RECLAMATION
Managing Water in the West

Pilot Study of Reservoir Sustainability Options: Bighorn Reservoir

Research and Development Office
Science and Technology Program
(Final Report) ST-2018-9344-01

U.S. Department of the Interior
Bureau of Reclamation
Research and Development Office

December 2018

Mission Statements

The U.S. Department of the Interior protects America's natural resources and heritage, honors our cultures and tribal communities, and supplies the energy to power our future.

The Department of the Interior protects and manages the Nation's natural resources and cultural heritage; provides scientific and other information about those resources; and honors its trust responsibilities or special commitments to American Indians, Alaska Natives, and affiliated island communities.

Disclaimer:

Information in this report may not be used for advertising or promotional purposes. The data and findings should not be construed as an endorsement of any product or firm by the Bureau of Reclamation, Department of Interior, or Federal Government. The products evaluated in the report were evaluated for purposes specific to the Bureau of Reclamation mission. Reclamation gives no warranties or guarantees, expressed or implied, for the products evaluated in this report, including merchantability or fitness for a particular purpose.

REPORT DOCUMENTATION PAGE		*Form Approved* *OMB No. 0704-0188*
T1. REPORT DATE: December 2018	**T2. REPORT TYPE:** Research	**T3. DATES COVERED** 2016 – 2018
T4. TITLE AND SUBTITLE Pilot Study of Reservoir Sustainability Options: Bighorn Reservoir		**5a. CONTRACT NUMBER** FA272
		5b. GRANT NUMBER
		5c. PROGRAM ELEMENT NUMBER 1541 (S&T)
6. AUTHOR(S) Robert C. Hilldale rhilldale@usbr.gov 303-445-3135		**5d. PROJECT NUMBER** ST-2018-9344-01
		5e. TASK NUMBER
		5f. WORK UNIT NUMBER 86-68240
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Robert C. Hilldale, BOR-TSC, PO Box 25007, Denver, CO		**8. PERFORMING ORGANIZATION REPORT NUMBER** N/A
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) Research and Development Office U.S. Department of the Interior, Bureau of Reclamation, PO Box 25007, Denver CO 80225-0007		**10. SPONSOR/MONITOR'S ACRONYM(S)** **R&D:** Research and Development Office **BOR/USBR:** Bureau of Reclamation DOI: Department of the Interior
		11. SPONSOR/MONITOR'S REPORT NUMBER(S) ST-2018-9344-01
12. DISTRIBUTION / AVAILABILITY STATEMENT **Final report can be downloaded from Reclamation's website: https://www.usbr.gov/research/**		
13. SUPPLEMENTARY NOTES This project was turned over to Robert Hilldale by Sean Kimbrel following Mr. Kimbrel taking a new position within Reclamation.		
14. ABSTRACT ***(Maximum 200 words)*** Sediment accumulation in the upper portion of Bighorn Reservoir has created challenges to boating recreation, specifically at the Horseshoe Bend marina, located on the western shore. Since dam construction Sediment Range Line 16 (located across the widest portion of Horseshoe Bend) indicates approximately 45.5 ft of sediment accumulation, using the 2017 bathymetric survey. A 2D, mobile bed, hydraulic and sediment transport model was used to determine the feasibility of constructing a longitudinal wall in Horseshoe Bend. The results of existing and proposed conditions were compared for both hydrographs. It was concluded that the proposed wall is mostly successful in limiting deposition in a lower inflow season and somewhat successful in a higher inflow year. It is expected that if dredging Horseshoe Bend is going to occur, the longitudinal wall is likely to extend the life of the dredging, decreasing the required dredging frequency.		

15. SUBJECT TERMS Bighorn Reservoir, 2D sediment modeling, sustainability					
16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT** U	**18. 53 PAGES**	**19a. NAME OF RESPONSIBLE PERSON** Robert C. Hilldale
a. REPORT U	**b. ABSTRACT** U	**c. THIS PAGE** U			**19b. TELEPHONE NUMBER**

S Standard Form 298 (Rev. 8/98)
P Prescribed by ANSI Std. 239-18

BUREAU OF RECLAMATION

Research and Development Office
Science and Technology Program

Sedimentation and River Hydraulics, 86-68240

(Final Report) ST-2018-9344-01

Title Pilot Study of Reservoir Sustainability Options: Bighorn Reservoir

ROBERT HILLDALE Digitally signed by ROBERT HILLDALE
Date: 2019.01.02 15:30:21 -07'00'

Prepared by: Robert C. Hilldale, M.S., P.E.
Hydraulic Engineer, Sedimentation and River Hydraulics Group, 86-68240

BLAIR GREIMANN Digitally signed by BLAIR GREIMANN
Date: 2019.01.02 15:35:14 -07'00'

Technical Approval: Blair Greimann, PhD, P.E.
Hydraulic Engineer, Sedimentation and River Hydraulics Group, 86-68240

BLAIR GREIMANN Digitally signed by BLAIR GREIMANN
Date: 2019.01.02 15:35:43 -07'00'

Peer Review: Blair Greimann, PhD, P.E.
Hydraulic Engineer, Sedimentation and River Hydraulics Group, 86-68240

Acknowledgements

The author would like to acknowledge the funding provided by the GP Regional Office for partial funding to survey Bighorn reservoir. Details and results of the complete reservoir survey are contained in a separate report.

Acronyms and Abbreviations

BOR – Bureau of Reclamation

cy = cubic yards

ft = feet

ft/s – feet per second, units for flow velocity

ft^3/s – cubic feet per second, units for discharge

HB or HSB – Horseshoe Bend

lb/ft^2 – pounds per square foot, units for shear stress

MT – Montana

RL – Range Line, or Sediment Range Line

USACE – U.S. Army Corps of Engineers

WY - Wyoming

Executive Summary

Sediment accumulation in the upper portion of Bighorn Reservoir has created challenges to boating recreation, specifically at the Horseshoe Bend marina, located on the western shore. Since dam construction Sediment Range Line 16 (located across the widest portion of Horseshoe Bend) indicates approximately 45.5 ft of sediment accumulation, using the 2017 bathymetric survey. During periods of low reservoir levels boating activity is limited and sometimes not available due to shallow water conditions. Under current, normal operations (not considering drought years) the reservoir levels are lowest in middle to late May and then begin to increase with increased inflow due to spring runoff.

The US. Army Corps of Engineers (USACE 2010) performed a sediment study looking at various alternatives to address the issue with a combination of operational changes and physical actions. Some of the proposed actions were not able to be incorporated due to operational constraints. However, there were multiple physical scenarios that may be incorporated to address the excessive aggradation in Horseshoe Bend. Two physical scenarios proposed by the USACE (2010) consist of lateral dikes in the reservoir upstream of the Lovell causeway to increase residence time and encourage deposition, and a longitudinal wall through Horseshoe Bend to encourage the transport of sediment through this area and decrease sediment deposition in the western portion. Dredging sediment is another alternative that could work in conjunction with these two constructed alternatives posed by the USACE (2010).

As a proof of concept, and to test the feasibility of implementing one or both of the proposed physical alternatives, a two-dimensional (2D), mobile bed, hydraulic and sediment transport model was utilized. The Sedimentation and River Hydraulics Group at the Bureau of Reclamation's Technical Service Center in Denver, CO performed a bathymetric survey of Bighorn Reservoir and obtained several sediment cores in and around Horseshoe Bend in 2017. This data collection and sediment information contained in the previous sediment study (USACE 2010) provided the data necessary to perform 2D hydraulic and sediment transport modeling of Horseshoe Bend. Comparisons were made between existing and proposed conditions under two hydrologic scenarios. The proposed condition modeled was a longitudinal wall through Horseshoe Bend that rises approximately 15 ft above the reservoir bed. There was not enough budget to model the other proposed scenario, lateral dikes upstream of the causeway.

Two hydrologic scenarios were used for this comparison. The period May through August (122 days) 2015 and 2016 was chosen for this model. The hydrology consisted of reservoir inflow from both Shoshone and Bighorn Rivers and reservoir water surface elevation. These data were obtained from the MT Area Office reservoir records. Year 2015 was used to represent a larger inflow year and 2016 was meant to represent a smaller inflow year. Reservoir sediment material was obtained from sediment cores collected and tested in 2017 for material properties, particle size distribution, and erosion rate parameters.

The results of existing and proposed conditions were compared for both hydrographs. It was concluded that the proposed wall is mostly successful in limiting deposition in a lower inflow season and somewhat successful in a higher inflow year. It is expected that if dredging

Horseshoe Bend is going to occur, the longitudinal wall is likely to extend the life of the dredging, decreasing the required dredging frequency.

Incorporating the lateral dike alternative upstream of the causeway may increase the performance of a longitudinal wall constructed in Horseshoe Bend. The construction of lateral dikes upstream of the causeway is worth consideration and should be considered as a next step in evaluating the sedimentation issue in the upper portion of Bighorn Reservoir. A short section on reservoir sustainability is included as well as an appendix on general dredging information.

Contents

Tables

Figures

Introduction

The construction of Yellowtail Dam in 1966 (U.S. Department of the Interior, 1981) impounded the Bighorn River to form what is now Bighorn Reservoir, which extends upstream (south) of Ft. Smith, Montana into northern Wyoming (Figure 1). The dam provides water for irrigation, power generation, flood control, and recreation opportunities. Since dam construction, sediment accumulation in the delta region of Bighorn Reservoir (primarily in Wyoming) has negatively impacted boating recreation near Lovell, WY (Figure 1) during periods of low reservoir levels. Figure 2 shows the sediment accumulation at Range Line (RL) 16 in Horseshoe Bend since dam construction. RL-16 is located in the broadest portion of Horseshoe Bend and is the nearest range line to the Horseshoe Bend Marina, which is the geographical focus of this study. The Natural Resources Conservation Service (Soil conservation Service 1994 as cited in USACE 2010) has estimated the average sediment load flowing into Bighorn Reservoir to be 4,000 tons/day (3,200 acre-ft annually, USACE 2010).

Figure 1: Location map of Bighorn Reservoir.

There are two primary objectives of this project: 1.) Perform a demonstration project to investigate the feasibility of modeling reservoir sedimentation with a 2-Dimensional (2D), mobile bed, hydraulics and sediment transport model; 2.) Investigate the feasibility of a wall constructed in the Horseshoe Bend area of Bighorn Reservoir to limit future aggradation that negatively impacts recreation.

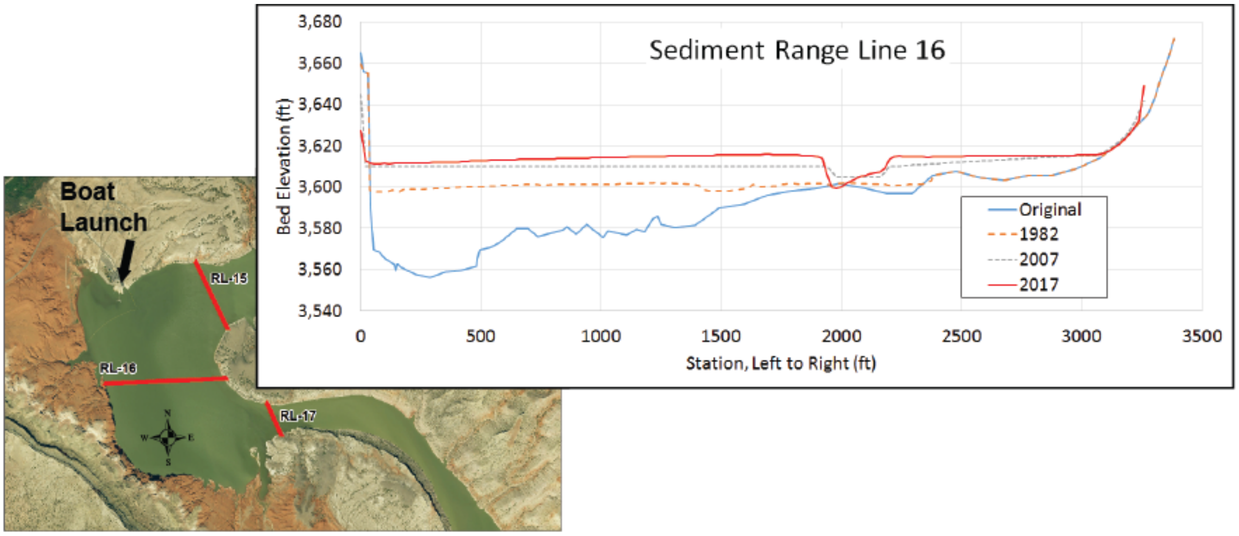

Figure 2: Diagram showing the location of Horseshoe Bend sediment range lines and plot of reservoir bed elevations since dam construction. Note the persistence of the channel through Horseshoe Bend. The perspective is looking downstream (north).

The US Army Corps of Engineers (2010), Omaha District performed a reconnaissance level sediment study to evaluate sediment management alternatives using a one-dimensional hydraulic and sediment transport model. The modeling utilized the 2007 survey to develop the geometry. This study evaluated six alternatives to manage sediment and enhance recreational opportunities in the south end of the reservoir, primarily in the vicinity of Horseshoe Bend. Refer to the USACE (2010) study to see the results of the evaluation of the following alternatives:

1. Maintain Higher Reservoir Levels During the Recreation Season.
2. Trap Sediment in the Pool Upstream of the Lovell Hwy 20 Causeway.
3. Flush Sediment Through the Horseshoe Bend Area.
4. Manage Sediment at Horseshoe Bend with a Separation Berm.
5. Manage Watershed Sediments.
6. Dredge Horseshoe Bend Sediments.

Alternatives 2 and 4 warranted further evaluation with the enhanced capabilities of a 2D, mobile bed, hydraulic and sediment transport model. The budget of the current study only allowed for an in-depth analysis of one alternative. It was decided that alternative #4 (above) would be evaluated due to the potential of a more immediate impact to recreation in Horseshoe Bend.

Proposal Development

Pilot Study Description

As described in USACE (2010), Alternative 4 proposes the construction of a longitudinal rock dike (Figure 3) that would artificially confine the Bighorn River to a smaller width. It is hypothesized that the narrower width will maintain sediment transport through the eastern portion of Horseshoe Bend and discourage sediment deposition in the western half of Horseshoe

Bend. This scenario was evaluated in this study to determine the effectiveness of such a structure.

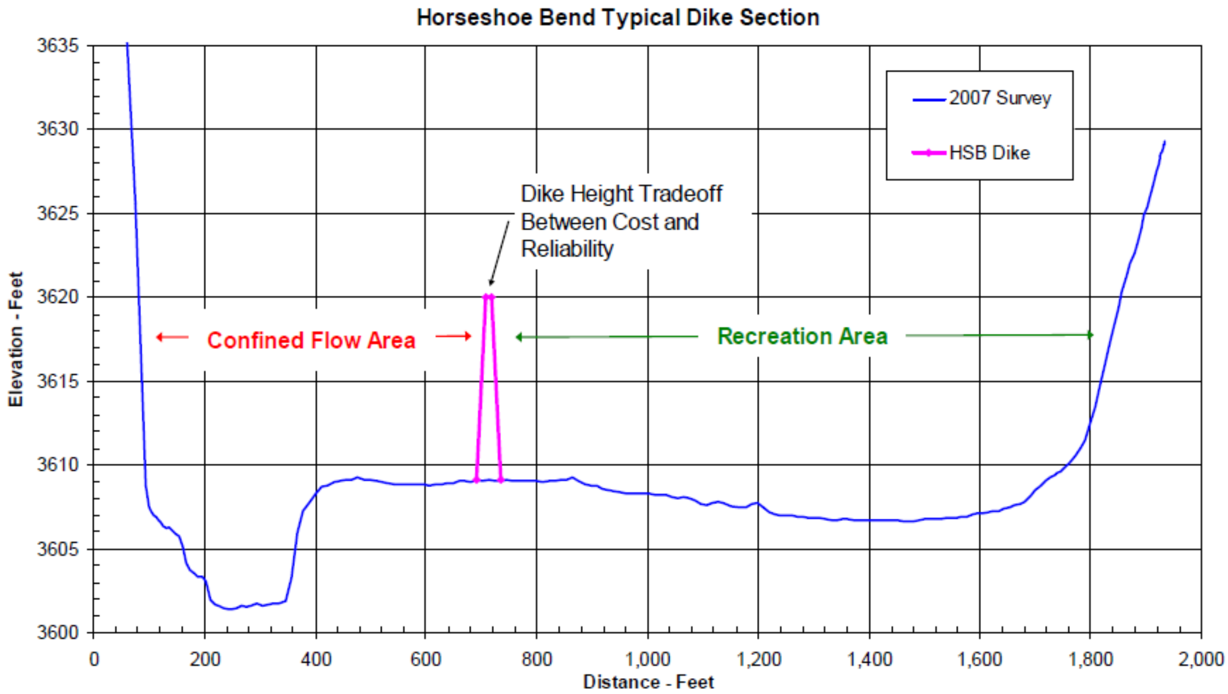

Figure 3: Alternative 4 as proposed by USACE (2010), as seen looking upstream (south) from Horseshoe Bend. Note the surface elevation is from the 2007 survey.

Alternative 2 proposes to construct a series of lateral dikes, constructed from native reservoir sediment (Figure 4). The intent of these lateral dikes is to increase residence time in the upper portion of the reservoir to increase deposition. Sediment deposits in this location would need to be periodically excavated or dredged as part of a regular maintenance program. It is feasible that this alternative could be implemented in conjunction with Alternative 4. The funding for this study did not allow for numerical evaluation of this alternative, however Alternative 2 is considered to be deserving of further investigation.

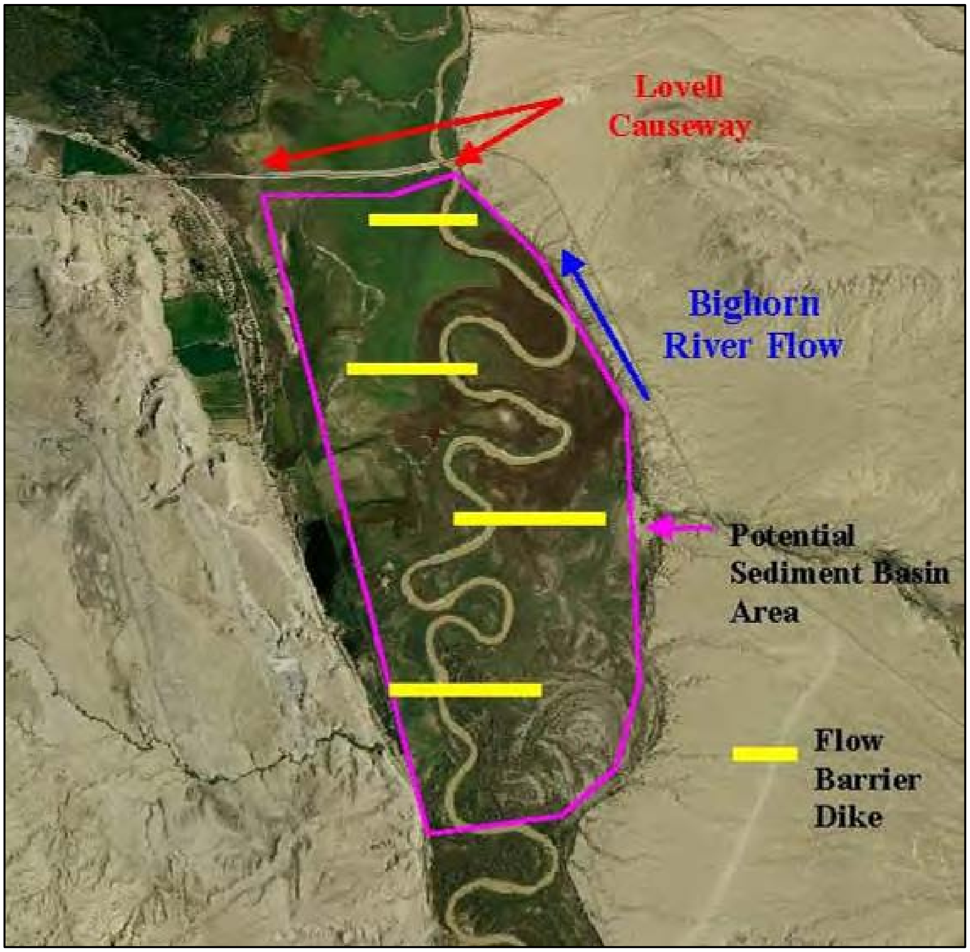

Figure 4: Conceptual layout of Alternative #2 to increase sediment retention in the upper reservoir (USACE 2010).

Horseshoe Bend Model Description

The current evaluation of sediment transport and hydraulics was accomplished using SRH-2D (Lai 2008, Lai 2010), a 2D depth-averaged hydraulic and mobile bed sediment transport model for simulating fluvial systems. This model has been developed by Reclamation’s Technical Service Center (Denver, CO) and has gained wide acceptance through extensive verification in previous publications (e.g. Lai and Greimann 2008, Lai and Greimann 2010, Lai 2011, Lai et al. 2011, Lai 2015). SRH-2D has recently been accepted for use by the Federal Highways Administration and approved by the Federal Emergency Management Administration. The following discussion includes the various information required for input to the model.

Surface Development

The modeling surface was developed from the 2017 hydrographic survey (Reclamation in progress). This survey was processed in the Montana State Plane projection, NAD83, NAVD88. The horizontal units are in US survey feet while the vertical units are International feet, consistent with the Montana State Plane projection. Because no LiDAR or photogrammetry survey exists to capture above-water topography, a single contour line at elevation 3,660 feet (maximum reservoir elevation) was digitized from a USGS 10 meter DEM to represent the upper bound around the reservoir model area. The surface is shown in Figure 5.

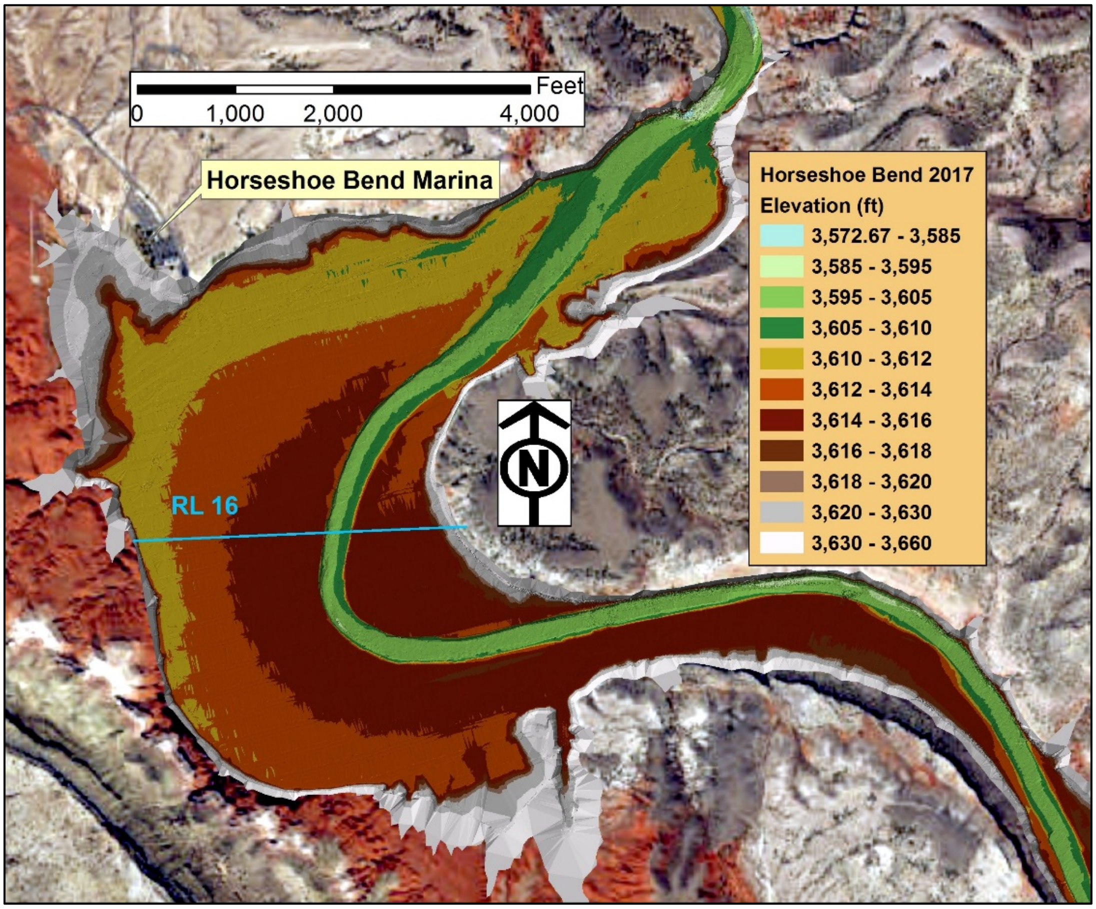

Figure 5: Surface representation of Horseshoe Bend in Bighorn Reservoir based on the 2017 bathymetric survey. This surface was used as the existing condition in the model for comparison to the proposed condition. Range Line (RL) 16 is shown for reference.

The design analyzed in this study consists of a wall immediately to the west of the channel running through Horseshoe Bend (Figure 6). The dimensions of this wall differ from USACE (2010) because it is assumed that native material will be used instead of rock. The alignment for the proposed wall is shown in Figure 7. The wall crest is set to elevation 3,630 ft, 10 ft higher than proposed by the USACE (2010). The proposed crest height was based on the current bed elevation (approximately 5 ft higher than the 2007 surface) and a balance of cost and effectiveness. A higher wall is likely to be more effective, isolating sediment for a longer period throughout the year. The crest height will be a balance among construction cost, effectiveness, and impact on recreation. A scenario where the south end of the wall did not connect to the shoreline was attempted but proved to be ineffective. When water levels are at or below approximately 3,632 ft boaters will have to navigate around the north end of the wall to get to the southern portion of the reservoir. Using native sediment for the wall construction may save cost over a rock wall, would reduce the reservoir bed elevation west of the wall by approximately 2 ft, and reduce risk to boaters.

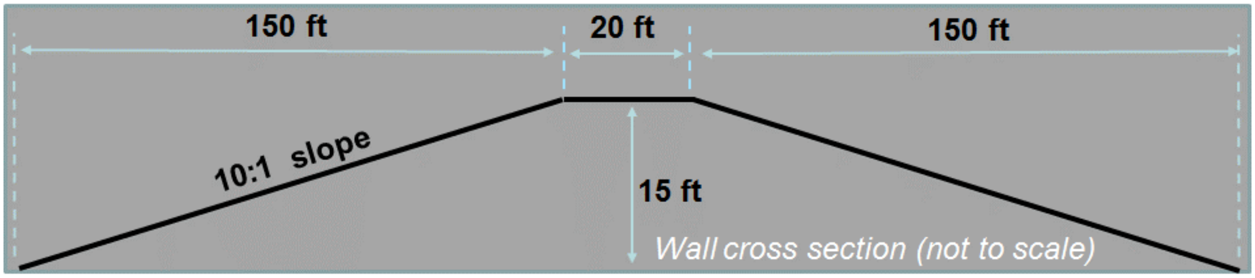

Figure 6: Typical cross section of a wall made from native reservoir sediment.

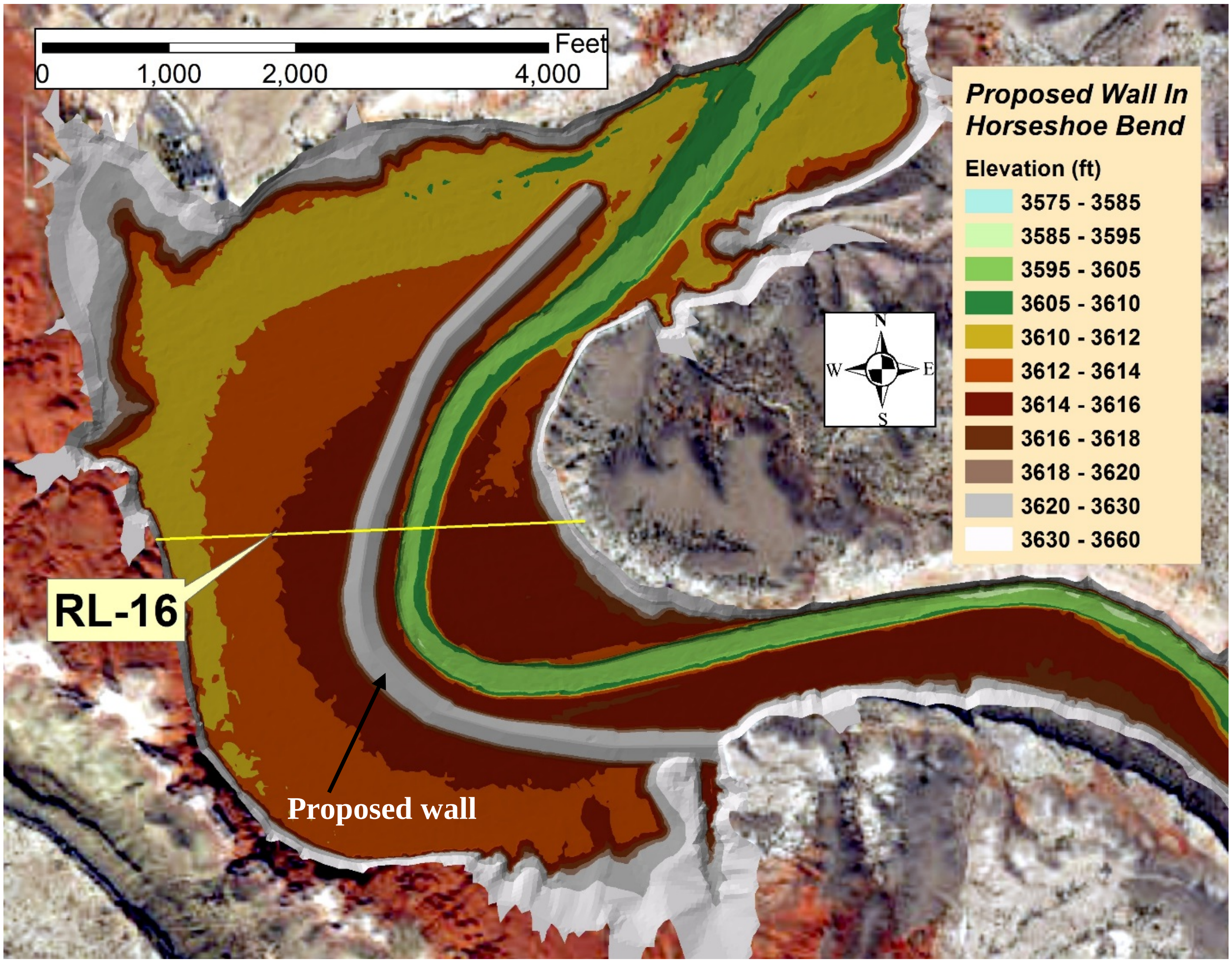

Figure 7: Horseshoe Bend reservoir surface that includes the proposed wall to the west of the channel. Range Line 16 is shown for reference.

Hydrology

The hydrology for the modeling is derived from Reclamation reservoir records, tracking hourly reservoir inflow and reservoir pool elevation for the period 1998 - 2016. The inflow includes both Bighorn and Shoshone Rivers. These data were provided by Reclamation's MT Area Office and the Yellowtail Field Office. The hourly data were adapted to provide daily averages for evaluation and model input (Figure 8). It was decided to use two hydrographs to simulate sedimentation in Horseshoe Bend. Due to excessive run time the simulations were necessarily limited to 4 months during peak inflow and reservoir level. The period of May through August, 2015 and 2016 were chosen to represent a higher and lower inflow condition. These hydrographs are shown in (Figure 9). The upstream boundary condition is the daily average inflow and the downstream boundary condition is the daily average reservoir elevation.

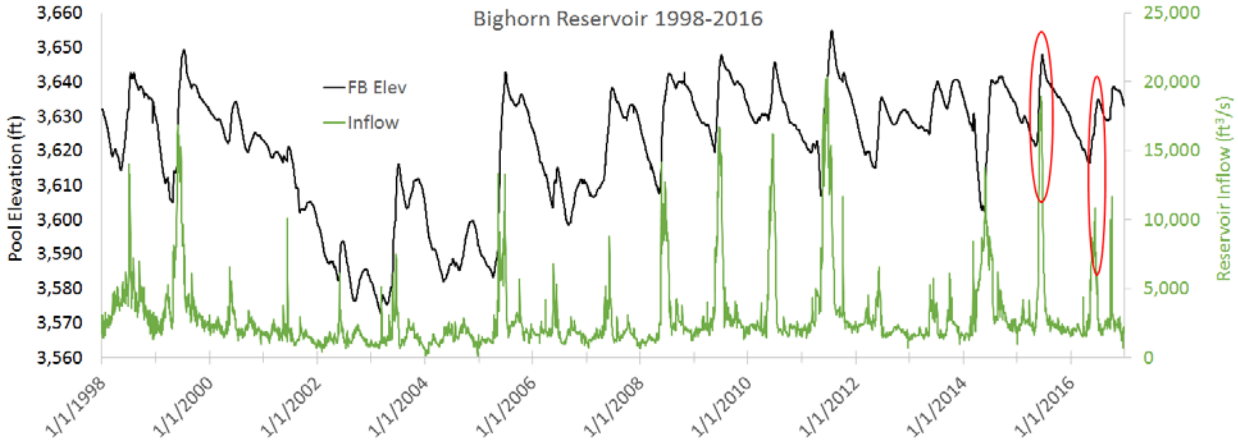

Figure 8: Plot of Bighorn Reservoir forebay (FB) elevations and inflow. The circled areas represent the two seasons evaluated, May – August, 2015 and 2016.

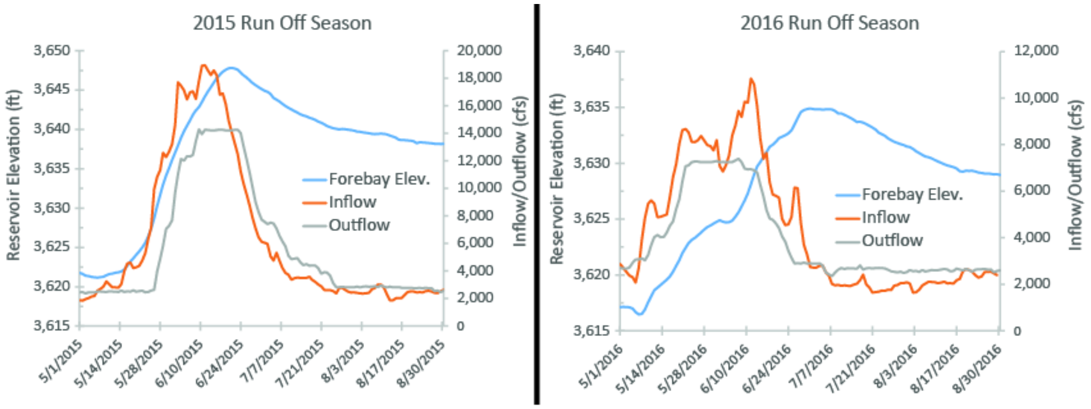

Figure 9: Hydrographs and reservoir levels used as upstream and downstream boundary conditions, respectively.

Sediment

Model input requires both incoming sediment from the Bighorn and Shoshone Rivers and bed sediment in Bighorn Reservoir. These data were taken from the USACE report and sediment cores, respectively.

Reservoir Bed Sediment

In July 2017 seven sediment core samples were collected from the bed of Bighorn Reservoir, five in the Horseshoe Bend area and two near the Shoshone River mouth (Figure 10). Soil physical properties and erodibility testing was performed by Reclamation (BOR 2017). Two of the cores were collected from the channel running through Horseshoe Bend (visible in Figure 5) and have a notably coarser distribution in the top foot of the soil profile (Figure 11). Another noteworthy observation from these data is the extremely fine sediment that has deposited in the Horseshoe Bend area outside of the channel. These samples (BH-2, 3, 5, and 6) show between 40% and 50% of sediment deposits finer than 0.001 mm (particles sized less than 0.004 mm are considered clay). This demonstrates the potential for a strongly cohesive material given that a clay content of 10% or more will assume control of sediment properties (Raudkivi 1990). Sediment outside the channel was generally classified as fat or lean clay (BOR 2017).

Within the channel sediment samples BH-4 and BH-7 indicate a particle size distribution dominated by sand-sized particles (> 0.0625 mm). The classification of channel sediment was classified as poorly graded sand (BOR 2017). This distribution demonstrates the greater transport capacity within the channel in Horseshoe Bend. As the reservoir is drawn down erosive forces increase within the channel, resulting in the coarser bed material.

Model input included two bed material gradations, one for the channel and one for all other locations. Sediment samples within Horseshoe Bend were separated into channel and overbank distributions, averaged, and input to their respective locations.

Incoming Bed Material

The sediment information being carried into the reservoir by the Shoshone and Bighorn Rivers was taken from the USACE (2010) sediment study for input to the current sediment model. These data were taken from USGS stream gages Shoshone River at Kane (06285100) and Bighorn River at Kane (06279500). Sediment data from these sources is sparse, shows wide variation, and mostly exists prior to 1965.

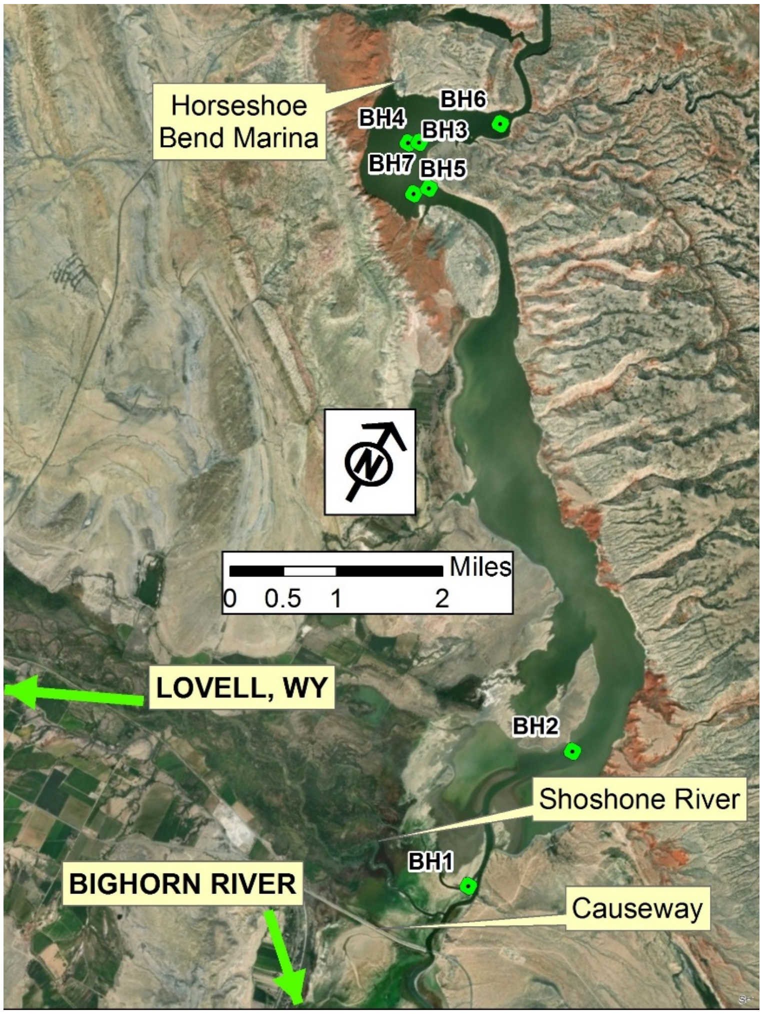

Figure 10: Location of sediment cores. BH4 and BH7 were collected in the channel.

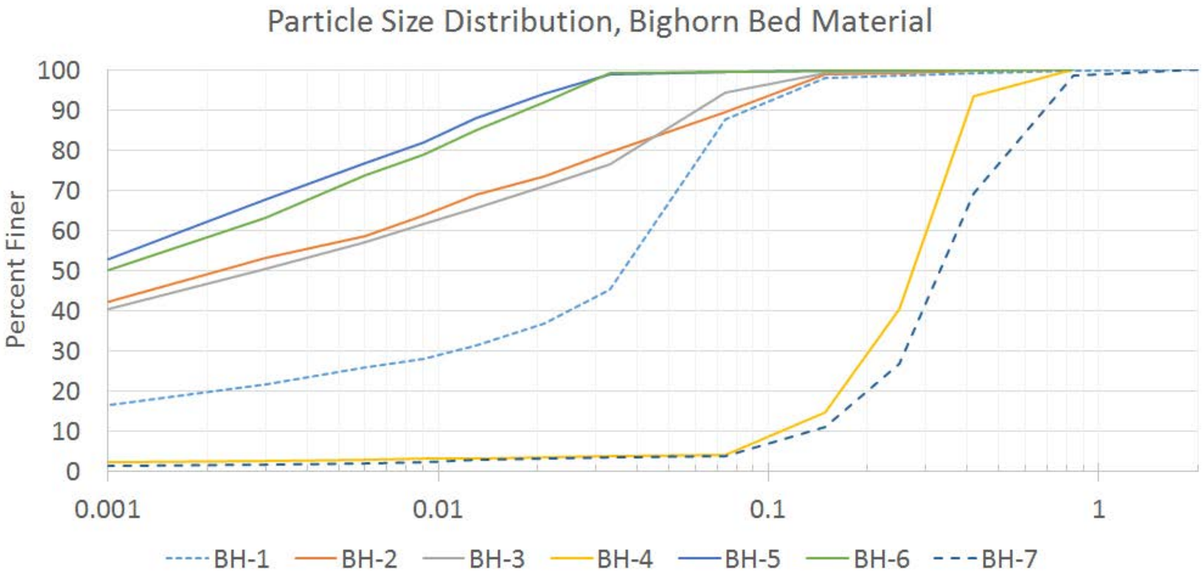

Figure 11: Particle size distribution in the surface layer of the sediment cores collected in 2017.

The following sediment input table (Table 1) is taken from USACE (2010). Because the upstream boundary for the current model is approximately 8 miles downstream of the gage locations, it was necessary to adapt the loads and size distributions accordingly. For sediment input to the current model the Bighorn River loads were reduced by 35% and the sand fractions were removed. The Shoshone River loads were also removed. Sediment input loads for the current model are shown in Table 2. The purpose of the reductions in sediment load and particle size distribution is explained in the Model Calibration sub-section.

Table 1: Incoming sediment loads from the Bighorn and Shoshone Rivers, adapted from USACE (2010).

Bighorn River			**Shoshone River**		
Reservoir Inflow	**Sed. Inflow 1947-1964**	**Sed. Inflow Post 1964**	**Reservoir Inflow**	**Sed. Inflow 1959-1964**	**Sed. Inflow Post 1964**
(ft^3/s)	**tons/day**	**tons/day**	**ft^3/s**	**tons/day**	**tons/day**
100	10	2	100	26	10
1,000	1,270	351	1,000	1,300	573
3,000	14,400	4,100	3,000	8,300	3,869
5,000	44,500	12,800	5,000	19,800	9,400
10,000	205,800	60,000	10,000	63,800	31,400
15,000	504,100	148,300	15,000	126,600	63,500
20,000	951,800	282,000	20,000	205,900	104,600
25,000	1,558,200	464,100	25,000	300,200	154,200
30,000	2,331,000	697,300	30,000	408,600	211,700

Table 2: Incoming sediment loads for the current sediment model. All particles are less than 0.0625 mm. These values were derived from the USACE (2010) sediment report and reduced accordingly. Note that loads are volumetric, in units of ft^3/s, as opposed to weight.

Reservoir Inflow	**Sediment Inflow**
(ft^3/s)	**(ft^3/s)**
10	0.0009
100	0.0969
1000	1.094
5000	3.380
10000	15.60
15000	38.05
20000	71.61
25000	116.7
30000	174.0

A significant parameter for modeling reservoir sedimentation is the particle fall velocity, or settling velocity. Typical values for settling velocity vary from 0.05 to 5 mm/s (Raudkivi 1990). The variability in this parameter is influenced by several factors, including; particle minerology (the type of clay), suspended sediment concentration, and water chemistry (primarily pH). The fall velocity used as input to the current model was set to a constant value of 0.05 mm/s for all sediment concentrations. The depositional environment in the current model domain makes this a sensitive parameter.

In conjunction with the particle fall velocity it is necessary to specify the shear stress below which deposition occurs. As with fall velocity, the depositional environment in the model domain makes this a sensitive parameter. The deposition parameter used in the current model was 0.05 lb/ft^2.

The erosion rate parameter was determined through jet testing of sediment core samples collected from the reservoir (BOR 2017). The erosion rate parameter is entered in units of ft/hr under a given condition of shear stress. The erosion rate values used in this model are shown in Table 3. Because this modeled condition is primarily a depositional environment this parameter is less significant.

Table 3: Table of erosion rates input to the current model (BOR 2017).

Applied Shear Stress	**Erosion Rate**
(lb/ft^2)	**(ft/hr)**
0.004	0
0.005	0.06
0.007	0.21
0.01	0.28

Other Model Parameters

Model run times are dependent on the length of the hydrograph and the number of cells in the mesh. The hydrograph for both the 2015 and 2016 hydrographs was 122 days (May through August). There were approximately 30,000 mesh cells for the existing and proposed surface conditions. Model run time was approximately 45 hours.

Manning's *n* was set to a global value of 0.02. The initial condition was set to a reservoir filled with clear water (no sediment) to an elevation equivalent to the elevation on May 1st for each hydrograph.

Adaptation coefficients for suspended sediment deposition and erosion were set to 0.25 and 1.0, respectively. These are the default values provided in Greimann et al. (2008). A constant value for the bed load adaptation length was set to 32.8 ft (10 meters). A constant active layer thickness of 0.02 ft was used. The parabolic turbulence model was used and a coefficient of 10 was assigned. This coefficient is significantly higher than normal applications and was set to this value to increase dispersion under very low velocity conditions throughout the reservoir.

Model Calibration

Specific model parameters, depending on sensitivity, can be adjusted to calibrate the sediment model. It was not feasible to run the model to simulate the period between the 2007 and 2017 bathymetry surveys because of the simulations times necessary and there were no sediment concentration values with which to calibrate this 2D hydraulic and sediment model. In the absence of absolute calibration data, the model was calibrated to match the deposition pattern indicated by the 2007 and 2017 surfaces. To obtain this deposition pattern, the 2007 surface was subtracted from the 2017 surface to obtain the difference (Figure 12). The figure indicates that the greatest amount of deposition is nearest the channel that runs through the middle of Horseshoe Bend, diminishing toward the shorelines.

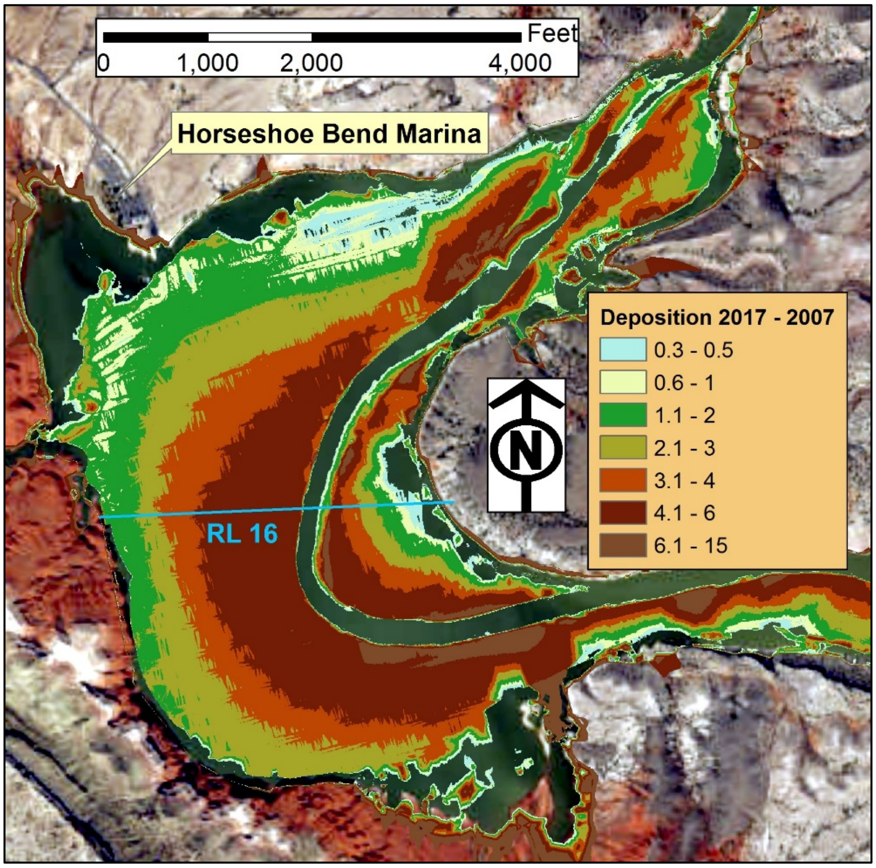

Figure 12: Surface difference, 2017 minus 2007, showing deposition between the two surveys.

The primary calibration parameters for the current model, in order of sensitivity, are; incoming sediment load, incoming sediment distribution, particle fall velocity, and parabolic turbulence constant (to influence dispersion). The sediment load and particle size distribution were both reduced to account for sediment deposition between the gage location and the upstream boundary of the model (approximately 8 miles). There were over 16 test runs to calibrate the model and evaluate various wall alignments and crest heights. The simulated deposition pattern modeling existing conditions closely matches that shown in Figure 12, although it does not match perfectly. It is likely that simulating a full year of a hydrograph, as opposed to 4 months of runoff, would show some erosion of some deposits when reservoir levels and incoming sediment loads are reduced.

Modeling Results

The model provides output data every 24 hours, including: bed material d_{50} (median particle size), Froude number, sediment concentration, erosion depth, bed elevation, shear stress, water elevation, velocity (including vectors). Time series results of spatial data can be difficult to present in a written report. Here the deposition at the end of each hydrograph (2015 and 2016) for each surface condition (existing and proposed) will be displayed.

Figure 13 and Figure 14 show deposition on the existing and proposed surfaces, respectively, for the 2015 hydrograph. Figure 15 and Figure 16 show deposition on the existing and proposed surfaces, respectively, for the 2016 hydrograph. The footprint of the wall is shown in the proposed condition figures for reference. These figures show only the condition at the final time step, simulation day 122.

Another way to evaluate differences between physical and hydrologic scenarios is to create difference maps. Figure 17 and Figure 18 are the result of subtracting deposition values at the final time step, proposed condition minus the existing condition, for each hydrologic scenario. Negative numbers indicate less deposition for the proposed condition.

The time series results are shown in Figure 19 and Figure 20 in graphical format. These plots show bed deposition along Range Line 16 (shown in Figure 12) every 20 days throughout the simulation. Time series concentration values at the model outlet are shown in Figure 21. It is expected that concentration at the downstream end of the model will increase if deposition is limited in Horseshoe Bend with sediment being evacuated through the eastern portion.

Discussion and Conclusions

Model interpretation

The simulated periods (May – August) represent the greatest inflow (water and sediment) to the reservoir in the years simulated. Although the results indicate some aggradation in the channel (east side of reservoir), it is expected that inflow with decreasing reservoir elevation during the following months will erode the sediment deposited during higher inflow and reservoir levels. Erosion and deposition at this location is more dependent on reservoir elevation than the flow rate entering the reservoir.

In the absence of proper calibration parameters, the model was calibrated to match the recent deposition pattern in Horseshoe Bend (Figure 12), with a focus on what are believed to be reasonable predictions of changes to the absolute bed elevations. The presentation of results in this report focused on relative changes in erosion/deposition, comparing results of various physical and hydrologic scenarios. There is greater confidence in the relative erosion/deposition values between scenarios presented in this report than the prediction of absolute bed elevation.

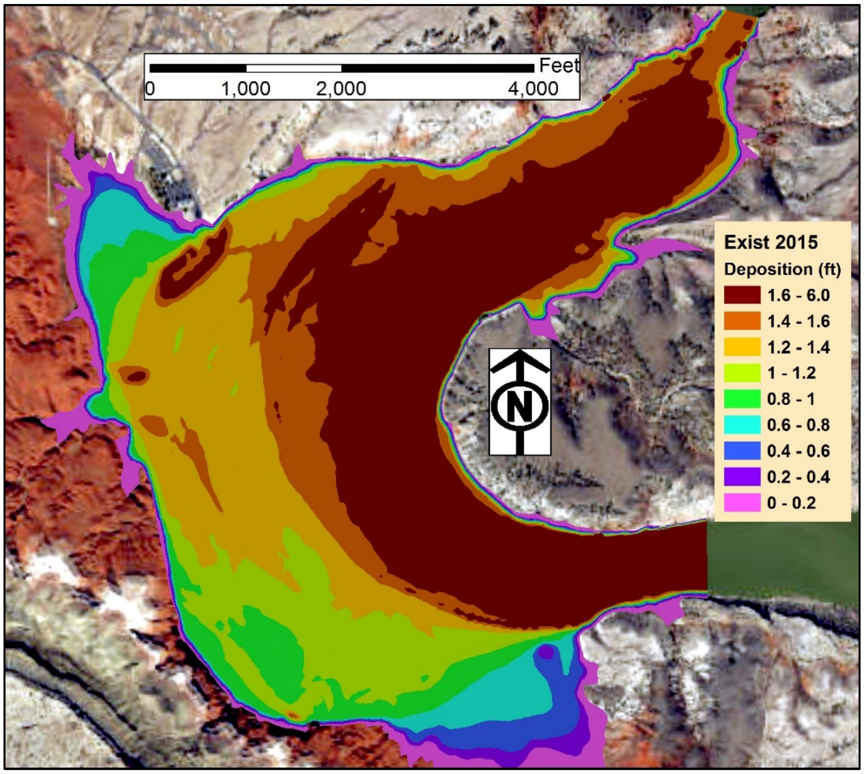

Figure 13: Spatial display of sediment deposition on the existing surface after 122 days of simulation of the 2015 hydrograph.

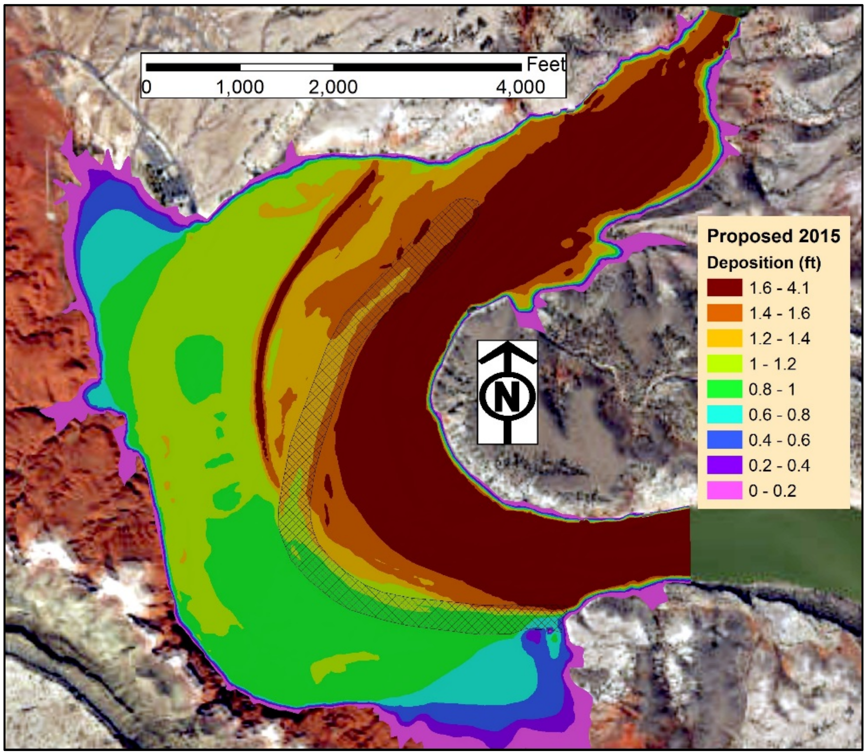

Figure 14: Spatial display of sediment deposition on the proposed surface after 122 days of simulation of the 2015 hydrograph.

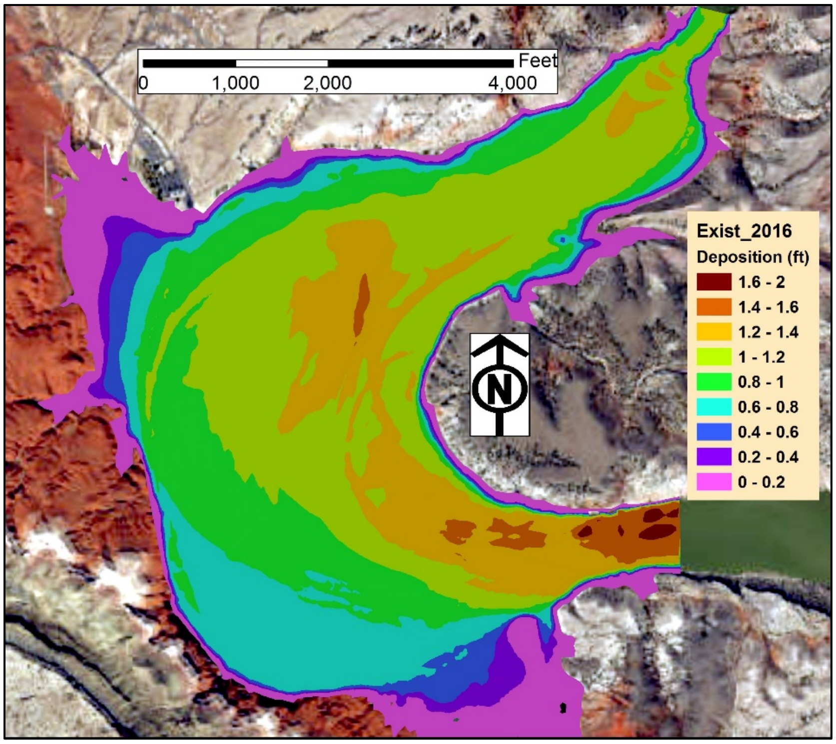

Figure 15: Spatial display of sediment deposition on the existing surface after 122 days of simulation of the 2016 hydrograph.

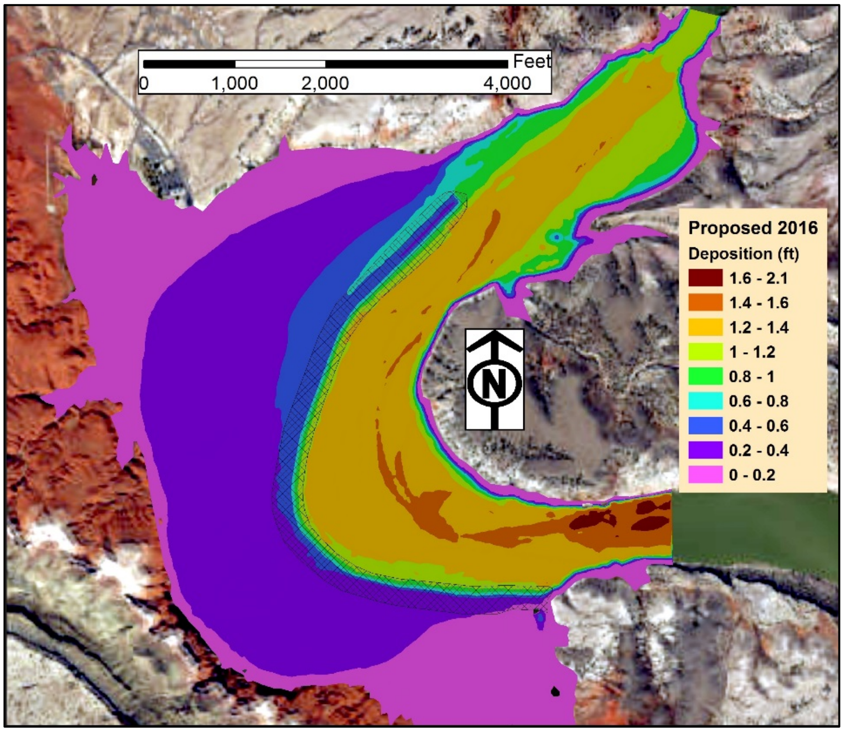

Figure 16: Spatial display of sediment deposition on the proposed surface after 122 days of simulation of the 2016 hydrograph.

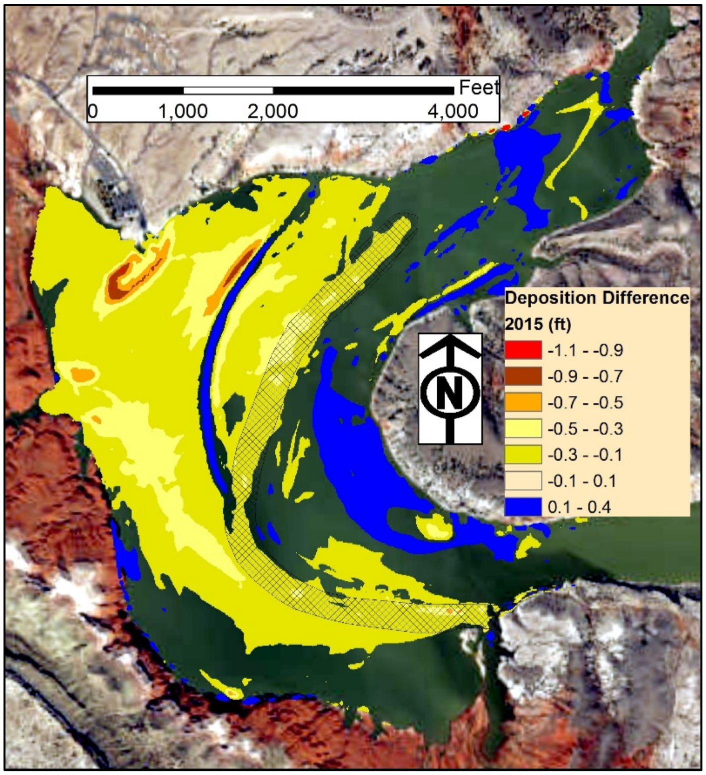

Figure 17: Difference map of proposed minus existing surfaces at the final time step. Negative numbers indicate less deposition under the proposed condition with the 2015 hydrograph.

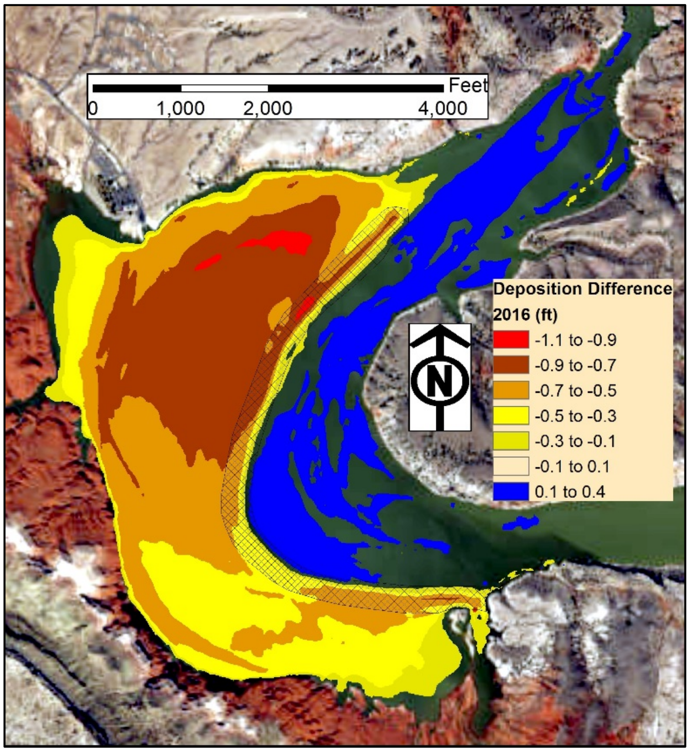

Figure 18: Difference map of proposed minus existing surfaces at the final time step. Negative numbers indicate less deposition under the proposed condition with the 2016 hydrograph.

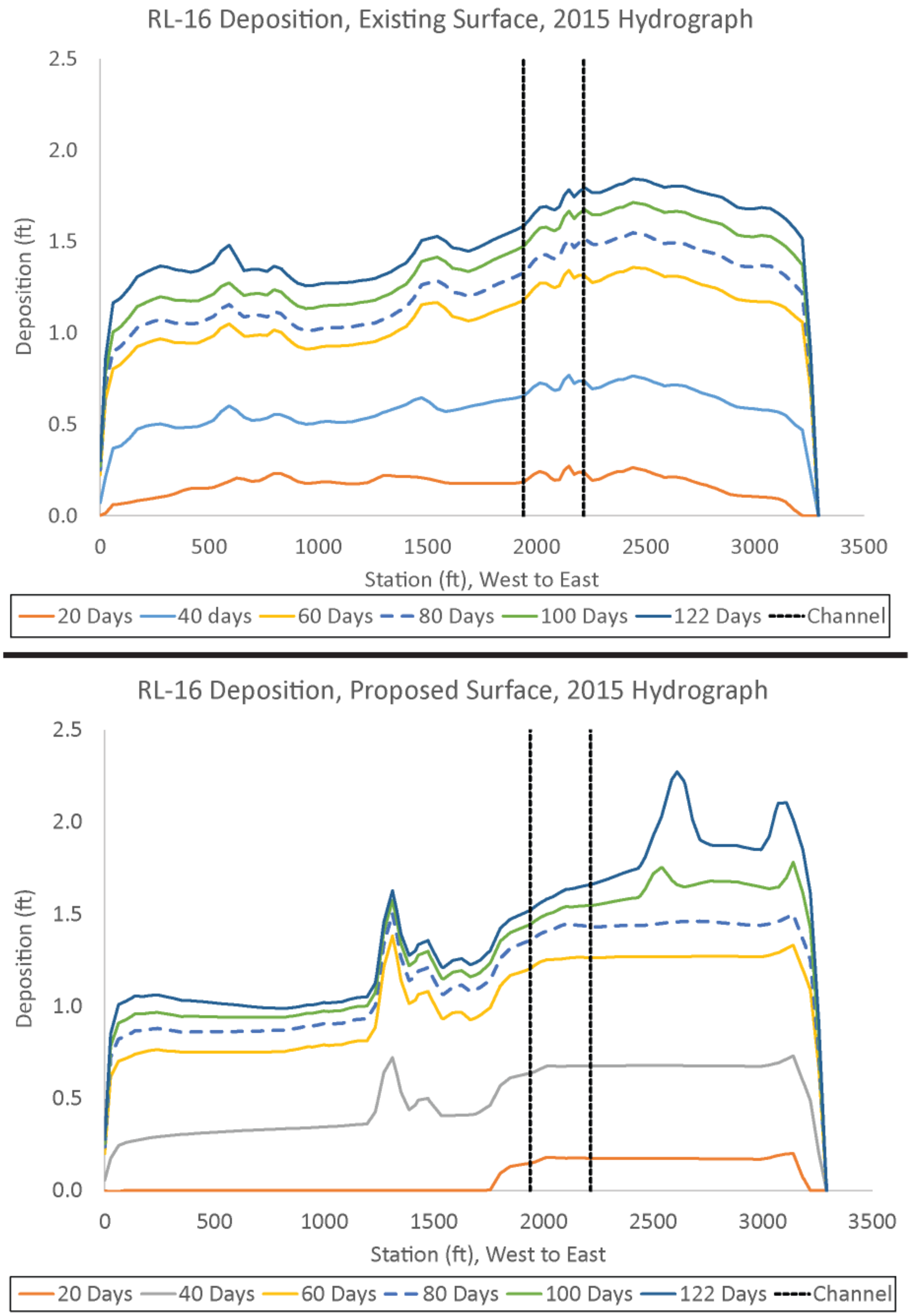

Figure 19: Plots of time series deposition across Horseshoe Bend at Range Line 16 for existing and proposed conditions, 2015 hydrograph. The location of RL-16 is shown in Figure 7. Vertical lines indicate the location of the channel.

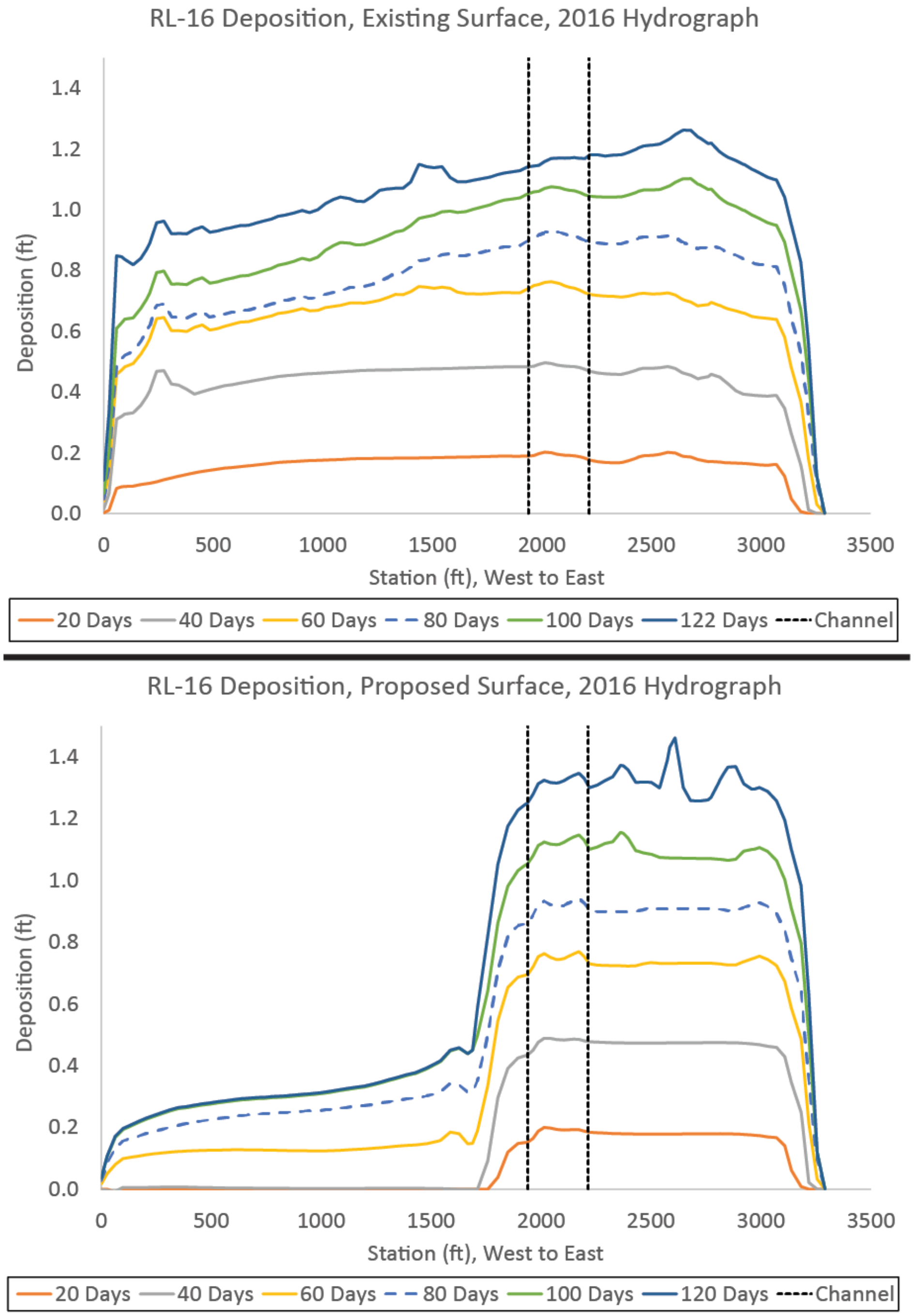

Figure 20: Plots of time series deposition across Horseshoe Bend at Range Line 16 for existing and proposed conditions, 2016 hydrograph. The location of RL-16 is shown in Figure 7. Vertical lines indicate the location of the channel.

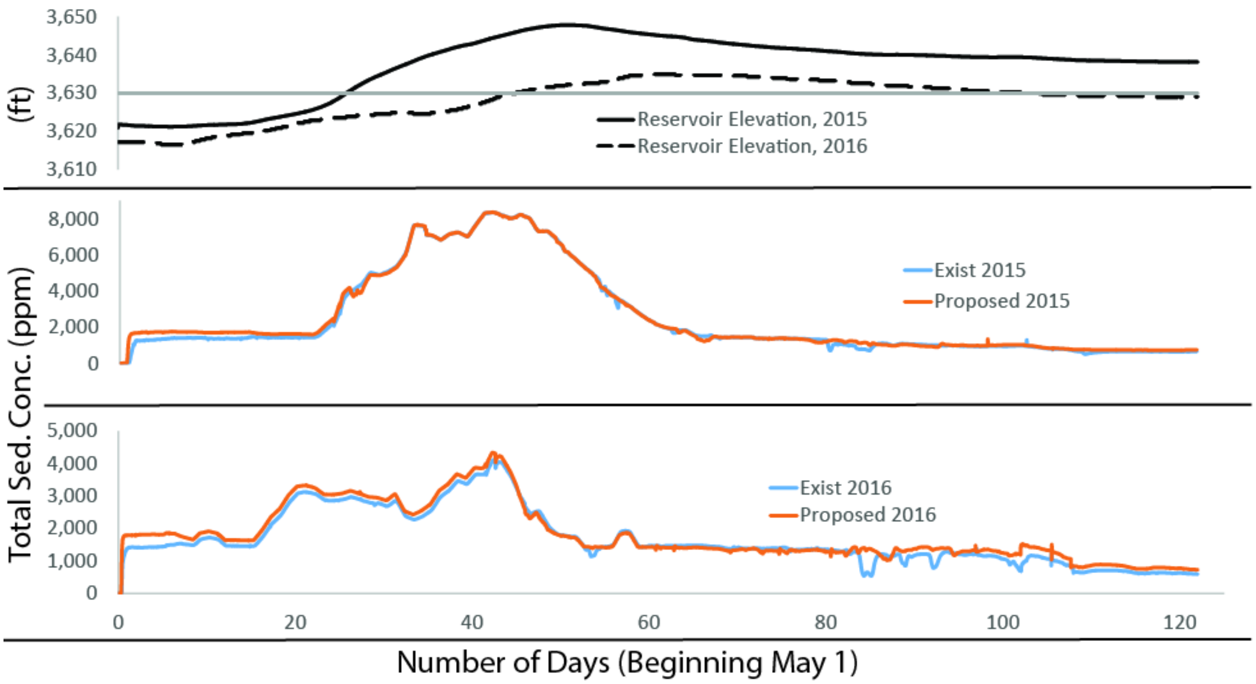

Figure 21: Time series of reservoir elevation and total sediment concentration at the model outlet. The horizontal line in the top plot represents the wall crest elevation, 3,630 ft.

Figure 13 and Figure 14 show the difference in deposition for the 2015 hydrograph, comparing existing and proposed conditions. This comparison indicates approximately 0.2 to 0.4 ft less deposition in the western portion of Horseshoe Bend. A thin arc of deposition (dark brown, > 1.6 ft deposition) is visible in Figure 14. This is a result of a temporary flow patterns during the period when flow is both overtopping the wall and flowing around the end of the wall. Figure 15 and Figure 16 show the deposition for the 2016 hydrograph, comparing existing and proposed conditions. This comparison indicates a decrease in deposition of approximately 0.8-1.0 ft in the western portion under the proposed condition. This same result can be seen in the time series plots (Figure 19 and Figure 20) of aggradation at Range Line 16. It is evident that the wall is more effective under lower inflow and lower reservoir level conditions. This is a function of the wall height.

Examining the sediment concentration at the model’s downstream boundary (Figure 21), it is expected that the proposed condition would increase the sediment concentrations downstream of Horseshoe Bend. This is in fact the case, the downstream sediment concentration shown in Figure 21 is greater for the proposed condition in 2016 than in 2015.

Implications for the Anticipated Effectiveness of a Wall

The results obtained from this study indicate that the construction of a wall west of the channel in Horseshoe Bend is likely to decrease deposition in the western portion during the period May through August. Decreased deposition in the western portion of Horseshoe Bend stands to benefit boating recreation, but is dependent on hydrology, reservoir levels, and the crest height of the wall. Based on these two simulations, it appears as though the wall provides greater benefit during periods of lower inflow and lower reservoir levels. This is likely to be true regardless of the wall crest elevation, but it appears that increasing the crest elevation increases the wall's effectiveness at preventing deposition in the western half of Horseshoe Bend. The wall crest elevation will be a significant consideration if a wall similar to what has been proposed goes to construction.

It is important to recognize that under both hydrologic conditions, some deposition is anticipated in the western portion of Horseshoe Bend. Future actions to maintain recreation (e.g. dredging) should be anticipated if the western portion of Horseshoe Bend is to remain at or near the current bed elevation.

Alternative #2 put forth by the USACE (2010) proposes to place alternating lateral dikes in the reservoir upstream of the causeway (see Figure 4). This action is expected to trap a portion of the incoming sediment in this location and can work in conjunction with a wall constructed in Horseshoe Bend. Should lateral dikes be constructed upstream of the causeway, the area will have to be periodically dredged or excavated to maintain the bed elevation at or near current levels. Should both Alternatives #2 and #4 be implemented, it is expected that any future dredging or other operations to reduce sediment in Horseshoe Bend will not need to be undertaken as frequently or to the same extent.

Reservoir Sedimentation and Sustainability

Reservoir elevation is the key management tool to control erosion and deposition in the delta of a reservoir. In addition to many other demands and requirements, reservoirs are generally managed to retain sediment in the delta portion of the reservoir and prevent sediment from reaching the dam's intake(s) and negatively impacting the ability operate as intended. Sediment does not have to entirely fill the reservoir to render it no longer effective. As sediment accumulates near the dam it aggrades around the intakes, preventing proper operation for irrigation and power generation. This has occurred at Sumner and Paonia Dams (written communication, National Reservoir Sedimentation and Sustainability Team 2018). Any action or operation that accelerates the downstream transport of sediment in Bighorn Reservoir will contribute toward a premature senescence of Yellowtail Dam. Future operation of Yellowtail Dam and Bighorn Reservoir must be considered when evaluating alternatives to control sediment in the delta.

Recent surveys indicate that the delta front is at RL-9, 26.5 miles downstream of the causeway. Because of the narrow reservoir and extremely fine sediment, the reservoir well downstream of the causeway and Horseshoe Bend is undergoing deposition. The proposed action (USACE Alternative #4) will result in more sediment being passed downstream of Horseshoe Bend (Figure 21).

Although dredging is a possibility for reducing bed elevation in Horseshoe Bend, there are significant costs and considerations related to that activity. The sediment dredged from the reservoir bed must be spoiled. Barging the sediment downstream of Horseshoe Bend is possible, but that activity serves to further reduce the life if the reservoir. The spoils could be removed from the reservoir and spoiled elsewhere, but there is significant cost to transporting the spoils. A beneficial use may exist for a portion of the spoils (e.g. mine reclamation, agriculture), but the volumes needed for beneficial use are a very small portion of the annual sediment load. For more discussion on general dredging activities refer to Randle et al. (2018b) Appendix A.

Constructing a longitudinal wall in Horseshoe Bend from reservoir sediment is a significant undertaking. If this action takes place, sediment could be excavated from the reservoir west of the proposed wall. It is estimated that the wall would require approximately 700,000 cy. Figure 22 shows an approximation of the area that could be excavated to a depth of 2 ft to obtain the required material volume, not considering soil expansion and compaction. Construction of a wall in this manner would require multiple construction seasons owing to short periods of reservoir levels that allow for construction in the dry and obtaining proper sediment moisture content for construction. Reservoir levels would have to remain below approximately elevation 3,610 ft for several weeks during construction. The reservoir elevation was last below 3,610 ft in May 2014 for 43 days (Figure 8). Aside from construction logistics, there are operational concerns as well. The wall is expected to sink into the reservoir deposits following construction due to the added surcharge, which will occur using rock or reservoir sediment.

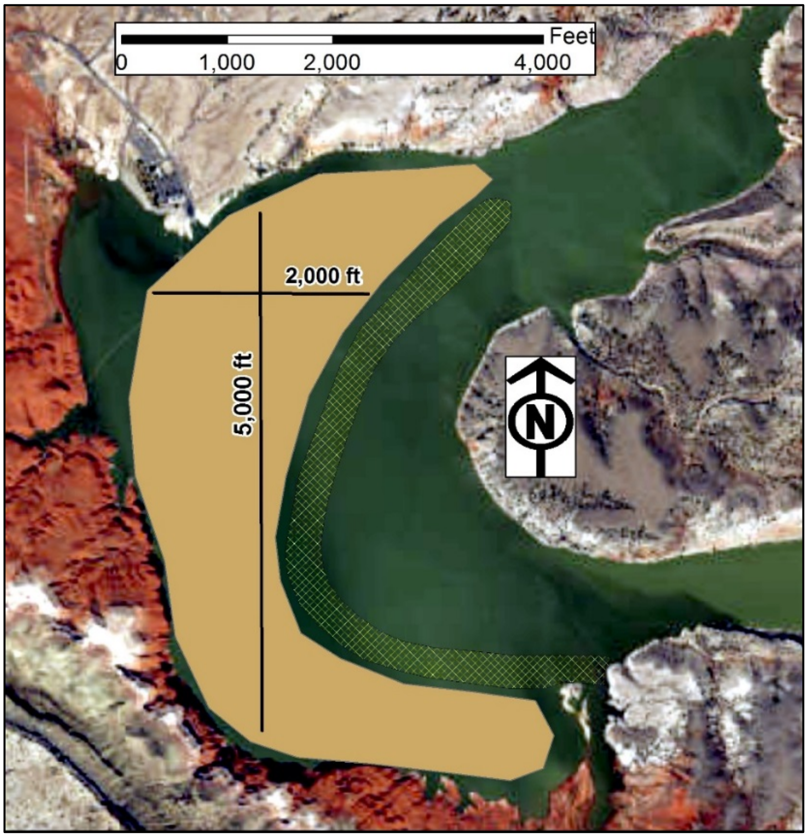

Figure 22: Diagram showing an approximation of the excavation area to obtain appropriate volumes for the construction of the wall. This area would have to be excavated to a depth of 2 ft.

Conclusions

This study has demonstrated the ability to utilize a 2D, mobile bed model to predict reservoir inflow and sedimentation for the purpose of comparing two physical and hydrologic scenarios. In addition, the model has indicated that the construction of a longitudinal wall, as proposed in

Horseshoe Bend, can reduce sediment deposition in the western portion of the study area. It is important to realize that deposition will still occur in the western portion of the study area, particularly during high inflow years. This study had indicated that the proposed wall is more effective during low reservoir levels and low inflow conditions.

Should the plan for construction move forward, further modeling and planning will need to take place. It is also worthwhile to consider implementation of lateral dikes upstream of the causeway, although their effectiveness has not yet been determined. Periodic excavation of reservoir sediment upstream of the causeway needs to be considered in conjunction with the construction of the lateral dikes, which will be expected to trap a significant amount of incoming sediment. Observed average annual sediment inflow from the Bighorn River is approximately 3,200 acre feet (USACE 2010). Even a fraction of this volume is a significant amount of sediment to excavate and spoil and deserves careful consideration.

References

BOR (2017). Bighorn Lake Sediment Erosion Testing Results, Technical Memorandum No. 8530-2017-33, Denver, CO.

Greimann, B., Lai, Y., and Huang, J. (2008). “Two-dimensional total sediment load model equations”, *J. Hydraulic Engineering*, vol. 134(8), pp. 1142-1146.

Lai, Y.G. (2008). “SRH-2D version 2: Theory and User’s Manual”. U.S. Department of the Interior, Bureau of Reclamation Technical Service Center, Denver, CO.

Lai, Y.G. (2010). “Two-dimensional depth-averaged flow modeling with an unstructured hybrid mesh”, *J. of Hydraulic Engineering*, 136(1), pp. 12-23.

Lai, Y.G. (2011). “Prediction of channel morphology upstream of Elephant Butte Reservoir on the middle Rio Grande”, Report SRH-2013-4, Technical Service Center, Bureau of Reclamation, Denver, CO

Lai, Y.G, and Greimann, B.P. (2008). “Modeling of erosion and deposition at meandering channels”, World Environmental & Water Resources Congress, May 12-16, Honolulu, HI.

Lai, Y.G, and Greimann, B.P. (2010). “Predicting contraction scour with a two-dimensional depth-averaged model, *J. Hydraulic Research*, 48(3), pp. 383-387.

Lai, Y.G., Greimann, B.P., Wu, K. (2011). “Soft bedrock erosion modeling with a two-dimensional depth-averaged model”, *J. of Hydraulic Engineering* 137(8), pp. 804-814.

Lai, Y.G. (2015). “Modeling of multilayer cohesive bank erosionwith a coupled bank stability and mobile-bed model”, *Geomorphology*, vol. 243, pp. 116-129.

Pasternack, G.B., A.T. Gilbert, J.M. Wheaton, and E.M. Buckland (2006). Error propagation for velocity and shear stress prediction using 2D models for environmental management. *J. of Hydrology*, vol. 328, 227 – 241.

Randle, T.J.; Ekren, S.W.; Hanson, W.H.; and Ramsdell, R.C. (2018). “Sediment Dredging of Reservoirs for Long-Term Sustainable Management,” in the proceedings of the United States Society on Dams A Balancing Act: Dams, Levees and Ecosystems, 38th Annual USSD Conference and Exhibition, April 30 to May 4, 2018, Miami, FL.

Raudkivi, A.J. (1990) “Loose Boundary Hydraulics”, 3rd Edition, Pergamon Press, Oxford.

USACE (2010). Bighorn Lake Sediment Management Study, Omaha District Corps of Engineers, Hydrologic Engineering Branch, Sedimentation and Channel Stabilization Section for the Bureau of Reclamation, Great Plains Region, Montana Area Office.

U.S. Department of the Interior (1981). Project Data, Water and Power Resources Service, Denver.

Appendix A – Sediment Dredging of Reservoirs for Long-Term Sustainable Management

SEDIMENT DREDGING OF RESERVOIRS FOR LONG-TERM SUSTAINABLE MANAGEMENT

Timothy J. Randle, Ph.D., P.E., D.WRE.[1]

Stanley W Ekren[2]
William H. Hanson[3]
Robert C. Ramsdell[4]

ABSTRACT

The nation's 90,000 dams and reservoirs are filling with sediment over time and sustainable sediment management solutions are needed to help preserve the water storage capacity. This capacity is critical for ensuring the stability and resiliency of water and energy supplies, flood risk management, and natural infrastructure (the networks of land and water that provide services to people) for much of the country. Dredging of sediment from reservoirs is one option for recovering or maintaining reservoir storage capacity, especially in cases where the reservoir cannot be drawn down for sediment management purposes. Recovery of water storage capacity lost to past decades of sedimentation would be most economically viable for small reservoirs where dredged sediment could be delivered to nearby disposal areas. Beneficial uses may offset some of the costs.

Past decades of sedimentation would likely have to be accepted in large reservoirs, but a long-term program could be employed to maintain existing storage capacity by annually dredging the inflowing reservoir sediments. A long-term dredging program would likely have to deliver dredged sediments to the downstream river channel where they would have been naturally transported without the dam and reservoir.

The design of a reservoir dredging program would have to consider the specific location and topography, sedimentation volume and grain size, reservoir depths, disposition of the dredged sediment, slurry pipeline length and alignment, permits, mobilization, and power for the dredge and pumps. The cost of dredging would have to be compared with the cost of other sediment management options, the cost of eventually losing the reservoir benefits, and the cost of dam decommissioning in the absence of sediment management.

INTRODUCTION

All rivers transport sediment (e.g., clay, silt, sand, gravel, and cobble) in widely varying amounts. However, reservoirs tend to trap all or a portion of these sediment loads (Morris and Fan, 1998 and Randle et al., 2017). If not managed, continued reservoir sedimentation threatens

---

[1] U.S. Bureau of Reclamation, P.O. Box 25007, Mail Code 86-68240, Denver, CO 80225, trandle@usbr.gov.
[2] Great Lakes Dredge & Dock Company, 2122 York Rd Oak Brook, IL 60523-1930, sekren@gldd.com
[3] Great Lakes Dredge & Dock Company, Washington D.C., WHHanson@gldd.com
[4] Great Lakes Dredge & Dock Company, 2122 York Rd Oak Brook, IL 60523-1930, RCRamsdell@gldd.com

the project benefits of the Nation's reservoirs over time and impacts the downstream environment. The Subcommittee on Sedimentation's National Reservoir Sedimentation and Sustainability Team (2017) has provided an excellent argument for managing sediment for long-term sustainability and resiliency of the nation's water supplies:

> *The nation's 90,000 dams and reservoirs constitute a critical component of the country's infrastructure. These dams and reservoirs provide fundamental societal needs such as ensuring the stability of water and energy supplies and flood risk management for much of the country. However, reservoir storage capacity has been steadily degraded, at times at an alarming rate, as the nation's dams and reservoirs have been and are filling with sediment (clay, silt, sand, gravel, and cobble). These dams and reservoirs serve both to provide fundamental societal needs such as ensuring the stability of water and energy supplies and flood risk management for much of the country. This extensive system of hydrologic stability and control structures ensures water supplies for municipal, agricultural, and industrial use and for hydropower, flood risk management, navigation, and recreation. The system of dams and reservoirs, just as other critical aspects of the country's infrastructure such as the interstate highway and bridge system, affects virtually every part of this country in a profound and in many instances at an existential level. In many situations, the ability of communities to continue to exist in relative safety or grow crops is dependent upon such structures. Essential to our ability to ensure the capacity of this system to continue to meet these purposes, now and into the future, is the need to maintain adequate storage capacity.*

In addition, reservoir sedimentation deprives the downstream river channel of sediment, which can lead to channel incision or degradation. Floodplains can be disconnected from an incised river channel and downstream habitats can be impaired for fish and wildlife. Reservoir sedimentation also reduces the amount of sediment delivered to coastal deltas, which can lead to coastal shoreline erosion. Restoring the continuity of sediment to rivers and coastal areas can enhance the natural infrastructure of land and water networks that provide services to people. The concept of natural infrastructure is described by Ozment, et al. (2015).

Over the long-term, maintaining existing reservoir capacity and operational control may be the most cost effective and feasible strategy to meet the needs identified above. There are three broad sediment management strategies to help preserve the natural infrastructure of reservoirs (Kondolf, et al., 2014 and Randle, et al., 2017) and a combination of these strategies may be needed:

- Reduction of sediment loads reaching the reservoir (watershed management practices).
- Prevention of sediment deposition within the reservoir (sediment bypassing or sluicing).
- Removal of sediments already deposited in the reservoir (drawdown flushing, dredging, or excavation), or a combination of these strategies.

This paper focuses on the dredging of sediment from reservoirs as one potential strategy for long-term sustainable management. Hydraulic dredging is performed through the water, so this option may be best suited to reservoirs with sediment deposits that are at least 10 feet thick and cannot be drawn down for sediment management purposes without impacting critical water supplies. Dredging costs can vary widely: \$3/yd^3 to \$60/yd^{3}or \$5,000/acre-feet to \$100,000/acre-feet. The actual dredging costs are project specific and are quite variable depending upon the regulatory and stakeholder requirements. Many dredging costs are driven by sediment pumping distances, location of placement areas, and environmental restrictions. Dredging costs have to be compared with other sediment management alternatives, building new storage capacity, or with the costs of eventually losing the reservoir storage capacity in the absence of sustainable management. The reallocation of storage within Chatfield Reservoir near Denver, CO to create more water supply storage and less flood storage is estimated to cost \$10,000/acre-feet (Douglas Raitt, written communication, 2018). New dam and reservoir construction is expected to cost significantly more. No action over the long term will eventually lead to lost reservoir benefits and retirement of the dam and reservoir (Randle, et al., 2017).

THE DREDGING SOLUTION

Many reservoirs may be small enough that the entire sedimentation volume, accumulated over decades of time, could be dredged and transported within a few years to an off-channel deposal site. There may be nearby beneficial uses of the dredged sediments for agriculture, construction, recreation, or habitat.

For large reservoirs, dredging the sedimentation volume accumulated over decades can be cost prohibitive. For example, dredging 10,000 acre-feet of sediment from a reservoir could cost \$50 million to \$100 billion. The cost to dredge 6,630 acre-feet of sediment (10.7 million yd^3) from Lake Decatur, IL will cost \$91 million (City of Decatur, Illinois, 2017). The cost of creating new storage with a new dam and reservoir somewhere else will likely be even more expensive. However, a long-term dredging program may be a viable option for sustainability. A long-term dredging program would focus on the inflowing sediment volume that deposits in the reservoir each year. For example, the annual dredging of 1,000 acre-feet of sediment could cost \$5 million/year to \$100 million/year. Such a strategy likely would have to accept whatever volume of reservoir sedimentation that had occurred prior to the start of the dredging program. There may be short-term beneficial uses of the reservoir sediment, but a long-term dredging program most likely would have to deliver sediment to the river channel downstream from the dam. This is where the sediment would naturally be transported if the dam and reservoir did not exist. The delivery of sediment to the downstream channel would offset the environmental impact that occurred from the reservoir sedimentation. Each downstream reservoir would also have to implement sustainable sediment management. These kinds of sediment management practices are being implemented in countries like Japan and Taiwan.

Important aspects of dredging include access to mobilize the dredge in the reservoir, power source for the dredge, depth of dredging, sediment types to be excavated, distance to the sediment discharge outfall, and management of discharged sediments.

Sediment slurry pipelines for long-term operations will have to be more resistant to abrasion than pipelines for temporary dredging operations. Electric motors can be more cost effective over the long term and create less pollution than diesel powered motors, provided an electric power source is available. Continual dredging from localized areas of the reservoir over the long term may be more important that navigating a dredge over large areas of the reservoir.

Current on-going Reservoir and Lake Dredging

The Iowa and Ohio Departments of Natural Resources have been actively dredging lakes and reservoirs within their respective states for the purpose of restoring and improving recreational use (Figure 1). These dredging programs are actively managed and funded. Other examples of local or state governments with dredging programs include the City of Decatur, IL, Kansas Water Office, States of South Dakota and Nebraska, and local governments in Texas and in Florida. In each case, the primary purpose of the dredging program is to restore water storage capacity for water supply and recreational use. Each agency has developed a funding source, or is in the process of securing continual funding source, in order to maintain their reservoirs.

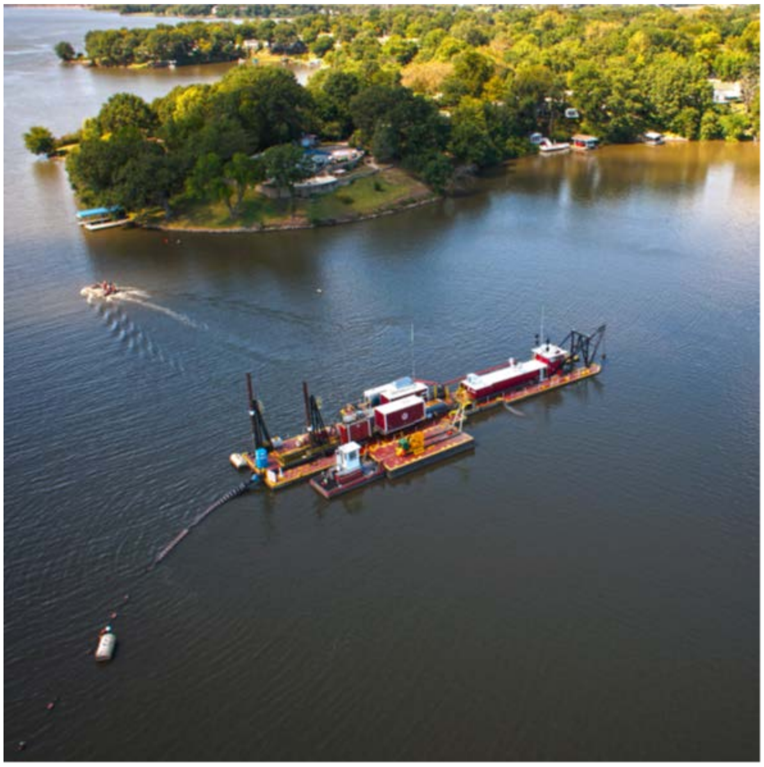

Figure 23. Example hydraulic dredging of Lake Decatur reservoir near Decatur, IL (photograph courtesy of GLDD Marketing Department).

Design Considerations

The following characteristics all need to be considered to determine viable dredging solutions unique for a particular reservoir: location, topography, and bathymetry; sediment types to be excavated (clay, silt, sand, gravel, cobble, woody material); volume of sediment to be removed; dredging depth; disposition of excavated sediment (including any beneficial uses); sediment slurry pipeline, environment compliance, mobilization of dredging equipment, power for dredge and pumps; and financial resources. Long-term sediment management plans should also consider possible ways to reduce future reservoir sediment inflows or reduce the portion of sediment trapped within the reservoir.

Location, Topography, and Bathymetry of the Reservoir.

The reservoir location will affect such things as the economic value of reservoir storage, dredging mobilization and operating costs, and the feasibility of beneficial uses. The reservoir topography and bathymetry (length, width, and depth) will affect access and the choice of the dredging equipment. The longer the distance that dredged material will have to be transported, the greater the cost. John Redmond Reservoir in Kansas had lost 40% of its water supply storage due to sedimentation (Griekspoor, 2016). Therefore, 3 million yd^3 of sediment were dredged from the reservoir in 2016 to recover some of the lost storage capacity. The dredged sediment was delivered to disposal areas downstream from the dam (Figure 2). A considerable cost savings could have been achieved if the pipeline was allowed to cross over the reservoir levee directly from the dredge site to the placement areas or into the downstream channel.

Figure 24. The dredge area of John Redmond Reservoir on the Neosho River in eastern Kansas was close to the dam and disposal areas. The red line on the drawing is the dredge discharge pipeline (figure courtesy of Jim Ho, GLDD AutoCAD Department).

A common characteristic of recent cases where reservoirs were dredged to maintain or recover lost storage capacity is that they were all located near populated areas or there was a major commercial user nearby. In addition they all had the required local support to successfully implement the project.

Reservoirs tend to sort where inflowing sediments are deposited. The coarsest particles (cobble, gravel, and sand) tend to deposit at the upstream end and often form a shallow delta while finer sediment particles (silt and clay) tend to deposit farther downstream along the reservoir bottom.

Subsequent reservoir drawdown can cause previously deposited sediment (especially the delta) to be eroded and transported farther downstream within the reservoir.

Portable cutter suction dredges may work best in shallow areas of the reservoir (2 to 100 feet deep). Mechanical dredges may be needed for deep areas of the reservoir and when large wood is mixed with the reservoir sediments. Reservoir sediment flushing or sluicing could be more cost effective than dredging, but this would require reservoir drawdown. If the sediment is cohesive and compacted, in theory a jetting system could be employed to cut and fluidize the sediment to improve flushing or sluicing efficiency.

Reservoir Sediment Investigation.

A thorough reservoir sediment investigation is needed to design a feasible dredging program. This reservoir sediment investigation should measure and determine the spatial distribution and thickness, particle grain-size distribution, bulk density, cohesion, abrasion characteristics, the presence of organic wood material, and the concentration of any contaminants. Historical records are needed to document the original reservoir topography and whether trees were removed or remain in place after the reservoir was filled. This information will assist in estimating the size and type of dredge required, project costs, and beneficial use opportunities. Accurate data will help to avoid surprises and project cost overruns during the dredging operation.

The sediment particle grain-size distribution is an important and necessary index test, especially for coarse sediments, because it describes the relative proportions of different sizes of sediment particles (e.g., clay, silt, sand, gravel, and cobble). Sediment grain size information is used in production calculations to estimate digging and pumping characteristics of a sediment. The grain-size classification system needs to be clearly defined. Sediment grain size is also one of the main criteria for determining suitability of fill sediment for reclamation and possible reuse opportunities. The information in a grain size curve is more valuable if it is supplemented by such descriptive information as color and particle shape, or by knowledge of grain packing and fabric when seen undisturbed.

The following is a list of recommendations regarding reservoir sediment investigations undertaken to determine relevant data for dredging projects (Johnson and Sraders, 2003):

- Penetrate to, and collect information from, well below the required dredging depth.
- Space borings evenly throughout the dredge areas.
- Pay particular attention to vertical control and lake level datum.
- Use the standard practices for borings, vibracores, and laboratory testing.
- Provide prospective bidders with complete geotechnical reports.
- Take as many borings as possible. Borings are much less costly than unsuccessful dredging projects.

Dredging Depth.

Standard portable cutter-suction dredges are available to work in water as deep as 60 feet. Dredging in water deeper than 60 feet will require a modified dredging plant. Larger harbor and coastal cutter suction dredgers and clamshell dredges have on occasion dredged in water as deep as 100 feet. The fixed hull and structural size of the dredging plant can support the equipment needed to excavate to that depth. Although not common, dredging is technically feasible in water as deep as 150 feet.

For the inland portable dredge market, digging depth is limited by the size of the dredge. Maximum digging depths will vary from 15 to 60 feet. In the United States, inland deep water dredging (deeper than 100 feet) has been limited to the mining industry. Deep dredging depth leads to greater complication, cost and risk. Technical specification requirements for deep-water dredging will reduce the number of competitive contractors.

For reservoirs behind high dams, dredging will tend to be more cost effective in the upstream and shallower portions of the reservoir. This will increase the distance that sediment would need to be pumped to reach the downstream channel, but dredging in the upstream portion of the reservoir will help preserve the downstream storage capacity.

Disposition of Excavated Sediment.

The yearly disposal of dredged sediment into the downstream channel may be a good solution for sustainable reservoir sediment management, provided that the sediments are not significantly contaminated and the sediment supply rates would not overwhelm the downstream channel. Reservoir sediment may have beneficial uses, other than the downstream channel, that could help pay for the dredging program:

- Soil augmentation for agriculture
- Land development
- Construction fill
- Concrete aggregate
- Wetland and other shallow water habitats (Figure 3 and Figure 4)
- Shoreline beach development or augmentation

Figure 25. Dredged reservoir sediment being used for soil augmentation at John Redmond Reservoir, KS.

Figure 26. Dredged reservoir sediment being placed in a Confined Disposal Area at John Redmond Reservoir, KS.

(photographs courtesy of Robert Strunk, GLDD Project Superintendent)

<u>Confined Disposal Facility.</u>

A confined disposal facility (CDF) is an engineered structure for containment of dredged sediment for either long term storage or temporary containment prior to beneficial use. In some situations, there may be a desire to confine dredged sediments for subsequent seasonal release into the downstream channel or storage for sellable aggregates. Nearby land availability, sediment types to be excavated, cost variables of different dredging methods, and pumping distance are the major considerations to determine the best CDF options for dredge sediment. Beneficial use of reservoir sediment may help offset the cost of dredging.

The lowest cost using a CDF as a placement method is a simple cutter suction hydraulic dredge, pump and discharge into a confined disposal area through a slurry pipeline (not requiring any additional booster pumps), and allowing the effluent to return to the reservoir without treatment. Booster pumps will be required to transport sediment longer distances, and at additional cost, through longer reservoirs, past the dam, and to the downstream channel.

The volume required for a CDF will be greater than the volume of dredged material, especially for compacted clay and silt-sized sediment. Settlement column testing should be conducted on fine sediment samples to determine the proper ratio of confinement to dredge volume. The USACE Design Manual (USACE, 2015) recommends a minimum of ratio of 2.0 for light silt and soft clay. The ratio will be less for sands and gravel with some silts. When reservoir sediment will be reused for agricultural purposes, the height of sediment confinement cells should not be greater than 8 feet. This will ensure reasonably fast dewatering and drying times and return the area to productive use.

A weir box is employed to maintain water level within a CDF. With proper water levels, energy from the slurry discharge is dissipated to help separate sediment and water in the ponding area. The weir box design will depend on the sediment particle size distribution and placed below the estimated settlement level during dewatering. A gravity feed system for the return water from the containment area is usually the least expensive option. However, pumps can be cost effective for some small projects.

Wind can cause mixing of water and sediment in the CDF, so the prevailing wind speed and direction should be taken into consideration when designing the orientation of the confinement area and the slurry pipeline inlet.

Active monitoring and management plans, both during and after dredging, will be needed to maximize the capacity of sediment confinement areas. When the sediment slurry entering the CDF contains a mixture of coarse and fine sediments, separation will occur. The heavier coarse sediments will accumulate near the pipe discharge, but the lighter fine sediments will stay suspended longer and settle at or near the outflow weir structure. The coarse sediment accumulation often will not be noticed, because it occurs where the water is deepest. However, the extent of the accumulation can reveal itself very quickly as the reclamation closes out. As the heavier coarse sediment is pushed towards the weir structure, the concentration of suspended sediment increases in the downstream effluent. Placement activities should be monitored and managed to minimize the potential for mud waves because they can emerge quickly and can decrease the efficiency and life of the CDF.

Sediment Slurry Pipeline.

Hydraulic dredges typically pump sediment through a slurry pipeline. The cost to pump sediment over long distances can be a significant portion of the total dredging cost. In addition, costs will increase if sediment has to be pumped to a higher elevation. Therefore, the location where the sediment will be delivered to, and the corresponding alignment and length of the pipeline, will have a direct bearing on the mobilization and dredging costs, especially when booster pumps are needed. Therefore, the slurry pipeline corridor needs to be carefully considered and early in the design process. A detailed accurate topographic map is needed that identifies all crossings of stream channels, roads, and oil & gas pipelines. A floating or submerged sediment slurry pipeline may be a cost effective option that avoids the stream channel crossings and impacts to cultural resources. A floating pipeline and booster pumps were used for the dredging of Strontia Springs Reservoir near Denver (Figure 5). A slurry pipeline, submerged about 15 feet below the water surface, was proposed for Lake Powell (Randle, et al., 2007). If the outfall of the slurry pipeline is downstream of the reservoir, the most direct route may be over the dam. The additional cost to develop a reasonable and safe means over the dam can still be less than the cost of alternate routes around the dam.

The sediment transport mechanisms through the pipeline are important to understand as well as the effects of the slurry on the pump. Slurries are mixtures of solid particles in a carrier fluid. The energy required to move slurry through a pipeline can be much greater than that for water alone (Turner, 1996). In addition, the presence of slurry in a pump affects its performance, increasing energy output and power demand, reducing pump efficiency and suction capability. Coarse sediment particle are much more abrasive to pipelines and pumps than fine sediment particles. There are three transport regimes through a pipeline in which solids are moved, each associated with a distinct range of particle sizes and slurry velocities (Figure 6).

Figure 27. Floating sediment slurry pipeline and pumping plant on Strontia Springs Reservoir near Denver, CO (Photograph taken by Tim Randle, October 2011).

Figure 28. Three transport regimes in a pipe; non-settling or homogeneous (left), partially stratified or heterogeneous (middle), and fully stratified (right).

In non-settling or homogeneous slurries, the particles are evenly distributed in the pipe and there is no change in slurry density across the entire profile of the pipe. These slurries are made up of fine sediments, such as clay, silt, or mud, in particle sizes less than 0.062 mm. The behavior of these slurries can vary greatly, depending on sediment type and concentration, and not much energy is needed to transport them.

Partially stratified, heterogeneous slurries remain suspended, but with higher concentrations near the bottom of the pipe. A portion of the sediment may travel as bed load on the bottom of the pipe. These slurries are made up of sand-sized and fine gravel-sized particles between 0.062 and 8 mm. They require more energy to pump than a fluid of similar density, particularly at low velocities.

Fully stratified slurries travel as bed load on the bottom of the pipe, with turbid water and any fine sediments flowing over the top. These slurries are made up of coarse gravel and coarser-sized sediments (even clay balls) with particle sizes greater than 8 mm. These slurries require the greatest energy to pump.

Pumping distance, sediment types and volume of dredging will determine the type of discharge pipeline employed. Slurry pipelines are most commonly high-density polyethylene (HDPE) or steel.

- HDPE is typically used for small and short-term dredging projects because it costs less and it is easier to mobilize and install than steel.
- Steep pipe is typically preferred for large and long-term dredging projects because it is more durable than HDPE. In addition, steel pipe may be needed for long distance pumping where boosters and high pressures are required. HDPE pressure is limited to 150 lb/in^2 with regular pipe wall thickness.
- The life of the pipe will vary depending on sediment types. For silts, soft clays and fine sands the performance of steel and HDPE is about the same. However, steel pipe will have a longer life than HDPE when pumping coarse sands and gravels.

Environmental Compliance and Required Permits.

The environmental compliance and permits that may be required for a reservoir dredging project are listed below:

- Environmental impact statement or environment assessment required for federal actions, including the issuing of federal permits, as required by the National Environmental Policy Act
- Section 106 programmatic agreement to ensure compliance of the National Historic Preservation Act
- Section 404 permit as required by the Clean Water Act
- Discharge permits for release of effluent water
- Dam safety permits for CDF areas (depending on the location)
- Floodplain fill permit for CDF areas (depending on the location)
- Stream obstruction permits, if slurry pipelines cross rivers or streams
- Water term permit to use water from the reservoir for dredging purposes
- Notice of intent for storm water runoff from construction activities

The permitting process may have a special focus on impacts to cultural, social, natural, and aquatic resources. If the sediment to be dredged is not contaminated, then there may be a finding of no significant impact. This would mean that an environmental assessment could be used instead of an environmental impact statement.

The Rivers and Harbors Act (Section 408) authorizes the Secretary of the Army to grant permission to other entities for the alteration, occupation or use of a USACE civil works project if the activity will not impair the public interest or usefulness of the project.

Mobilization of Dredging Equipment.

The mobilization cost for dredging includes getting all the dredging equipment, slurry pipelines, and any confined disposal facilities ready and in place for dredging operations. The mobilization cost is a function of the schedule, project complexity, and contract risk (Hanson, 2017). The mobilization cost for dredging equipment increases with distance and the difficulty of access to the reservoir, dredging depth, and with the distance that sediment will be transported from the dredge area to the discharge point. The most efficient and cost-effective type and size of the dredging equipment will depend on the specific location characteristics of reservoir. The mobilization cost becomes less significant for long-term dredging projects than for short-term projects.

Power for Dredge and Pumps.

The use of electric or diesel power to operate a dredge and pumps at a given reservoir will depend on the volume of sediment to be removed, duration of the dredging project, and proximity to an electric power source. Diesel driven dredging equipment will be utilized on the vast majority of short-term sediment removal projects, based on the simplicity or ease and lower mobilization cost relative to an electric dredge. On long-term or larger projects, the mobilization cost and hook up for an electric dredge will be offset by the lower energy cost during dredging operations. A quick rule of thumb is that electric power is one-half the cost of a gallon of diesel. An electric dredge would require a power line and substation to provide service. A dam with a hydroelectric power plant may provide a great opportunity for an electric dredge. The most basic questions that need to be asked are listed below:

- Does the utility have enough power available on the local grid to accept the load of the dredge? The full-load power demand for a 22-inch diameter cutter suction dredge is nearly 3,000 kW (or 3 MW). A typical household load would be 8 kW, so a 22-inch cutter suction dredge at full power consumes the energy equivalent of 500 homes.
- Is a shore-side site available for the substation that is within the range of the submarine power cable?

When high-voltage, high-power lines are available, the challenge may be finding a suitable shore-side location for the substation and running the power lines to it. The additional mobilization cost for electric dredge includes permits, design work, and the power line and shoreline substation setup. This cost will vary by location, length of powerline to be installed, and state requirements. The mobilization cost for a long-term dredging project will be less important (a much smaller portion of the total project cost) than the mobilization cost for a short-term dredging project.

From the shore substation to the dredge, electric power is delivered via a submarine cable. For most cases, there are no integral diesel engines other than an emergency standby generator, which generally will power lights and communications in the event of problems with shore-based power.

CONCLUSIONS

Hydraulic dredging may be a good option to recover or maintain reservoir storage capacity, especially where the reservoir cannot be drawn down for sediment management purposes. The use of dredging to recover decades of past sedimentation may only be financially feasible in small reservoirs. For large reservoirs, a long-term dredging program would be needed to keep up with the annual sediment loads entering a reservoir and accept the sedimentation volume that occurred prior to the dredging program. The annual delivery of sediment to the downstream river channel would restore sediment continuity and offset the environmental impact caused by the artificial reduction of sediment loads caused by a dam. However, the seasonal patterns of sediment delivery to the downstream channel will be important. The cost of dredging would have to be compared with the cost of other sediment management options and the cost of eventually losing the reservoir benefits and the cost dam decommissioning in the absence of sediment management.

REFERENCES

City of Decatur, Illinois (2017). *Lake Decatur Basins 1 through 4 Dredging Project Fact Sheet*, https://www.decaturil.gov/wp-content/uploads/2016/11/Lake-Decatur-Dredging-Fact-Sheet.pdf, accessed November 30, 2017.

Griekspoor, P.J. (2016). John Redmond Reservoir Phase 1 dredging complete, Great Lakes Dredge and Dock removed 3 million cubic feet of sludge from John Redmond Reservoir. Kansas Farmer, Nov 23, 2016. http://www.kansasfarmer.com/story-john-redmond-reservoir-phase-1-dredging-complete-9-149743.

Hanson, W.H. (2017). *Mobilization Costs . . . . . What Gives?, Great Lakes Dredge and Dock*, http://aapa.files.cms-plus.com/SeminarPresentations/2008QualityPartnership/Dec2008QPI_Hanson_William.pdf, accessed November 26, 2017.

Johnson, K.D. and Sraders, G.A. (2003). "Geotechnical Investigations for Dredging Projects - A Contractor's Perspective" Proceedings of the Western Dredging Association (WEDA XXIII) and Texas A&M University (TAMU 34) Dredging Seminar, Oakbrook, Illinois.

Kondolf, G.M.; Gao, Y; Annandale, G.W.; Morris, G.L.; 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, C.T. (2014). "Sustainable sediment management in reservoirs and regulated rivers: Experiences from five continents." Earth's Future, 2, doi:10.1002/2013EF000184.

Morris, Gregory L. and Fan, Jiahua (1998). *Reservoir Sedimentation Handbook*, McGraw-Hill Book Co., New York.

Ozment, S., DiFrancesco, K., and Gartner, T. (2015). The role of natural infrastructure in the water, energy and food nexus, Nexus Dialogue Synthesis Papers. Gland, Switzerland: IUCN.

Randle, T.J.; Lyons, J.K.; Christensen, R.J.; and Stephen, R.D. (2007). Colorado River Ecosystem Sediment Augmentation Appraisal Engineering Report, U.S. Department of Interior, Bureau of Reclamation, Technical Service Center.

Randle, T.J.; Kimbrel, S.; and Collins, K.L. (2017). "Reservoir Sedimentation and Sustainability" in the proceedings of the United States Society on Dams, *It's a Small World: Managing Our Water Resources*, 37th Annual USSD Conference, Anaheim, California, April 3-7, 2017.

Subcommittee on Sedimentation, National Reservoir Sedimentation and Sustainability Team (2017). *Management of Reservoir Sedimentation for Long-Term Sustainability*, April 9, 2017.

Turner, T.M. (1996). *Fundamentals of Hydraulic Dredging, Second Edition*, ASCE Press, Reston, VA, 258 pp.

U.S. Army Corps of Engineers (USACE) (2015). *Dredging and Dredged Material Management*, Engineering Manual 1110-2-5025.

Data Sets that Support the Final Report

If there are any data sets with your research, please note:

- Share Drive folder name and path where data are stored: T:\Jobs\DO_NonFeature\Science and Technology\2016-EBC-Pilot Study of Reservoir Sustainability Options
- Robert Hilldale, rhilldale@usbr.gov, 303-445-3135
- Model set-up and results, sediment core testing data, site photos, GIS data
- Bighorn Reservoir, Reservoir Sedimentation, Mobile Bed 2D Sediment Transport Model
- Approximate total size of all files: 9 GB