CWTS report 2016-05, August 2016

USACE RESERVOIR SEDIMENTATION in the Context of Climate Change

Aerial view of Shenango River Lake and Dam in Hermitage, Pennsylvania

By Ariane Pinson, Bryan Baker, Paul Boyd, Rachel Grandpre, Kathleen White, and Meg Jonas

Preferred Citation: Pinson, A., B. Baker, P. Boyd, R. Grandpre, K.D. White, and M. Jonas. (2016) U.S. Army Corps of Engineers Reservoir Sedimentation in the Context of Climate Change. Civil Works Technical Report, CWTS 2016-05, U.S. Army Corps of Engineers: Washington DC.

EXECUTIVE SUMMARY

The US Army Corps of Engineers (USACE) is the largest operator of dams in the United States. Each USACE dam was planned, designed and built to provide specific benefits to the American public, including navigation, flood risk reduction, hydropower generation, recreation, and water supply. Most of the USACE dams have operated for more than 50 years, with some approaching 100 years of operation. Sedimentation impacts all of these dams to varying degrees by reducing reservoir volumes over time. Even though sedimentation was taken into account in design, there may be gradual loss of functionality with respect to a dam's authorized purpose(s) over time.

Since 2011, the USACE Civil Works Strategic Plan has stressed sustainable solutions for the 21st century. For our reservoirs, this requires that we take into account all of the factors that impact their performance and reliability. Among these is climate change, which has been identified as a major cause of future vulnerability to reservoirs due to its role in changing sedimentation patterns. Both observed and projected hydroclimate trends impact the rate of sediment delivery to reservoirs. Important drivers include increasing heat waves, changes in drought frequency and magnitude, altered freeze-thaw cycles, changes in snow volume and the onset of snowmelt, increased heavy precipitation, and changes in the frequency, magnitude, and duration of floods.

A reservoir storage baseline is necessary to determine which reservoirs are vulnerable to increased (or decreased) sedimentation resulting from past and future changes. As part of the effort to set a reservoir sediment baseline, six USACE districts were selected for detailed analysis as a representative sample of reservoirs in a variety of environmental settings. Some reservoirs have experienced impacts from sedimentation, resulting in a loss of storage capacity for water supply, flood risk reduction, recreation and other authorized purposes. For the majority of reservoirs, repeated, accurate surveys are vital to determining current sedimentation status from which to estimate future decreases in reservoir storage due to sedimentation. Information obtained from the pilot districts was used to develop a web portal to collect and house reservoir sediment information from across the Nation, including analytical data supporting efficient and sustainable reservoir sediment management.

This progress report summarizes the findings of the six pilot districts and the information housed in the new web portal. We provide recommendations on how to best achieve planned reductions in existing data gaps and how to identify the minimum survey frequency required to accurately project sedimentation impacts to reservoir project benefits. Only by understanding the rate at which sedimentation is encroaching on the authorized reservoir purposes can USACE develop plans to sustainably manage its reservoirs and maximize reservoir service life.

This page is intentionally left blank.

TABLE OF CONTENTS

Executive Summary ..... **ii**
Table of Contents ..... **iv**
List of Figures vi
List of Tables vii
Introduction **8**
Reservoir Sustainability and the Need for Reservoir Sedimentation Planning 8
The Climate Preparedness and Resilience (CPR) Program 10
Enhancing Reservoir Sedimentation Information (RSI) for Climate Preparedness and Resilience 11
Overview of Climate Change Impacts on Reservoir Sedimentation **12**
Review and Analysis of Reservoir Sedimentation Information (RSI) **17**
Overview 17
RSI Data Types 17
RSI Initial Data Collection Methods 18
Summary by RSI Category 22
Developing an RSI Update Strategy **30**
RSI Update Strategy Overview 30
RSI Baseline Data 30
Project Data Needs Related to Authorized Purposes 30
Navigation 31
Flood Risk Management 32
Aquatic Ecosystem Restoration 33
Hydropower 34
Recreation 35
Water Supply 35
Dry Dams 36
Other Determinants of RSI Data Needs 37
Geomorphology and Regional Characteristics 37
Size 37
Shape 38
Basin Schemes 38
Data Needs Based on Reservoir Sustainability 39
Understanding Changes Over Time 39
Sediment Yield 40
Wildfire 41

Sediment Management 43
RSI Data Collection 45
Data Collection Methods 46
Range and Contour Methods 46
Topographic Data Resolution 47
Bathymetric and Hydrographic Survey Techniques 48
Innovative Techniques 48
Datum Requirements 49
Sediment Sampling 49
Data Collection Frequency 50
Prioritization 51
Reservoir sediment Information PORTAL 52
Conclusions and Recommendations 57
Recommendations 57
References Cited 60
Appendix A: Projected Climate Changes Which Affect Sediment Yield By Region 69
Northeast 69
Midwest 69
Great Plains 70
Northwest 71
Alaska 71
Southeast 72
Southwest 73
Hawai'i 74
APPENDIX A References Cited 76
APPENDIX B District RSI Status 79
Omaha District (NWO) 79
Sediment Surveys and Area-Capacity Curves 79
Baltimore District 82
Los Angeles District 85
Fort Worth District 87
Huntington District 89
Walla Walla District 91

List of Figures

Figure 1. Factors that Contribute to Changes in Reservoir Sedimentation Rates 12

Figure 2. Changes in snowpack snow water equivalence (SWE, a measure of the amount of water available for spring/summer runoff) in the Southwestern US (Melillo et al. 2014). 13

Figure 3. Regions of the United States as defined in the National Climate Assessment (Melillo et al., 2014) 15

Figure 4. Map Showing the Distribution of USACE Reservoirs in the Conterminous United States, with the Locations of Districts Participating in the Initial Phase of this Study..... 18

Figure 5. Project Summary Form Spreadsheet Example (truncated) 20

Figure 6. Water surface plot for the Missouri River between RM 853 and RM 830 (the area between Fort Randall Dam and Gavins Point Dam) (USACE 2013b) 26

Figure 7. Map of Mainstem Dams on the Missouri River 27

Figure 8. Typical USACE Reservoir Storage Pools and Divisions 31

Figure 9. Debris removal at Mount Morris Dam (USACE 2015) 37

Figure 10. Some of the nearly 100 tons of debris washed down into Cochiti Lake, New Mexico, in the weeks immediately following the 2011 Las Conchas Wildfire, which burned in the mountains above the lake USACE (2012c) 42

Figure 11. Strategies for Managing Sedimentation in Reservoirs (after Kondolf et al. 2014: Figure 1) 44

Figure 12. Visualization of Traditional Cross Section Survey vs LiDAR techniques..... 49

Figure 13. Area Capacity Graph from RSI Portal for Fort Randall Dam (USACE Northwestern Division, Omaha District) 53

Figure 14. Volume Summary Graph from RSI Portal for Fort Randall Dam (USACE Northwestern Division, Omaha District) 54

Figure 15. Reservoir storage projected half-life graph from RSI Portal for Fort Randall Dam (USACE Northwestern Division, Omaha District). The graph also displays a reservoir storage half-life with 25% increase and decrease in sediment yield into the reservoir..... 55

Figure 16. Portion of the Overview Tab from the RSI Portal Filtered to the Omaha District in Northwestern Division 56

Figure 17. Example Project Summary Table from Master Notebook (truncated)..... 85

List of Tables

Table 1. Summary of Projected Climate Changes which Affect Sediment Yield by Region (from data in Melillo et al., 2014) 16
Table 2. District-Specific RSI Needs 19
Table 3. Summary of RSI Spreadsheet Project Summary Form Fields 20
Table 4. Project Information Spreadsheet Example 21
Table 5. Summary of District Project Information 23
Table 6. Summary of Sediment Surveys 24
Table 7. Summary of Sediment Data Collection 28
Table 8. Summary of RSI Pilot District's High-Priority Data Gaps 29
Table 9. Examples of Constituents Measured for Water Quality 33
Table 10. NWO Sediment Survey and Area-capacity Curve Data Summary 80
Table 11. NWO Active USGS Sediment Gages 81
Table 12. NWO Sediment Sample and Sediment Chemistry Data Summary 81
Table 13. NAB Sediment Survey and Area-capacity Curve Data Summary 83
Table 14. SPL Sediment Survey and Area-capacity Curve Data Summary 86
Table 15. SWF Sediment Survey and Area-capacity Curve Data Summary 88
Table 16. LRH Sediment Survey and Area-Capacity Curve Data Summary 90
Table 17. NWW Sediment Range Section Surveys and Sedimentation Reports 93

INTRODUCTION

The US Army Corps of Engineers (USACE) reservoir projects are typically multifunctional structures operated to meet several, sometimes competing, purposes, among which are navigation, flood risk reduction, hydropower, water supply, recreation, and fish and wildlife benefits (USACE, 1987). Though sedimentation is planned for in the design of reservoirs, it can interfere with some or all of these benefits in several ways. Sediment impacts include reducing reservoir storage volume, decreasing the firm yield (the minimum outflow necessary for the project to meet authorized water supply functions), reducing access to recreation areas, blocking water intakes or outlet structures, abrasion of outlet works, and altering water quality. In the long term, reservoir sedimentation at some reservoirs could result in loss of storage volume greater than the design. Therefore, planning for reservoir sustainability with respect to sedimentation is an important component of ensuring that USACE reservoirs continue to meet their authorized purposes reliably under dynamic future conditions. Early climate change adaptation pilot studies (USACE, 2012a and 2012b) undertaken to test the flexible framework for adaptation put forth by the Council on Environmental Quality (CEQ, 2011) identified differing climate change impacts to sedimentation as an issue critical to USACE climate preparedness and resilience. Because observed climate changes are already impacting sedimentation and projected climate changes are anticipated to affect the magnitude of sediment yield to reservoirs in the United States, the USACE Climate Preparedness and Resilience (CPR) Community of Practice (CoP) is developing strategies for data collection and planning with consideration given to both the severity and impacts of potential future sedimentation. These strategies will inform the prioritization of systematic data collection on reservoir sedimentation and sustainability status nationwide. Systematic collection and compilation of data on reservoir sedimentation was last undertaken in the 1960s, with data collected in a database for approximately one-quarter of USACE reservoirs.

Reservoir Sustainability and the Need for Reservoir Sedimentation Planning

Over time, incoming sediment will deposit in every reservoir storing water, unless it is designed to pass sediment. This results in losses of storage, reductions in water supply reliability and flood risk reduction capacity, and impacts outlet works, turbines, marinas, and other infrastructure. The rate of sediment infilling directly translates to the life expectancy of a reservoir, a measure that can be determined by repeated surveys of the capacity of the reservoir or by assessments of sediment flowing into the reservoir from contributing rivers (e.g., Graf, 2010; Podolak and Doyle, 2015). This sediment deposition also means that some stream reaches below the reservoir can become starved of sediment, leading to erosion of bed and banks, diminished sand bars for animal nesting habitat, and other impacts on the channel, its ecology, and nearby infrastructure (Randle et al., 2015). At the same time, the USACE dam inventory is aging, there are few plans for replacing old dams, there are few locations where replacement structures could be built, and there are prohibitive monetary, social, and environmental barriers to new dam construction. Consequently, there is renewed interest in shifting from our current practice, which plans for sediment accumulation within reservoirs, to a more sustainable strategy for managing sedimentation. Sediment management can prolong the lifespan of existing structures so they can continue to provide socioeconomic benefits, with the potential to improve ecosystem benefits.

Uncertainty about sediment conditions is exacerbated where constraints on standard operations and maintenance (O&M) budgets have limited periodic sediment surveys and studies to evaluate the effects of these changes. Therefore, it is essential that USACE establish baseline information on reservoir sediment levels and remaining storage capacity, and then determine how future global and climate changes will impact sedimentation. The CPR CoP project "Enhancing Reservoir Sedimentation Information for Climate Preparedness and Resilience" is playing a key role in developing a path forward for USACE to adapt to climate change impacts to sedimentation at its many projects. This work is conducted together with the Hydrology, Hydraulics and Coastal (HH&C) CoP and the Water Supply Working Group (WSWG). This collaborative and comprehensive systems approach will support sustainable and adaptive management of USACE reservoirs in a way that minimizes sedimentation impacts. The project encompasses several actions, and complements those of others, among which are:

- An assessment of the current status of USACE reservoir sedimentation to identify the number and geographic distribution of reservoirs currently experiencing the most severe sedimentation problems. This baseline reservoir sediment analysis is based on a web portal that accesses an Oracle database containing reservoir sedimentation information (RSI). This database, developed by the CPR and HH&C CoPs, can be used to help assess rates of storage loss nationally and regionally so that USACE can prioritize where sedimentation surveys and studies are most needed. This information also supports the WSWG in its assessment and prioritization of reservoir reallocations.
- An evaluation of future climate-related sediment impacts to USACE reservoirs to expand the sediment baseline and help prioritize reservoirs facing future volume losses. The CPR CoP, working with external experts, is expanding the indicators that can be used in conjunction with updated climate hydrology and the USACE watershed vulnerability analysis to compare potential future sediment conditions.
- Improved descriptions of potential sediment management options, including a range of potential measures suitable for different locations. This can help to identify the most cost-effective, efficient sediment management strategies to pass sediment through reservoirs, or bypass sediment around reservoirs (e.g., Kondolf et al., 2014.). Additional measures (e.g., retention ponds, contour cropping, and stabilization of highly erodible soils) can minimize or reduce sediment input to rivers and reservoirs. Some of these measures are being or could be implemented by other Federal agencies, and additional implementation could be targeted through close collaboration and information sharing with these agencies.
- Through an Advisory Committee on Water Information (ACWI) Subcommittee on Sedimentation (SOS) resolution, federal agencies are encouraged to initiate reservoir sustainability plans. Beginning with the most vulnerable reservoirs, a sediment management plan could help to guide future adaptation. Working with an external expert, Dr. Gregory Morris (GLM Engineers), the Coastal and Hydraulics Laboratory (CHL) of the USACE Engineer Research and Development Center (ERDC) has initiated the first phase, to evaluate four Corps reservoirs with significant sedimentation problems and suggest sustainable sediment management strategies.

- Participation with the National Reservoir Sedimentation and Sustainability Team (NRSST) under the SOS is essential for developing methods and sharing lessons learned with subject matter experts from federal agencies, other governmental agencies, academia, and consulting.

The ability to address reservoir sedimentation in a sustainable manner is expected to benefit all reservoir project purposes. This report is an important step in supporting future sustainable sediment management strategies for the Nation's reservoirs under changing future conditions, and supports the USACE Civil Works Strategic Plan (USACE 2011a, 2015a).

The Climate Preparedness and Resilience (CPR) Program

Global changes facing USACE reservoirs include increasing water demand and the potential for increased sedimentation rates, both of which impact key reservoir functions such as navigation, flood risk reduction, hydropower generation, recreation, and water supply. USACE reservoirs included sediment yield in project design, and normally allowed a certain volume for sediment deposition over the project life. However, these design estimates assumed that historic patterns of temperature, precipitation and drought provided a reasonably accurate model of future regional conditions over the project lifetime. Water resources planners now recognize that this assumption of stationary conditions is not correct (Brekke et al., 2009; Milly et al., 2008). Climate change and variability has already been observed to impact temperature, precipitation, and other hydroclimate variables that are important in water resources management (e.g., Georgakakos et al., 2014). At the same time, future global and regional climate changes are expected to result in altered hydrology manifested as changes in the form (snow vs. rain) and intensity (peak, seasonal, average) of precipitation, the ground state (frozen, saturated, unsaturated), altered evapotranspiration, and impacts to other factors that affect runoff and sedimentation, such as increased wildfire. These changes may contribute to changes in land use and land cover that may exacerbate reservoir sedimentation.

All of these changes combined may differ significantly from historic conditions and current trends. Consequently, USACE policy directs agency staff to use the best available and actionable science to assess vulnerability to changing climate, and to plan and implement climate preparedness and resilience measures (Darcy, 2014). The CPR CoP recognizes that actionable science has reached a "tipping point" where there is now a sufficient understanding of climate change processes to apply adaptive measures at local-to-regional scales. Building on existing science and knowledge, the CPR CoP is developing methods, policies and processes for effective adaptation of our projects, systems and programs to climate change. USACE CPR activities are described in the annual adaptation plans (e.g., USACE, 2014), including this CPR CoP activity to assess climate vulnerability of reservoirs through the “Enhancing Reservoir Sedimentation Information for Climate Preparedness and Resilience” (RSI) project.

Enhancing Reservoir Sedimentation Information (RSI) for Climate Preparedness and Resilience

Sedimentation at many USACE reservoirs is negatively impacting the ability to provide authorized project purposes. The RSI project was initiated when our early assessments (Brekke et al., 2009; USACE, 2012a; USACE, 2012b) indicated that climate change affects sedimentation rates nationwide. These changes can affect USACE project performance, reliability and lifespan as well as project operations and maintenance costs. However, the effects differ regionally, and hence vulnerability assessments must be performed to identify where and how these impacts will affect USACE missions and operations. Many USACE dams are nearing the end of their design life, and while this does not automatically mean that the reservoir sediment capacity has also reached its design volume, it is an indicator that a status check is appropriate. Finally, sedimentation has become a natural resource issue at a national level, both from the water quality point of view and from the resource management perspective. For example, EPA (2016) cites sediment as the sixth largest cause of impaired waters, while the importance of river sediment supply to sustain river deltas is increasingly being recognized (e.g., Kondolf et al., 2014; Nittrouer and Viparelli, 2014). All of these factors compel USACE to establish baseline information on reservoir sediment levels and remaining storage capacity now, and determine how climate change and other drivers will impact sedimentation. Prioritizing RSI data gaps and filling those gaps are essential in developing a sustainable path forward while continually evaluating and adapting to foreseeable future sedimentation impacts at USACE reservoirs. The CPR RSI activity is focused on six goals:

- Collect, compile, and assess the existing baseline status of USACE RSI.
- Develop indicators relating climate-impacted hydrology and reservoir sedimentation for use in estimating future climate impacts to reservoir sedimentation.
- Provide a comprehensive summary of USACE reservoir conditions in a national database and develop a national USACE reservoir vulnerability assessment taking into account both current and future conditions.
- Conduct pilot studies on reservoir sedimentation to assess the applicability and effectiveness of current and future data collection methods.
- Develop a specific RSI update strategy that incorporates the impact of global and climate change.
- Review and update existing methods and policies to support sediment data collection and studies, and update existing guidance (Engineering Circulars, Engineering Manuals and Engineering Regulations).

This report supports the first two goals: the initial assessment and comprehensive summary. The subsequent goals are currently being addressed by the RSI team and will continue over the next several years.

OVERVIEW OF CLIMATE CHANGE IMPACTS ON RESERVOIR SEDIMENTATION

Many factors contribute to sediment yield in a basin (Figure 1), and changes in one or a few of these factors can have cascading impacts throughout the system as equilibrium thresholds are exceeded. A major factor in a reservoir's functional lifespan is the rate of sedimentation in the reservoir pool, which incrementally impinges on the available water volume behind the dam for its authorized purposes. Changes in reservoir sedimentation rates – due to operational changes, climate change, changes in vegetation or land use patterns, and/or other changes in the watershed – can significantly impact a reservoir's functional lifespan (e.g., Kondolf et al., 2014; Annandale, 2013; Graf et al., 2010; Morris and Fan 1998).

Climate change represents an additional and perhaps compounding challenge for water resources planning: observed current trends and anticipated changes will impact soil freeze-thaw conditions, alter precipitation form, intensity, duration, frequency, and seasonality, impact snow volume and the initiation of snowmelt, as well as change antecedent soil moisture and vegetation cover. These changes have the potential to significantly alter patterns of sedimentation in our Nation's watersheds. Although there is some uncertainty about the direction and magnitude of change at the regional and local levels, at large scales the direction of observed and projected changes is becoming increasingly clear.

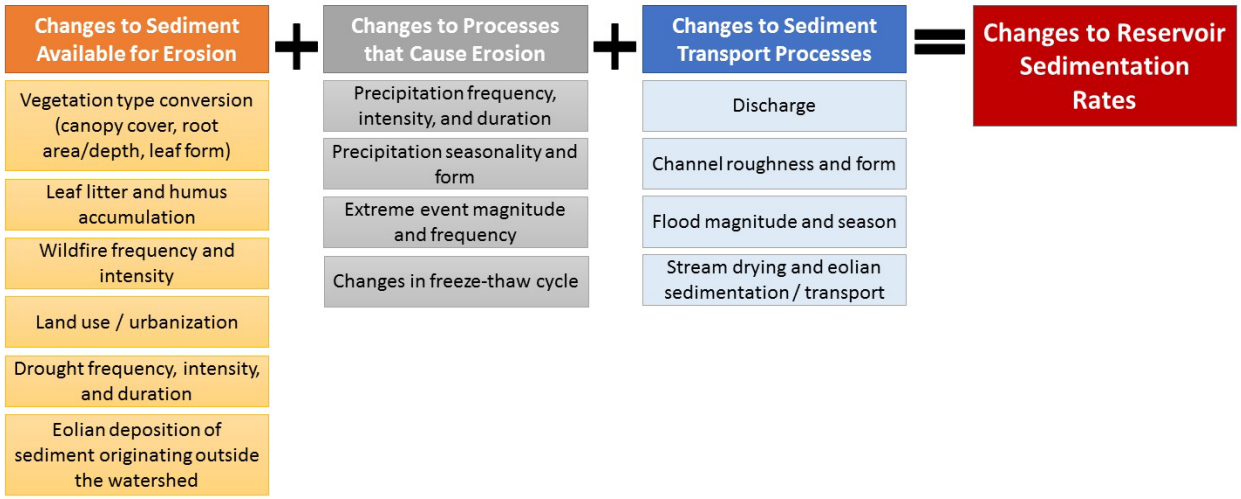

Figure 1. Factors that Contribute to Changes in Reservoir Sedimentation Rates

One of the biggest impacts of climate change is already underway: shifts in the boundary between the subtropics and the mid-latitudes (Fu and Lin, 2011; Seidel et al., 2008). This boundary shifts northward in summer and southward in winter. Warming is anticipated to strengthen this circulation, which would have the effect of expanding the subtropical dry zone poleward in all seasons. This mechanism is likely to be particularly important in the southern tier of states whose climates are already influenced by subtropical highs, including the Southeast, southern Great Plains, Southwest, and Hawai'i. Increased temperatures, particularly in the warm season, are likely to drive up evaporation rates, changing the precipitation-evaporation balance in

many areas (Trenberth et al., 2014). This mechanism is likely to contribute to seasonal drought in some years, even in regions where precipitation increases are expected overall.

Increased winter and spring temperatures in mountain headwaters regions are likely to lead to reductions in the snowpack and as a result, winter precipitation will fall increasingly as rain instead of snow and there may be increases in snowpack sublimation. These changes are anticipated to result in advances in the timing of spring runoff, decreases in spring runoff volumes, and decreases in summer and fall base flows. (Knowles et al., 2006; Mote et al., 2005; Stewart et al., 2004, 2005). These changes are particularly important for streams that head in the Sierra Nevada and Rocky Mountains, and for regions dependent on these streams.

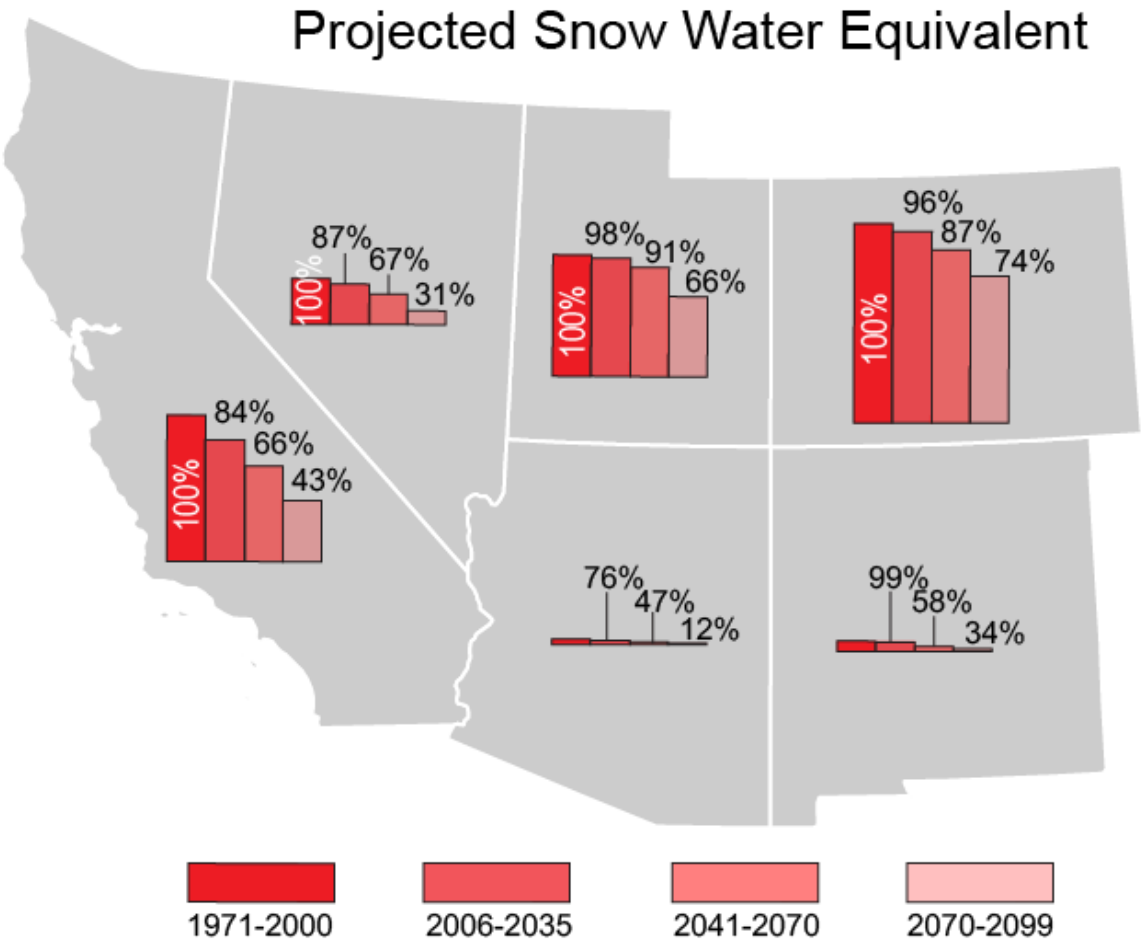

Figure 2. Changes in snowpack snow water equivalence (SWE, a measure of the amount of water available for spring/summer runoff) in the Southwestern US (Melillo et al. 2014).

Another projected impact of climate change is likely to be the shift from frequent, small precipitation events to larger and more intense, but less frequent events. More extreme precipitation events result in less infiltration / soil moisture recharge and more runoff than a comparable amount of precipitation delivered more slowly. In addition, as precipitation becomes concentrated into fewer events, longer dry spells between events becomes more likely.

Further uncertainty arises from the effects of changes in sea surface temperature on global climate, particularly changes in El Niño-Southern Oscillation (ENSO) and the Pacific Decadal

Oscillation (Trenberth et al., 2014). Both contribute significantly to changes in precipitation by affecting the path of the jet stream over mid-latitude North America and elsewhere. While changes in the frequency and intensity of ENSO events remain uncertain, recent modeling suggests that impacts of ENSO phase on global weather patterns (ENSO teleconnections) may not change significantly (Maloney et al., 2013).

Projected changes to climate for the regions shown in Melillo et al. (2014) are summarized in Table 1, and described in greater detail in Appendix A. These changes are described in terms of their influence on sedimentation below:

- Increased frequency of very heavy precipitation events may result in increased land surface erosion and increased contribution of sediment to streams (Nearing et al., 2004). In addition, higher stream flows are able to transport larger sediment loads (Morris and Fan, 1988). Together, these could result in increased sediment yields to reservoirs even if annual precipitation totals remain the same.
- In a warmer climate, with warmer sea surface temperatures and greater thermal energy, warm air masses are likely to contain more moisture. This is expected to drive increases in intensity and frequency of severe convective storms and may increase hurricane intensity and rainfall, though evidence for impacts on hurricanes is less certain as yet (Melillo et al., 2014). As with increased heavy precipitation, additional sources of heavy rainfall and high stream flows may increase stream sediment loads.
- Precipitation falling as rain instead of snow may result in increased sediment loads because stream and river flows will be higher and flashier and will have greater sediment transport capacity. In addition, rainfall includes a much higher kinetic component that, especially when it occurs during dormant vegetation periods, causes greater erosion during initial soil contact than snowfall (IPCC, 2007).
- Conversely, a shift to a drier climate regime that dramatically reduces vegetation cover can also result in increased sediment loads and higher peak discharges (Schumm, 2005).
- Higher peak flows can result in changes in channel morphology. As peak flows increase, channels will enlarge in response (both incising and widening) throughout entire watersheds (Ritter et al., 1995). This has two major impacts on sediment yield:
    - A larger channel has more surface area (bed and bank) exposed to any erosive flow. An incised channel has higher banks, meaning that normal lateral channel migration results in increased sediment delivery to the channel. An incised channel also imposes secondary impacts on inflowing tributaries through base level lowering.
    - A larger channel contains a higher percentage of flow in the channel, resulting in less attenuation of a flood wave as it passes downstream. For any given event, this will result in increased peak flows, higher sediment transport capacity, and increased sediment yield.
- Hotter, drier weather and earlier snowmelt runoff result in a higher number of wildfires and an increased number of acres burned. Sediment yields from burned areas are significantly higher than for unburned areas. For example, post-fire annual sediment yields increased by two orders

of magnitude in small watersheds in the San Gabriel Mountains of California (Wohlgemuth, 2003).

- Decreased snow cover and earlier snowmelt may both cause increased sediment yields by leaving more area open to erosion by rainfall. When earlier snowmelt coincides with rainfall, the impact may be accelerated due to the lack of canopy interception when deciduous vegetation is dormant (IPCC, 2007). Earlier snowmelt can also coincide with periodic freeze-thaw cycling that leaves soil and river banks more prone to failure (e.g., Henry, 2007).

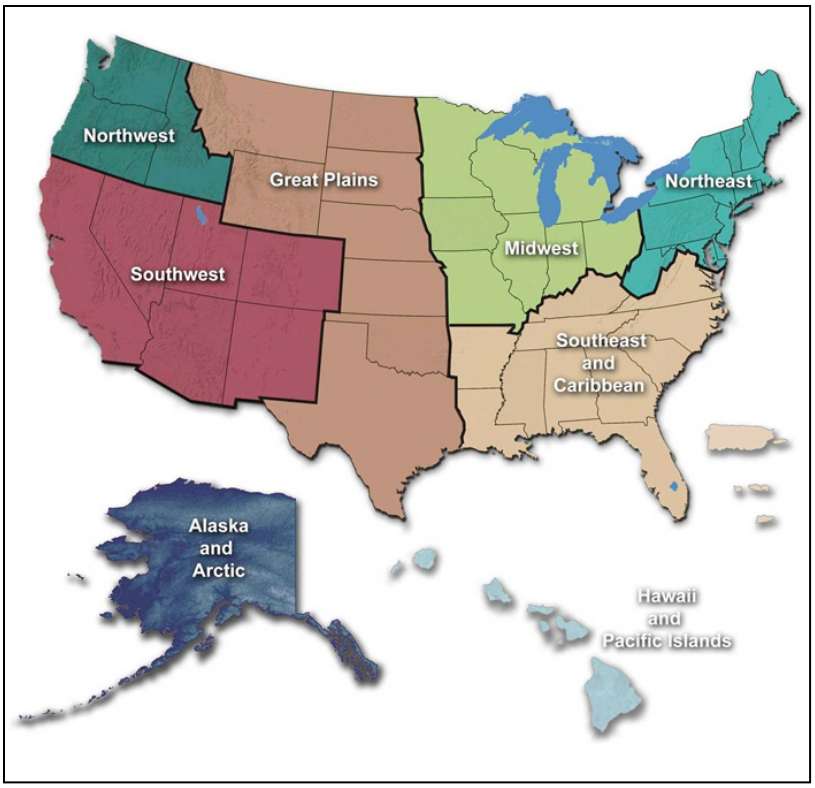

Figure 3. Regions of the United States as defined in the National Climate Assessment (Melillo et al., 2014)

- The retreat of glaciers may increase sediment yield in some places (IPCC, 2014) by increasing the sediment contributing area of the watershed. This new area is unvegetated and frequently rich in unconsolidated, highly erodible material (Walling, 2009). However, sediment loads in glacier-fed streams may also decrease in response to changes in precipitation and other factors (Lawler et al., 2003), and glacial erosion/sediment production may be greater for lower latitudes than in Polar Regions (Koppes et al., 2015). A better understanding of the climate factors that govern meltwater sediment loads is needed.
- Increased thawing of permafrost along streams and rivers can cause increased failure of streambanks and delivery of sediments from overland flow (Vonk et al., 2015).

Table 1. Summary of projected climate changes which affect sediment yield by region (from data in Melillo et al., 2014)

REGION	PROJECTED CHANGE
Northeast	• Increased frequency of heavy precipitation events • Increase in average annual precipitation • Increase in annual runoff and related streamflow • Reduced snowpack accumulation • Earlier and/or rapid melting of snowpack, resulting in earlier snowmelt-related streamflow
Midwest	• Increased frequency of heavy precipitation events • Average precipitation: north gets wetter; south dries a little in most models • Annual runoff and related river-flow are projected to increase in the Upper Midwest • Reduced snowpack accumulation in the Upper Midwest: • Earlier and/or rapid melting of snowpack, resulting in earlier snowmelt-related streamflow in the Upper Midwest:
Great Plains	• Increased frequency of heavy precipitation events • Northern: increased average precipitation • Central: no change in average precipitation (mixed modeling results) • Southern: decreased average precipitation • Increased annual streamflow in Missouri River Basin • Reduced snowpack accumulation in the Upper Great Plains • Earlier and/or rapid melting of snowpack, resulting in earlier snowmelt-related streamflow in the Upper Great Plains: • Late summer/fall hydrologic drought (decreased streamflows) possible due to changes in mountain snowpack
Northwest	• Increased frequency of heavy precipitation events • Increase in winter, spring and fall average precipitation; decrease in summer • Increased annual runoff and related streamflow • Reduced snowpack accumulation • Earlier and/or rapid melting of snowpack, resulting in earlier snowmelt-related streamflow • Increased incidence of wildfires • Increased hydrologic drought (decreased streamflows) due to changes in mountain snowpack
Alaska	• Increased frequency of heavy precipitation events • Increased average precipitation • Increased annual runoff and related streamflow • Shrinking glaciers • Thawing permafrost • Increased incidence of wildfires • Higher summer temperatures, loss of glaciers, and changes in permafrost may lead to reduced streamflows, particularly in the south
Southeast	• Increased frequency of heavy precipitation events • Drier west, especially in the southwestern portion of the region • Increased chance of hydrologic drought (decreased streamflows) across southern portion • Increased precipitation in Northern, Eastern areas • Decreased annual runoff and related streamflow • Increased risk of hurricanes and other extreme events

REGION	PROJECTED CHANGE
Southwest	• Increased frequency of heavy precipitation events • Northern: increased average precipitation in winter and fall, decreased in spring and summer • Central and southern – decreased average precipitation • Decreased annual runoff and related streamflow • Increased incidence of wildfires • Reduced snowpack accumulation • Earlier and/or rapid melting of snowpack, resulting in earlier snowmelt-related streamflow • Potential complete loss of snowpack in NM below 36° south
Hawai'i and Pacific Islands	• Increased frequency of heavy precipitation events • Decrease or no change in average precipitation

REVIEW AND ANALYSIS OF RESERVOIR SEDIMENTATION INFORMATION (RSI)

Overview

The first step to develop a baseline for reservoir sedimentation was to explore sedimentation data currently collected at USACE reservoirs, including the kinds of data collected and the frequency of data collection. The project team obtained detailed information from six districts representing a variety of geomorphological and hydroclimatic conditions. The participating districts included Omaha, Baltimore, Los Angeles, Fort Worth, Huntington, and Walla Walla (Figure 4). The districts collectively contain 141 dams impounding water all or part of the time, representing approximately 30% of USACE dams where impounding water is necessary to fulfill its authorized purposes. Figure 4 shows the distribution of USACE reservoirs in the conterminous United States, with the symbol size scaled to reservoir volume.

This section of the report provides an overview of the data collection methods used by these districts, followed by discussion of the findings for each district, and concluding with a summary of findings common across all the districts that were surveyed.

RSI Data Types

The study reviewed RSI within the six participating districts, including types of RSI, storage methods, and organization. The teams identified a list of RSI types (Table 2) that districts have been collecting and compiling. Of these, the first four items on the list are considered the most important RSI in assessing rates of reservoir sedimentation: topographic and/or hydrographic sedimentation surveys, including metadata; area-capacity curves and changes with time; aerial imagery; and sediment samples (e.g., cores, surface samples). The importance of other items depends on the authorized purposes of a particular reservoir, and its sedimentation issues (e.g., rate, deposition zones, characteristics such as grain size and presence of contaminants).

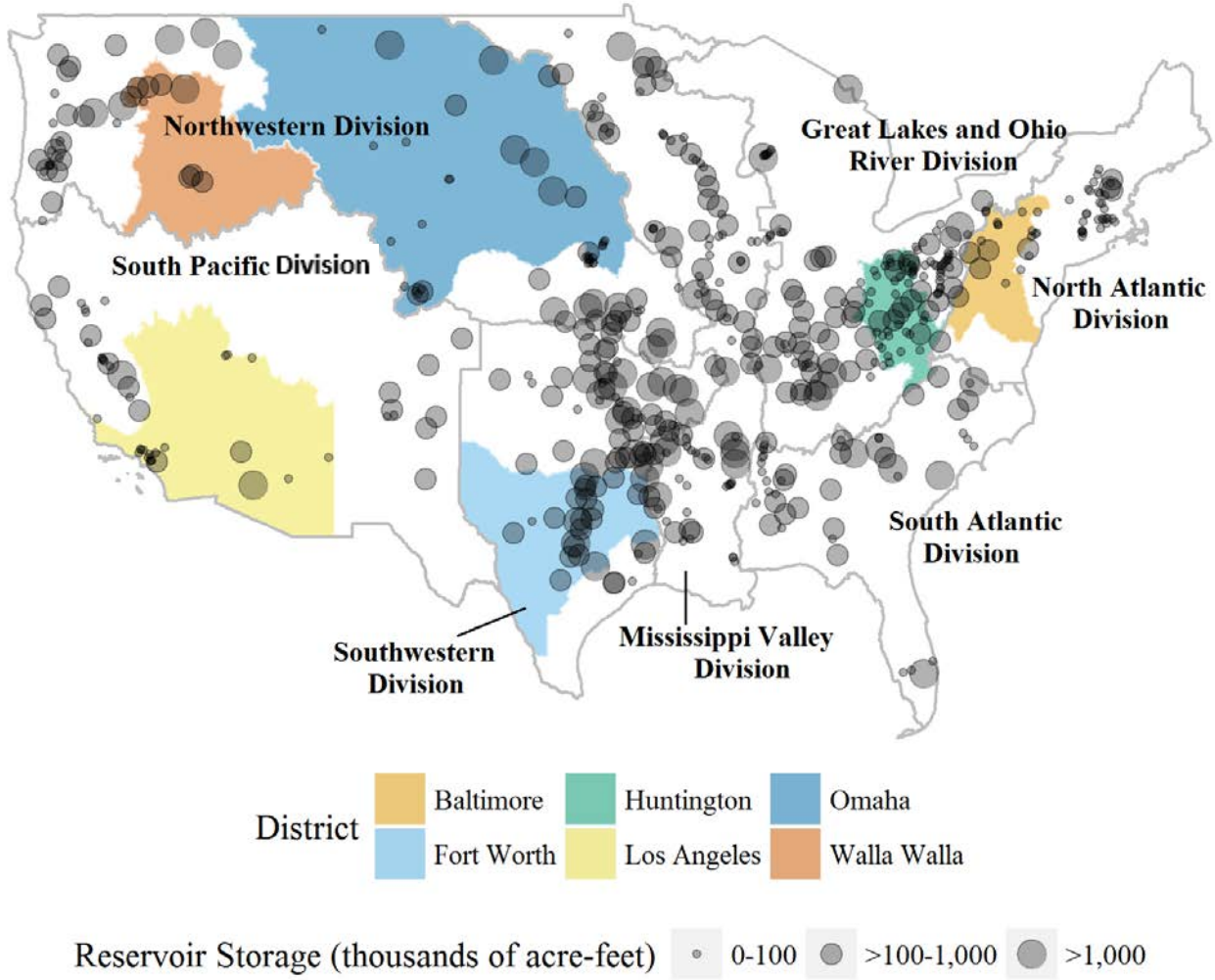

Figure 4. Map showing the distribution of USACE reservoirs in the conterminous United States, with the locations of districts participating in the initial phase of this study

RSI Initial Data Collection Methods

During the initial discussions with participating districts, team members discussed RSI needs and a few districts provided a summary of their RSI status. This information was used to create RSI spreadsheet templates to be filled-in by district managers or staff participating in the study. The goal of the spreadsheets was to help account for and catalogue the RSI data for each district, including documenting the existence of sedimentation surveys, sediment load measurements, and Sediment Studies Work Plan (SSWP), and to help develop a standard format to guide the design of the RSI database. The data was initially collected on a set of individual project forms for each district, plus a project summary form. Table 3 describes some of the data fields included in the form while Figure 5 shows an example of a truncated district summary form.

Individual forms were created for each project within a district. These forms include more detailed RSI for each project, including a time-sequenced history of sediment surveys and other RSI. The data format is noted (e.g., Hydrologic Engineering Center – Data Storage System (HEC-DSS), PDF, Excel, paper, or other). An example data sheet is shown in Figure 5.

Table 2. District-specific RSI needs

Most important	1.	Topographic and/or hydrographic sedimentation surveys , including metadata on the collection method, dates, and datum
	2.	Area-capacity analyses and changes over time
	3.	Aerial imagery or photography
	4.	Sediment samples and sediment characteristics such as chemistry, quality, and size distribution
	5.	Measured sediment load, inflow
	6.	Project information (pool levels, authorized purposes, water control) including original design information
	7.	Sediment rating curves
	8.	Stream gage and sediment gage locations, and associated information
	9.	Sediment management activities (e.g., dredging, flushing, sluicing, etc.)
	10.	Volume depletion at different pools
	11.	Sediment models
	12.	Past sediment studies
	13.	Sediment Studies Work Plan (SSWP)
	14.	Operational impacts, e.g., stage-frequency shifts, reallocation of pools/storage
	15.	Environmental factors driving data collection
	16.	Studies that include climate change impact analysis
	17.	Additional anecdotal evidence observations
	18.	Funding over time and funding sources

Table 3. Summary of RSI spreadsheet project summary form fields

DATA TYPE FIELD	FIELD INFORMATION
Authorized Project Purpose(s)	• Project authorized and/or operational purposes
Sediment Survey	• Date of the latest and previous sediment surveys • Survey method
Reservoir Pool and Spillway Information	• Original reservoir storage • Reservoir storage calculated from the most recent survey • Volume lost between the original and most recent surveys • Percentage loss between the original and most recent surveys
Permanent/Dead Storage	• Permanent or dead storage volume (if applicable)
Sediment Allowance	• Reservoir sediment allowance in years - number of years until the reservoir is expected to be full of sediment and no longer operational. If unknown, the field entry is the reservoir design life - OR - • Reservoir sediment allowance volume (ac-ft) - volume of sediment allowance based on the reservoir design life

Project Name	Authorized Project Purpose(s)									Date of Dam Closure	Sediment Survey		
	F	N	I	WS	WQC	R	H	FA	FW		Date of Latest Survey	Date of Previous Survey	Survey Type
Raystown Lake	X					X	X			Oct-73	Oct-96	1973	Single Beam
Bush Dam	X												
Sayers Dam	X												
Tioga Dam	X												

Conservation Pool				Spillway Crest			
Original Storage (ac-ft)	Per Latest Survey (ac-ft)	Loss (ac-ft)	Loss (%)	Original Storage (ac-ft)	Per Latest Survey (ac-ft)	Loss (ac-ft)	Loss (%)
514,000	513,021	979	0.2	762,000	- - -	- - -	- - -
1,740	1,864	+ 124	+ 7.1	75,000	74,941	59	0
				9,000	100,505	+1505	+ 1.5
				2,000	62,307	+ 307	+ 0.5

Spillway Design Surcharge						Permanent/ Dead Storage (ac-ft)	Sediment Allowance (years)
PMF Max WSE	Date of PMF	Original Storage (ac-ft)	Per Latest Survey (ac-ft)	Loss (ac-ft)	Loss (%)		
821.5	- - -	871,000	- - -	- - -	- - -	1,373	- - -
962.7	- - -	117,000	117,000	0	0	0	- - -
677.8	- - -	186,600	188,100	+ 1,500	+ 0.8	13	- - -
1165.8	- - -	143,000	143,500	+ 500	+ 0.4	0	- - -

Figure 5. Project summary form spreadsheet example (truncated)

Table 4. Project information spreadsheet example

Project Name:	Coldbrook							
Location of Reservoir/Dam								
Latitude:	43° 27' 14" N (Google Earth)							
Longitude:	103° 29' 21" W							
City, State, County:	Hot Springs, South Dakota, Fall River County							
Basin:	Missouri River/Cold Brook							
District:	Omaha – NWO							
Division:	Northwestern – NWD							
Dam Description								
Date of Dam Closure:	1953							
Type of Dam:	Rolled Earthfill							
Dam Length:	925 ft							
Top of Dam Elevation:	3675.0 ft (NGVD29)							
Drainage Area:	70.5 sq. miles							
Reservoir Surface Area:	(1972) 279 acres at elevation 3667.2 ft (NGVD29)							
Spillway Length:	200 ft							
Reservoir Pool Elevation	Main reservoir pools and maximum elevations (NGVD29)							
Flood Surcharge:	3667.2 ft							
Flood Control:	3651.4 ft							
Multipurpose:	3585.0 ft							
Spillway Pool:	Not applicable							
Storage Capacity	Storage capacity per latest survey (based on 1972 survey)							
Flood Surcharge:	10,898 acre-ft							
Flood Control:	7,250 acre-ft							
Multipurpose:	520 acre-ft							
Spillway Pool:	Not applicable							
Sediment Gage(s):	No sediment gages							
Authorized Project Purpose:	Flood Control	Navigation	Water Supply	Water Quality Control	Recreation	Hydropower	Flow Augmentation	Fish & Wildlife
	X				x			x

List data gaps:

(1) There are no sediment data of any type or water surface profile data for this project.

(2) Area & capacity tables for early survey years cannot be located. Tables for these years need to be recalculated.

(3) Elevation data are presented in vertical datum NGVD29. This data should be converted to NAVD88 per USACE standards.

Describe sources of funding, and provide an estimate of additional funding required to fill in the data gaps:

Funding sources include O&M base line, O&M non-routine, and O&M end-of-year-reprogrammed funds.

Additional information (e.g. sediment management activities):

Summary by RSI Category

A review of the current status of district RSI has been completed for the six districts participating in this RSI pilot study (Table 5). In general, the districts indicated sufficient funding has not been available to support essential RSI needs or even to maintain a routine sediment survey schedule. None of the districts interviewed have prepared a SSWP as outlined in EM 1110-2-4000 (USACE, 1989) to document and identify potential sediment problems, including reservoir sedimentation. These SSWPs were meant to be used at the district level to guide consideration of sediment impacts when developing sediment studies and related surveys. All but one of the districts interviewed prepare an annual report of sedimentation activities that is sent to their respective USACE division office. In general, these reports identify sedimentation activities for the past year and describe RSI needs for the upcoming year. The reports typically include associated costs for the critical RSI needs, or the estimates are included in the O&M budget in which RSI updates are prioritized by need for the upcoming year.

Sediment Surveys: Some districts have not received the financial resources to update topographic or bathymetric surveys (or both) on a regularly scheduled basis to estimate sedimentation rates as suggested in EM 1110-2-4000 (Table 6). However, there are exceptions: the Omaha District, which has received O&M funds over the last few years to update all six of the Missouri River mainstem project surveys and about half of the 22 tributary projects. The Baltimore District receives funding for sediment surveys from federal and local sponsors. All of their 13 reservoirs with permanent pools were resurveyed between 1996 and 2000. The surveys included both bathymetric and topographic surveys, and five of the reservoirs were resurveyed by boat between 2010 and 2012. The Los Angeles District has only one dam that maintains a pool; the remaining 15 are dry dams, with storage primarily reserved for flood risk reduction. The District has been able to survey about half of its reservoirs over the past 10 years. Survey methods used over the past 10 to 12 years have primarily been photogrammetry and LiDAR for the dry dams, and single-beam hydrographic surveys for the wet dam. A few of the dams in the District have not been surveyed in more than 40 years.

Hydrographic single-beam surveys are used for the 25 Fort Worth and 35 Huntington District reservoirs. For Fort Worth, there are nine reservoirs requiring new surveys. Some of these reservoirs have water supply contracts requiring them to be resurveyed every 15 years. The Huntington District has been able to fund several sediment surveys over the past few years, but 13 reservoirs have not been resurveyed in more than 10 years and require updates. Table 6 provides a summary of the sediment surveys for these districts.

Datum: In general, most of the districts use the 1929 vertical datum to store data. However, the Los Angeles District indicated there have been some datum issues. Original surveys may have been done using MSL, NGVD29, NAVD88, or some local datum. These projects using NGVD29 datum are not compliant with Engineer Regulation (ER) 1110-2-8160 Policies for Referencing Project Elevation Grades to Nationwide Vertical Datums (USACE 2009a). Noncompliance could result in datum errors that impact calculations of storage volume.

Sediment Studies and Models: Sediment studies rely on spatial and time series data sets describing geometry, hydrology, hydraulics, sediment, and land use parameters. EM 1110-2-4000 (USACE, 1989) provides general guidance and engineering procedures on these requirements while ER 1110-2-8153 (USACE, 1995) provides the procedure and rationale for

conducting sediment investigations. Although EM 1110-2-4000 is in the process of being updated, the current version provides useful information on the reporting requirements of sediment studies that will most likely be included in the updated EM. The existing EM suggests that a field reconnaissance will provide the engineer with a good idea of the existing problems to include in the outline of a sediment study plan. The complexity of the study will depend on the availability of historical data as well as current data. If sufficient RSI is available, long-term stability trends may be assessed along with reservoir response to land use changes and past improvements. In general, only project-based sediment studies have been conducted in the study districts. There have been no sediment studies in these six districts that addressed climate change apart from the Omaha District's Garrison Dam climate adaptation pilot study (USACE 2012c).

Table 5. Summary of district project information

DISTRICT	PROJECT INFORMATION
Omaha	• 28 flood risk management projects (6 on mainstem Missouri River; 22 on tributary streams). • *Summary of Engineering Data* lists mainstem project information. The summary is normally contained in project reports. • Summaries for tributaries in water control manuals. • No permanent/dead storage designation for the mainstem dams.
Baltimore	• 15 USACE-owned flood risk management projects (including 2 dry dams). • 2 major basins within district (Susquehanna and Potomac). • Projects all located on headwater streams (none on mainstem rivers).
Los Angeles	• 16 reservoirs (all dry except Alamo Dam). • All dams have flood risk management as an authorized purpose, some have other authorized purposes as well as operational purposes, e.g., facilitate recharge. • 3 main pools: surcharge, flood risk reduction, and debris pool (Sepulveda – no debris pool).
Fort Worth	• 25 reservoirs – first priority flood risk management; second priority water supply. • Most of the district reservoirs have uncontrolled spillways above the conservation pool.
Huntington	• 35 flood risk management projects (31 permanent pools and 4 dry dams). • Typical design life 50 to 70 years. • Muskingum Watershed Conservancy District owns majority of reservoirs within that basin, while the dams are owned by LRH.
Walla Walla	• 22 reservoir and river projects.

Area-Capacity Analyses: In general, area-capacity or elevation-capacity curves are updated once a survey has been complete and sufficient funding is available. Since the 1990s, this data is stored in electronic format for all districts. The Fort Worth and Los Angeles Districts use HEC-DSS to store the data, while the other districts use Excel. Most districts also store the data in water control manuals, sedimentation survey reports and/or binders set up for each project.

Table 6. Summary of sediment surveys

DISTRICT	SEDIMENT SURVEYS
Omaha	• Project status: Mainstem projects resurveyed between 2007 and 2012; tributary projects resurveyed between 1983 and 2010, excluding Cedar Canyon Dam detention basin that was surveyed only once at time of closure (1959). • Survey methods: Primarily range line and hydrographic (single-beam) surveys. • Data format: Electronic (HEC-DSS). • Organization: Master list of all projects (Excel), including survey dates and status (i.e., partial or complete surveys).
Baltimore	• Project status: All permanent pool reservoirs surveyed 1996-2000; two new surveys in 2010 for water supply; three new surveys in 2012; one new survey planned for 2013. Arkport Dam and Indian Rock Dam (dry dams) aerial surveys conducted in 2004. • Survey methods: Historic surveys: range lines with established monuments; since 1996, hydrographic single-beam surveys and aerial surveys (when funding available). • Data format: Electronic format since 1996; most pre-1993 range line surveys (paper format) lost. • Organization: Master notebook with hydrographic surveys and other project information.
Los Angeles	• Project status: No ongoing survey routine; 8 reservoirs surveyed within last 10 yrs; some reservoirs not surveyed in more than 40 yrs. • Survey methods: Dry dams: mostly aerial surveys (past 30 yrs); photogrammetry and LiDAR surveys (past 10-12 yrs); Alamo (wet dam): hydrographic survey. • Data format: Electronic, diapositives (DiAP) and paper formats. • Organization: Survey group houses sediment survey data: stored off-site; files are difficult to locate. Range line data has been lost (references to historic data in water control manuals).
Fort Worth	• Project status: 9 of the 25 reservoirs have not been resurveyed in more than 10 yrs; some reservoirs have not met contract terms to resurvey and re-allocate every 15 yrs. • Survey methods: Historic range lines with established monuments (in-house surveys not done in 25-30 yrs); since 1994, hydrographic single-beam surveys (TWDB); Tulsa District has conducted some of the SWF surveys. • Data format: Since 1994 electronic format; historic surveys paper format. • Organization: TWDB stores survey files online – *public access* (including GIS shapefiles).
Huntington	• Project status: Permanent pools: 13 reservoirs need to be resurveyed (>10 yrs since last survey); dry dams (4 total): no sediment surveys have been conducted (only original topographic mapping). • Survey methods: Range line & hydrographic surveys (single-beam method used since 1997); one LiDAR survey at Bluestone Lake (2009). Sediment surveys conducted in-house until 1990s. Since the 1990s, contracted out. • Data format: Electronic format (Excel) since 1997; paper format (text file) pre-1997. • Organization: ProjectWise software used to manage all project files: hierarchical organization beginning with a project folder.

Historical or pre-1990s area-capacity data are mostly in paper format – apart from the Los Angeles District where all storage data has been transferred to HEC-DSS. Several districts also indicated that some original area-capacity data or historical data may have been lost or misplaced. For example, during an office move in 1993, most area-capacity and survey information for the Baltimore District was misplaced. The Omaha District has historical area-capacity data in microfiche or paper format, with a few missing tables that need to be recalculated.

Water Surface Profiles (WSP): Data for WSPs have been collected at the Omaha and Huntington Districts. The Omaha District collects most WSP data in-house, but occasionally uses WSP data collected by the US Geological Survey (USGS) or an outside contractor. The Huntington District collected WSP data as part of original reservoir design, but the data have not been updated since that time.

To collect a water surface profile, a steady release is made from a reservoir and sufficient time is allowed for the river to adjust to the steady flow. In-house survey crews collect the water surface profile in the downstream reach of the dam. That data is used to plot changes in water surface over time to bed changes. This is in support of navigation or other impacts due to a changing river bottom. The data is used to monitor water surface changes due to delta formations and used to calibrate model flows and sediment models.

Figure 6 shows a water surface profile plot for the Missouri River between river mile (RM) 853 and RM 830 for a discharge of 30,000 cfs (the area between Fort Randall Dam and Gavins Point Dam in Figure 7) (USACE, 2013b). The 30,000 cfs water surface profile plot shows a trend of increasing water surface elevation between 1954 and 1995 which is expected since the sediment is depositing in this reach due to back water from Gavins Point Dam. The trend of increasing water surface elevation with time was disrupted in 2011, when a large flood entrained sediment from the Niobara River Delta (at RM 843.55) and deposited it downstream. As a result, the 2012 water surface elevations in this reach are comparable to 1995 levels.

Sediment Sampling: Sediment cores and bed material samples are no longer routinely collected by any of the six pilot districts, though Omaha and Fort Worth districts once collected sediment data on a routine basis. Omaha District stopped collecting in-house suspended sediment samples and density measurements in the 1980s. They do take advantage of bed and suspended sediment data collected regularly at six USGS sediment gages with a cost share agreement as part of the Cooperative Stream Gaging Program as per ER 110-2-1455 (USACE, 1984). Fort Worth District collected sediment data until the early 1990s. Table 7 provides a summary of the sediment sampling and sediment chemistry/quality RSI for each of the six pilot districts.

Sediment Management Activities: Sediment management activities are generally reflected in O&M records of activities for project maintenance. Shoaling and dredging operations have occurred at some of the Omaha District projects. Fort Worth indicated that dredging is done only to keep intakes open for water supply – not for regaining storage capacity. The district indicated that removing sediment for the purpose of regaining storage has been ineffective in the past given the cost to dredge versus the amount of storage gained. Erosion at the banks is an issue with some of the Fort Worth reservoirs. Although the eroded areas provide more storage in the flood pools, volume is lost in the conservation pools.

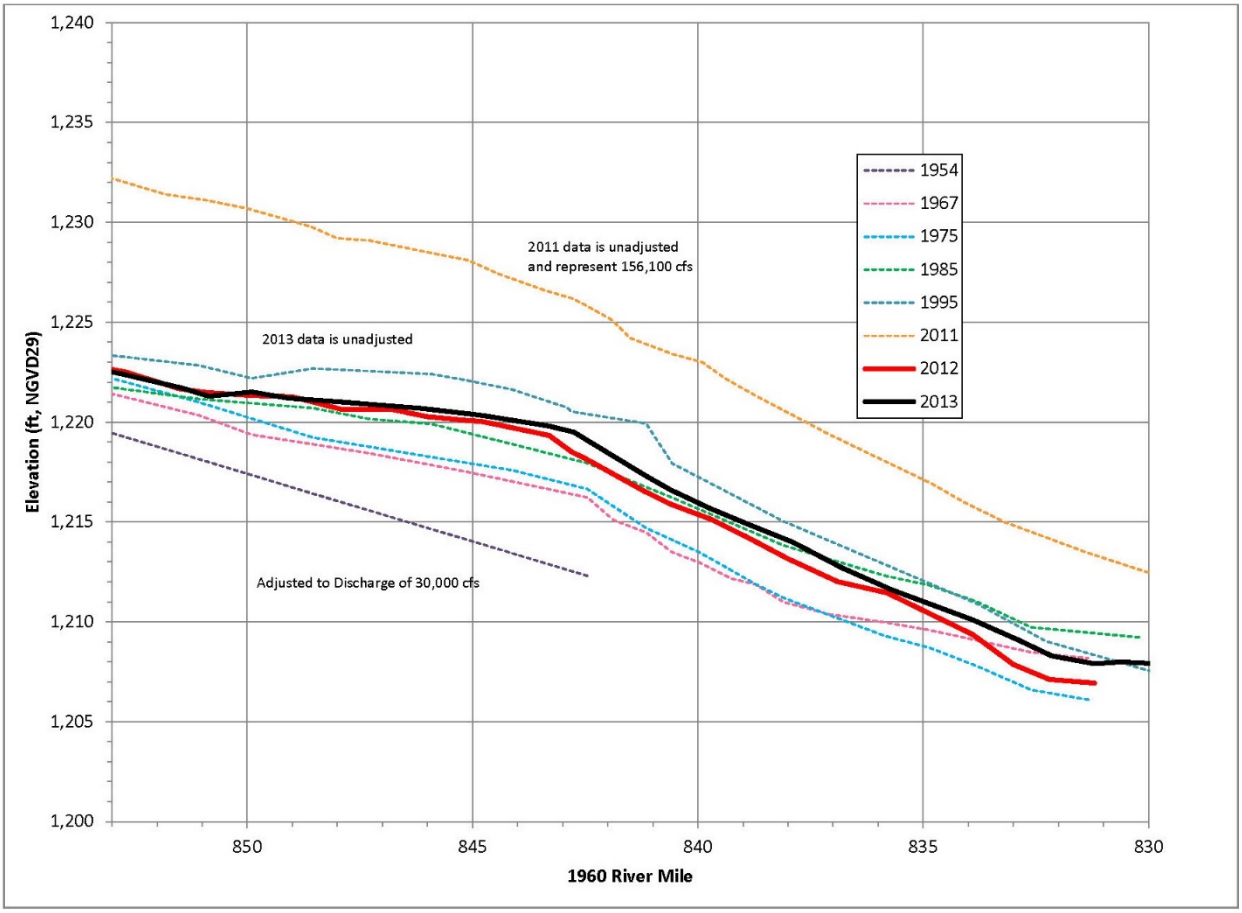

Figure 6. Water surface plot for the Missouri River between RM 853 and RM 830 (the area between Fort Randall Dam and Gavins Point Dam) (USACE 2013b)

The only other pilot district where dredging has been used is in Baltimore District at Hammond Lake, for improved boat access. The Baltimore District indicated that Almond Lake was originally designed as a dry dam that was regulated for flood risk reduction following dam completion in 1949. Beginning in 1965, a small pool was maintained every summer at elevation 1255 ft. to provide recreational opportunities (fishing and boating). During the remainder of the year, the pool was lowered to elevation 1250 ft. to provide full flood risk management capability. Over time, sediment began to accumulate in the pool, and recreation opportunities diminished. The water control plan for the reservoir was revised in 1987 to raise the conservation pool to elevation 1260 ft. year-round to provide continued recreational use. However, after 25 years the effects of sedimentation are once again beginning to adversely affect recreation usage at the project. According to district managers, the conservation pool storage space has been reduced by almost 50% since project completion.

Los Angeles District reservoir gates are checked and cleaned annually. There are also some gravel removal activities that take place, but this is not a routine activity. The district also indicated that there are some sediment issues with seasonal flooding resulting from heavy rains

falling on steep, mountainous headwaters areas. Four reservoirs (Painted Rock, Alamo, Whitlow Ranch, and Mojave) were identified as needing to be resurveyed due to sedimentation during a major flood event in 2005 and/or high sediment inflows in other years. Huntington District indicated there are no current or past dredging activities. Beach City Lake has lost most of its conservation pool to sediment, but this affects recreation and not flood risk management. Another sediment issue occurs at Fishtrap Lake (completed 1968) where the conservation pool had to be raised due to sedimentation.

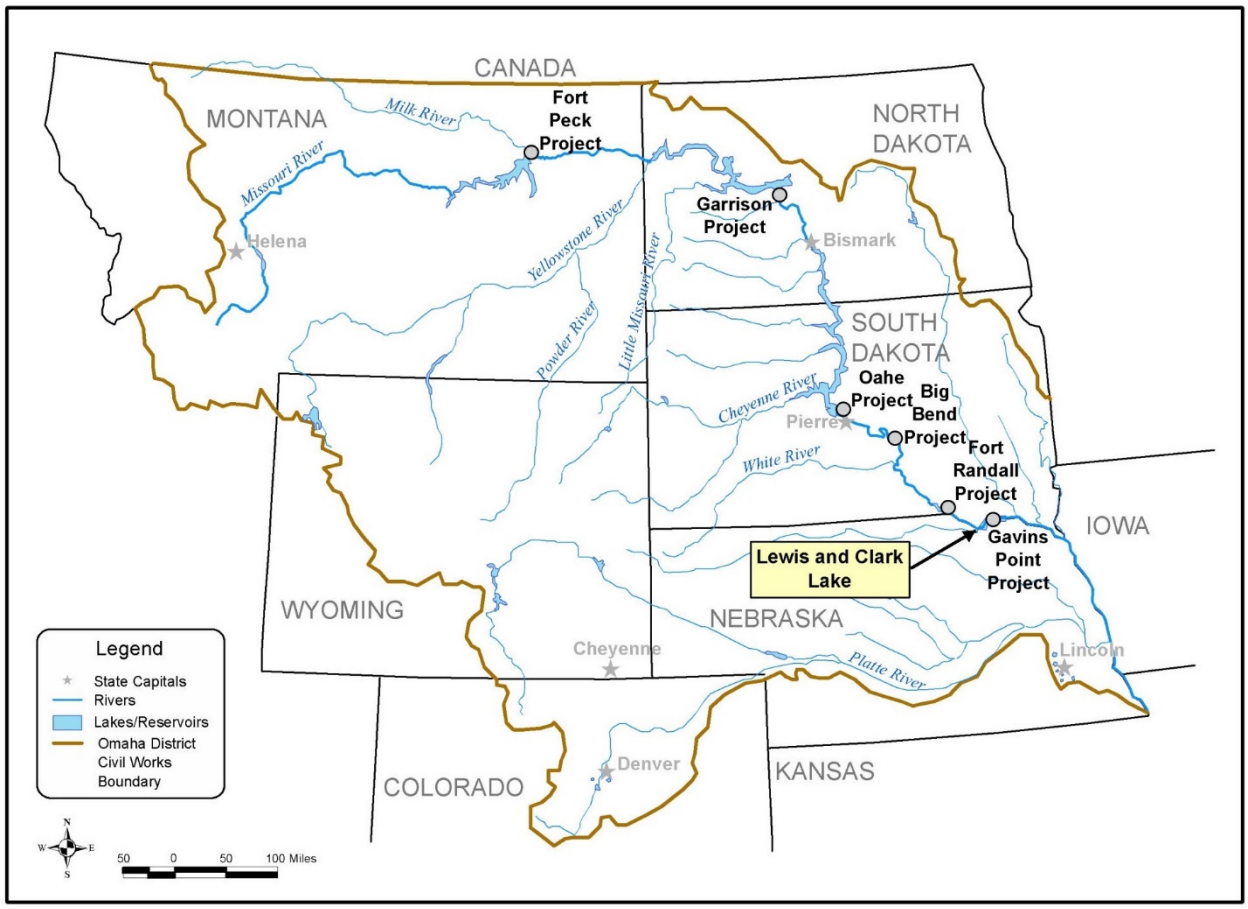

Figure 7. Map of mainstem dams on the Missouri River

Table 7. Summary of sediment data collection

DISTRICT	SEDIMENT SAMPLES	SEDIMENT CHEMISTRY/ QUALITY
Omaha	• NWO stopped collecting in-house suspended sediment samples and density measurements in the 1980s. • USGS manages current bed & suspended data at 6 stations (2/3 funded by the USGS and 1/3 cooperative funding) - *USACE receives a paper copy of USGS bed material data; data also located electronically on USGS website.* • Bed material samples collected when funding & manpower permit - *mostly HEC-DSS format.* • Other sediment data stored in reports, microfiche, paper, electronic, and input cards. • Several projects have no sediment data of any type • No cohesive sediment analysis - first done in 2012 at Lewis and Clark Lake.	• Temperature, turbidity, dissolved oxygen (DO), total suspended solids (TSS), dissolved solids collected by water quality group (collected monthly during non-ice season – driven by state standards). • Electronic and paper format - stored within the water quality group and in a national database - well organized files. • Water quality group also monitor quality in pools as well as releases. • Elutriate testing on sediment samples.
Baltimore	• No sediment data (unless project based). • Some sediment data collected at Jennings for a sediment budget study in 1996. • Sediment data not a big need since not much sedimentation unless a big flood event occurs (except at Almond Lake where the conservation storage space has been reduced by almost 50% since dam closure in 1949).	• No sediment quality testing. • Water quality testing 3 times a year during the summer months – tests included temperature, dissolved oxygen, pH, sulfates, nitrates, etc. • Sayers has sediment quality concern – dust particles allegedly carrying toxic substances.
Los Angeles	• No sediment data collected as part of overall program. • Some sediment data collection in the past on a project needed basis (stored with Project Manager).	• Not collected (unless project based).
Fort Worth	• Sediment cores collected until early 1990s – some had sieve and density analysis (paper format). • Measured sediment load - original estimates from SCS annual rates for 50- and 100-year design - *no record of the data, only have the final estimated sediment reserve capacity.*	• Water quality group disbanded – mainly water studies, not sediment.
Huntington	• Not collected.	• Water quality group conducts sediment elutriate testing: sediment sampling & analysis for organics, metals, etc. (electronic format).

RSI Data Gaps: Overall, the districts identified the main data gap as routine performance of sediment surveys, including bathymetric and topographic data collection. Most districts identified USACE O&M as the primary source of funding for RSI. The Baltimore and Fort Worth Districts indicated there has been some project-based sponsorship from state or local sources. Table 8 provides a summary of the RSI data gaps identified for the districts interviewed in this study. The Omaha District was the only district to indicate a high-priority need for sediment gages and related sediment rating curves.

Based on these results, we project that all USACE districts have RSI data gaps that will need to be addressed, with gaps and needs comparable to those identified in the study districts. The final plan for filling data gaps will probably include a combination of these elements: screening and prioritizing gaps, development and implementation of rapid assessment methods for evaluating sedimentation impacts (e.g., low-cost methods used to screen the approximately 200 reservoirs without recent surveys), bathymetric and aerial topographic surveys, development of new area-capacity curves, and maintenance of RSI data for reservoirs which are currently up-to-date (ongoing RSI updates).

Table 8. Summary of RSI pilot district's high-priority data gaps

DISTRICT	RSI DATA GAPS
Omaha (28 projects)	• Post-flood LiDAR surveys and aerial imagery • New surveys for Pipestem Lake and most of the Salt Creek Lakes • Updated area-capacity tables for three reservoirs • Increased number of suspended sediment gages • Sediment rating curves for modeling
Baltimore (17 projects)	• Update hydrographic surveys at 7 reservoirs • Raystown Lake topographic data • Topography at six reservoirs • Regular re-surveys every 10 years or after major flood events
Los Angeles (16 projects)	• 4 resurveys (topographic data) • Data processing (area-capacity curves) and report for 4 resurveys • Updated area-capacity curve at Whittier Narrows

Fort Worth (25 projects)	• Updated survey, area-capacity curve, and report at:
	  o Over-drafted reservoirs
	  o Water supply pools with 10 to 15 years since last survey
	  o Reservoirs flushed-out for sediment management activities
	• Post-flood LiDAR*

Huntington (35 projects)	• 14 reservoirs need to be resurveyed • 6 reservoirs require updated area-capacity curves and sediment survey reports
Walla Walla (22 projects)	• **Walla Walla did not identify data gaps.**

**Post-flood LiDAR not included in estimate*

DEVELOPING AN RSI UPDATE STRATEGY

RSI Update Strategy Overview

Based on the initial RSI data gathering phase for the six pilot studies, a strategy is planned to prioritize and update RSI to incorporate new and changing conditions that impact the ability of USACE reservoirs to meet their authorized purposes. The strategy includes a characterization of classes of projects that may require a similar level of effort to update, a characterization of changes on a regional or national basis that may apply to groups of projects, development of efficient and cost-effective methods and processes to assist in updates, and policy and guidance updates for ERs and EMs as appropriate. This section presents a discussion of baseline data needs: related to reservoir purpose, geography, and size, and based on observed and projected climate change.

RSI Baseline Data

Ideally, complete baseline data sets should exist for every reservoir in the portfolio. At a minimum, baseline data should be sufficient to estimate the sediment volume and storage rate of change in a reservoir. This requires topographic and/or bathymetric surveys obtained for at least two points in time. The first point of data collection for reservoirs is ideally based on pre-impoundment topographic mapping or the earliest available data. This data is used to construct an initial stage-area-volume relationship for the reservoir (area-capacity curve). Data from subsequent surveys are used to develop updated curves. Comparison between data sets supports estimates of the amount and patterns of deposition between the surveys. Current guidance on survey frequency (Appendix K of EM 1110-2-4000) is 5 to 10 years, depending on the quantities of sediment anticipated and the need for the information. Additional guidance on data collection frequency is discussed below.

In addition to a baseline data set, each project may require additional RSI data specific to factors such as authorized purposes, geographic location, reservoir size, and the observed and projected impacts of climate change. The project purpose impacts both the type of RSI collected and frequency of data collection while the other considerations have more effect on frequency and methods of data collection.

Project Data Needs Related to Authorized Purposes

The authorized purpose(s) of USACE projects can drive the specific data collected as well as the priority for updates within a district. For example, three of the 15 projects within the Baltimore District have water supply as an authorized project purpose. The district indicated that these projects were the highest priority for data updates, so that they can monitor the amount of storage loss due to sediment deposition, and the resulting storage available for water supply.

Water storage units in a reservoir are termed “pools.” These pools represent the amount of water volume within the reservoir allocated for a specific purpose. Figure 8 illustrates typical pool zones for reservoirs that impound water. Most large dams have a flood zone or flood control pool as well as one or more pools allocated for navigation, water supply, recreation, fish and wildlife

and other uses, often collectively termed the conservation pool. The dam outlet is located at some elevation above the bottom of the reservoir, and the pool below this outlet is the inactive pool (also called the deadpool), because water in this pool is not available for use downstream. The inactive pool often demarcates the expected volume of sediment to be trapped in the reservoir over its lifetime. A common myth is that all sediment deposited in a reservoir is located in the inactive pool and that as long as the amount of sediment does not exceed the volume of the inactive pool, sedimentation does not affect the amount of water in the other pools. However, sediment deposits tend to occur at locations where water changes slope from steep to mild, such as the upstream end of the pool where the mainstem river enters the pool, or where tributaries enter the pool. Reservoir pool levels fluctuate over the course of a year, and between years, so that sediment deposited in one location may be moved further as pool levels and inflows change. As a result, deposition can impact any of the pools. The following sections address specific data collection needs based on authorized purposes.

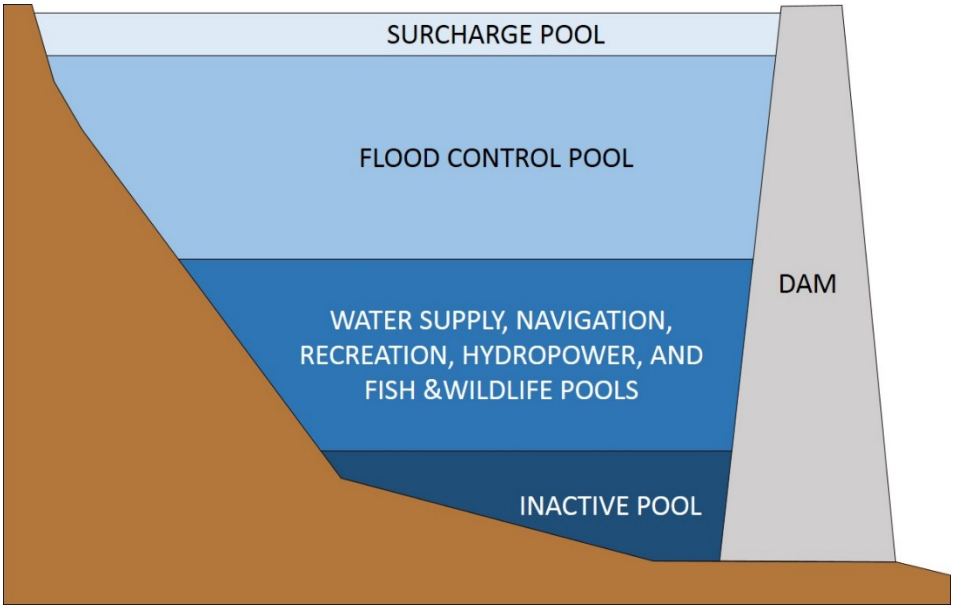

Figure 8. Typical USACE reservoir storage pools and divisions

Navigation

Reservoirs created as part of a lock and dam system are usually run-of-river and do not impound a significant amount of storage. Sedimentation and shoaling that occurs at these projects requires detailed information about depositional patterns to analyze the sediment problems and develop potential solutions. Sedimentation in a lock and dam reservoir can induce flood management risks at upstream locations. For example, this occurs at the Lower Granite hinge pool on the Snake River in Washington. RSI typical of riverine sediment transport studies would be useful for lock and dam projects, including inflowing sediment amounts and characteristics as related to

hydrologic conditions, bed sediment characteristics, and river geometry and roughness characteristics to compute shear stresses. Systems that rely on a self-scouring navigation channel require RSI on sediment transport rate and particle size distribution.

Some reservoirs authorized for the purpose of navigation are not part of a lock and dam and have sediment mitigation needs that cannot be remedied through solutions such as self-scouring channels. For example, the mainstem Missouri River dams consists of six reservoirs (Figure 7) that store 73 million acre-feet of water (USACE, 2006: VII-5). In its natural state, the Missouri River transported a sediment load averaging 25 million tons per year in the vicinity of Fort Peck, Montana; 150 million tons per year at Yankton, South Dakota; 175 million tons per year at Omaha, Nebraska; and approximately 250 tons per year at Hermann, Missouri near its confluence with the Mississippi River (USACE, 2006: III-2). As sediment collects in each reservoir, navigation is impacted because the navigation season is determined by the amount of water in the six projects every March 15 as per the Missouri River Mainstem Reservoir System Master Water Control Manual (USACE, 2006). As sediment collects in the reservoir the navigation season will be impacted, due to loss of water storage that would be used to maintain the downstream navigable waterway

Flood Risk Management

Section 7 of the Flood Control Act of 1944 (16 U.S.C. 460d; P.L. 78-534, December 22, 1944; 58 Stat. 887), as amended, states that:

> *"Hereafter, it shall be the duty of the Secretary of War to prescribe regulations for the use of storage allocated for flood control or navigation at all reservoirs constructed wholly or in part with Federal funds provided on the basis of such purposes, and the operation of any such project shall be in accordance with such regulations: Provided, That this section shall not apply to the Tennessee Valley Authority, except that in case of danger from floods on the Lower Ohio and Mississippi Rivers the Tennessee Valley Authority is directed to regulate the release of water from the Tennessee River into the Ohio River in accordance with such instructions as may be issued by the War Department (58 Stat. 890; 33 U.S.C. 709)."*

Reservoirs with an authorized purpose of flood risk reduction are completely or partially designed to store floodwaters and thereby reduce peak flows downstream for a certain range of flood events. If the reservoir is operated seasonally, the level of the reservoir pool must be brought to the bottom of the flood pool before the start of the wet season, according to the reservoir's Water Control Manual and rule curves. The flood pool is used to store floodwaters while gradual releases are made from the dam to draw down the pool elevation in preparation for the next flood event. Dry dams have no permanent water storage and are designed for flood risk reduction. Storage loss due to sedimentation in the flood zone decreases the volume of water able to be stored and therefore increases flood risk. Significant loss of storage space may require reoperation of the reservoir.

Aquatic Ecosystem Restoration

Alteration of flow and sediment transport by a dam can impact aquatic ecosystem restoration both upstream and downstream from reservoirs. The primary impacts are alterations to the hydrological and chemical characteristics of the water, which in turn affect water quality and fish and wildlife habitat.

Water Quality: Water quality is important for water supply storage supporting municipal, industrial, and/or agricultural usages as well as overall environmental health in aquatic ecosystems. Table 9 lists common constituents measured for water quality. Drinking water regulations establish the acceptable limits for many constituents (e.g., Clean Water Act 33 U.S.C. §1251 et seq.). If water quality modeling is anticipated for the reservoir (e.g., CE-QUAL-W2 (Cole and Wells, 2015)), RSI data supporting model inputs and/or calibration can include inflow hydrograph characteristics (flow, sediment properties and concentrations of sediment, as well as bed sediment information). Biological analyses may also be necessary for constituents that attach to sediment. In terms of sediment properties, required data can include sediment concentrations, size class distributions, settling velocities, critical shear stresses for erosion and deposition (especially for cohesive sediments), porosity, and bulk density (Morris and Fan, 1998), as well as parameters for adsorption kinetics (the rate at which contaminants prefer to attach to sediment or detach to return to the water column). Consideration should be given to measurements for inflows, for circulation within the reservoir itself, and for outflows. Locating points for samples that are spatially and/or temporally representative require engineering judgment on the part of the modeler.

Table 9. Examples of constituents measured for water quality

PHYSICAL ANALYSIS		
Water Temperature	Conductivity	Total Suspended Solids (TSS)
Total Dissolved Solids (TDS)	Turbidity	Odor/Color/Taste
CHEMICAL ANALYSIS		
Heavy Metals	Dissolved Oxygen (DO)	Biochemical Oxygen Demand (BOD)
Nitrate	pH	Chemical Oxygen Demand (COD)
Pesticides		
BIOLOGICAL ANALYSIS		
Escherichia coli (E. coli)	Coliform	Ephemeroptera

Fish and Wildlife Habitat: Reservoir sedimentation can have both positive and negative effects on fish and wildlife habitat (McCartney et al., 2001). Many aquatic and wildlife species dependent on a riverine environment are unable to survive in a lake environment. For example, many native fish species may not be able to tolerate the warmer temperatures and lower levels of

dissolved oxygen typical of the upper portions of a reservoir, particularly during seasonal stratification (McCartney et al., 2001). Other species may be unable to complete their life cycle due to an inability to migrate up and down the river. On the other hand, sediment deposition and delta formation in a reservoir, and bed aggradation upstream from a reservoir, can create new wetland habitat (McCartney et al., 2001; Palmieri et al., 2001, cited in Kaemingk et al., 2007).

While coarser sediment is likely to be deposited in the delta at the head of the reservoir, finer sediment and reworked delta deposits (due to reductions in reservoir water levels, for example) can be transported further into the reservoir, and contribute to increased turbidity in parts of the reservoir. The remainder of the reservoir, however, may remain clear due to lower water velocities favoring sedimentation (Blevins, 2006). As a result, changes in stream inflow discharges are likely to create non-uniform impacts to fish and wildlife species within the reservoir depending on location and time of year life-cycle needs (USACE, 2009b). RSI needs for fish and wildlife habitat are similar to those required for modeling water quality.

Downstream Effects: Sediment trapping in reservoirs and the release of clear water can lead to downstream channel scour and degradation of downstream habitats (Morris and Fan, 1998). In addition, sediment deposited in a reservoir may contain pollutants, and nutrients (including agricultural fertilizers) in the reservoir may become adsorbed onto the surface of sediment grains. Subsequent release of this sediment through sediment management or other activities can thus mobilize pollutant and nutrient loads. A recent example of this has been Lake Okeechobee in Florida, where heavy rains led to the release of nutrient- and fertilizer-rich lake water to reduce pressure on flood control dikes. The water passed through the St. Lucie and Caloosahatchee rivers and entered the shallow bays on Florida's southeast and southwest coasts, producing intense algal blooms harmful to wildlife.

Hydropower

Reservoir sedimentation can decrease reservoir storage capacity and can sometimes increase head loss by restricting cross-sectional flow area and potentially even intake area (Gulliver and Arndt, 1991). In some cases, low-level outlets near the hydropower intake are necessary to keep the intake clear of sediment and debris via sluicing, and to help retain reservoir storage capacity, at the cost of releasing the sluicing water instead of running it through the turbines (Kondolf et al., 2014). These outlets are usually placed at the bottom of the reservoir.

High sediment concentrations passing through the intake can also erode turbine runners, creating a loss of efficiency and increasing the replacement frequency. Tradeoffs to consider in sediment sluicing are the cost of the facility construction, less efficient operation, and hydropower revenue lost compared to more frequent replacement and maintenance. In addition to the baseline data, suspended sediment samples may be needed to anticipate impacts to hydromachinery. If sediment transport and/or turbidity current modeling is anticipated, additional RSI data would include measurement of water and sediment inflows, and characterization of the grain size distribution of the inflows. Information about the bed sediment size distribution and stratigraphy may also be needed depending on the model employed.

Water availability for hydropower generation may be affected by sedimentation. For example, aggradation in the reach between Garrison Dam and Lake Oahe on the Missouri River in North Dakota has increased the potential for ice dam formation in that reach. Consequently, during the

winter months releases from Garrison Dam are reduced compared to the rest of the year, resulting in reductions in electricity generation at the hydropower facility (USACE, 2009b).

Recreation

Recreational uses usually include fishing and boating, but can also include activities that are enhanced by a healthy ecosystem such as bird watching or hiking. Fishing can be impacted by the same processes described above in the section on Fish and Wildlife Habitat. Recreational boating can be impacted by sedimentation through shoaling and/or silting up of launching facilities. In these locations, more detailed sampling and analysis of deposition patterns near the facilities may be of higher priority than studies focused on new bathymetry to update area-capacity curves. For numerical or physical modeling studies of depositional issues, the sediment data described in the water quality section should be considered (Michalec, 2015).

The evaluation of impacts on recreation resources conducted by Berger (USACE, 2009b) revealed that drought conditions and sedimentation/aggradation processes can result in access restrictions and temporary park or access closures. However, it appears that prolonged drought conditions have a much larger impact on recreational use than on sedimentation.

Bays or arms just off the main channel have historically been the primary location for boater access; however, these areas are susceptible to sediment aggradation. Even temporary closures of shoreline recreational sites can prevent access to areas within the river and reservoirs, resulting in direct impacts to the recreation resources. The loss of boater access results in longer drives to launch boats, trip cancellation, poor aesthetics, and safety hazards. In addition, boat access site managers are forced to spend more time and resources operating and maintaining the boat ramps, keeping them free of sediments to maintain boater access. The number of visitors affected by sedimentation is difficult to estimate and could likely be much higher than reported. It is important to note that sedimentation at boat ramps can also increase operational and maintenance costs for the users (USACE, 2009b).

Water Supply

For dams with water supply as an authorized purpose, the stage-storage volume relationship is used to estimate the amount of water remaining for municipal, industrial, and agricultural use. The stage-storage volume relationship can also be important when estimating the reliability of water supply under various climate scenarios. RSI important for these reservoirs should address whether sediment deposition in the conservation pool reduces storage or impacts water intake operations.

Changing drought conditions and the resulting increased demand for water supply have heightened concerns about the impacts of reservoir sedimentation on the part of USACE and our stakeholders (Pinson et al., 2015; USACE, 2016). A Presidential Memorandum released on 21 March 2016 (Executive Office of the President, 2016a) established a National Drought Resilience Partnership (NDRP), made up of 13 federal agencies including USACE. The NDRP improves Federal coordination of drought-related efforts to reduce the impact of current drought events on communities and better prepare them for future droughts. An action plan

accompanying the Presidential Memorandum lays out specific actions for agencies (Executive Office of the President, 2016b).

USACE is supporting the NDRP Action Plan by taking advantage of drought-induced low reservoir levels to increase knowledge of the state of reservoir sedimentation. USACE will identify and pursue ways to reduce the cost of reservoir surveys and share data from these surveys. As part of this effort, USACE tested an Airborne Laser Scanning (ALS) system in California during the recent drought to refine the data acquisition process. This testing included modifications to the system for specific aircraft, collection of LiDAR data for one drought-impacted reservoir, and reduction of the data. This activity led the RSI team to develop geospatial analysis tools allowing users to rapidly calculate area, capacity, and inundation data for reservoir elevations using 3D data from ALS and similar surveys. The team plans to develop additional geospatial analysis tools to help compare sediment and storage volume information developed using the latest data-rich collection techniques with sparser data acquired using past techniques. USACE has established an enterprise data system, the Geospatial Repository and Data Management System (GRiD), which supports efficient transfer of large data sets USACE-wide.

Dry Dams

Dry dams are more common in arid regions of the U.S., but can also be present in other areas where flood wave attenuation is desired without maintaining a permanent pool. The same general RSI are desired; however, the method and frequency of data collection may be different. Because there is no pool, topographic data can usually be obtained by conventional methods without the use of boats or by remote sensing, such as LiDAR. RSI for dry dams may usually be collected on a less frequent basis, such as after major storm events.

At some dry dams, sedimentation routinely interferes with their flood risk management function. Mount Morris Dam is one such case. Mount Morris Dam is a dry dam on the Genesee River in New York and operated by Buffalo District (LRB) for the purposes of flood risk reduction in the vicinity of Rochester. Rates of sediment and debris accumulation behind this dam are high, and routinely impair one or more of the several outlet conduits near the base of the dam (USACE, 1975). Sediment removal is conducted regularly during periods of the year when the reservoir is dry (Figure 9). In 2015, the district awarded a five-year contract for the annual removal of 3,200 cubic yards of floatable material (such as trees, tires, and other debris) and 9,000 cubic yards of sediment from behind the dam (USACE, 2015).

Prado dam is an example where sedimentation has negatively impacted water storage in an arid region, threatens critical habitat of endangered species, upsets ecosystem values, and reduces the supply of sand to replenish beaches. Since Prado Dam was completed in 1941, sediment has accumulated at an average rate of 700 AFY (Orange County Water District, 2016).

Figure 9. Debris removal at Mount Morris Dam (USACE 2015)

Other Determinants of RSI Data Needs

Geomorphology and Regional Characteristics

The local and regional geomorphology and regional environmental characteristics of a reservoir and its contributing watershed all impact the amount and type of sediment entering the reservoir (e.g., predominant geology, soil types, land use and land cover, runoff characteristics, upstream flow regulation). The frequency and intensity of wildfire and post-fire flooding (described in more detail below) can impact sediment delivery to reservoirs. Other common factors that increase the rate of storage loss are steep, bare and highly erodible soils in the contributing watershed, and agricultural or forestry practices that do not mitigate erosion. The geographic setting is usually not a factor in selecting types of data to be collected, unless there are ancillary circumstances, such as sediment quality and water quality impacts due to naturally high levels of certain pollutants as a result of geology. Although geomorphology and regional characteristics do not generally affect the types of RSI collected, they may dictate the methods and frequency of data collection, especially if a change in land use or fire causes a change in sediment loading.

Size

Reservoirs are often classified as hydraulically large or small based on storage capacity versus a measure of inflow such as mean annual runoff or mean annual depositional volume. As would probably be expected, the percentage of sedimentation impacting small reservoirs is often many times greater than for large ones. This has a direct impact on the frequency and resolution of data

collection, but does not affect the types of data that are needed. For example, Fort Peck Dam is on the Missouri River at river mile (RM) 1772 in northeastern Montana (Figure 7). Construction of the Fort Peck project was initiated in 1933, embankment closure was made in 1937. The project was regulated for the authorized purposes of navigation and flood control in 1938. The Fort Peck Dam embankment is nearly 4 miles long (excluding the spillway) and rises over 250 feet above the original streambed. Fort Peck Dam remains the largest dam embankment in the United States (126 million cubic yards of fill), the second largest volume embankment in the world, and the largest "hydraulic fill" dam in the world. Fort Peck Lake is the third-largest Corps reservoir in the United States. When full, the reservoir is 134 miles long. At closure in 1938 Fort Peck Lake stored 19,557,492 acre-feet, and had lost 1,185,012 acre-feet through 2007. This results in an overall loss of 6.1% of the total storage (USACE, 2013a).

Gavins Point Dam is on the Missouri River at RM 811 on the Nebraska-South Dakota border. Construction was initiated in 1952, and closure was made in July 1955, with initial power generation beginning in September 1956 (USACE, 2006). At closure in 1955 Lewis and Clark Lake stored 574,712 acre-feet, and has lost 148,883 acre-feet through 2011. This results in an overall loss of 25.9% of the total storage (USACE, 2013b).

When comparing the two reservoirs, the storage loss at Fort Peck Lake is larger in absolute volume, but smaller as a percentage of capacity than at Gavins Point. Considering the two reservoirs in the context of the system of dams on the Missouri River, the storage lost at Fort Peck Lake exceeds the total storage originally in Lewis and Clark Lake, effectively removing Lewis and Clark Lake from the system when considering total reservoir storage.

Shape

Sediment deposition patterns will necessarily be different between reservoirs with one or more, long, narrow arms and those where the length and width of the reservoir are similar (Ferrari, 2006; Morris and Fan, 1998) as delta formation, turbidity currents, and loss of storage due to sedimentation at different elevations will be affected by the reservoir shape. The shape of the reservoir will impact data collection methods and perhaps the frequency and resolution of collection, but not the types of RSI that are needed. For example, for smaller reservoirs or for reservoir surveys with complex bathymetry where greater detail is required, single-beam sonar data collection intervals of 100-200 feet may be required (Reclamation, 2006). However, for larger reservoirs, or for reservoirs with flat-bottom conditions, survey spacing intervals in excess of 500 feet might yield sufficient detail (Reclamation, 2006). Traditional range-line surveys may be required in situations that may prohibit use of GPS (Reclamation, 2006).

Basin Schemes

Reservoirs that are part of a basin operated as a system (e.g., the Missouri, Ohio, and Columbia Rivers) require a system-wide approach to sedimentation issues. Upstream trapping of sediment in reservoirs interrupts natural sediment transport that would occur within rivers and contributes to sediment starvation downstream to deltas and coasts (Kondolf et al., 2014). The shape of the watershed and the location of the reservoirs within the watershed prescribe the runoff area contributing to the sediment yield to each reservoir. Using this information and historical surveys, system managers can prioritize RSI updates in reservoirs where sediment problems are greatest. Prioritizing sediment problems is often not as simple as measuring the gross storage

loss. In the example of Fort Peck Lake and Lewis and Clark Lake in the previous section, the Fort Peck Lake storage loss dwarfs that of Lewis and Clark Lake. However, the sedimentation problems at Lewis and Clark Lake have acute impacts on flood stages, recreation, water supply and quality, and fish and wildlife that may not be as prevalent at Fort Peck Lake.

So while the sedimentation lifetime in Fort Peck Lake, estimated at more than 1,000 years (USACE, 2013a), is many times higher than Lewis and Clark Lake, estimated at under 200 years (USACE, 2013b), RSI updates may be a higher priority for Lewis and Clark Lake to assess faster developing impacts.

Data Needs Based on Reservoir Sustainability

A recent reservoir sustainability workshop sponsored by the Federal Advisory Committee on Water Information, Subcommittee on Sedimentation and the U.S. Society on Dams (Randle and Collins, 2013), discussed past and current RSI data collection efforts associated with reservoir sustainability and the effects of changing climate. One key question asked was "what data needs to be collected now to address anticipated future problems?" EM 1110-2-4000 (USACE, 1989) does not specifically outline data needs for sustainability effort but does suggest that if historical and contemporary hydraulic, hydrologic, topographic, and sediment data are available, the future long-term stability of the project can be evaluated along with an assessment of future maintenance requirements.

Understanding Changes Over Time

Observed changes in climate are already leading to increased hydrologic variability. The increased variability can reduce water supply reliability during droughts and increase rates of reservoir sedimentation during floods, both of which can impact water quality and fish and wildlife habitat. These impacts can reduced reservoir reliability and overall sustainability. Initial studies of changes in reservoir sediment yield under changing future climates suggest changes in sedimentation rates that vary regionally. For example, a study of Cochiti Lake, New Mexico (USACE, 2012a), projected declining average monthly flows across all seasons along the Rio Grande, leading to declines in sediment transport into the reservoir. Paradoxically, a review of the literature suggests that increased regional aridity may lead to changes in vegetation and surface cover that is likely to result in increased surface erosion, resulting in a transport-limited stream network in which sediment accumulation occurs in tributary channels and is flushed downstream primarily during local flood events. Similar reductions in sediment yield are projected for Elephant Butte Reservoir, New Mexico (Huang and Makar 2013). Conversely, a study of Garrison Dam showed an increase in sediment loading and inflows under all future climate scenarios, but these increases do not appear to be significant enough to affect reservoir operations (USACE, 2012b).

Many techniques for estimating regional spatial variation in reservoir sedimentation at a national scale rely heavily on estimates of drainage area and time-averaged estimates of sediment accumulation rates in representative reservoirs (Graf et al., 2010), rather than more complex models that incorporate climate and land surface processes. These models assume relative constancy in the average rates of erosion, sediment transport and deposition of sediment in reservoirs; however, in many parts of the country climate change is anticipated to alter important

hydrologic variables, resulting in changes to the rate of sediment transport to the nation's reservoirs and affecting the long-term sustainability of these flood risk management and water supply facilities.

To better understand how climate change may impact reservoir sedimentation, and how these impacts may vary geographically, the next phase of the RSI project seeks to evaluate the hydroclimatic and other variables with the strongest correlation with current reservoir sedimentation rates, and then use this information to make a first-order assessment of how climate change will, by altering these variables, affect reservoir sedimentation nationwide. The result of this effort will be an online screening tool identifying those reservoirs likely to experience the greatest sedimentation impacts in the future.

Sediment Yield

Sediment yield is defined as the total sediment outflow from a watershed or drainage basin, measureable at a cross section of reference in a specified period of time (ASCE, 2006). This total sediment discharge from the watershed is often used to define the incoming sediment load to a reservoir. Sediment yield depends on the rate of erosion within a watershed and how efficiently alluvial fans, floodplains, and flood control infrastructure trap sediment before it reaches a reservoir. Key factors affecting sediment yield include rainfall amount and intensity, soil type and geological formation, ground cover, land use, topography, upland erosion rate, drainage network density, slope, shape and channel alignment, runoff, sediment grain size and other characteristics and channel hydraulic characteristics (Strand and Pemberton, 1982). Because sediment yield can vary over time, and under climate change is likely to continue to vary, repeat sediment surveys are critical for identifying those reservoirs where sedimentation is currently a problem and where it is likely to be a problem in the future.

Sediment entering a reservoir is usually distributed below the top of the conservation pool, although if a reservoir is held at the flood pool elevation for any length of time sediment may also accumulate in this pool (Reclamation, 2006). A large fraction of incoming sediment accumulates as a stream mouth delta at the head of the reservoir. EM 1110-2-4000 (USACE, 1989) indicates that sediment yield should be computed for every USACE reservoir. The American Society of Civil Engineers (2008) indicates there are two basic strategies for measuring sediment yield: (1) by the volume of sediment deposited in reservoirs, and (2) continuous monitoring of fluvial sediment discharge (stream flow, suspended sediment concentration, and bedload) (Reclamation, 2006). Ideally, both strategies can be used and compared. However, if data is limited, only one method may be feasible. In order to determine sediment yield from a sediment survey, a representative trap efficiency (i.e., the percentage of total inflowing sediment retained in the reservoir) must be determined for the period between two consecutive sediment surveys. The trap efficiency multiplied by the sediment yield gives the volume of deposition. The trap efficiency of a reservoir depends on sediment grain size as well as the size, depth, shape and operation rules of the reservoir (Reclamation, 2006). Larger reservoir sizes typically have larger trap efficiencies and can store larger sediment volumes. Sediment yield obtained from reservoir survey data (annual average tons per square mile) is often reasonably consistent within a physiographic region and can be much more accurate than data from suspended sediment measurements (Burns and MacArthur, 1996). As RSI data is

collected, it can be used to improve estimates for unsurveyed reservoirs with similar characteristics.

Wildfire

Wildfires can drastically alter the land cover in a reservoir basin: the most intense burns can replace dense forest with barren ground over hundreds to thousands of acres. A national level assessment of the impacts of wildfires of reservoir sedimentation in USACE reservoirs has not been completed (Jonas et al., 2010), though a number of case studies are in progress. While an exact frequency for RSI data collection post-wildfire is difficult to identify, the frequency should be increased to capture the likely significant changes in reservoir sedimentation rate.

Wildfire and Sedimentation: The most frequent factor in the relationship between wildfires and sedimentation is the often increased surface runoff from rainfall events due to the loss of canopy and surface stabilizing vegetation. The most intensely burned areas also experience loss of soil organic matter (humus and roots) and increased hydrophobicity (tendency to repel water) (DeBano, 2000; Clark, 2001), along with structural, mineralogical, biological and chemical changes to soils (Neary et al., 2005). Wildfires also consume downed timber and brush, altering hillslope friction and time of concentration, resulting in increased peak discharge (Moody and Martin, 2004).

Along with increased runoff comes increased erosion and downstream sediment transport that can dramatically increase sedimentation in reservoirs. In 1996, the Buffalo Creek Fire burned approximately 50 km^2 upstream from the Stronita Springs Reservoir near Denver Colorado, and a subsequent major flood following this fire transported twice the annual bedload into the reservoir and about three times the annual total load into the reservoir over a two day period (Moody and Martin, 2004).

Wildfire Trends: Over the past two decades, wildfires in the western U.S. have increased in size by an order of magnitude (Joint Fire Service Program, 2004). Since the early 1980s, the number of fires per year greater than 1,000 acres has increased 450% and the area burned has increased close to 930% (Westerling et al., 2014). Higher fire severity has also been reported in some forests (Miller et al., 2009). These changes have been driven by increasing drought coupled with higher tree and understory densities as a result of active fire suppression since the 1900s and patterns of livestock grazing since the 1850s (Westerling et al., 2014).

Larger wildfires produce larger areas of moderate to high burn intensity resulting in extensive areas of canopy loss and soil alteration and, therefore, opportunities for greater erosion and more extensive flooding during storm events. Reported first-year, post-fire suspended sediment exports from forested catchments show an increase of 1-1,459 times unburned sediment exports (Smith et al., 2011). The time it takes for landscape recovery, at which time hydrologic conditions return to their historic values, is uncertain and varies by fire severity and extent, topography, climate and other factors.

For example, in 2011 the Las Conchas wildfire burned approximately 156,000 acres in watersheds adjacent to and upstream of Cochiti Lake, New Mexico. Approximately one-third of this acreage burned moderately to severely, resulting in complete canopy loss and soil alteration in these areas. Subsequent precipitation on the burn scar consisting of a 50%-chance-event storm

resulted in a greater than 400% increase in discharge (USACE 2011b) and flushed approximately 100 tons of woody debris and a significant pulse of sediment into Cochiti Lake (Figure 10).

Similar changes have been observed at reservoirs in southern California where debris flows following a wildfire are a common occurrence. As much as 120,000 cubic yards of sediment and debris have been produced per square mile of a burned watershed after a major storm (LADPW, 2006). Much of this sediment is trapped in USACE and local or private debris basins and reservoirs, incurring large sediment removal costs.

Figure 10. Some of the nearly 100 tons of debris washed down into Cochiti Lake, New Mexico, in the weeks immediately following the 2011 Las Conchas Wildfire, which burned in the mountains above the lake USACE (2012c)

Climate Change and Wildfire. Wildfire is anticipated to increase under a warming climate due to increases in drought intensity and duration (Wehner et al., 2011); even areas where precipitation is projected to increase may see increases in seasonal drought (Georgagakos et al., 2014). Although there is scientific consensus that the conditions favorable for wildfire ignition, spread, and crowning will increase as climate warms, there are only a few quantitative estimates of that increase. For the U.S. as a whole, Bachelet et al. (2007) estimate an increase in area burned by a factor of 1.08 by 2031-2060 and by a factor of 2.61 by 2071-2090. Fire seasons are anticipated to be longer and stronger across all regions of the United States by mid-century, and high fire years are expected to occur two to four times per decade by mid-century as compared to once per decade under current climate conditions (NASA, 2012). These projected changes in wildfire frequency and size, coupled with landscape-scale changes in vegetation and other factors, are likely to result in increased erosion and sediment transport in the nation's rivers and increased rates of reservoir sedimentation in some regions of the country.

Sediment Management

Different strategies for management of reservoir sedimentation are abundant in the literature (e.g., Morris and Fan, 1998; Sumi and Kantoush, 2011; Kondolf et al. 2014). Typical strategies include using a bypass channel to divert sediment-laden high flows around a reservoir, or constructing the reservoir off the main channel and diverting water to the reservoir only when sediment loads are low (Kondolf et al., 2014). For example, a sediment bypass channel at the Asahi Dam on the Shingu River in Japan prevented accumulation of as much as 750,000 m^3 of sediment in the period 1998-2006 (Mitsuzumi et al., 2009). Sediment sluicing has been implemented at China's Three Gorges dam, where flows in the high-flow season are passed through to flush sediment prior to initiating water storage for the low-flow season (Kondolf et al., 2014). Sluicing has also been implemented at the John Redmond reservoir in Kansas primarily through changes in operating rules, which has resulted in reductions in trap efficiency by 3%, resulting in reductions of almost 45,000 metric tons of sediment deposition per year (Lee and Foster, 2013).

Selection of the best management strategy or action is not always straightforward, even in the present. However, given the physical characteristics of a reservoir or system and projected future conditions, it may be possible to identify one or more potential future management strategies. Tracking the effectiveness of various sediment management techniques and how they work in certain environmental conditions will be important so that they can be applied appropriately throughout the USACE portfolio.

Sumi and Kantoush (2011) and Kondolf et al. (2014) broadly classify management methods into three categories:

1. Sediment Yield Reduction – reduce sediment inflow to the reservoir
2. Sediment Routing – pass sediment around or through the reservoir
3. Sediment Removal – remove deposited sediment via hydraulic or mechanical means

Further subcategories are defined based on timing, location, and details of individual measures (summarized in Figure 11). Sumi (2013) has also identified, at least for Japanese dams, ranges of applicability of the various methods based on the ratio between reservoir life (equal to the total storage capacity divided by the mean annual sediment load) and turnover rate of water (total capacity divided by mean annual runoff).

<u>Sediment Yield Reduction:</u> For the first option, sediment yield reduction, the USACE can apply the experience gained in the Delta Headwaters Project (DHP) (Martin et al., 2010), formerly the Demonstration Erosion Control Project. This interagency project was initiated in the early 1980s and covers over 2500 square miles (17 watersheds) in the highly erodible Yazoo River Basin in northwest Mississippi. Both upland treatment measures and in-channel measures (such as grade control and bank protection) were used to reduce watershed sediment yields, improve habitat and water quality, and achieve other goals. The project has resulted in reductions in sediment yields in some basins of 30-44%, and offers significant lessons learned that can be applied elsewhere. Longer-term reductions in sediment supply are anticipated (Martin et al., 2010). Actions such as forestation programs, terracing, land treatments, check dams, grade control, and bank protection have been demonstrated to reduce the amount of sediment leaving the watersheds.

In order to establish the reduction in sediment yield in reservoirs due to watershed sediment yield reduction measures, baseline topographic and bathymetric measurements in the reservoir are needed both before and after the programs are implemented. A minimum of two points in time before implementation are needed to establish the base sedimentation rate, and at least one resurvey after implementation is necessary to establish the change (hopefully a reduction) in sedimentation rates. If specific sources of sediment in the upper watersheds are being targeted, additional information to enable "fingerprinting" of sediment sources would be necessary (e.g., Davis and Fox, 2009).

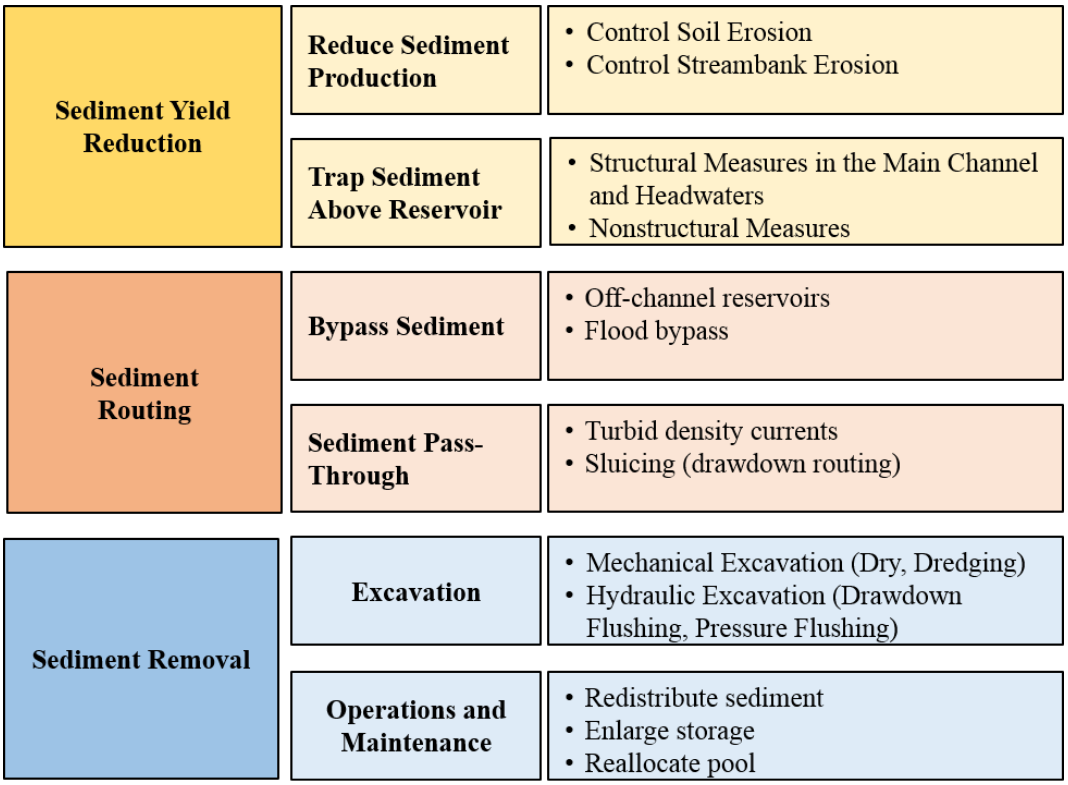

Figure 11. Strategies for managing sedimentation in reservoirs (after Kondolf et al. 2014: Figure 1)

Sediment Routing. Sediment routing is usually seasonal or dependent on inflows to move the sediment around the reservoir (bypassing) or through the reservoir (sluicing or turbidity current venting). Sediment transport modeling is almost always needed to estimate the effectiveness of the routing plan. Therefore, collection of hydrologic and sediment data to perform the modeling is needed. Typically, historical data is needed to document trends in deposition amounts, patterns, and properties so that these may either be extended for future conditions with no assumed change or may serve as a basis for estimated changes due to climate change or other future events.

Sediment Removal. Sediment removal can be a seasonal or hydrologically-influenced management strategy as in the case of flushing or redistribution within the reservoir, or can be less dependent on inflows as in the case of mechanical removal via dry excavation or dredging. For flushing or moving the sediment deeper into a reservoir, the same type of information previously described for sedimentation modeling is needed. For dry excavation or dredging,

successful dredging depends on the total sediment volume to be dredged; the cohesiveness and grain size of the sediment; sediment density and consolidation; depth of sediment below water surface; sediment layer thickness; presence of debris, waste, and other impurities in the sediment; meteorological and flood conditions at the dredging site; environmental restrictions (such as turbidity); and disposal possibilities (Batuca and Jordaan 2000). In many high-mountain regions, rates of sedimentation can be very high. For example, the Romanche River in the French Alps is impounded behind Chambon Dam, which contains a hydropower facility. Sedimentation rates of 100,000 to 200,000 m^3/yr have been documented, requiring regular dredging to protect the bottom gate of the dam (Jodeau et al. 2014). Rapid sedimentation can also occur in other setting, such as at John Redmond Lake, Kansas, where sedimentation has reduced lake surface area from 9,800 acres to 8,800 acres and water storage capacity from 82,200 acre-feet to 50,200 acre-feet. A 30-year dredging program has been implemented at this lake with the goal of removing close to 3 million cubic yards of sediment and maintaining the capacity at about 55,000 acre-feet (Taylor, 2016).

Pressure flushing, opening submerged gates or intakes, is often used to remove deposited sediments around discharge gates or hydropower intakes. It is done with a full reservoir, does not have to use much water, but has a small radius of influence on deposited sediment. This method is used yearly for a very short time at the Cherry Creek Reservoir near Denver to keep sediment from preventing the use of the spillway gates.

Drawdown flushing is a strategy that has been considered for hydropower projects. This techniques involves completely draining a long, narrow reservoir through low-level gates that permit unobstructed passage of flowing water (flushing discharge). Careful consideration must be given to the effects of this sediment on downstream reaches (Kondolf et al., 2014). Finally, if a reservoir is completely drawn down, intentionally or due to drought, dredging and mechanical removal of sediment can be accomplished (Kondolf et al., 2014).

A partial drawdown flush was executed at Lake Sharpe on the Missouri River in the fall of 1967 (USACE, 1986) and again in 1996 (USACE, 1997) as part of a test to determine if sediments could be moved from a tributary delta that was encroaching across the lake. The results were inconclusive, and it was suggested that the flush was not a large enough drawdown for long enough to result in significant sediment movement. In addition, the observed change was within the normal error window of the data collection tools. Modern tools for collecting RSI might have resulted in different conclusions.

RSI Data Collection

Reservoir sustainability assessments rely on an understanding of the factors that may introduce uncertainty into historic RSI, including how changes in technology impact the assessment of sediment yield and the rate at which reservoir capacity is lost over time. Historically, sedimentation rates were approximated using cross-section data collected using standard survey (range) lines at set intervals across a reservoir (Figure 12 left side). This series of bathymetric cross sections could be combined with mathematical models to estimate sediment accumulation volumes. Repeated data collection efforts could be used to assess change in sedimentation over time.

General sediment survey guidance is provided in Appendix K, Section 46 of EM 1110-2-4000 (USACE, 1989). Although the EM provides these general guidelines, there currently is no formal regulation on the frequency of data collection or the type of methods to follow. In terms of frequency, the EM suggests scheduling resurveys of sediment ranges at intervals of 5 to 10 years, depending on the quantities of sediment anticipated and probable needs for the RSI. The EM also indicates that partial or complete resurveys may be advisable after a major flood event. District managers have indicated that it could be helpful for updated policy or guidance to be more specific about time periods for periodic resurveys depending on conditions, provide updated guidelines for appropriate survey technology selection, and ensure compliance with existing datum requirements (e.g., ER 1110-2-8160). This section provides a general discussion of the data collection methods, resolution, frequency, and prioritization that could be considered when updating EM 1110-2-4000 or a preparing a new ER that addresses collecting reservoir sedimentation data.

Data Collection Methods

USACE currently monitors reservoir sediment primarily through periodic reservoir topographic surveys, or hydrographic or bathymetric surveys. The purpose of the surveys is to update reservoir bottom topography, compute area-capacity curves to reflect changes in storage volumes as a result of sedimentation, characterize deposition patterns, and identify any shifts in the stage-area and stage-storage curves. A complete reservoir sedimentation survey provides a contour map of the reservoir bottom and above-water areas to a predetermined maximum elevation. Surveys are usually performed by either the range or contour method, described in more detail below. Hydrographic or bathymetric surveys collect underwater depth or bottom elevation information. While bathymetric surveys capture information about areas normally under water (e.g., conservation and inactive pools), topographic and photogrammetric methods are performed to map the areas above the pool that are often only wet during large events (i.e., in the flood pool).

For dry dams, such as the majority of the Los Angeles District reservoirs, topographic survey techniques are typically applied. The most common techniques are traditional land surveys, photogrammetry, and airborne laser (such as LiDAR). Morris and Fan (1998) suggest using repeated aerial photography for reservoirs subjected to a wide range in stage or which are regularly emptied. Aerial photography or remote sensing images can be used to measure the pool surface area at each level to generate the elevation-area relationship. For reservoirs at low stages, sonar bathymetric data can be combined with topographic data from terrestrial real-time kinematic global positioning systems (Kohn, 2012) or LiDAR (McPherson et al., 2011) to determine stage-area and stage-volume relations, and other reservoir attributes.

Reconnaissance-level sediment survey methods that do not result in an updated area-elevation-capacity curve are occasionally performed. Examples include visual observation, test pits, check ranges, and longitudinal profiles.

Range and Contour Methods

The range and contour methods generally use a combination of hydrographic and topographic methods for reservoirs with permanent pools.

The accuracy of the range method is largely determined by the placement of the sediment ranges, and how well they represent the intervening bathymetry. For underwater data collection prior to computerized data collection and analysis systems, the range-line method was considered the only practical method for collection due to its relatively low field and analysis costs (Blanton, 1982). The method was used most often on medium to large reservoirs.

The contour method relies on electronic measuring techniques and computerized collection and analysis systems to handle massive amounts of digital data (x, y, z coordinates). In contrast, the range method uses a series of permanent range or cross-section lines across the reservoir that are resurveyed at intervals and used to compute changes in storage volume based on the changes in range geometry (Morris and Fan, 1998). The contour method is typically used to survey reservoirs before inundation (Ferrari and Collins, 2006).

Of the two methods, the contour approach is the more accurate technique to obtain the complete surface of the reservoir bed (Morris and Fan, 1998; Ferrari and Collins, 2006), although it can also be more costly, especially for large reservoirs (Reclamation 2006). For smaller to midsize reservoirs, the approach can be cost effective due to the advances in automated survey techniques (Morris and Fan, 1998).

Often, a combination of the methods is used when the reservoir topography varies significantly (ASCE, 2006). Jain and Singh (2003) indicate that the selection of a method depends on the quantity and distribution of sediment indicated by field inspections, shape of the reservoir, purpose of the survey, and desired accuracy. Changing from one survey type to the other (e.g., from range to contour) can significantly affect estimates of deposition rate or volume change (ASCE, 2008). ASCE (2008) and Morris and Fan (1998) suggest that when updating from the range method to contour surveying, reservoir volume should be computed using both methods to determine the bias between the two methods.

Topographic Data Resolution

Topographic data resolution refers to the size of a grid cell that represents geographic features. High resolution data corresponds to small grid cell dimensions. Typical resolutions include 30-, 10-, and 3-meter as found in USGS digital elevation models (DEMs). A DEM for a reservoir sedimentation survey must be sufficiently detailed to delineate accurate contours from which areas can be computed (USACE, 2002). For modeling, the coarsest resolution that is still sufficient for accuracy requirements is often used to maximize efficiency of computation time and data storage. If high resolution data is available, many practitioners will re-sample the data at a coarser resolution for modeling while retaining the higher resolution data for visualization (D'Avello, 2011).

LiDAR is commonly used for high-resolution topographic surveys. This technique uses airborne optical remote sensing to collect surface data of the Earth. The overlying vegetation and buildings are removed in processing the data to provide an image of the ground surface that can be shown in greater detail. LiDAR images can be combined with bathymetry data to produce a high-resolution DEM of a reservoir both above and below the water. DEMs produced from LiDAR data are typically delivered at resolutions of three meters or less (D'Avello, 2011).

Full DEMs are usually prepared using digital information from contour survey methods and not range line methods, as surface information between the range lines is unknown.

Bathymetric and Hydrographic Survey Techniques

Bathymetric data for a contour survey are typically collected from a boat using a single-beam (SBS) or multibeam sonar (MBS) for both range line and contour surveys. For most USACE reservoirs evaluated in this study, single-beam sonar was used to collect bathymetric data, although Walla Walla District indicated that MBS had been used at two of their reservoirs in 2011. Although it provides a much lower spatial resolution than MBS systems (Parnum et al., 2009), the density of coverage using a SBS system is usually sufficient for most USACE reservoirs. However, USACE (2002) indicates that a MBS system may be necessary if more detail is required for scour studies near the dam or outlet works. For shallow-water areas (ranging from one to ten feet), Alvarado and Robinson (2011) indicate a SBS system is preferred over a MBS system. Regardless of the technique selected, sonar data collected along range lines should be spaced at intervals close enough so that the reservoir bottom can be adequately defined for mapping purposes. Typically, lines are spaced between 200 and 400 feet apart, but the distance can be increased if the reservoir is fairly uniform (USACE, 2002). Sonar data along range lines can also be spaced as close as 100 to 200 feet for smaller reservoirs if higher accuracy is required for volumetric computations, but on large reservoirs such narrow spacing is typically considered uneconomical (Ferrari and Collins, 2006; USACE, 2002). Hydrographic surveys should be performed when the reservoir is at a high water level.

In contrast, locations above the water level should be surveyed from aircraft or satellite using photogrammetric or laser techniques and merged with the hydrographic survey data (Morris and Fan, 1998). Preferentially this data should be collected when the reservoir is at a low elevation to obtain maximum areal extent and perhaps a zone where bathymetric and aerial measurements overlap.

Innovative Techniques

More recently developed LiDAR methods produce a detailed topographic map of exposed and inundated reservoir areas, respectively (Figure 12 right side). Using this technology to conduct repeat surveys results in a much more accurate estimate of sediment volume change and rates of capacity loss in reservoirs.

Because of differences in data quality and density between cross section surveys and LiDAR data, the two cannot be directly compared in order to derive an estimate of sediment volume change across the period of record. Therefore, RSI updates in the future will require a method for accurately comparing the sediment volume estimates made from coarse-resolution data obtained from range line surveys with the high resolution estimates from LiDAR data. USACE is working on methods for comparing and combining collected LiDAR data to the geospatial information encapsulated in the RSI Oracle database, with the goal of enabling first order estimation of sedimentation rates based on the combined information. USACE is also developing a set of change detection tools in order to use legacy datasets to compare reservoirs over time, and integrating this information into the GRiD system for ease of use (Finnegan and Butler, 2015).

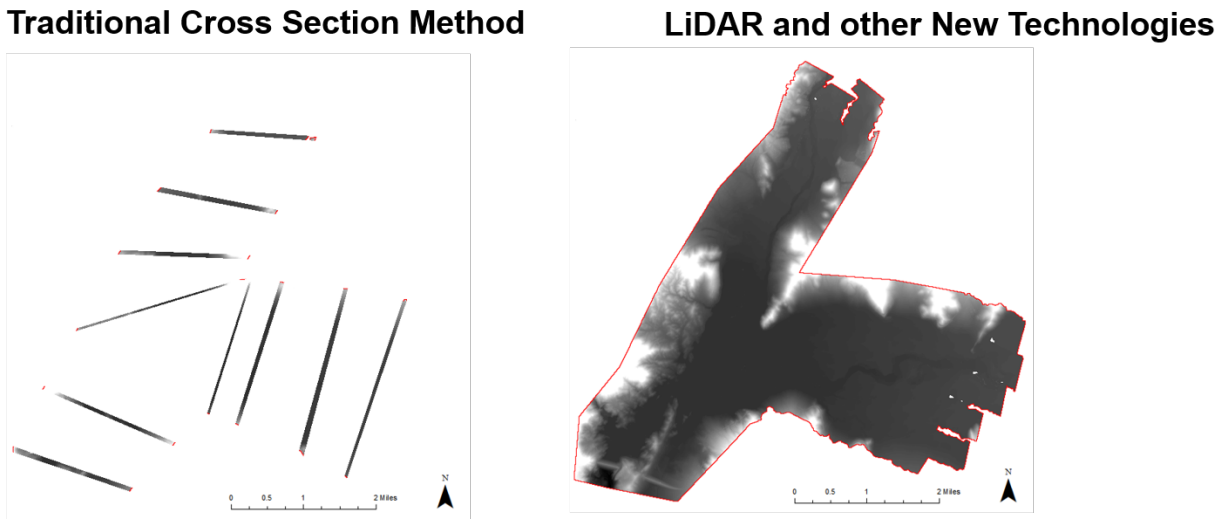

Figure 12. Visualization of Traditional Cross Section Survey vs LiDAR techniques

Datum Requirements

ER 1110-2-8160 (USACE, 2009a) establishes USACE policies for datum referencing and requires that USACE project elevation grades be accurately referenced to a consistent nationwide framework, or vertical datum (i.e., the National Spatial Reference System – NSRS). EM-1110-2-6056 (USACE, 2010) provides technical guidance for referencing project elevation grades to nationwide vertical datums. The current vertical reference datum within the NSRS is the NAVD88. ER 1110-2-8160 indicates that all newly authorized and existing projects shall be evaluated to ensure that designed and constructed grades are adequately connected and referenced to the 1988 vertical datum. Most USACE coastal projects have been brought into compliance with the ER, but many inland projects are still referenced to older datums, including NGVD29. ER 1110-2-8160 indicates that many of these older reference datums have unknown origins and may have significant elevation grade errors relative to the current 1988 vertical datum. As stated previously, projects using NGVD29 datum are not compliant with Engineer Regulation (ER) 1110-2-8160 Policies for Referencing Project Elevation Grades to Nationwide Vertical Datums (USACE 2009a). Noncompliance could result in datum errors that impact calculations of storage volume.

Sediment Sampling

Accurate estimation of the amount of sediment entering a reservoir is important for the management of a project. While a sediment yield analysis can determine a gross estimate of storage loss in a reservoir, it does not take into consideration the consolidation of sediments or the spatial distribution of sediments within the reservoir. To address these concerns, sediment sampling should be performed on incoming and previously deposited sediments.

The total sediment load at any point is the sum of the suspended load and bed load (ASCE, 2006). The suspended load, which includes both wash load and bed material load, can be determined using suspended sediment samplers. Bed load is notoriously more difficult to collect and often must be estimated by means other than sampling. Sediment transport measurements are usually made for streams and tributaries carrying material to the reservoir and not within the

reservoir itself. The procedures for collecting all forms of sediment samples have been standardized by the U.S. Geological Survey in Edwards and Glysson (1999).

Sediment data collection strategies will vary depending upon the needs of a project. In general, sediment data collected include the physical properties of the grains or deposits and the sediment discharge. Sediment samples to determine the specific weight, bulk density, and grain-size distribution can be collected at the same time as the sedimentation survey or separately. The number of samples collected depends on the size of the reservoir, the type and texture of the inflowing sediment, and the location and number of inflowing streams. In general, at least one sediment sample is taken at each range line. Sediment samples for specific weight and gradation can be collected using core type samplers for sand sizes and finer. Pebble counts are usually necessary for gravels and coarser materials. Radioactive probes can measure in-situ wet bulk densities (Morris and Fan, 1998). Field experiments may also be performed to parameterize sediment behaviors for modeling, such as erosion and settling velocity for fine-grain cohesive sediments (Demirbilek et al., 2010)

Data Collection Frequency

The highest-priority RSI issue identified by the six districts participating in the study is the need for hydrographic and topographic sediment resurveys (Table 2). Hydrographic resurveys are important to provide estimates of reservoir storage in the normally occupied conservation pool, while topographic surveys provide information to estimate reservoir storage in the normally vacant flood pool.

Many USACE reservoirs have not been resurveyed in more than 10 years or have not been resurveyed since dam closure. Although there is some general guidance on the scheduling of sediment resurveys provided in Appendix K of EM 1110-2-4000 (USACE, 1989), more specific guidelines for individual projects based on multiple factors, including sediment accumulation rate and authorized purposes, would be helpful to set priorities. For example, reservoirs that have high accumulation rates should be resurveyed more often compared to those with lower rates (Jain and Singh, 2003). Scheduling of resurveys should also consider RSI priority for reservoirs with special uses. As per Public Law 88-140; 77 Stat. 249, the “Permanent Rights to Storage” law, water supply contracts can be amended in response to reductions in reservoir capacity over time due to sedimentation. Consequently, USACE water supply contracts typically require districts to perform a sediment survey every 15 years, unless the District Engineer determines that a survey is unnecessary, or unless both parties agree that the survey does not need to be performed. Ultimately, the rate of project performance depletion should drive data collection frequency.

Currently, EM 1110-2-4000 suggests scheduling sediment resurveys at intervals of 5 to 10 years, depending upon the quantities of sediment anticipated and probable needs for such information. The EM also indicates that partial or complete resurveys may be required after a major flood event. However, budget limitations often make it difficult to fund sediment resurveys at the suggested rate or after major flood events. This is especially true for large reservoirs, such as those within the mainstem Missouri River, where resurveys can be quite expensive. The amount of sediment expected during a single large flood event compared to the available storage capacity within the reservoir may be a significant criterion in terms of data collection frequency.

The geographical location and size of a project should also be considered. Though some may assume that a project in an arid region that remains dry the majority of the time may not require a resurvey as often as a project in a wet region that has had significant flood events, this is not necessarily the case. Episodic high-intensity rainfall in arid regions may experience sedimentation that requires more frequency resurveys. Dry dams may only require resurveys after significant flood events, while a reservoir with known sedimentation issues may require sedimentation resurveys more frequently. For example, Baltimore District's Almond Lake is a reservoir that could benefit from a sediment resurvey every 5 to 10 years because the conservation storage space has been reduced by almost 50% since project completion, and sedimentation is a continuing problem. In contrast, Arkport Dam, a dry dam in the Baltimore District that was designed exclusively for flood risk reduction, may not need to be resurveyed until after the next major flood event, which might not occur for 15 to 20 years.

Morris and Fan (1998) provide some guidelines on reservoir survey intervals, suggesting the resurvey frequency should be based on the individual site characteristics. Reservoirs with low rates of volume loss may only require a resurvey every 20 years or even longer. However, for reservoirs losing volume rapidly, or where the impact of sediment management is being evaluated, a survey interval of two or three years may be more appropriate. Jain and Singh (2003) indicate that, in general, reservoirs should be resurveyed every three to 10 years unless a special circumstance occurs that would warrant a survey sooner, such as a major flood carrying heavy sediment loads to the reservoir. A dam closure upstream in the same catchment would also be considered a special circumstance to resurvey the reservoir due to the reduced sediment transport downstream of the new dam. ASCE (2008) indicates that a reservoir resurvey may be performed at intervals of five to 20 years, but can vary depending on budgetary constraints, rate of storage depletion, the type and importance of the project uses, and management requirements. They also suggest that in order to identify long-term sediment accumulation trends, data collection should include at least 20 years of survey record with several resurveys during that time. In general, large reservoirs require less frequent resurveys, but more frequent surveys are required if reservoirs are operating under conditions of greater risk, such as flood risk management or water supply storage in urban areas. Additional information on survey frequency and scheduling is provided in Ferrari and Collins (2006).

Prioritization

The amount of funding available for RSI data collection is not expected to increase significantly in the near future. Therefore, a system or prioritization is needed both at the national and district levels to ensure the most effective use of limited resources, particularly as changing climate is now and will continue to impact reservoir sedimentation in ways that are not fully understood. Prioritization could be based on a weighting system that considers some of the following questions:

- Do Dam Safety Action Classifications (DSACs) or other safety issues require more frequent or more detailed RSI collection?
- What are the projected impacts of climate change on reservoir sedimentation?
- Is storage loss occurring at the design rate, or exceeding this rate? How far along is this reservoir in terms of its design life?

- If there is no sediment survey data, can we update the sediment yield estimate using current information?
- What are the types of data collected and why are they being collected?
- How often is the data being collected?
- What is the cost of collecting certain types of RSI?
- What are the potential risks and impacts of deferring collection?
- Are all district projects the same, or are some different?
- Within a portfolio, are there different data requirements based on uses, sizes, or locations?
- Is a single update strategy reasonable for an entire district?
- Are there accelerated storage losses that require more frequent monitoring?
- Does storage loss progress at a relatively uniform rate, or is it related to infrequent events?
- Are there regulatory requirements that come to bear in data collection? Can these be economically leveraged for RSI?

Ultimately, RSI prioritization and resourcing will be based both on local needs (from the districts and their local partners) and national needs (coming from HQ). Determining the RSI data gaps at the district level is an important step in establishing a strategy for prioritizing and updating RSI. The RSI team has made good progress by establishing that baseline data in a new USACE RSI database and beginning to develop tools to compare data from newer data-rich methods to data from older methods.

RESERVOIR SEDIMENT INFORMATION PORTAL

Data capture of reservoir survey and area capacity data from multiple agencies has been conducted in the past in association with the USGS Reservoir Sedimentation (RESSED) database in accordance with the ACWI SOS. The RESSED database provides access to sedimentation-survey data for selected United States reservoirs from multiple agencies with reservoir responsibilities, including USACE. USACE first issued a data call in 2008 to collect reservoir sedimentation data from USACE-managed reservoirs, including, but not limited to, sediment management practices, general hydrology, land usage, and obstacles to sediment management practices (e.g., regulatory, liability, chemical contamination of sediments).

Improved knowledge about climate impacts to reservoir sedimentation prompted a change to a geospatial RSI database consistent with established USACE enterprise databases, such as the Corps Water Management System (CWMS) and the National Inventory of Dams (NID). RSI is stored in the USACE CorpsMap Oracle database, and access to this database is provided by the RSI web portal, a centralized system designed to support efficient dissemination of information, and limits the need for data calls while improving response time. The RSI portal was developed to facilitate entry of reservoir sedimentation data by USACE districts and provide a comprehensive summary of USACE reservoir conditions. The portal populates an Oracle database that interfaces with CorpsMap and other enterprise databases used in USACE. Existing data was harvested from the most recent version of the RESSED database.

The RSI portal is currently expanding to also incorporate Reclamation data. Further development will eventually allow access to RSI by other non-USACE agencies as a replacement to the original RESSED database. The RSI portal stores and displays reservoir information to assist with evaluation of sedimentation trends and reservoir life expectancy, particularly with respect to a changing environment. The reservoirs identified and used in the portal originate from the National Inventory of Dams (NID) database operated and maintained by USACE. The RSI portal allows credentialed users to add and modify sediment-related data for a reservoir. For each reservoir, the user can add years of a survey and metadata such as survey type, start and end dates, vertical datum used, and a comment field. Furthermore, area-capacity tables can be uploaded by year of survey for a reservoir (an example area-capacity graph from the portal is shown in Figure 13).

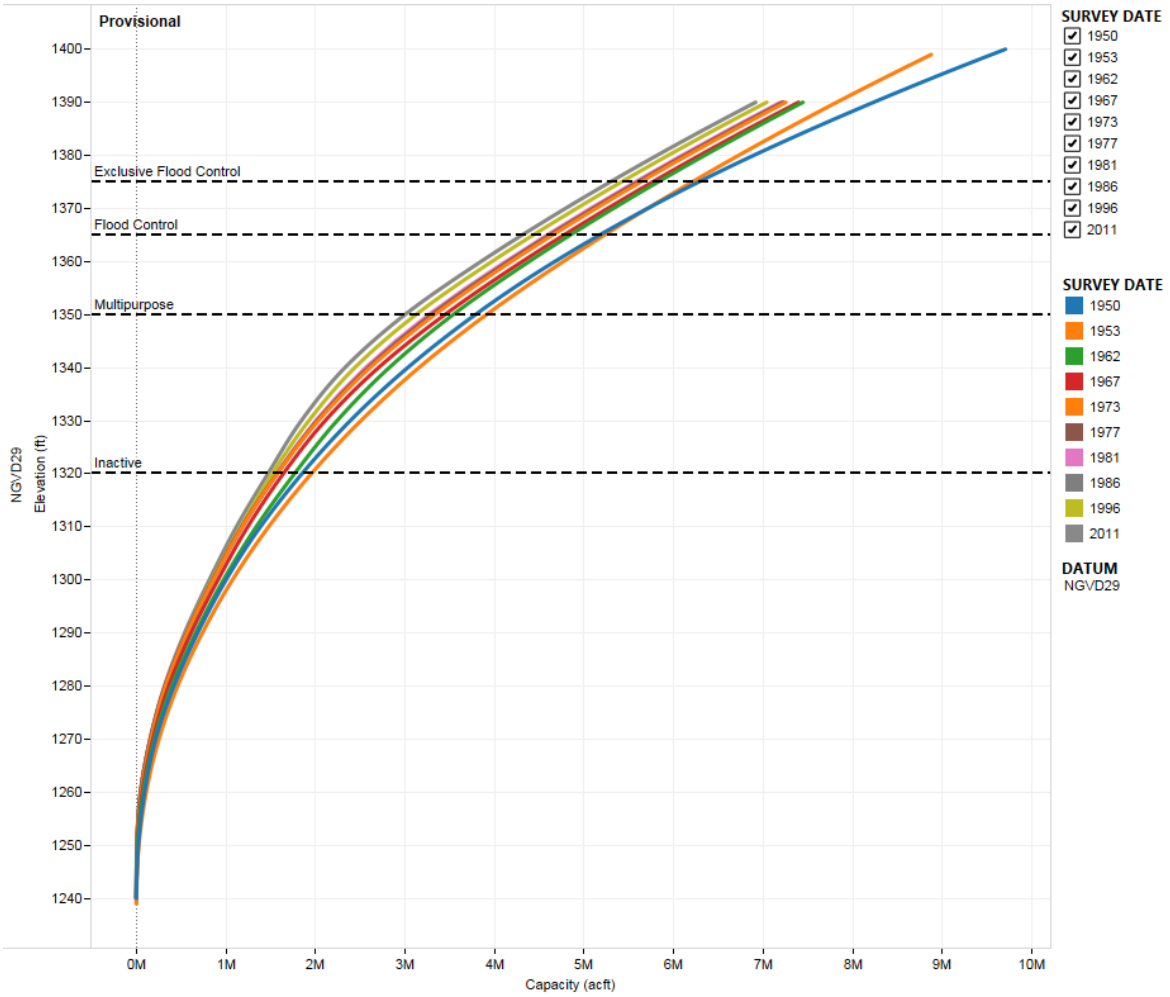

Figure 13. Area-capacity graph from RSI portal for Fort Randall Dam (USACE Northwestern Division, Omaha District)

The area-capacity data are used for several calculations and graphics in the portal. If two or more area-capacity tables are loaded, the storage loss in the pools of the reservoir are computed (see Figure 8 and Figure 14). The portal also calculates the average annual loss based between two surveys if three or more area-capacity curves are loaded since the initial curve, which is assumed to be at the time of construction. Additionally, the average annual storage loss is used for future

projection of loss and the reservoir storage half-life is computed. As an initial screening to evaluate future storage losses associated with changes in sediment yield, the reservoir storage half-life is projected with 25% increase and 25% decrease in sediment yield into the reservoir (Figure 15). Charts and graphs are generated to visualize the calculations for each reservoir.

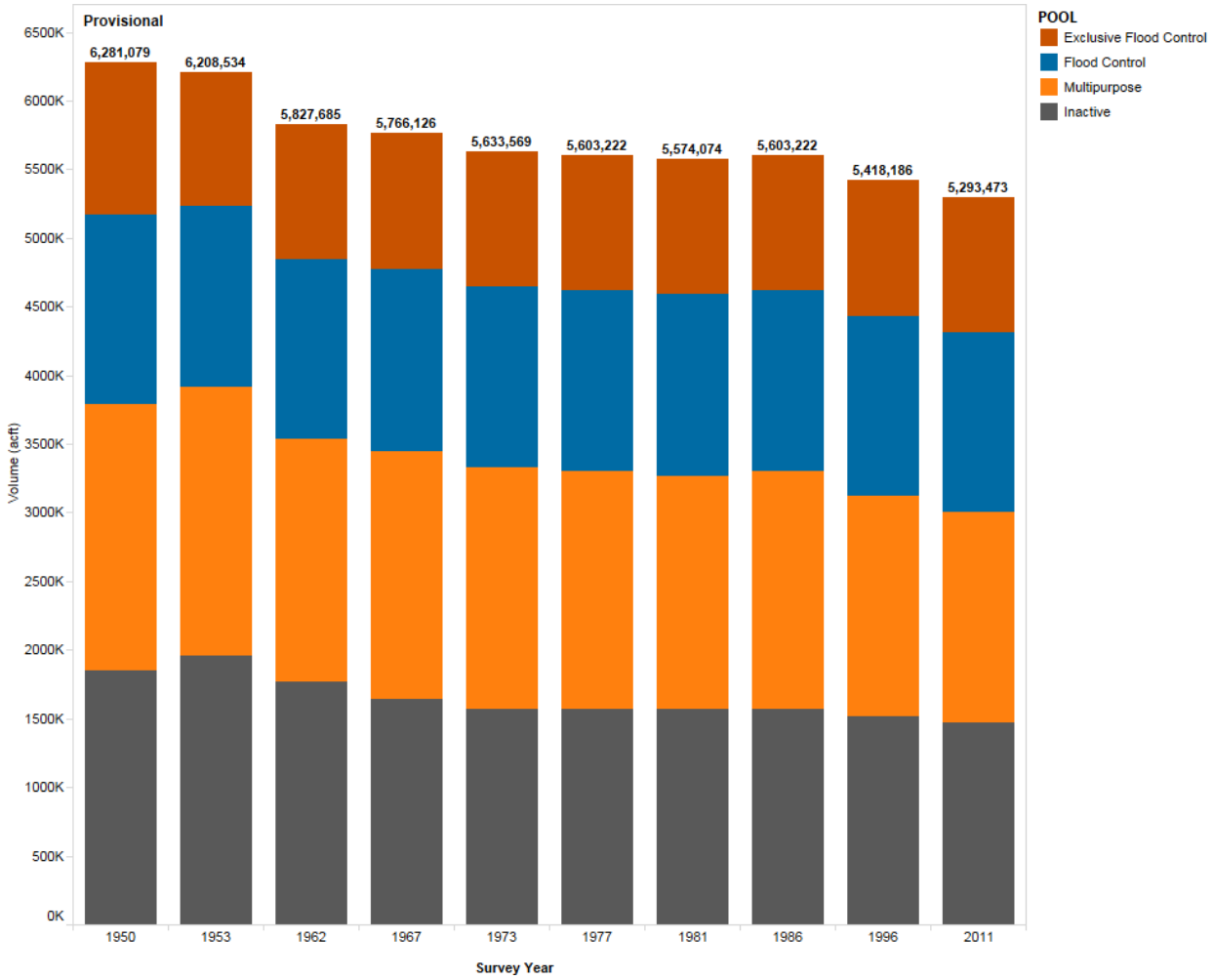

Figure 14. Volume summary graph from RSI Portal for Fort Randall Dam (USACE Northwestern Division, Omaha District)

Finally, the Portal provides an overview tab showing aggregated reservoir conditions related to sediment depletion. By default, the top 10 reservoirs in terms of volume lost are displayed. Filtering capability exist to explore volume loss in divisions and districts (Figure 16).

Testing of the RSI system production site was initiated in FY15 using survey and area-capacity data input from the pilot districts. The district input phase was completed in June 2016. The district data Quality Assurance/Quality Control (QA/QC) was enhanced based on lessons learned during the initial rollout and is anticipated to be complete by the end of calendar year 2016.

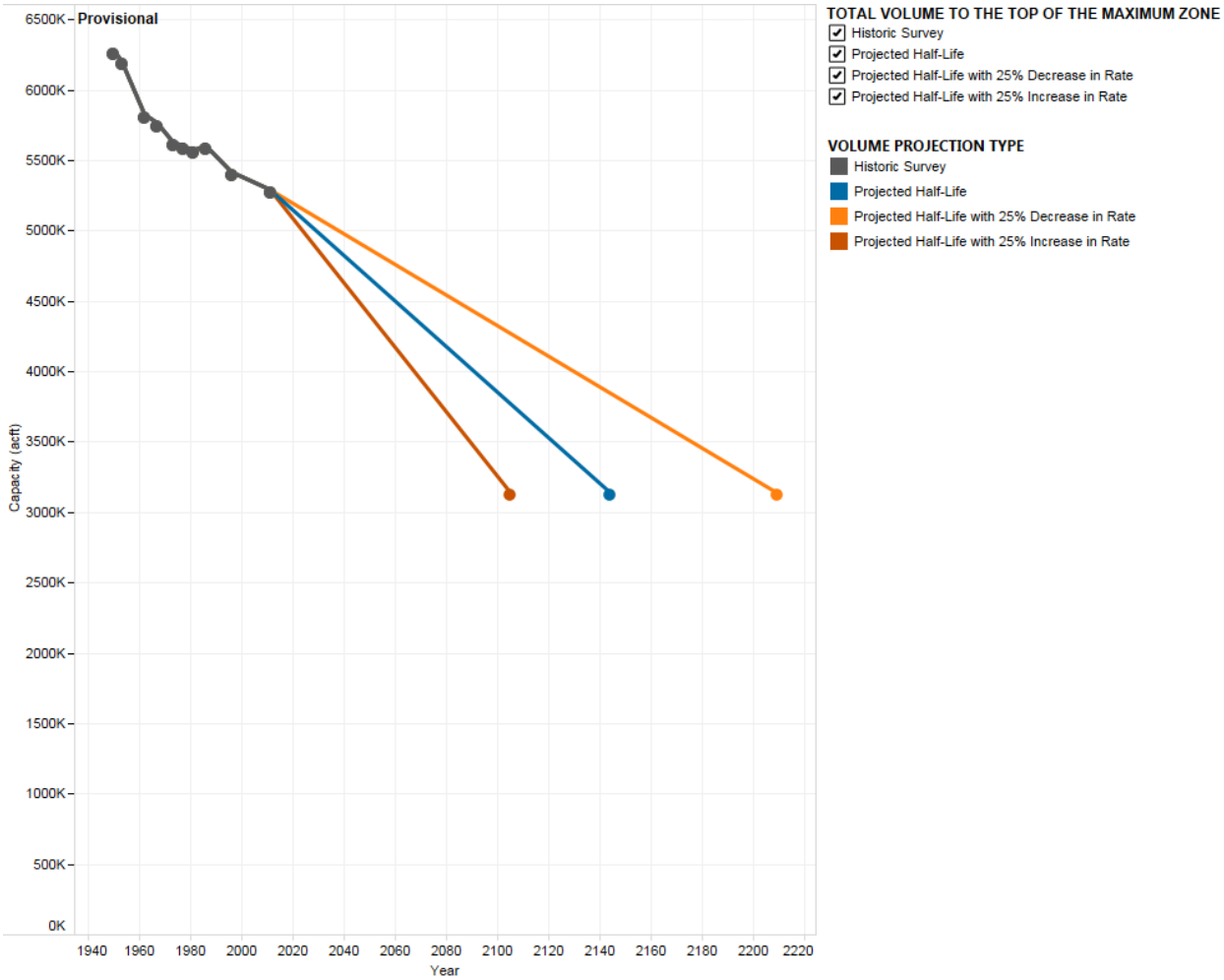

Figure 15. Reservoir storage projected half-life graph from RSI Portal for Fort Randall Dam (USACE Northwestern Division, Omaha District). The graph also displays a reservoir storage half-life with 25% increase and decrease in sediment yield into the reservoir.

The QA/QC of the RSI web portal verifies and corrects data quality issues associated with the reservoir sedimentation data that was imported from existing databases such as the NID, CWMS, and RESSED. Additionally, the QA/QC is addressing any supplemental data added to the database, such as the design sediment depletion rate and lifespan of the dam, recording instances where reservoirs have seasonal or other variations in authorized pool elevations, and documentation of any actions taken to remove or manage sediment at any dams. Districts have also been asked to upload any existing LiDAR and multibeam survey raw data to the Geospatial Repository and Data Management System (GRiD) (Finnegan and Butler, 2015) to build a USACE enterprise database for these data and to better translate between different survey methods that have varying levels of coarseness.

Capabilities planned to be added to the database in the future include new visualizations, predictions of storage loss, and the ability to store and standardize cross-section survey data for reservoirs.

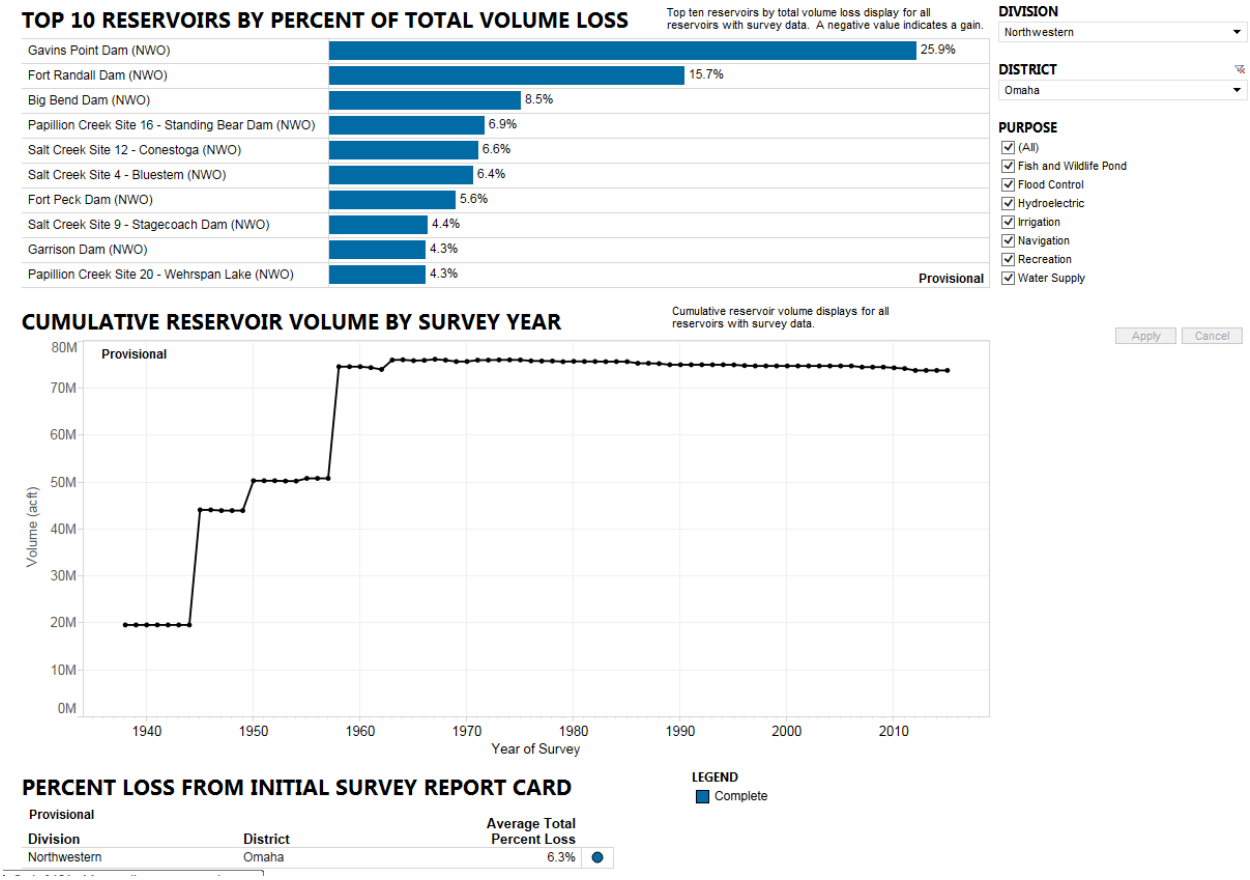

Figure 16. Portion of the overview tab from the RSI Portal filtered to the Omaha District in Northwestern Division

The USACE Committee on Channel Stabilization is collaborating with Reclamation and the USGS to accomplish RSI-related goals. Lessons learned will be incorporated in policies, processes, methods and guidance. The RSI team is focused on six goals that are aligned with the Committee on Channel Stabilization: 1) assessing existing knowledge about USACE RSI; 2) prioritizing baseline RSI development; 3) identifying current data gaps and developing a strategy to update RSI; 4) reviewing and updating existing methods and policies to support sediment data collection and studies (EM & ER updates); 5) prioritizing needs for and support of necessary baseline surveys and reservoir sedimentation studies; and 6) providing a comprehensive summary of current USACE reservoir conditions in order to identify project vulnerabilities to sedimentation.

The last publication of USACE guidance on reservoir sedimentation was over three decades ago, which makes it imperative that USACE update its guidance to account for global and climate changes that have occurred over the past 30 years and to update its understanding of the current state of reservoir sedimentation to support sustainable reservoir management. Reservoir managers are beginning to focus on using RSI to account for global and climate change and potential sediment issues associated with these changes.

CONCLUSIONS AND RECOMMENDATIONS

Accurate measurements of previous and current storage, and estimates of storage loss rates, are required to project the future sediment and storage volume conditions at USACE reservoirs. A pilot assessment of six representative districts indicated that significant data gaps remain in our understanding of current rates of sedimentation at USACE reservoirs nationwide, and that resource constraints and other factors prevent the use of existing recommendations for survey intervals at many reservoirs.

Climate change impacts to reservoir sedimentation in the future are anticipated to be significant, and regionally variable. An important next step for the RSI project is to develop means for identifying those reservoirs at greatest future risk for increases in sedimentation, especially where sedimentation might impinge on water supply, flood risk management, navigation, ecosystem restoration and recreational pools.

The RSI project has developed a Reservoir Sediment Information web portal to store and track completed sediment surveys and compute sedimentation rates and changes in area-capacity relationships in USACE and other reservoirs. The portal enables prioritization of future sediment information collection efforts. This portal is meant to be constantly updated as new surveys are conducted, facilitating analysis of sedimentation trends and changes to reservoir life expectancy.

The RSI team is exploring low-cost data collection methods such as LiDAR to deploy to rapidly collect highly-accurate, data-rich topographic information for reservoirs where low water levels have exposed all or part of the reservoir bottom surface. Additionally, the team is building tools to efficiently translate storage and volume information from traditional cross section computation methods to the more data-rich methods available today.

Recommendations

1. Climate change is projected to affect hydrology and sediment yield. The direction and magnitude of these changes will determine their impact. In most regions, the projections are for increased hydrologic variability. Increased heavy precipitation and wildfire associated with heat waves and drought can result in increased sediment yield. On the other hand, in some locations, river sedimentation may change, resulting in aggradation of river channels and little deposition within the reservoir itself (e.g., USACE, 2012a). Additional work is needed to define the impacts of climate change on sediment yield and the overall sustainability of USACE.

    a. **Recommendation:** Determine the potential impact of climate change on the inflowing water and sediment load to USACE reservoirs in different regions. Answer questions such as the following: How significant are the impacts of climate change? Do we expect sediment yield to USACE reservoirs to increase (or decrease) by 5%, 10%, or more? How will these impacts vary regionally and temporally? The answers to these questions will help bound the magnitude and direction of the sediment loads that will reach USACE reservoirs.

   b. **Recommendation.** Develop methods to track changes in sediment yield and hydrology that can be used to estimate sedimentation occurring between reservoir surveys.

2. USACE reservoir projects were designed with a sediment lifespan, meaning that a certain amount of volume loss was anticipated over the project lifetime.

   a. **Recommendation**. Use RSI to identify reservoirs that are experiencing sedimentation rates beyond the design rate, and develop appropriate strategies to manage sediment and improve reservoir sustainability.

   b. **Recommendation.** Collaborate with the USACE Subcommittee on Sedimentation and the USACE National Reservoir Sedimentation Team on reservoir sustainability issues.

3. A strategy is needed to fill RSI gaps, including prioritization and a central funding source.

   a. **Recommendation.** Develop a consequence-based analysis to prioritize reservoir surveys.

   b. **Recommendation.** Consider raising priority for reservoirs with one or no surveys so that initial sedimentation rates can be calculated.

   c. **Recommendation.** The recommended survey interval in EM 1110-2-4000 should be modified in the guidance update to reflect prioritization criteria.

   d. **Recommendation.** Review the survey intervals in water supply contracts, assess compliance, and identify changes if needed.

   e. **Recommendation**. Develop methods for comparison of dissimilar historic information (e.g., range surveys *vs.* contour surveys) to effectively monitor reservoir sedimentation rates, and evaluate departures.

   f. **Recommendation.** Develop criteria and tools for ranking sediment surveys within other district O&M priorities facing constrained funding.

4. Survey costs and data reduction are the largest component of RSI data. Survey costs vary greatly from one district to another, and districts use different methods for collecting survey data and for obtaining surveys (in-house survey crews; contractors; other). The reduction of survey data (the conversion of survey data into an area-capacity curve) is performed differently in different districts, resulting in non-standard results across the nation and, over time, at individual locations. Pool nomenclature varies from one district to another and affects our ability to report reservoir volumes and sedimentation impacts nationally. There is a need to standardize methodologies and nomenclature so that data can be shared nationally.

   a. **Recommendation.** Standardize pool nomenclature nationally, and set a schedule for implementation.

b. **Recommendation.** Automate survey computations so that all capacity computations are performed in a consistent manner across districts.

c. **Recommendation.** Develop standardized methods for addressing the discrepancies that occur when the survey method is changed from range line surveys to contour surveys. Some districts have revised and adjusted the original elevation-area-capacity curves to be compatible with the results from recent survey methods (since the difference in resolution of the survey methods causes discrepancies). Evaluate the different methods used to address the discrepancies, come up with a recommendation, and include this computation method in the automated survey computations in the RSI database.

d. **Recommendation.** Determine the most cost-effective survey methods for different categories of reservoirs. Currently districts use many different survey methods (e.g., check ranges, range line surveys, bathymetric surveys, and a combination of aerial and bathymetric surveys).

e. **Recommendation.** Evaluate the use of surrogate data and/or other indicators and methods to project reservoir sedimentation rates, and to predict the impact of climate change on reservoir sedimentation rates. This will assist in prioritizing surveys and other work.

f. **Recommendation.** Examine remote sensing technologies for reduced cost data collection where appropriate (e.g., dry dams).

5. There is a need to improve information sharing about sediment management measures. The majority of successful reservoir sediment management projects have been performed in other countries. Projects in which watershed sediment yield has been reduced (such as the Delta Headwaters Project (Martin, 2010)) have not been well documented.

   a. **Recommendation.** Reach out to national and international experts, including dam owners and consultants to identify potential sediment management methods that can be applied to USACE dams and reservoirs.

   b. **Recommendation.** Document sediment management case studies within USACE, other federal agencies, and other entities for methods, including reducing watershed sediment yield.

   c. **Recommendation.** Reinvigorate compliance with ER 1110-2-4001, Notes on Sedimentation Activities, as a corporate method of transferring sediment knowledge.

   d. **Recommendation.** Work through the ACWI SOS to re-establish the interagency report, “Information on Sedimentation Activities,” as a way to share information between federal agencies.

6. Sediment sampling data (density, sediment grain sizes, yield, etc.) is scarce and is usually not available in electronic form.

a. **Recommendation.** Digitize and include sediment sampling data in the RSI web portal.

b. **Recommendation.** Establish standardized methods for collecting sediment data (cores, density, grain sizes, sediment load) and include in a future update of EM 1110-2-4000.

c. **Recommendation.** Use data from other reservoirs in the same region to estimate sediment sampling data where there are gaps for USACE reservoirs.

d. **Recommendation**. The spatial distribution of reservoir sediments often plays a key role in understanding project sediment behavior. For this reason, including geospatial information with samples is a best practice that should be included in guidance updates.

7. Sediment reports and studies are not available USACE-wide, and older reports are often not available in electronic form. Annual reports on sedimentation activities are prepared by some districts but are not shared USACE-wide.

   a. **Recommendation.** Develop guidelines for the electronic storage and archiving of paper sediment reports and studies.

   b. **Recommendation.** Use the RSI portal as a vehicle for sharing sediment reports and studies within USACE, to include the Annual Reports on Sedimentation Activities and the SSWPs.

   c. **Recommendation.** Refresh the guidance that requires sediment study work plans (ER 1110-2-8153).

REFERENCES CITED

Alvarado A and Robinson D (2011) Hydro Survey: Multi-beam vs. Single Beam (Part 1 & 2). Hydraulically Inclined, Ayres Associates online blog, accessed 22 June 2015, online at http://ayresriverblog.com/2011/08/02/hydro-survey-multi-beam-vs-single-beam-part-1/ .

Annandale GW (2013) Quenching the Thirst: Sustainable Water Supply and Climate Change, CreateSpace, North Charleston, SC

ASCE (2006) Sedimentation Engineering, edited by VA Vanoni. ASCE Manuals and Reports on Engineering Practice, No. 54 – Classic Edition, American Society of Civil Engineers, Reston, VA.

ASCE (2008) Sedimentation Engineering – Processes, Measurements, Modeling, and Practice, edited by Marcelo H. Garcia. ASCE Manuals and Reports on Engineering Practice, No. 110, American Society of Civil Engineers, Reston, VA.

Bachelet D, Lenihan JM, and Neilson RP. 2007. Wildfires and global climate change: the importance of climate change for future wildfire scenarios in the western United States.

Regional impacts of climate change: four case studies in the United States. Pew Center on Global Climate Change.

Batuca DG and Jordaan JM Jr. (2000) Silting and Desilting of Reservoirs. A.A. Balkema, Rotterdam, The Netherlands.

Blanton JO III (1982) Procedures for Monitoring Reservoir Sedimentation: Technical Guideline for Bureau of Reclamation, Denver, CO.

Blevins, DW (2006) The response of suspended sediment, turbidity, and velocity to historical alterations of the Missouri River: U.S. Geological Survey Circular 1301.

Brekke LD, Kiang JE, Olsen JR, Pulwarty RS, Raff DA, Turnipseed DP, Webb RS, and White KD (2009) Climate Change and Water Resources Management - A Federal Perspective. U.S. Geological Survey Circular 1331.

Burns MM and MacArthur RC (1996) Sediment deposition in Jennings Randolph Reservoir, Maryland and West Virginia. In Proceedings of the Sixth Federal Interagency Sedimentation Conference, 10-14 March 1996, Las Vegas, Nevada.

Bureau of Reclamation (2006) Erosion and sedimentation manual. U.S. Department of the Interior, Bureau of Reclamation, Denver, Colorado.

Cole, TM and Wells, SA (2015) CE-QUAL-W2: A two-dimensional, laterally averaged, hydrodynamic and water quality model, version 3.72. Department of Civil and Environmental Engineering, Portland State University, Portland, OR.

Council on Environmental Quality (2011) Implementing Climate Change Adaptation Planning in Accordance with Executive Order 13514: Federal Agency Climate Change Adaptation Planning Support Document. 4 March 2011.

County of Los Angeles Department of Public Works and Los Angeles County Flood Control District (2013) Sediment management strategic plan (2012-2032), March 2013

D'Avello T (2011) Job Aides to Assist in the Development and Analyses of Raster Data for Digital Soil Mapping. National Soil Survey Center, Geospatial Research Unit.

Darcy JE (2014) USACE Climate Preparedness and Resilience Policy Statement. U.S. Army Corps of Engineers, Office of the Assistant Secretary of the Army (Civil Works), June 2014.

Davis CM, and Fox JF (2009) A study of sediment transport processes along the stream corridor using isotopic and elemental organic carbon and nitrogen tracers. Proceedings of the 33rd Annual IAHR Congress, Aug 9-14, 2009, Vancouver, British Columbia, Canada.

DeBano LF, (2000) The role of fire and soil heating on water repellency in wildland environments: a review, Journal of Hydrology, Vol. 231/232, pp. 195-206.

Demirbilek Z, Lin L, Smith J, Hayter E, Smith E, Gailani J, Norwood G, and Michalsen D (2010). Waves, hydrodynamics and sediment transport modeling at Grays Harbor, WA. U.S. Army Corps of Engineering Engineer Research and Development Center Coastal and Hydraulics Laboratory Technical Report ERDC/CHL TR-10-13.

Edwards TK and Glysson GD (1999) Field Methods for Measurement of Fluvial Sediment. U.S. Geological Survey Techniques of Water Resources Investigations, Book 3, Chapter C2, 89p.

Environmental Protection Agency (2016) National Summary of Impaired Waters and TMDL Information. Online at https://iaspub.epa.gov/waters10/attains_nation_cy.control?p_report_type=T, accessed 19 May 2016.

Executive Office of the President (2016a) Presidential Memorandum: Building National Capabilities for Long-Term Drought Resilience. Washington, DC. Federal Register document 2016-06901, 24 March 2016.

Executive Office of the President (2016b) Long-Term Drought Resilience: Federal Action Plan of the National Drought Resilience Partnership. Washington, DC.

Ferrari RL (2006) Reconnaissance Techniques for Reservoir Surveys. U.S. Bureau of Reclamation, Denver, Colorado.

Ferrari RL and Collins K (2006) Chapter 9: Reservoir survey and data analysis. In Erosion and Sedimentation Manual, U.S. Department of the Interior, Bureau of Reclamation, Technical Service Center, Sedimentation and River Hydraulics Group, Denver, CO.

Finnegan DC and Butler H (2015) Point cloud storage and management: the Geospatial Repository and Data (aka GRiD) Management System. LiDAR News Magazine 5(3), online at http://www.lidarmag.com/PDF/LiDARNewsMagazine_FinneganButler-StorageAndManagement_Vol5No3.pdf, accessed 22 June 2016.

Fu Q and Lin P (2011) Poleward shift of subtropical jets inferred from satellite-observed lower-stratospheric temperatures. Journal of Climate 24:5597-5603.

Gulliver, JS, and Arndt, REA Eds. (1991). Hydropower Engineering Handbook, McGraw-Hill, New York, NY.

Georgakakos, A, Fleming P, Dettinger M, Peters-Lidard C, Richmond TC, Reckhow K, White K, and Yates D (2014) Ch. 3: Water Resources. Climate Change Impacts in the United States: The Third National Climate Assessment, JM Melillo, TC Richmond, and GW Yohe, Eds., U.S. Global Change Research Program, 69-112. doi:10.7930/J0G44N6T.

Graf WL, Wohl E, Sinha T, and Sabo JL (2010) Sedimentation and sustainability of western American reservoirs, Water Resources Research, 46, W12535, doi:10.1029/2009WR008836.

Huang J, and Makar P (2013) Reclamation's research on climate change impact on reservoir capacity, World Environmental and Water Resources Congress, 2013, 1202-1212.

IPCC (Intergovernmental Panel on Climate Change) (2007) Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, 2007. Parry ML, Canziani OF, Palutikof JP, van der Linden PJ and Hanson CE (eds). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

IPCC (Intergovernmental Panel on Climate Change) (2014) Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of

Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Field CB, Barros VR, Dokken DJ, Mach KJ, Mastrandrea MD, Bilir TE, Chatterjee M, Ebi KL, Estrada YO, Genova RC, Girma B, Kissel ES, Levy AN, MacCracken S, Mastrandrea PR, and White LL (eds.). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1132 pp.

Jain, SK and Singh, VP (2003) Water Resources Systems Planning and Management. Elsevier, The Netherlands.

Jodeau M, Cazilhac M, Poirel A, Negrello P, Pinte K, Bouchard J-P, and Bertier C (2014) innovative in-situe measurements, analysis and modeling of sediment dynamics in Chambon reservoir, France. Pp. 53 – 62. In *Reservoir Sedimentation*, ed. Schleiss AJ, de Cesare, G, Franca MJ, and Pfister M. Special Session on Reservoir Sedimentation of the Seventh International Conference on Fluvial Hydraulics (River Flow 2014), IHR Committee on Fluvial Hydraulics, EPFL Lausanne, Switzerland, 3-5 September 2014.

Jonas M, Pinkard F, and Remus J (2010) USACE reservoir sedimentation: data, assessment and guidance. 2nd Joint Federal Interagency Conference, Las Vegas, NV June 27-July 1, 2010.

Joint Fire Service Program (2004) Joint Fire Service Program 2003 Business Summary. US Department of Agriculture, Forest Service, Pacific Northwest Research Station, Seattle, WA, USA.

Kaemingk MA, Graeb BDS, Hoagstrom CW, and Willis DW (2007) Patterns of fish diversity in a mainstem Missouri River reservoir and associated delta in South Dakota and Nebraska, USA. River Research and Applications 23: 786-791.

Keener VW, Hamilton K, Izuka SK, Kunkel KE, Stevens LE and Sun L (2013) Regional climate trends and scenarios for the U.S. National Climate Assessment: Part 8. Climate of the Pacific Islands. NOAA Technical Report NESDIS 142-8.

Knowles N, Dettinger MD and Cayan DR (2006) Trends in snowfall versus rainfall in the Western United States. Journal of Climate 19:4545-4559.

Kohn MS (2012) Bathymetry of Groundhog Reservoir, Dolores County, Colorado, 2011: U.S. Geological Survey Scientific Investigations Map 3202, scale 1:8,000 [http://pubs.usgs.gov/sim/3202/].

Kondolf CG, Gao Y, Annandale GW, Morris GL, Jiang E, Zhang J, Cao Y, Carling P, Fu K, Guo Q, Hotchkiss R, Peteuil C, Sumi T, Wang H-W, Wang Z, Wei Z, Wu B, Wu C, and Yang CT (2014) Sustainable sediment management in reservoirs and regulated rivers: experiences from five continents. Earth's Future 2:256–280.

Koppes M, Hallet B, Rignot E, Mougino J, Smith Wellner J, and Boldt K (2015) Observed latitudinal variations in erosion as a function of glacier dynamics. Nature 526(7571):100-103.

LADPW (Los Angeles Department of Public Works) (2006) Sedimentation Manual, Second Edition, March 2006.

Lee C and Foster G (2013) Assessing the potential of reservoir outflow management to reduce sedimentation using continuous turbidity monitoring and reservoir modeling, Hydrol. Processes, 27, 1426–1439, doi:10.1002/hyp.9284.

Maloney ED, Camargo SJ, Chang E, Colle B, Fu R, Geil KL, Hu Q, Jiang X, Johnson N, Karnauskas KB, Kinter J, Kirtman B, Kumar S, Langenbrunner B, Lombardo K, Long LN, Mariotti A, Meyerson JE, Mo KC, Neelin JD, Pan Z, Seager R, Serra Y, Seth A, Sheffield J, Stroeve J, Thibeault J, Xie S-P, Wang C, Wyman B and Zhao M (2013) North American Climate in CMIP5 Experiments: Part III: Assessment of Twenty-First-Century Projections. Journal of Climate 27:2230-2270.

Martin M, Biedenharn D, Little C, Smith K, and Watson C (2010) Analysis of Three Delta Headwaters Project (DHP) Streams using the Sediment Impact Analysis Method (SIAM) Model, 2nd Joint Federal Interagency Conference, Las Vegas, NV

McCartney MP, Sullivan C, and Acreman MC (2001) Ecosystem Impacts of Large Dams. Background Paper Nr. 2 prepared for the International Union for Conservation of Nature and Natural Resources and the United Nations Environmental Programme, New York.

McPherson KR, Freeman LA, and Flint LE (2011) Analysis of Methods to Determine Storage Capacity of, and Sedimentation in, Loch Lomond Reservoir, Santa Cruz County, California, 2009. U.S. Geological Survey Scientific Investigations Report 2011–5141.

Melillo JM, Richmond TC and Yohe GW (eds.) (2014) Climate Change Impacts in the United States: The Third National Climate Assessment. U.S. Global Change Research Program.

Michalec, B (2015) Evaluation of an Empirical Reservoir Shape Function to Define Sediment Distributions in Small Reservoirs. Water 7, DOI: 10.3390/w7084409

Miller JD, Safford HD, Crimmins M, and Thode AE (2009) Quantitative evidence for increasing forest fire severity in the Sierra Nevada and southern Cascade Mountains, California and Nevada, USA. Ecosystems 12:16-32.

Milly, PCD, Betancourt J, Falkenmark M, Hirsch RM, Kundzewicz ZW, Lettenmaier DP, and Stouffer RJ (2008) Stationarity is dead: Whither water management? Science, 319(5863), 573-574.

Mitsuzumi, A, Kato M, and Omoto Y (2009), Effect of sediment bypass system as a measure against long-term turbidity and sedimentation in dam reservoir, in 23rd ICOLD Congress, Q89-R8, Brasilia, Brazil.

Moody JA and Martin DA (2004) Wildfire impacts on reservoir sedimentation in the western United States. In Proceedings of the Ninth International Symposium on River Sedimentation, October 18-21, 2004, Yichang, China

Morris GL and Fan J (1998) Reservoir Sedimentation Handbook, Design and Management of Dams, Reservoirs, and Watersheds for Sustainable Use. McGraw-Hill Book CO., New York, NY.

Mote PW, Hamlet AF, Clark MP and Lettenmaier DP (2005) Declining mountain snowpack in western North America. Bulletin of the American Meteorological Society 86:39-49.

NASA (2012) Climate Models Project Increase in U.S. Wildfire Risk Press Release 12-419 (December 4, 2012).

Nearing, MA, Pruski, FF, and O'Neal, MR. 2004. Expected climate change impacts on soil erosion rates: A review. Journal of Soil and Water Conservation 59(1):43-50.

Neary DG, Ryan KC, DeBano LF (eds) (2005, revised 2008). Wildland fire in ecosystems: effects of fire on soils and water. General Technical Report RMRS-GTR 42 Vol. 4, Ogden, Utah: US Department of Agriculture, Forest Service, Rocky Mountain Research Station.

Nittrouer, JA, and Viparelli E (2014). Sand as a stable and sustainable resource for nourishing the Mississippi River delta. Nature Geoscience, 7(5), 350-354.

Orange County Water District (2016) The Prado Basin CA Feasibility Study. Fountain Valley, CA. Online at: http://www.ocwd.com/media/4273/prado-basin-feasibility-study-and-map_v14-c.pdf, Accessed June 18, 2016

Parnum I, Siwabessy J, Gavrilov A, and Parsons M (2009) A comparison of single beam and multibeam sonar systems in seafloor habitat mapping. Proceedings of the 3rd International Conference & Exhibition on Underwater Acoustic Measurements: Technologies & Results, Nafplion, Greece, pp. 155-162.

Pinson, A, Jordan A, Baker B, White KD, Vermeeren R, and Fagot K (2015), USACE Drought Contingency Planning in the Context of Climate Change. Civil Works Technical Report, CWTS 2015-15, US Army Corps of Engineers: Washington, DC.

Podolak, CJP, and Doyle MW (2015), Reservoir sedimentation and storage capacity in the United States: Management needs for the 21st century, J. Hydraulic Engineering, 141(4), 02515001, doi:10.1061/(ASCE)HY.1943-7900.0000999.

Randle TJ, Kimbrel S and Collins KL (2015) Reservoir sustainability workshop and National Reservoir Sedimentation Team, April 19-23, 2015. In Proceedings of the Joint Federal Interagency Conference 2015, Reno, Nevada.

Randle TJ and Collins KL (2013) Reservoir sustainability workshop, Lakewood, Colorado, July 10-12, 2012. In Changing Times – The Challenges and Risks of Managing Aging Infrastructure Under a New Financial Reality. 33rd Annual U.S. Society on Dams Conference, Phoenix, AZ.

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

Ritter DR, Kochel RC, and Miller JR (1995) Process Geomorphology, Third Edition. Wm. C. Brown Publishers, Dubuque, Iowa.

Schumm SA (2005) River Variability and Complexity. Cambridge University Press, Cambridge, UK.

Seidel DJ, Fu Q, Randel WJ, and Reichler TJ (2008) Widening of the tropical belt in a changing climate. Nature Geoscience 1:21-24.

Smith HG, Sheridan GJ, Land PNJ, Nyman P, and Haydon S (2011) Wildfire effects on water quality in forest catchments: A review with implications for water supply. Journal of Hydrology 396(1-2):170-192.

Strand RI and Pemberton EL (1982) Reservoir Sedimentation Technical Guidelines for Bureau of Reclamation, U.S. Bureau of Reclamation, Denver, Colorado.

Stewart IT, Cayan DR, and Dettinger MD (2004) Changes in snowmelt runoff timing in western North America under a 'business as usual' climate change scenario. Climatic Change 62:217-232.

Stewart IT, Cayan DR, and Dettinger MD (2005) Changes toward earlier streamflow timing across western North America. Journal of Climate 18:1136-1155.

Sumi T (2013 – in press). Reservoir sedimentation database and selecting suitable sediment management options in Japan. In Changing Times: Infrastructure Development to Infrastructure Management, Proceedings of the 80th Annual Meeting of the International Committee on Large Dams, Seattle, WA, USA.

Sumi T and Kantoush SA (2011) Sediment management strategies for sustainable reservoirs. In Dams and Reservoirs Under Changing Challenges, Proceedings of the 79th Annual Meeting of the International Committee on Large Dams, Lucerne, Switzerland, CRC Press, Leiden, The Netherlands.

Taylor BK (2016) A dual case study of two approved inland dredging requests pursuant to Section 408: A comparative processing and procedural analysis of review level, requirements, and lessons learned. In Proceedings, Twenty-First World Dredging Congress (WODCON XXI), 13-17 June, Miami, Florida.

Trenberth KE, Dai A, van der Schrier G, Jones PD, Barichivich J, Briffa KR, and Sheffield J (2014) Global warming and changes in drought. Nature Climate Change 4:17-22.

U.S. Army Corps of Engineers (USACE) (1975) Draft Environmental Impact State: Operation and Maintenance, Mount Morris Flood Control Project, Livingston County, NY. U.S. Army Corps of Engineers, Buffalo District, February 1975.

U.S. Army Corps of Engineers (USACE) (1984) Engineering Manual (EM) 1110-2-1455, Cooperative Stream Gaging Program (Reports Control Symbol, DAEN-CWH-3). 29 June 1984.

U.S. Army Corps of Engineers (USACE) (1986) Missouri River Big Bend Aggradation Assessment, Engineering Division, Omaha District. April 1986.

U.S. Army Corps of Engineers (USACE) (1987) Engineering Manual (EM) 1110-2-3600, Management of Water Control Systems. 30 November 1987.

U.S. Army Corps of Engineers (USACE) (1989) Engineering Manual (EM) 1110-2-4000, Sedimentation Investigations in Rivers and Reservoirs. 15 December 1989.

U.S. Army Corps of Engineers (USACE) (1995) Engineering Regulation (ER) 1110-2-8153, Engineering and Design – Sedimentation Investigations. September 30, 1995.

U.S. Army Corps of Engineers (USACE) (1997). Missouri River: Big Bend Sedimentation Analysis, Hydrologic Engineering Branch, Omaha District, February 1997.

U.S. Army Corps of Engineers (USACE) (2002) Engineering Manual (EM) 1110-2-1003, Engineering and Design – Hydrographic Surveying. January 1, 2002 (changes April 1, 2004).

U.S. Army Corps of Engineers (USACE) (2006). Missouri River Mainstem Reservoir System Master Water Control Manual, Missouri River Basin, Reservoir Control Center, USACE, Northwestern Division-Missouri River Basin, Omaha, NE Revised March 2006.

U.S. Army Corps of Engineers (USACE) (2009a) Engineering Regulation (ER) 1110-2-8160, Engineering and Design: Policies for Referencing Project Evaluation Grades to Nationwide Vertical Datums. March 1, 2009.

U.S. Army Corps of Engineers (USACE) (2009b) Impacts of Siltation of the Missouri River in the State of North Dakota: Summary Report, prepared by The Louis Berger Group, Inc. for the US Army Corps of Engineers Omaha District and the Missouri River Joint Water Board. 29 June 2009.

U.S. Army Corps of Engineers (USACE) (2010) Engineering Manual (EM) EM-1110-2-6056, Standards and Procedures for Referencing Project Evaluation Grades to Nationwide Vertical Datums. December 31, 2010.

U.S. Army Corps of Engineers (USACE) (2011a) Sustainable Solutions to America's Water Resources Needs: Civil Works Strategic Plan 2011-2015. US Army Corps of Engineers, Washington, DC

U.S. Army Corps of Engineers (USACE) (2011b) Technical assistance report for Santa Clara Pueblo, Las Conchas fire response, Santa Clara Canyon debris retention facilities. Ms. on file, Albuquerque District.

U.S. Army Corps of Engineers (USACE) (2012a) Climate Change Associated Sediment Yield Changes on the Rio Grande in New Mexico: Specific Sediment Evaluation for Cochiti Dam and Lake, revised. US Army Corps of Engineers, Washington, DC, online at http://www.corpsclimate.us/docs/RioGrandeClimateChangeSedimentYieldImpactAtCochiti_D15Amended.pdf.

U.S. Army Corps of Engineers (USACE) (2012b) Climate Change Associated Sediment Yield Impact Study: Garrison Dam Specific Sediment and Operation Evaluations. US Army Corps of Engineers, Washington, DC, online at http://www.corpsclimate.us/docs/Garrison_Climate_Study_Final.pdf.

U.S. Army Corps of Engineers (USACE) (2012c) After Action Report Final Las Conchas Fire Emergency Measures, U.S. Army Corps of Engineers, Albuquerque District. Ms. on file, Albuquerque District.

U.S. Army Corps of Engineers (USACE) (2013a) Missouri River Basin Sediment Memorandum 08a, Sedimentation Conditions at Fort Peck Lake, Omaha District, August 2013.

U.S. Army Corps of Engineers (USACE) (2013b) Missouri River Basin Sediment Memorandum 29, Sediment Conditions at Lewis and Clark Lake, Omaha District, October 2013.

U.S. Army Corps of Engineers (USACE) (2014) USACE June 2014 Climate Change Adaptation Plan. US Army Corps of Engineers, Washington, DC, online at http://www.corpsclimate.us/docs/USACE_Adaptation_Plan_v50_2014_June_highres.pdf

U.S. Army Corps of Engineers (USACE) (2015a) Sustainable Solutions to America's Water Resources Needs: Civil Works Strategic Plan 2014-2018. US Army Corps of Engineers, Washington, DC, online at http://www.usace.army.mil/Portals/2/docs/civilworks/news/2014-18_cw_stratplan.pdf

U.S. Army Corps of Engineers (USACE) (2015b) Debris removal underway at Mount Morris Dam. USACE Press Release, 14 August 2015. Online at: http://www.lrb.usace.army.mil/Media/News-Releases/Article/613615/debris-removal-underway-at-mount-morris-dam/__redir/1/, accessed 7 July 2016.

U.S. Army Corps of Engineers (USACE) (2016) Report to Congress: US Army Corps of Engineers Western Drought Contingency Actions. US Army Corps of Engineers, Washington, DC. Online at: http://www.corpsclimate.us/docs/Western_DCPs_2016_Report_Final.pdf.

Vonk, JE, Tank, SE, Bowden, W., Laurion, I, Vincent, WF, Alekseychik, P, Amyot, M, Billett, M, Canario, J, Cory, RM and Deshpande, BN (2015) Reviews and syntheses: Effects of permafrost thaw on Arctic aquatic ecosystems. Biogeosciences Discussions 12: 1-97.

Walling DE. 2009. The Impact of Global Change on Erosion and Sediment Transport by Rivers: Current Progress and Future Challenges. The United Nationals World Water Assessment Programme (WWAP), Scientific Paper, United Nationals Educational, Scientific and Cultural Organization (UNESCO), Paris, France.

Wehner, M, Easterling DR, Lawrimore JH, Heim RR, Vose RS, and Santer BD (2011) Projections of Future Drought in the Continental United States and Mexico. Journal of Hydrometeorology 12:1359-1377.

Westerling A, Brown T, Schoennagel T, Swetnam T, Turner M, and Veblen T (2014) Briefing: climate and wildfire in western US Forests. In Sample VA and Bixler RP, Eds., Forest conservation and management in the Anthropocene: Conference proceedings. Proceedings. RMRS-P-71. Fort Collins, CO: US Department of Agriculture, Forest Service. Rocky Mountain Research Station.

Wohlgemuth P (2003) Hillslope erosion and small watershed sediment yield following a wildfire on the San Dimas Experimental Forest, southern California. Online at http://www.firescience.gov/projects/03-2-3-13/project/03-2-3-13_03_2_3_13_Deliverable_02.pdf , accessed 22 June 2015.

APPENDIX A: PROJECTED CLIMATE CHANGES WHICH AFFECT SEDIMENT YIELD BY REGION

This section discusses how climate is projected to change across the United States. The National Climate Assessment (Melillo et al., 2014) divides the United States into eight regions (Figure 3), and tabulates observed and projected climate changes by region. These changes are listed in Table 1. Projected changes to precipitation and drought patterns are discussed on a regional basis in the remainder of this section.

Northeast

The Northeast (Figure 3) has a temperate climate characterized by warm, humid summers and cold, humid winters, with temperatures in all seasons decreasing from south to north. Precipitation is approximately 40 inches per year, higher closer to the coast and in upstate New York due to lake-effect snows. Precipitation primarily results from large-scale extra-tropical storm systems in all seasons. The Northeast has experienced the greatest historical increase in extreme precipitation than any other region in the U.S.: between 1958 and 2010, there was a 74% increases in the amount of precipitation falling in very heavy rains (Melillo et al., 2014).

Under a warming climate, precipitation is anticipated to increase, with increasing frequency of heavy precipitation events. According to the National Climate Assessment, the Northeast has experienced a greater recent increase in extreme precipitation than any other region in the United States, with a 70% increase observed in the amount of precipitation falling in very heavy events (between 1958 and 2010).

Streamflow in the Northeast is heavily dependent on snowpack, and on the timing and speed of snowmelt, particularly as many surface water systems in the region have limited storage. Over the last century, significant changes in the timing of winter-spring streamflows have occurred in those parts of the Northeast that have a substantial annual snowpack (Hodgkins and Dudley, 2006; Hodgkins et al., 2003) due to changes in late winter air temperature (Hodgkins et al., 2003). Snowmelt-related streamflows are projected to continue to become earlier in the next century (Hayhoe et al., 2007; Kunkel et al., 2013c).

Midwest

Climate in the Midwest (Figure 3) is affected by its mid-latitude, continental interior location. Positioned far from the ameliorating effects of oceans, the region is subject to deep cold and snow conditions in winter and humid, subtropical air masses in summer. In winter, the polar jet stream is often located near or over the region, enabling the regular movement of storms systems through the region (Kunkel et al., 2013b). In the spring, as the polar jet migrates northward, it is replaced by warm, humid subtropical air masses. The combination of sharply contrasting air masses and strong winds aloft allow for frequent development of thunderstorms and tornadoes. In summer, the Bermuda high helps guide warm, humid air into the region from the Gulf of Mexico, and summer is typically the rainiest season (Kunkel et al., 2013b). Especially in spring and fall there is a gradation between the drier north and wetter south. Like the Northeast, agriculture in the region is typically not irrigated, and therefore the region is highly vulnerable to summer drought (Kunkel et al., 2013b). As with the southeast, the Bermuda High acts as a

gateway to summer precipitation. In certain positions, it helps funnel moisture into the region, but if it moves farther west/inland, it can serve as a barrier to moisture entering the region.

Climate model projections of mean annual precipitation mid-century (2041-2070) show the northern portion of the region becoming wetter by as much as 3-6%, increasing to 6-12% greater than currently by the end of this century (Kunkel et al., 2013b). Little change is projected for the southern part of the region. Increases in precipitation are simulated for fall, winter and spring throughout the region (Kunkel et al., 2013b), but in summer, there is a great deal more variation: decreases of up to 15% may occur in southwestern Missouri, and decreases of 5-10% may occur in a broad band across Missouri, Illinois, Indiana and Ohio (Kunkel et al., 2013b). By contrast, Minnesota, Wisconsin and northern Michigan are projected to see a 0-10% increase in summer precipitation (Kunkel et al., 2013b). The models do not project significant increases in the average annual maximum number of consecutive days with less than trace precipitation (0.1 inches) (Kunkel et al., 2013b) in 2055 compared to 1980-2000. Significant decreases in the number of days with trace precipitation are modeled for northern Minnesota (Kunkel et al., 2013b). Together these indicate that models do not project significant increases in drought frequency for the region.

Great Plains

The Great Plains (Figure 3) includes all the states sandwiched between Montana and North Dakota to the north and Texas to the South. With the exception of western Montana and western Wyoming, it is a continental interior region characterized by relatively flat topography. The Rocky Mountains to the west largely block moisture from the Pacific Ocean, so most of the moisture entering the region originates in the Gulf of Mexico, with distance from the Gulf influencing the frequency and amount of the moisture reaching different portions of the region (Kunkel et al., 2013a). Because there are no significant mountain ranges to the north of this region, outbreaks of Arctic air can occur, bringing bitterly cold temperatures to the region in winter.

Precipitation is spatially variable, with some portions of the far southeastern part of the region receiving more than 60 inches per year, while portions of the far western region receive less than 10 inches per year (Kunkel et al., 2013a). Winter precipitation is typically in the form of midlatitude cyclones that follow the track of the jet stream. Summer is the rainiest season; The Bermuda High draws warm, humid air into the eastern and southern parts of the region, producing short-lived rainfall and thunderstorms. In the far southwestern portion of the region (esp. West Texas), summer precipitation peaks during the North American Monsoon (July, August, September). In coastal Texas, hurricanes in the late summer and fall provide the bulk of the precipitation (Kunkel et al., 2013a).

An analysis of precipitation trends for the period 1895-2011, broken out by sub-region, shows no trend in any season, or annually. However, a significant increase in the occurrence of extreme precipitation events over this time period was observed (Kunkel et al., 2013a). In addition, temperature increased approximately 0.13 to 0.33°F/decade in the northern Great Plains, and by a smaller amount in the winter and spring on the southern Great Plains (Kunkel et al., 2013a).

Model projections of future precipitation indicate a pronounced north-south gradient of future precipitation with southern areas showing a decrease in precipitation and northern areas showing

an increase (Kunkel et al., 2013a). Seasonally, models project winter precipitation increases across most of the Great Plains; increases north and east and decreases south and west in the spring and summer, except for central Texas where summer precipitation is projected to increase; and an increase in fall precipitation everywhere except the western-most portions of the region (Kunkel et al., 2013a).

Losses to winter snowpack are projected in the Rocky Mountains in the Southwestern states. Warmer winter and spring temperatures, and reduced winter precipitation, are anticipated to reduce spring runoff, cause that runoff to occur earlier in the year, and reduce late summer and fall base flows in streams heading in the Southern Rocky Mountains and traversing the Southern Plains, including the Arkansas, Red, White, Canadian and Platte Rivers (see Southwest section).

Northwest

The Northwest (Figure 3) has a Mediterranean climate characterized by wet winters and dry summers. Rainfall is heaviest along the Pacific coast, but declines markedly as west-to-east moving storm systems traverse successive north-south trending mountain ranges (Coast Mountains, the Cascade Range, the Olympic Mountains, and the Rocky Mountains). Precipitation is heaviest on the windward (western) side of the mountains. For instance, on the western slopes of the Olympic Mountains, the annual precipitation may exceed 16.4 feet of water equivalent, while low elevation areas on the lee side of the Cascades may receive less than 8 inches. ENSO is currently an important cause of regional drought (Mote et al., 2013).

Coupled Model Intercomparison Project 3 (CMIP3) models project warming in the Northwest of 3-11°F by 2100, with the largest gains in the summer, and a 3-5% increase in average annual precipitation with a range of -10% to +18% for 2070–2099 (Mote and Salathé, 2010). The models exhibit great variation in fall, winter and spring precipitation, but strongly agree that summer precipitation will decline by as much as 30%, likely resulting in lower summer stream flows and greater wildfire incidence (Mote et al., 2013). Drying is more likely in some seasons in the interior Columbia Plateau area than elsewhere. Models projecting the warmest temperatures also project the greatest summertime drying (Mote et al., 2013). Model discrepancy in precipitation change is driven by uncertainty in how far north the boundary between the low and high latitudes will be: models agree that high latitude areas will get wetter, and low latitude areas drier, but disagree about where this boundary will lie (similar issues drive uncertainties across the central Great Plains).

A critical change across the Northwest may involve changes in snowmelt dominant watersheds: warmer winter air temperatures are projected to cause snowmelt-dominant and mixed rain-snow watersheds to gradually trend towards mixed rain-snow or rain-dominant watersheds (Raymondi et al., 2013). This is likely to result in reduced peak streamflow, increased winter flow, and reduced later summer flow in these watersheds. By the 2080s, a complete loss of snowmelt dominant basins is projected for the Northwest under the A1B (moderate emissions) scenario (Raymondi et al., 2013).

Alaska

Alaska's climate is influenced by its high latitude location and topography (Stewart et al., 2013), which results in cold, short winter days and long summer days. Solar radiation is weak, even in

summer. East-west trending mountain ranges are important topographic barriers to the northward movement of precipitation to the interior and northern portions of the state.

During the cooler months of the year, the climate across most of the state is dominated by cold, dry polar air; sea ice reduces evaporation, contributing both to cold and aridity, particularly in areas north of the Alaska and Aleutian Ranges. In winter, the Aleutian Low strengthens over the Gulf of Alaska, generating storms in southern Alaska from late fall to late spring (NOAA National Weather Service, n.d.). The Aleutian Low weakens in summer and retreats poleward, and the summer climate in the Gulf of Alaska area is dominated by the North Pacific High pressure system (clear skies, few storms) (NOAA National Weather Service, n.d.).

Temperature trends in Alaska for the period 1949-2011 show warming of 2.5 to 9.0°F across the year, with the interior and north warming faster than other regions. Regardless of emissions scenario, models project continued significant warming across most of the state, with the highest rates of warming in the northern third of the state (Stewart et al., 2013). Warming is already increasing evaporation, melting the permafrost, and lengthening the growing season (Markon et al., 2012). These trends are anticipated to continue into the future, contributing to decreases in soil moisture and increases in wildfire (Markon et al., 2012). Warming is also accelerating mountain glacier melting, which in the short run may increase water availability to hydropower projects in the southeast, but in the long run may lead to increased hydrologic drought once glaciers melt completely (Markon et al., 2012).

Average annual precipitation has increased an average of 10 percent across the state over the period 1949-2005 (Shulski and Wendler, 2007). Increases have occurred primarily in the fall, winter and spring, while summer precipitation has decreased or remained near-average across much of the state (Shulski and Wendler, 2007). In addition, extreme precipitation events have also increased, with the greatest increase occurring in the summer. Precipitation is forecast to increase across the state for all future periods (Stewart et al., 2013). Consequently, meteorological drought is unlikely to increase in frequency under modeled future climate conditions in this region. However, declines in permafrost, extension of the growing season, loss of mountain glaciers, warmer temperatures, and increased evapotranspiration may contribute significantly to hydrologic and agricultural (soil moisture deficit) drought increases during the summer months (Markon et al., 2012).

Southeast

The Southeast (Figure 3) has a warm, humid climate with hot summers and warm winters. Precipitation over the Southeast is controlled by the location of the Bermuda High. In summer, the high is typically positioned off the Atlantic Coast. Its clockwise rotation pulls moisture from the Atlantic and Gulf of Mexico into the region, leading to frequent thunderstorm activity in the afternoon and evening hours (Konrad and Fuhrmann, 2013). The Bermuda High is not stationary, but shifts position within and between seasons. When the Bermuda High builds westward across the region, this shuts off the transport of humid air into the region, resulting in hot dry weather, heat waves, and poor air quality. If the Bermuda High persists over the region or immediately south of the region for an extended period, drought conditions typically develop (Konrad and Fuhrmann, 2013). Changes in the location of the Bermuda High also affect the tracks of hurricanes as they move across the region (Konrad and Fuhrmann, 2013).

In winter, the Bermuda High shifts southeastward, enabling the jet stream to expand southward and bring with it cyclonic storm systems (Konrad and Fuhrmann, 2013). The combination of a cold front with humid air drawn in from the Gulf can produce snowstorms or ice storms, particularly in the northern part of the region above latitude 35°N.

The Southeast is prone to droughts as deficits of precipitation can rapidly lead to shortage of freshwater (particularly as demand is high due to rapid population growth and development). Droughts are typically of short duration (one to three years), and may be ameliorated during the late summer and fall by hurricanes (Konrad and Fuhrmann, 2013). Flooding and drought can occur simultaneously in the region. For example, in the lower Mississippi Valley in 2011, flooding due to large winter headwaters, snowpacks and heavy rains in the Midwest coincided with extreme drought in Tennessee, Arkansas, Mississippi and Louisiana (Konrad and Fuhrmann, 2013).

The tree ring record in the Southeast, which extends back some 1,000 years, shows no long term trend in precipitation and soil moisture in the region, and indicates that the severity and duration of several prominent 20th and early 21st Century droughts are not unusual: decade-long droughts have occurred periodically in the region (Konrad and Fuhrmann, 2013).

Model projections of future precipitation based on CMIP3 model data and downscaled data from the North American Regional Climate Change Assessment Program (NARCCAP) indicate a 2-4% decline in average annual precipitation in Louisiana and South Florida, with 6% increases in North Carolina and Virginia by mid-Century (Konrad and Fuhrmann, 2013). Precipitation may increase across most of the region except in summer, where a decrease of up to 15% may occur in parts of Arkansas, Louisiana, and South Florida (Konrad and Fuhrmann, 2013). The intensification and westward expansion of the Bermuda High during summer is a robust feature of several models (Konrad and Fuhrmann, 2013). In the Caribbean (including Puerto Rico), drying is projected to occur in both summer and winter months.

Hydrologic drought is expected to increase in frequency and intensity across the lower Mississippi River Valley and the Gulf Coast, but decrease in frequency across the northern tier and the mid-Atlantic (Strzepek et al., 2010). Significant model uncertainties exist, however (Konrad and Fuhrmann, 2013).

Southwest

The Southwest (Figure 3) covers the six-state area of California, Nevada, Utah, Arizona, New Mexico and Colorado. The Southwest is currently positioned at the northern margin of the subtropics, which is one of the primary reasons for its aridity, the other being its continental interior location in the rain shadow of the Sierra Nevada and Rocky Mountains (Sheppard et al., 2002). Currently, most of the region lies within the subtropical dry zone during the summer, where it experiences warm, dry conditions. In Arizona and New Mexico, a monsoonal climate emerges in July, August and early September. However, California and Nevada experience largely dry summers. Eastern New Mexico and eastern Colorado receive significant summer precipitation due to orographic effects and the interaction between mid-latitude cyclonic systems with moisture brought into the eastern plains by the Bermuda High (see Southeast, Great Plains sections). Arizona and New Mexico receive most of their precipitation during the summer

monsoon. ENSO currently exerts a significant influence on interannual precipitation variability in the region.

In winter, the boundary between the subtropics and the mid-latitudes diminishes equator-ward, permitting the jet stream to bring large storms to the region. California receives the bulk of its rain from storm systems that originate over the Pacific. These storms follow the jet stream eastward, bringing diminishing quantities of snow to the eastern portion of the Southwest until the high plains are reached. In the lee of the Rocky Mountains, winter storms tend to reform and gain strength, bringing severe winter conditions to eastern Colorado and eastern New Mexico.

Precipitation declines are projected, particularly for the fall, winter, and spring (Melillo et al., 2014), with projected decreases in headwaters streamflow into the Rio Grande by approximately one-third, and diverted flow from the San Juan River by approximately one-fourth (Reclamation, USACE and Sandia, 2013). Comparable declines in Colorado River flow are expected (Melillo et al., 2014). Modeling by Seager et al. (2007) projects that the average climate of the Southwest by the middle of the 21st century will resemble that of climate during a multi-year drought of today, with droughts much worse than any since the medieval period. The median values across multiple model runs indicate steady declines in both winter and summer precipitation are anticipated over the 21st century (Seager and Vecchi, 2010). Temperature increases combine with precipitation decreases to produce increasingly arid winters across the region (Seager and Vecchi, 2010). Because of the gradual drying of the region, even the models with the wettest future climates failed to project a return to conditions similar to the wetter climate of the 1980s and 1990s (Seager and Vecchi, 2010). By the end of the twenty-first century, conditions similar to the droughts of the 1930s and 1950s are projected to become “normal” (Wehner et al., 2011).

Hawai'i

Located in the central Pacific, Hawai’i is the only state located entirely within the tropics. Its climate is humid, characterized by equable temperatures (similar in all seasons). Because Hawai’i is a volcanic island chain, its steep vertical relief results in significant temperature differences along a topographic gradient. Summers are typically drier than winters.

Precipitation is carried to the islands on the trade winds, which blow predominantly from the north or northeast (NOAA, 1985). The trade winds are the result of outflow from the North Pacific High. In summer, the North Pacific High reaches its greatest spatial extent and northernmost position, steering the trade winds southeastward. This results in light to medium rainfall events resulting from orographic uplift of humid air (Keener et al., 2013). Consequently, there is a profound difference in especially summer precipitation between the windward and leeward sides that is most pronounced at lower elevations (NOAA, 1985). In winter, reductions in the strength of the North Pacific High and its more southerly position lead to reductions in trade wind flows, and permit mid-latitude storms, tropical cyclones and other storm systems to approach the islands from the west (Keener et al., 2013). There may be as many as two to seven major winter storms in a year (NOAA, 1985). The Hawaiian Islands are sensitive to the ENSO cycle: during El Niño events, weakened trade winds lead to reductions in rainfall and dry conditions throughout the island chain (Keener et al., 2013).

A general downward trend in precipitation has been noted statewide over the last century that is evident in both observations and GCMs (Keener et al., 2013). The decline in precipitation is

associated with increasing frequency of trade wind inversions (which retard storm formation), a decline in trade wind occurrence, and higher rates of warming at high elevations (Keener et al., 2013). There has also been a trend toward fewer extremely high rainfall events and more frequent light intensity events (Keener et al., 2013). All the major Hawaiian Islands have also experienced more prolonged drought since 1980 compared to the period 1950-1979, estimated as the increase in the annual maximum number of consecutive dry days (Keener et al., 2013).

Analysis of CMIP3 model projections for future periods centered in 2035, 2055, and 2085 suggest an increase in precipitation in the southern part of the Hawaiian Islands and a decrease north across all emissions scenarios. However, the magnitudes of projected changes are small compared to interannual variation in precipitation, and the models are not in strong agreement (Keener et al., 2013). Precipitation overall is projected to be greater under the high emissions scenario than the low emissions scenario, possibly driven by higher sea surface temperatures in the former. Models also project a weakening of sea surface temperature gradients and atmospheric circulation across the Pacific, which may result in reductions in winter precipitation in Hawai'i resulting in more frequent wintertime drought. This is a continuation of an observed slow weakening of the atmospheric circulation overlying much of the tropical Pacific during the 20th Century (Keener et al., 2013).

Model projections of precipitation and drought in Hawai'i are complicated by the small geographic scale of the islands, their great relief, and the importance of localized processes (orographic lift, trade wind inversions, cloud formation, high altitude temperatures that occur at spatial scales too small to be resolved by existing models. The existing projections for precipitation and drought must therefore be considered preliminary (Keener et al., 2013).

To fill this gap, USACE, together with local experts such as the University of Hawaii at Manoa, and a team based at the National Center for Atmospheric Research (NCAR) is building on enhanced tools developed for the contiguous U.S. and other new data to characterize current and future hydroclimates in each Hawaiian Island. This work has four main elements: climate mapping, climate downscaling, hydrological modeling, and streamflow forecasting under climate-changed futures. Data from weather networks in Hawai'i have been compiled and quality-controlled, introducing newly produced or recovered data in many instances, through a collaboration with University of Hawaii at Manoa. This station data is now being used to construct both deterministic and probabilistic historical datasets with 250-m grids. Historical simulations with the Weather Research and Forecasting (WRF) model (Zhang et al., 2012) are underway in Hawaii applying WRF for 1.5-km grids, a scale at which interactions between the atmosphere and the terrain can be explicitly resolved; preliminary results show that WRF captures the islands' precipitation features well.

APPENDIX A REFERENCES CITED

Fu Q and Lin P (2011) Poleward shift of subtropical jets inferred from satellite-observed lower-stratospheric temperatures. Journal of Climate 24:5597-5603.

Hayhoe K, Wake C, Huntington T, Luo L, Schwartz M, Sheffield J, Wood E, Anderson B, Bradbury J, DeGaetano A, Troy T, and Wolfe D (2007) Past and future changes in climate and hydrological indicators in the US Northeast. Climate Dynamics 28:381-407.

Henry, Hugh AL (2007) Soil freeze–thaw cycle experiments: trends, methodological weaknesses and suggested improvements. Soil Biology and Biochemistry 39(5): 977-986.

Hodgkins GA and Dudley RW (2006) Changes in late-winter snowpack depth, water equivalent, and density in Maine, 1926–2004. Hydrologic Processes 20:741-751.

Hodgkins GA, Dudley RW, and Huntington TG (2003) Changes in the timing of high river flows in New England over the 20th century. Journal of Hydrology 278:244-252.

Keener VW, Hamilton K, Izuka SK, Kunkel KE, Stevens LE, and Sun L (2013) Regional climate trends and scenarios for the U.S. National Climate Assessment: Part 8. Climate of the Pacific Islands. NOAA Technical Report NESDIS 142-8.

Knowles N, Dettinger MD and Cayan DR (2006) Trends in snowfall versus rainfall in the Western United States. Journal of Climate 19:4545-4559.

Konrad CE and Fuhrmann CM (2013) Climate of the Southeast: past, present and future. In Ingram KT, Dow K, Carter L, Anderson J (eds.) Climate of the Southeast United States: Variability, change, impacts and vulnerability. Island Press, Washington DC, pp. 8-42.

Kunkel KE, Stevens LE, Stevens SE, Sun L, Janssen E, Wuebbles D, Kruk MC, Thomas DP, Shulski MD, Umphlett NA, Hubbard KG, Robbins K, Romolo L, and Akyuz A (2013a) Regional climate trends and scenarios for the U.S. National Climate Assessment: Part 4. Climate of the U.S. Great Plains. NOAA Technical Report NESDIS 142-4.

Kunkel KE, Stevens LE, Stevens SE, Sun L, Janssen E, Wuebbles D, Redmond KT, and Dobson JG (2013b) Regional climate trends and scenarios for the U.S. National Climate Assessment: Part 3. Climate of the Midwest U.S. NOAA Technical Report NESDIS 142-3.

Kunkel KE, Stevens LE, Stevens SE, Sun L, Janssen E, Wuebbles D, Rennells J, DeGaetano A, and Dobson JG (2013c) Regional climate trends and scenarios for the U.S. National Climate Assessment: Part 1. Climate of the Northeast U.S. NOAA Technical Report NESDIS 142-1.

Maloney ED, Camargo SJ, Chang E, Colle B, Fu R, Geil KL, Hu Q, Jiang X, Johnson N, Karnauskas KB, Kinter J, Kirtman B, Kumar S, Langenbrunner B, Lombardo K, Long LN, Mariotti A, Meyerson JE, Mo KC, Neelin JD, Pan Z, Seager R, Serra Y, Seth A, Sheffield J, Stroeve J, Thibeault J, Xie S-P, Wang C, Wyman B, and Zhao M (2013) North American Climate in CMIP5 Experiments: Part III: Assessment of Twenty-First-Century Projections. Journal of Climate 27:2230-2270.

Markon CJ, Trainor SF and Chapin FS (eds.) (2012) The United States National Climate Assessment - Alaska Technical Regional Report. U.S. Geological Survey Circular 1379, Reston, Virginia.

Melillo JM, Richmond TC and Yohe GW (eds.) (2014) Climate Change Impacts in the United States: The Third National Climate Assessment. U.S. Global Change Research Program.

Mote PW, Abatzoglou JT, and Kunkel KE (2013) Climate: variability and change in the past and the future. In Dalton MM, Mote PW, Snover AK (eds.) Climate change in the Northwest: implications for our landscapes, waters, and communities. Island Press, Washington DC, pp. 25-40.

Mote PW, Hamlet AF, Clark MP, and Lettenmaier DP (2005) Declining mountain snowpack in western North America. Bulletin of the American Meteorological Society 86:39-49.

NOAA (1985) Narrative summaries, tables and maps for each state with overview of State Climatologist programs, Third Edition, Volume 1: Alabama-New Mexico and Volume 2: New York-Wyoming. Online at http://www.wrcc.dri.edu/climate-narratives/, accessed 15 July 2014, Gale Research Company.

NOAA National Weather Service (n.d.) Aleutian Low. NOAA National Weather Service.

Raymondi RR, Cuhaciyan JE, Glick P, Capalbo SM, Houston LL, Shafer SL, and Grah O (2013) Water resources: implications of changes in temperature and precipitation. In Dalton MM, Mote PW, Snover AK (eds.) Climate change in the Northwest: implications for our landscapes, waters, and communities. Island Press, Washington DC, pp. 41-66.

Seager R, Ting MF, Held I, Kushnir Y, Lu J, Vecchi G, Huang HP, Harnik N, Leetmaa A, Lau NC, Li CH, Velez J, and Naik N (2007) Model projections of an imminent transition to a more arid climate in southwestern North America. Science 316:1181-1184.

Seager R and Vecchi GA (2010) Greenhouse warming and the 21st century hydroclimate of southwestern North America. Proceedings of the National Academy of Sciences of the United States of America 107:21277-21282.

Seidel DJ, Fu Q, Randel WJ, and Reichler TJ (2008) Widening of the tropical belt in a changing climate. Nature Geoscience 1:21-24.

Sheppard PR, Comrie AC, Packin GD, Angersbach K, and Hughes MK (2002) The climate of the US Southwest. Climate Research 21:219-238.

Shulski M and Wendler G (2007) The Climate of Alaska. University of Alaska Press.

Stewart BC, Kunkel KE, Stevens LE, Sun L, and Walsh JE (2013) Regional Climate Trends and Scenarios for the U.S. National Climate Assessment Part 7. Climate of Alaska. NOAA Technical Report NESDIS 142-7.

Stewart IT, Cayan DR, and Dettinger MD (2004) Changes in snowmelt runoff timing in western North America under a 'business as usual' climate change scenario. Climatic Change 62:217-232.

Stewart IT, Cayan DR, and Dettinger MD (2005) Changes toward earlier streamflow timing across western North America. Journal of Climate 18:1136-1155.

Strzepek KG, Yohe G, Neumann J, and Boehlert B (2010) Characterizing changes in drought risk for the United States from climate change. Environmental Research Letters 5:doi:10.1088/1748-9326/1085/1084/044012.

Trenberth KE, Dai A, van der Schrier G, Jones PD, Barichivich J, Briffa KR, and Sheffield J (2014) Global warming and changes in drought. Nature Clim. Change 4:17-22.

U.S. Bureau of Reclamation (Reclamation), U.S. Army Corps of Engineers (USACE), and Sandia National Laboratories (Sandia) (2013) West-Wide Climate Risk Assessment: Upper Rio Grande Impact Assessment. U.S. Bureau of Reclamation, Upper Colorado Region, Albuquerque Area Office (December 2013), Albuquerque, NM.

Wehner M, Easterling DR, Lawrimore JH, Heim RR, Vose RS, and Santer BD (2011) Projections of future drought in the continental United States and Mexico. Journal of Hydrometeorology 12:1359-1377.

Wohlgemuth P (2003) Hillslope erosion and small watershed sediment yield following a wildfire on the San Dimas Experimental Forest, southern California. Online at http://www.firescience.gov/projects/03-2-3-13/project/03-2-3-13_03_2_3_13_Deliverable_02.pdf , accessed 22 June 2015.

Zhang C, Wang Y, Lauer A, and Hamilton K (2012) Configuration and evaluation of the WRF model for the study of Hawaiian regional climate. Monthly Weather Review 140:3259-3277.

APPENDIX B DISTRICT RSI STATUS

The following sections describe the RSI gathered from the pilot districts, based on interviews with district staff.

Omaha District (NWO)

Lewis & Clark Lake

There are 28 reservoirs within the Omaha District (NWO). Six of the reservoirs are on the mainstem Missouri River, while 22 are on tributary streams. Reservoirs are all permanent pools apart from Cedar Canyon Dam (Red Dale Gulch), which is a detention structure with no permanent storage located on one of the tributary streams.

Sediment Surveys and Area-Capacity Curves

Funding constraints and other priorities have limited NWO capability to collect RSI since the 1980s. However, over the past five or six years NWO has been able to update the mainstem reservoir sediment surveys and about half of the tributary surveys using Operations and Maintenance (O&M) baseline, non-routine, and end-of-year reprogrammed funds. Surveys since the 1980s have been primarily hydrographic, single-beam surveys along range lines from water edge to water edge. As funding becomes available, and on a project-need basis, land surveys are also conducted. For the most recent set of mainstem dam surveys, the surveys were mostly complete for both land and bathymetric data. The current NWO practice is to maintain the end points of each range line monument to support repeatability, although the district indicated there is no regular schedule of maintenance. A partial hydrographic survey using range lines (water edge to water edge) was recently completed on Lake Oahe, and a complete survey and updated area capacity curve were completed for Lake Sharpe in 2012.

Typically, once a survey has been completed, NWO updates the area-capacity curve. There are, however, a few reservoirs for which the area-capacity curves have not been updated due to insufficient staff resources. These reservoirs include Gavins Point, Olive Creek, and Conestoga. In other cases, curve information is not available. For example, the curve for Cottonwood Springs has not been updated since 1970, although there have been several surveys since this time. NWO has not been able to recreate the curve from old topographic maps, and intermediate files to produce a new curve are missing. When funding becomes available, NWO plans to have a LiDAR (Light Detection and Ranging) survey conducted in order to re-calculate a curve using the contour interval method. Table 10 summarizes the sediment survey and area-capacity curve data for NWO.

Vertical Datum: NWO indicated that survey data is collected using the North American Vertical Datum of 1988 (NAVD88), but reported using the National Geodetic Vertical Datum of 1929 (NGVD29) as the common benchmark. The NAVD88 data is then archived as part of the project files.

Table 10. NWO sediment survey and area-capacity curve data summary

RSI TYPE	RSI DESCRIPTION
Sediment Surveys	• **Survey methods:** Primarily range line and hydrographic (single-beam) surveys. LiDAR survey in 2011 at Gavins Point Dam. *Note: District maintains the survey monuments at the end points of range lines as needed.* • **Data format:** Electronic (HEC-DSS). • **Organization:** Master list of all NWO projects (spreadsheet), including survey dates and status (i.e., partial or complete data sets). • **Project status:** Mainstem projects resurveyed between 2007 and 2012; tributary projects resurveyed between 1983 and 2010 - excluding Cedar Canyon Dam detention basin surveyed only once at time of closure (1959).
Area-capacity Curves	• **Data format:** Pre-1990s – most paper files transferred to electronic format; post-1990s tables/curves in Excel format. *Note: Some area-capacity data has been lost (e.g., Cottonwood Springs) or stored in microfiche and paper format.* • **Data status:** Area-capacity curves are generally updated after survey completion – *unless funding is limited (such as for Gavins Point, Olive Creek, and Conestoga).*

Aerial Imagery and Photography: Aerial images and photography are available from the 1940s to the present. Most of the older black-and-white print photos are stored in cabinet files or scattered in NWO branches or sections. The historical photography is mainly of the mainstem, and for a particular reservoir and year may be difficult to locate. More recent aerial imagery since 2000 has been project-driven as opposed to being supported by O&M funding. These files are stored electronically on the NWO server. Due to limited funding, other imagery sources are often used, such as NAIP (National Agriculture Imagery Program) imagery administered by the USDA (U.S. Department of Agriculture). NAIP images are typically taken every two to three years and are available for free download through the USDA Geospatial Data Gateway.

Sediment Sampling: NWO stopped collecting in-house suspended sediment and density measurements in the 1980s. However, bed-material samples are still collected when funding and manpower permit. Most of the bed-material data are stored in U.S. Army Corps of Engineers' Hydrologic Engineering Center Data Storage System (HEC-DSS) format with project data on the server; however, some bed data are still on compact disc and computer input card files. There are six USGS gage stations actively collecting sediment data in NWO (see Table 11). Some historical sediment data also exists in paper format from sediment gages operated in the 1920s, 30s, and 40s. Currently, there has only been one cohesive sediment analysis, which was conducted at Lewis and Clark Lake in 2012.

Sediment chemistry data is collected monthly during the non-ice season by the USACE water quality section. The data is stored in electronic and paper format with the water quality group and also stored in the national database. Table 12 summarizes NWO sediment samples and sediment chemistry data.

Sediment Studies and SSWP: Several sediment studies exist containing sediment data. Most of these reports have been transferred from paper to PDF format and are stored on the district server. The district has never prepared a SSWP. Instead, the district prepares a Sedimentation

Program Management Plan, which includes an annual "Notes on Sedimentation Activities." The annual sedimentation report includes all sedimentation activities that occurred throughout the year, and provides a list of items needed to update the RSI for the upcoming year.

Table 11. NWO active USGS sediment gages

STREAM NAME	LOCATION	STATION NUMBER	DATA COLLECTED
Yellowstone River	Sidney, MT	06329500	Suspended sediment
Bad River	Fort Pierre, SD	06441500	Suspended sediment
White River	Oacoma, SD	06452000	Suspended sediment
Missouri River	Sioux City, IA	06486000	Bed, suspended sediment, flow velocity
Missouri River	Omaha, NE	06610000	Bed, suspended sediment, flow velocity
Missouri River	Nebraska City, NE	06807000	Bed, suspended sediment, flow velocity

Table 12. NWO sediment sample and sediment chemistry data summary

RSI TYPE	RSI DESCRIPTION
Sediment Samples	• **Data status:** District stopped collecting in-house suspended sediment samples & density measurements in the 1980s. Some bed material samples collected when funding permits. USGS manages current bed and suspended data. Several projects have no sediment data. • **Sediment gages:** Six active USGS gages. • **Data format:** In-house bed material stored mostly in HEC-DSS format; USGS bed material data available on USGS website; other sediment data stored in reports, microfiche, paper, electronic, and input cards.
Sediment Chemistry/ Quality	• **Data type:** Temperature, turbidity, dissolved oxygen, total suspended solids, and dissolved solids are collected by the water quality section (collected monthly during non-ice season – driven by state standards). • **Data format:** Electronic and paper format - stored within the water quality section of the USACE and also stored in the national database - well organized files.

Data Gaps: NWO identified several high-priority data gaps in the RSI during the pilot study:

- Post-flood LiDAR surveys and aerial imagery
- New surveys for Pipestem Lake and most of the Salt Creek Lakes
- Updated area-capacity tables for Lake Sakakawea, Lake Oahe, and Lake Sharpe
- Increase number of suspended sediment gages
- Sediment rating curves to support future reservoir modeling

- Ten additional sediment gages are needed, particularly at tributaries to monitor inflowing sediment loads to the mainstem reservoirs.

RSI Organization: NWO stores sediment surveys and water surface profiles in HEC-DSS format. In addition, most of the bed material data is in HEC-DSS format. Area-capacity curves are stored in electronic format as scanned PDFs of paper files, but files since the 1990s have been stored in Excel spreadsheets. Several of the early survey area-capacity tables cannot be located and may be lost or stored in boxes, on microfiche or paper format, which are difficult to locate for a particular year and reservoir.

RSI data in electronic format is mostly stored on the NWO server by project. However, some data is stored separately within other NWO sections. For example, the water quality data is stored with the water quality group and some of the original survey/topography data is stored in the Geotechnical Engineering Branch as mainly flat paper maps and paper drawings. Vintage photography and historical aerial images are stored in file cabinets with no consistent organization system. Older sediment data and area capacity curves are stored in paper or microfiche format on shelves or in boxes. Some of the area-capacity files have also been misplaced or lost. There has been an effort in recent years to convert the majority of the RSI data to electronic format. However, there is still old bed material data stored in input file cards and old reports with sediment data that need to be transferred to electronic format.

Baltimore District

Jennings Randolph Lake

The Baltimore District (NAB) manages 17 reservoirs. Of these, two are not USACE-owned and were excluded from this study. Of the 15 USACE-owned reservoirs, two are dry (Arkport Dam and Indian Rock Dam) and do not require hydrographic surveys. For the other 13 reservoirs, both hydrographic and topographic surveys are used to estimate remaining storage capacity. RSI files are managed within the Water Control Team within the Water Resources Section of NAB. There is no separate unit for sedimentation. The primary job of the team is water control, so the focus with regards to sediment is loss of storage. This section provides a summary of the RSI findings during the site visit with the district and information provided in the RSI spreadsheets.

Sediment Surveys and Area-capacity Curves: Hydrographic and aerial surveys for all NAB permanent-pool reservoirs were conducted between 1996 and 2000. The hydrographic surveys were conducted with the pool 1 to 2 feet above normal water surface elevation to maximize coverage. Pool levels were lowered for the aerial surveys for the same reason. The two sets of data were then merged to develop a triangulated irregular network (TIN) for each reservoir. Subsequent to these surveys, five permanent pool reservoirs have been resurveyed over the last few years, and a sixth resurvey is planned at Jennings Randolph Lake. The two NAB dry dams

(Arkport and Indian Rock) were surveyed in 2004 for the first time since closure (1939 and 1942, respectively). Each aerial survey (all 15 reservoirs, including the two dry dams) was accompanied by a field photogrammetric control survey to establish control points for interpreting the aerial photography. Since 2010, hydrographic surveys were performed on six NAB reservoirs, including Cowanesque, Curwensville, Tioga, Hammond, East Sidney, and Jennings Randolph.

NAB staff noted that sediment survey methods using range lines with established monuments have not been used since the 1980s. In addition, results from the original range line and planimeter methods do not compare well with the single-beam hydrographic and topographic surveys obtained since 1996. Original elevation-area-capacity tables and curves have been revised and adjusted to reflect results from recent survey methods. Table 13 summarizes the sediment survey and area-capacity curve data for NAB.

Vertical Datum: Range line and hydrographic surveys are reported in NGVD29.

Aerial Imagery and Photography: Color aerial photography was collected for all NAB projects in the spring of 1997. Field photogrammetric control surveys to accompany the aerial photos were conducted primarily between 1996 and 2000, with a few photo control surveys for the smaller projects (such as the dry dams) conducted in the 2000 to 2004 timeframe. All existing aerial surveys and maps pre-1996 are in paper format with no intent to convert to digital.

Sediment Sampling: NAB does not collect sediment data unless there is a project-based need. Some sediment data was collected at Jennings Randolph Lake for a sediment budget study in 1996. Overall, NAB indicated that sediment data is not a major gap in the RSI at this time because there is not much sedimentation occurring. However, there is one reservoir – Almond Lake – that has an ongoing sedimentation problem. According to NAB, the conservation pool storage space has been reduced by almost 50% since project completion in 1949. There has also been some sediment quality concern at Sayers Dam concerning alleged toxins in dust particles blown off the exposed lake bed when the lake is drawn down for additional flood capacity during the winter. The environmental concern has led to changes in how the reservoir is being regulated.

Table 13. NAB sediment survey and area-capacity curve data summary

RSI TYPE	RSI DESCRIPTION
Sediment Surveys	• **Survey methods:** Historic range lines with established monuments; since 1996 hydrographic single-beam surveys and topographic surveys (when funding available). • **Data format:** Electronic format since 1996. • **Organization:** Master notebook with hydrographic surveys and other project information. • **Project status:** All permanent pool reservoirs surveyed between 1996 and 2000 (hydrographic & aerial). Five hydrographic resurveys between 2010 and 2012. Arkport Dam and Indian Rock Dam (dry dams) updated topographic survey in 2004 (aerial). One new hydrographic survey planned for 2013 at Jennings Randolph Lake.
Area-capacity Curves	• **Data status:** Contractor prepared area-capacity curves for the 1996-2000 surveys; original elevation-area-capacity tables and curves have been revised to reflect results from recent survey methods. • **Data format:** Electronic format since 1996.

Sediment Studies and SSWP: Jennings Randolph Lake is the only project where there has been any formal effort to predict future trends in reservoir sedimentation. A report was prepared by NAB 1996. The district has never prepared a SSWP. Instead, NAB prepares three annual reports containing sediment information: Water quality report (30-40 pp), Notes on Sedimentation (2-3 pp), and Water control report (30-40 pp). The annual sediment report includes the current year's work, a reservoir sedimentation plan for the upcoming year, and a description of completed surveys, storage losses, and any sediment impact-related issues.

Data Gaps: NAB identified several high-priority gaps in their RSI as well as lower priority items.

High priority:

- Update hydrographic surveys at three reservoirs
    - Raystown Lake, which also needs topographic data for the flood storage zone
    - Bush Dam
    - Sayers Dam
- Topography/aerial imagery needed for eight reservoirs
- Regular re-surveys every 10 years or after major flood events

Lower priority:

- Update hydrographic surveys at four reservoirs
    - Almond Lake (Note: While Almond lake had a high sedimentation rate, it has a relatively small conservation pool so the overall reduction in capacity is low and the main impacts are to recreation with most of the flood storage capacity remaining.)
    - Whitney Point Lake
    - Stillwater Lake
- Aylesworth Creek Lake
- Topography/aerial imagery needed for six reservoirs

NAB would like to have regularly scheduled sediment surveys every 10 years or after a major flood event in order to keep RSI up to date. Currently, there are seven reservoirs that have not been surveyed since 1996 or 1997, which are identified as high (3) or low (4) priority.

RSI Organization: Much of NAB's historic sedimentation data (i.e., pre-dam topographic surveys, photos, area/capacity computations, and subsequent range line surveys) were misplaced during an office move in 1993. Any existing pre-1993 data is primarily in paper format. Original reservoir data is stored on CDs, and are not on the network. Since the 1993 move, all new survey files and RSI data are stored in electronic format on the NAB network. Sediment surveys after 1996 are prepared by a contractor with a brief report and provided to NAB on a DVD. The files are then stored on the network in files by project name. RSI project files are also stored in a

master notebook. An example of a project summary page included in the notebook is shown in Figure 17. The table includes information on when surveys were completed, where the data is stored, who conducted the surveys, etc. NAB also has an internal website with the updated reservoir storage and other project-related information.

PROJECT / AREA	AERIAL PHOTOGRAPHY		HYDROGRAPHIC SURVEYS	TOPOGRAPHIC SURVEYS	BATHYMETRIC AND TOPOGRAPHIC MAPPING	CHANGE IN STORAGE	
	LOW ALTITUDE SHOTS	HIGH ALTITUDE SPOT				BELOW CONSERVATION POOL	AT SPILLWAY POOL
NORTH BRANCH POTOMAC RIVER							
JENNINGS RANDOLPH	KITZMILLER TO LUKE						
DATE	02 APR 1997	02 APR 1997	08-09 APR 1997	OCT 1997	APR 1998	SUMMER POOL @ 1466'	FLOOD POOL @ 1468'
LAKE ELEV ON SURVEY DATE	1464.1	1464.1	1466.5 TO 1467.2	-----	-----	LOSS -6.8% (-6481 AF)	LOSS -6.8% (-6552 AF)
CONTRACTOR	PHOTOSCIENCE		TVGA	TVGA	HORIZONS		FLOOD POOL @ 1500' LOSS -6.3% (-8203 AF)
SAVAGE	LAKE TO WESTERNPORT						
DATE	02 APR 1997	02 APR 1997	21 & 23-24 MAY 1996	NONE	SEP 1997	SUMMER POOL @ 1467'	FLOOD POOL @ 1468.5'
LAKE ELEV ON SURVEY DATE	1462.8	1462.8	1468.4 TO 1468.7	-----	-----	LOSS -3.3% (-651 AF)	LOSS -3.0% (-600 AF)
CONTRACTOR	PHOTOSCIENCE		CENAB-OP	-----	CENAB-OP		
UPPER SUSQUEHANNA RIVER BASIN							
EAST SIDNEY	LAKE						
DATE	27 APR 1997	30 APR 1997	12-13 NOV 1996	AUG 2000	JAN 2001	WINTER POOL @ 1140'	FLOOD POOL @ 1203"
LAKE ELEV ON SURVEY DATE	1140.6	1142.3	1153.5 TO 1164.8	-----	-----	LOSS -27.4% (-465 AF)	LOSS -2.4% (-789 AF)
CONTRACTOR	PHOTOSCIENCE		TVGA	TVGA	HORIZONS	SUMMER POOL @ 1150' LOSS -15.2% (-509 AF)	

Figure 17. Example project summary table from master notebook (truncated)

Los Angeles District

There are 16 reservoirs within the Los Angeles District (SPL) – all are dry dams except for Alamo Dam. In addition to the 16 reservoirs, there is one debris basin (Haines) included in this pilot study. SPL indicated that four of the reservoirs were designed to be self-regulating (Pine Canyon Dam, Mathews Canyon Dam, Mojave Dam, and Whitlow Ranch Dam). This section provides a summary of the RSI findings and information provided in the RSI spreadsheets.

Sediment Surveys and Area-capacity Curves: Topographic surveys for the past 10 to 12 years have been conducted using LiDAR and aerial photogrammetry methods for the dry dams. For the one wet dam, bathymetric surveys have been performed (the last survey was in 1985). Eight of the 16 reservoirs have been resurveyed within the past 10 years. Some of the remaining reservoirs have not been surveyed in more than 40 years, while two of the reservoirs have never been surveyed since dam closure.

Typically, once a new survey is completed, SPL updates the area-capacity curve. However, there are some surveys without an area-capacity analysis. For some curves, the date of the survey on which it was based is unclear. A “best guess” was based on the date provided on a particular area-capacity table. The best guess was also applied to whether a survey was partial or complete

for a certain year. For example, an area-capacity curve for Fullerton Dam is labeled "based on original survey of 1941 and bottom resurvey of 1944." It was assumed ("best guess") that the 1941 survey was a complete survey and the 1944 survey was just the lower elevations of the reservoir.

Reservoir area-capacity curves are in the form "elevation vs. storage" and "elevation vs. area" tables or curves and stored in a binder for each of the projects. Since the 1990s, the curves are updated in Excel using a Reservoir Inundation Calculator (RIC) developed by the USACE Remote Sensing/GIS Center of Expertise (RS/GIS CX) located at the Engineer Research and Development Center (ERDC) Cold Regions Research and Engineering Laboratory (CRREL). The RIC works with ArcGIS 9.3 or below and is currently being updated for use in the RSI portal. Besides the hard-copy files kept in project binders, most area-capacity related curve data are also stored in HEC-DSS files on the SPL network. Area-capacity tables generally have dates that indicate on which survey year they are based. There are some tables with several dates, and the actual survey date is unclear. Table 14 summarizes the sediment survey and area-capacity curve data for the district.

Datum Issues: SPL indicated that there have been some datum issues with original surveys, which may have been performed using MSL, NGVD29, NAVD88, or some local datum. The elevations used in the area-capacity tables have been converted to the NGVD29 datum so that all of the dams have consistent vertical datums. The dams that seem to have local datums are Brea, Carbon Canyon, Fullerton, and Mathews Canyon (unknown for Pine Canyon). The dams that seem to have datums that correlate to NGVD29 are Alamo, Hansen, Lopez, Prado, San Antonio, Santa Fe, Sepulveda, and Whittier Narrows. Datums for the remaining dams are uncertain. SPL noted that NGVD29 and MSL were, for the most part, very similar, but may have been incorrectly interchanged for several surveys.

Sediment Sampling: Sediment data is not collected as part of the overall program. However, sediment data is sometimes collected on a project basis. Any sediment sample information that exists is typically stored with the project manager, and not included in the reservoir folder on the network. There are no sediment gages located at any of the reservoirs.

Table 14. SPL sediment survey and area-capacity curve data summary

RSI TYPE	RSI DESCRIPTION
Sediment/ Aerial Surveys	• **Survey methods:** Dry dams – mostly terrain models (photogrammetry & LiDAR surveys); Alamo (wet dam) – hydrographic survey. • **Data format:** Electronic, diapositives (DiAP) and paper formats. • **Organization:** Survey Section houses sediment survey data – stored at a warehouse off-site. Files difficult to locate – no clear organization. Historic range line data lost, but referenced in water control manuals. • **Project status:** No ongoing survey routine.
Elevation-storage Tables	• **Data format:** HEC-DSS, Excel and paper format. • **Data status:** Area-capacity curves are generally updated after survey completion using a reservoir inundation calculator from CRREL. The program creates elevation/area-capacity tables from the survey data.

Sediment Studies and SSWP: Sediment reports are stored in the library of the SPL Hydrology & Hydraulics Branch in paper format and on the network in PDF files. SPL has never prepared a SSWP. Instead, they prepare an "Annual Report on Sediment Activities." The annual reports are uploaded to the SPL Reservoir Regulation (ResReg) intranet webpage.

Data Gaps: SPL identified several high-priority data gaps in the RSI as well as lower priority items. These priority RSI items are listed below:

High priority:

- Four reservoirs (Painted Rock, Alamo, Whitlow Ranch, and Mojave) need to be resurveyed due to the 2005 major flood event and/or high sediment inflows
- One reservoir (Whittier Narrows) requires updated area-capacity curve (resurveyed in 2012)

Lower priority:

- Resurveys for four reservoirs with 17-70-plus years since last survey
- Resurveys at four reservoirs due to record flood events since last survey

RSI Organization: SPL is working to organize some of the RSI files, as funding permits, to make them more easily accessible. Sediment surveys are stored with the SPL Survey Section off-site in the South El Monte Base yard. The survey team has several historical surveys that need to be organized and documented, but due to staffing and time constraints, it may take some time. To complete this work. There is an effort underway to transfer all paper files to HEC-DSS format and to make sure that sediment survey dates and area-capacity computation dates are correct (many computation dates were incorrectly assumed to be the same date as the survey). The district uses a Reservoir Regulation website that links to water control manuals, sediment yield or loss of storage estimates between surveys, general design memoranda (GDMs), annual reports on sediment activities, and general project information. There are also project folders on the SPL network, but most RSI data are not included.

Fort Worth District

The Fort Worth District (SWF) manages 25 USACE reservoirs primarily for flood risk management, water supply, and hydropower. Water supply reduction due to sedimentation is of concern to reservoir management. This section provides a summary of the RSI findings during the site visit with the district and information provided in the RSI spreadsheets.

Sediment Surveys and Area-capacity Curves: Single-beam bathymetric surveys have been conducted by the Texas Water Development Board (TWDB) since 1994. Land surveys have not

been performed since the 1980s due to lack of funding. All surveys conducted by the TWDB are available for download from their website. Once a survey is complete, the TWDB generates a digital terrain model (DTM). Some new surveys may be compared directly with original surveys due to different survey methods. Sediment surveys are generally updated on a 10-year cycle with state assistance; however, there are some reservoirs that have not been updated in more than 20 years. Some water supply contracts require that a reservoir survey be updated every 15 years, but this may not have occurred. Table 15 summarizes the sediment survey and area-capacity curve data for SWF.

Vertical Datum: Survey data are reported in NGVD29 and NAVD88.

Aerial Imagery and Photography: The little aerial imagery that exists has been obtained mainly at reservoir locations with erosion or channel stability issues. Photography files are stored as original print or digital format – most images are several years old with no dates attached to them.

Sediment Sampling: Sediment cores were collected until the early 1990s. Some of the core samples had sieve and density analysis testing. These data are stored in paper format.

Table 15. SWF sediment survey and area-capacity curve data summary

RSI TYPE	RSI DESCRIPTION
Sediment Surveys	• **Survey methods:** Historic range lines with established monuments (in-house surveys not done in 25-30 yrs); since 1994, hydrographic single-beam surveys (TWDB). • **Data format:** Since 1994, electronic format; historic surveys paper format. • **Organization:** TWDB stores survey files online – *public access* (including GIS shapefiles). • **Project status:** 9 of the 25 reservoirs have not been resurveyed in more than 10 yrs; some reservoirs have not met contract terms to resurvey and re-allocate every 15 yrs.
Area-capacity Curves	• **Data status:** TWDB generates new area-capacity curves after survey completion; pre-1994 curves stored mostly in paper format. • **Organization:** Water control manuals store area-capacity curves – *many manuals need to be updated;* large HEC-DSS database for area-capacity curves – stored by data type, and not so much by project. • **Data format:** Electronic format (HEC-DSS) since 1994; historic curves in paper format.

Sediment Studies and SSWP: Preliminary sediment studies were done for the original design of the SWF reservoirs' sediment reserve. There have been no sediment studies or sediment modeling conducted since that time. Like SPL, SWF prepares an annual report that includes water supply, flood risk management, sediment activities, and other project-related activities that occurred throughout the year in lieu of an SSWP.

Data Gaps: The district identified several major gaps in the RSI data:

- New hydrographic surveys for:
    - Over-drafted reservoirs
    - Water supply pools with 10-15 years since the last survey

  - Reservoirs with major flood events since the last survey
  - Reservoirs flushed-out for sediment management activities
- Post-flood LiDAR at Wright Patman Lake for 2010 hydrographic survey

SWF would like to conduct regularly scheduled sediment surveys every 10 to 15 years, or after a major flood event, in order to keep RSI up to date. This schedule would require one to two surveys each year instead of the current routine of one survey every two years. Currently, there are eight reservoirs that have not been surveyed since 1997 – two of which have not been surveyed in 30 years or more. Over-drafted reservoirs (due to increased population and water demand) need updated surveys to monitor conservation pool storage capacity. Other reservoirs have experienced major flood events since the last survey, and need to be updated. Another gap in the RSI data is a post-flood LiDAR survey at Wright Patman Lake to compare with the 2010 hydrographic survey.

Funding Sources: The Planning Assistance to States (PAS) program funded the early 1990s surveys. Survey costs were split between Federal (50%), State (25%), and local (25%) funds. Since 2006, SWF notes that with performance-based funding, it can be difficult to fund actions needed to keep RSI current. Federal funds from the Texas Water Allocation Assessment (TWAA) are being used to sponsor sediment surveys every couple of years.

RSI Organization: Sediment surveys conducted since 1994 are stored on the TWDB website and on DVDs. Area-capacity curves are stored in a large HEC-DSS database. Most RSI files are not stored on the server in project folders, but instead are stored by data type. Hard copies of survey data, area-capacity curves, and project information are contained in the water control manuals. These manuals, however, need to be updated with recent survey information.

Huntington District

The Huntington District (LRH) manages 35 reservoirs for flood risk reduction. Four of the reservoirs are described as dry dams that provide little to no permanent storage.

Sediment Surveys and Area-capacity Curves: LRH uses EM-1110-2-4000 as a guideline for survey scheduling. The EM suggests that new surveys be scheduled at intervals of 5 to 10 years, depending on the quantities of sediment anticipated and probable needs for such information. The EM also suggests new surveys after each major flood. Nearly half of the LRH reservoirs have been resurveyed over the past 10 years, though due to funding constraints, several reservoirs have not been surveyed in more than 10 years, and a few have not been surveyed in nearly 30 years. The four dry dams have never been surveyed since closure in 1936-1937. Since the 1990s, sediment surveys have been contracted out, whereas pre-1990 the surveys were conducted in-house. Survey data is stored electronically on the LRH network in individual project folders.

Elevation-capacity curves are used instead of area-capacity curves. Since 1997, this data is stored in Excel spreadsheet files. Original curve data is located in the water control manuals (paper format). Most area-capacity related data obtained prior to the 1990s is stored in paper format. Table 16 summarizes the sediment survey and area-capacity curve data for the District.

Vertical Datum: Range line and hydrographic surveys are reported in NGVD29.

Table 16. LRH sediment survey and area-capacity curve data summary

RSI TYPE	RSI DESCRIPTION
Sediment Surveys	• **Survey methods:** Range line and hydrographic surveys (single-beam method used since 1997); one LiDAR survey at Bluestone Lake (2009); sediment surveys conducted in-house until 1990s; since the 1990s, contracted out. • **Data format:** Electronic format (Excel) since 1997; paper format (text file) pre-1997. • **Organization:** Bentley ProjectWise used to manage all project files: hierarchical organization beginning with a project folder. • **Project status:** Permanent pools: 13 reservoirs need to be resurveyed (>10 yrs since last survey); Dry dams (4 total): no sediment surveys have been conducted (only original topography mapping).
Elevation-capacity Curves	• **Data status:** Many original area-capacity curves located in water control manuals; curves never updated. 1977 survey for Beech Fork unknown if elevation-capacity curve exists, but may be difficult to locate, missing or not computed. • **Organization:** Bentley ProjectWise used to manage all project files. • **Data format:** Excel files since 1998; paper format (text file) pre-1998.

Aerial Imagery and Photography: Historic imagery is generally stored on the server with project data, though some historical images may be found in Operations and Management (original prints and negatives). Black and white prints were converted to digital SID and TIFF files. Digital images at Bluestone Lake were taken in 2009 during the LiDAR survey.

Sediment Sampling: The district does not collect sediment data for sieve or density analyses. The only sediment data collected is by the water quality group. Sediment is collected for elutriate testing. Sediment samples are analyzed for organics and metals. This data is stored within the water quality group in electronic format.

Sediment Studies and SSWP: LRH has not conducted any sedimentation studies. No SSWP or annual sediment activity notes have been prepared.

Data Gaps: LRH identified several high- and low-priority data gaps in their RSI:

- High priority:
  - Fourteen reservoirs need to be resurveyed (> 10 years since last surveyed)
  - Six reservoirs require updated sediment survey reports (resurveyed in 2006 or 2009)
- Lower priority:
  - Conversion of paper elevation-capacity curves to electronic format

- Sediment surveys for the four dry dams
- Resurveys for reservoirs affected by 2005 floods

LRH would like to conduct regularly scheduled sediment surveys every 5 to 10 years or after a major flood event in order to keep RSI up to date per sediment survey guidelines described in EM-1110-2-4000. However, funding to support RSI updates has been a challenge. Currently, there are 16 permanent pool reservoirs that have not been surveyed in more than 10 years, and two of them have not been surveyed since the mid-1970s. The four dry dams have never been surveyed, but LRH staff indicate that surveys are needed to determine any changes to reservoir surface area (i.e., compare original topography maps with new surveys). Other gaps in the RSI data include sediment reports for six reservoirs where surveys were completed in 2006 or 2009.

RSI Organization: ProjectWise software is used to store and manage RSI survey data collected since 1997/1998. Individual project folders are set up in the program to store the survey data and accompanying sedimentation reports and elevation-capacity curves. Data still in paper format, including survey data, elevation-capacity curves, sedimentation reports, and original water surface files need to be transferred to electronic format as funding allows. Some of these reports and files may be difficult to locate. Any sediment chemistry data is stored with the water quality group. RSI survey files and capacity curves prior to 1997 are mostly in sediment survey reports still in paper format.

Walla Walla District

Dworshak Dam

The Walla Walla District (NWW) manages seven reservoirs and several river projects (22 projects total), including four run-of-river dams on the Lower Snake River. Reservoirs and river projects are generally surveyed with a 10-year frequency. An exception is for the relatively new reservoirs, including the Snake River and Clearwater reservoirs (Lower Snake projects). These reservoirs are surveyed every two to three years for environmental reasons; therefore, the RSI data at these sites is fairly well documented. Capacity problems due to sediment have been an issue at some of the smaller projects. Larger projects, such as Lucky Peak, appear to have no real sediment issues. Shoaling has occurred in navigation channels due to local erosion and landslides into rivers. NWW completed a Programmatic Sediment Management Plan for the Lower Snake River in 2014. Navigation maintenance dredging is scheduled to be completed in early 2015. This is the first maintenance dredging that has occurred since 2006, due to an injunction related to a lawsuit filed following publication of the 2002 Dredged Material Management Plan.

NWW staff indicate there is a need to conduct sediment impact assessments at several of the reservoirs to fill some of the RSI data gaps. Sediment sampling is generally only done at new projects. Gradation analysis and sediment quality testing (e.g., metals) are conducted. However, NWW indicated sediment sampling and analysis needs to be conducted on a routine schedule at all project locations, not just during project initiation. Sediment data is stored in the USACE

Sediment Qual2 database. The database is managed by a separate sediment quality monitoring group that meets in Portland. The district performed sediment range surveys on the lower three (of four) Snake River reservoirs, as well as on Dworshak reservoir.

Table 17. NWW Sediment Range Section Surveys and Sedimentation Reports

PROJECT	LOCATION	SURVEY FREQUENCY	LAST SURVEY	NEXT SURVEY	MULTI BEAM	LIDAR	SEDIMENT LOAD	SEDIMENT IMPACT ASSESSMENT REPORT	RIVER MILES OF RANGES	# OF RANGES	AVERAGE DISTANCE
Lower Granite	Snake	2-3 YR	2012	2015?	2011	- - -	2009-2011	2012	41.4	66	0.63
	Clearwater	2-3 YR	2012	2015?	2011	- - -	2009-2011	2012	7.85	33	0.24
	Asotin Creek	10 YR	2006	2016	- - -	- - -	- - -	- - -	0.36	7	0.05
Little Goose	- - -	10 YR	2013	2023	- - -	- - -	- - -	- - -	36.45	55	0.66
	Deadman Creek	10 YR	2013	2023	- - -	- - -	- - -	- - -	2	10	0.2
	Meadow Creek	10 YR	2013	2023	- - -	- - -	- - -	- - -	1	3	0.33
	Schultz Bar	10 YR	2013	2023	- - -	- - -	- - -	- - -	- - -	- - -	- - -
Lower Monumental	Main Reservoir	10 YR	2013	2023	- - -	- - -	- - -	- - -	28.2	33	0.85
	Palouse River	10 YR	2005	2015	- - -	- - -	2009-2011	2012	5.48	9	0.61
	Toucannon	10 YR	2005	2015	- - -	- - -	- - -	- - -	1	3	0.33
	Alkali Creek	10 YR	2005	2015	- - -	- - -	- - -	- - -	1	3	0.33
Ice Harbor	- - -	10 YR	2013	2023	- - -	- - -	- - -	- - -	31.21	38	0.82
McNary	- - -	10 YR	2007	2017	- - -	- - -	- - -	- - -	50.54	30	1.68
Snake River below Ice Harbor	- - -	10 YR	2007	2017	- - -	- - -	- - -	2012	9.75	11	0.89
Yakima River	- - -	10 YR	2007	2017	- - -	- - -	- - -	- - -	7.25	13	0.56
Walla Walla River Estuary	Mount	10 YR	2006	2016	- - -	- - -	- - -	- - -	9.18	21	0.44
Walla Walla River	Milton-Freewater	- - -	- - -	- - -	- - -	2010	- - -	2010	- - -	- - -	- - -
Mill Creek	Above diversion dam	10 YR	2010	2020	- - -	2009	- - -	2011	0.5	7	0.07
Bennington Lake	- - -	10 YR	2008	2018	- - -	2009	- - -	2011	0.5	8	0.06
Lucky Peak	- - -	20 YR	1994	2014	- - -	- - -	- - -	- - -	17.5	33	0.53
Snake River (near Jackson, WY)	- - -	10 YR	2007	2012	- - -	2007	- - -	2009	15.4	44	0.35
Dworshak	- - -	- - -	2014	2023	- - -	- - -	- - -	- - -	53	33	1.61

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing the burden, to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.
PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
30-06-2016	Civil Works Technical Series	September 2013 - June 2016

4. TITLE AND SUBTITLE
U.S. Army Corps of Engineers Reservoir Sedimentation in the Context of Climate Change

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
A.O. Pinson (Albuquerque District), B. Baker (ERDC Cold Regions Research and Engineering Laboratory), P. Boyd (Omaha District), R. Grandpre and K. D. White (Institute for Water Resources), M. Jonas (USACE Headquarters)

5d. PROJECT NUMBER
P2 329421

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Directorate of Civil Works
U.S. Army Corps of Engineers
Washington, DC

8. PERFORMING ORGANIZATION REPORT NUMBER
CWTS 2016-05

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Institute for Water Resources
7701 Telegraph Road (Casey Building)
Alexandria, VA 22315

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
CWTS 2016-05

12. DISTRIBUTION/AVAILABILITY STATEMENT
Available through National Technical Information Service, Operations Division
4285 Port Royal Road
Springfield, VA 22161

13. SUPPLEMENTARY NOTES

14. ABSTRACT
Observed and projected changes in climate that impact reservoir sedimentation include changes in snowmelt, drought, and increases in heavy precipitation. Accurate measurements of sediment storage and estimates of storage loss rates are required to assess the sustainability of USACE reservoirs under changing conditions. A review of reservoir sediment information (RSI) at six districts indicated that data gaps impede understanding of sedimentation rates at USACE reservoirs nationwide. This report presents information on the progress of a project to enhance RSI for climate preparedness and resilience.

15. SUBJECT TERMS
Reservoir Sedimentation | Sediment Transport | Reservoir Sedimentation Database | Climate
Reservoir Sediment | Climate Change | Reservoir Sediment Information

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			19b. TELEPHONE NUMBER *(Include area code)*
U	U	U	UU		

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18