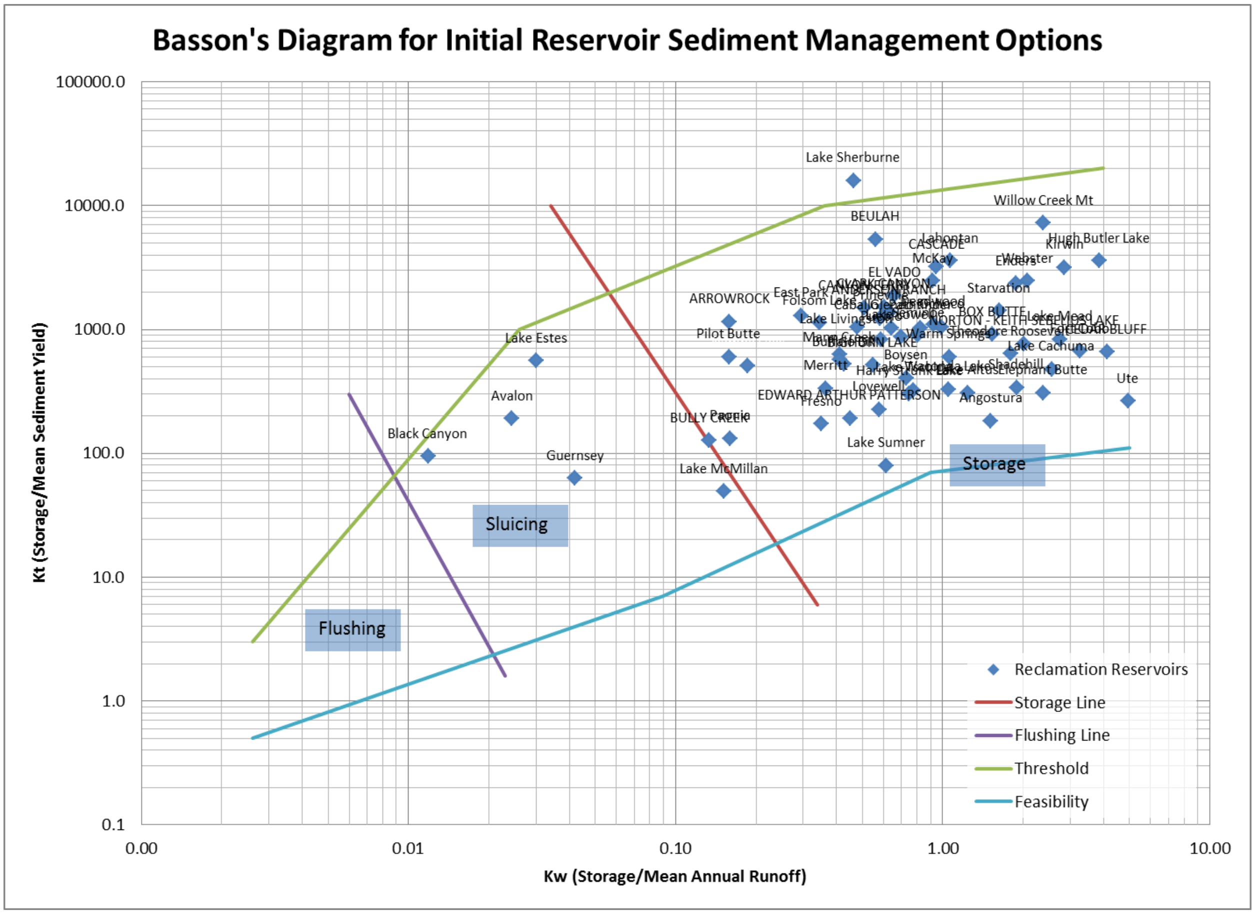

Figure 3. Diagram from Basson and Rooseboom (1997) for Determining Reservoir Risk and Preliminary Reservoir Sediment Management Options

Necessity of a Sediment Management Plan

The state of developing sediment management plans for achieving reservoir sustainability at Reclamation facilities is currently at a reactive basis for reservoirs which are already experiencing impacts from reservoir sedimentation. No programmatic-level allocation of resources is in place at Reclamation for proactive, comprehensive, sustainable sediment management of facilities.

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 3. 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. Actions rely on a plan, a reservoir sediment management plan.

Based on this criterion set by Basson and Rooseboom (1997) for South African reservoirs, comparing Reclamation's surveyed inventory, only the former Lake McMillan falls below a value of 50. If the criterion were set to a value K_t less than 300, meaning reservoirs which have "full life" expectancies less than 300 years, these facilities would have a sustainable sediment management plan developed first. This criterion encompasses most reservoirs with already known sediment issues, 13 of the 83 surveyed reservoirs (16%) in RESSED would lie within this criterion, or 5% of all the Reclamation reservoirs reported in Reclamation's DataSpace Console.

Eventually, all reservoirs need to be managed sustainably for future generations. The process is envisioned that a continued development of sustainable sediment management plans would occur for most Reclamation reservoirs that have inflowing sediments.

Define Preliminary Sediment Management Options

With the development of relative reservoir risk and the unveiling of preliminary potential sediment management options model in Figure 3, 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 4 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, and only shifts 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.

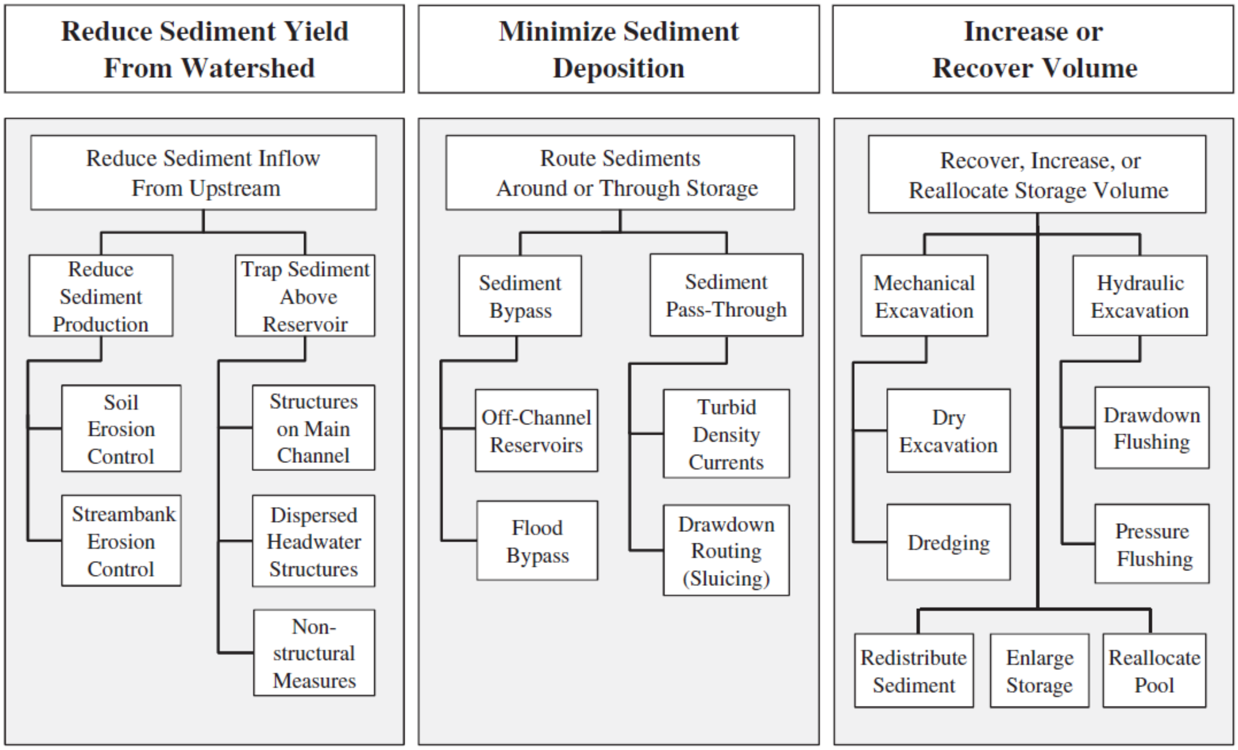

Figure 4. Diagram of Sediment Management Options for Reservoir Sustainability (taken from Kondolf et al. 2014)

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 4. The first category, watershed management, is to reduce the amount of sediments entering there reservoir (thereby reducing sediment yield) may require involvement with other federal agencies, such as the U.S. Forest Service and Bureau of Land Management.

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, which could be the development of offstream reservoirs where sediment-laden flows pass downstream and clear water flows are diverted from the river to the reservoir, or 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.

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.

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

Timing of Methods

The timing of reservoir sediment management methods is generally determined by method 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 would have to occur while the reservoir is or nearly at full pool for the dredger to access and remove deposited sediments. 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.

Define Stakeholders and Constraints

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
b. Operational Constraints
    a. Allocation of Use
    b. Carryover Storage
c. Economic Constraints
    a. Loss of Revenue
    b. Reduction of Benefits
d. Environmental Constraints
    i. Downstream Impacts
        1. Infrastructure
        2. Water Quality
        3. Permitting
        4. Other reservoirs
    ii. Upstream Impacts
    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 be at a loss of benefits in order to sustainably manage a reservoir.

Ultimately, the benefits will be lost if the reservoir fills with sediment and the dam must be decommissioned at great expense to future generations.

Assess Feasibility and Economic Viability of Options

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 make a reservoir sustainable. 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 the reservoir has silted up.

The goal of making a resource, in this case a reservoir, 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, and to develop a "life cycle" approach, 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 and economically, 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 all 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), which is accessible at: http://www-wds.worldbank.org/external/default/WDSContentServer/WDSP/IB/2006/01/18/000160016_20060118174458/Rendered/PDF/349540v10Reservoir0conservation0RESCON.pdf

Environmental Considerations

In order to achieve reservoir sustainability, a change in the operation and maintenance of the reservoir may be required, which 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).

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 the law of the land, such as the National Environmental Protection Act, Clean Water Act, and Endangered Species Act (Utah Division of Water Resources, 2010). Sources providing more information regarding 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).

Develop and Implement a Sediment Management Plan

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.

Monitor and Revise Plan if Necessary

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

Development of reservoir sustainability plans for Reclamation reservoirs will be no less site-specific and unique as the site conditions and operational that each unique Reclamation reservoir inherently encompasses. The reservoir sustainability guidelines outlined in this document are:

a. Determine the magnitude of the sediment problem: gather information
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

This document details the general steps and guidance that could be followed in developing a reservoir sustainability plan. The dam owner and investigator 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. (2010), Morris and Fan (1998), and Basson and Rooseboom (1997).

Findings from this research recommend the development of additional Geographic Information System (GIS) data within Reclamation's DataSpace Console 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 determining the relative risk of reservoir sedimentation in all Reclamation reservoirs, short of a comprehensive reservoir survey program for all Reclamation reservoirs.

Case Studies for Reference

A wealth of reservoir sustainability case studies to reference are located in Morris and Fan (1997), Basson and Rooseboom (1997), and Utah Division of Water Resources (2010). Kondolf et al (2014) also details specific cases by sediment management method. Reclamation case studies to reference are:

a. Paonia Dam
b. Black Canyon
c. Lake Powell

References

Annandale, G.W. (2013). *Quenching the Thirst: Sustainable Water Supply and Climate Change,* CreateSpace, Northe Charleston, S.C.

Basson, G.R., and Rooseboom, A. (1997). Dealing with Reservoir Sedimentation. Water Research Commission Report No. TT 91/97, Pretoria, xxxiii+395 pp.

Brown, T. C. (2006), Trends in water market activity and price in the western United States, *Water Resour. Res., 42,* W09402, doi:10.1029/2005WR004180.

Bureau of Reclamation (1992). *Statistical Compilation of Engineering Features of Bureau of Reclamation Projects.* United States Department of Interior. Bureau of Reclmation. Denver, CO.

Dendy F.E., Champion, W. A., and Wilson, R. B. (1973). Reservoir sedimentation surveys in the United States. American Geophysical Union, Washington D.C.. 17: 5-7. doi: 10.1029/GM017p0349.

García, M. H. (2008). *Sedimentation Engineering*, Manual 110 , Chapter 12, ASCE, Reston, Va.

Gray, J.R., Bernard, J.M., Stewart, D.W., McFaul, E.J., Laurent, K.W., Schwarz, G.E., Stinson, J.T, Jonas, M.R., Randle, Timothy, and Webb, J.W., 2010, *Development of a National, Dynamic Reservoir Sedimentation Database.* Proc. 9th Federal Interagency Sedimentation Conference, June 27–July 1, Las Vegas, Nevada, 12 p.

Kondolf, G.M. et al. (2014). Sustainable Sediment Management in Reservoirs and Regulated Rivers: Experiences from Five Continents. *Earth's Future, 2,* 256-280, doi:10.1002/2013EF000184.

Minear, J. T., and G. M. Kondolf (2009), Estimating reservoir sedimentation rates at large spatial and temporal scales: A case study of California, Water Resour. Res., 45, W12502, doi:10.1029/2007WR006703.

Morris, G.L., and Fan Jiahua. (1997). *Reservoir Sedimentation Handbook*. McGraw-Hill. New York.

Murthy, B. N. (1977). *Life of reservoir,* Central Board of Irrigation and Power, New Delhi.

Palmieri, A., Farhed, S., Annandale, G. W., and Dinar, A. (2003). "The RESCON Approach: Economic and Engineering Evaluation of Alternatives Strategies for Managing Sedimentation in Storage Reservoirs." The World Bank, Washington, D.C.

Reclamation DataSpace Version 10.0.0.0. (2006-2011). U.S. Bureau of Reclamation\The Michael Thomas Group Inc. Accessed Aug 15, 2014.

Reclamation (2006). Erosion and Sedimentation Manual. U.S. Department of Interior. Bureau of Reclamation. Technical Service Center Sedimentation and River Hydraulics Group. Denver, CO.

Utah Division of Water Resources (2010). Managing Sediment in Utah's Reservoirs: Utah State Water Plan.