Final Report

Modeling Mississippi River dredging strategies after the lock closure at Upper St. Anthony Falls

HEC-RAS Sediment Modeling:
Mississippi River, Upper St. Anthony Falls to Lake Pepin

US Army Corps of Engineers
St. Paul District

June 2018

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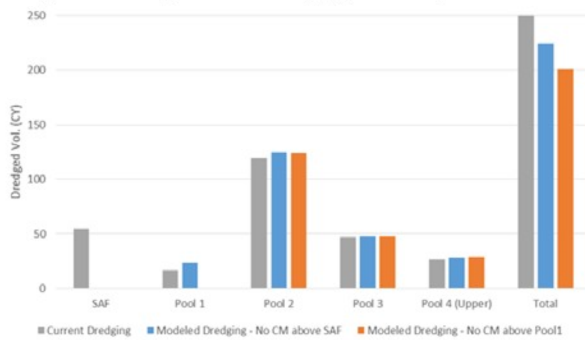
Executive Summary

With the closure of the Upper St. Anthony Falls (USAF) lock in 2015, new opportunities have arisen to investigate alternative channel maintenance strategies in the upper navigation pools of the Mississippi River near Minneapolis and St. Paul, Minnesota. In the elimination of all lockages through Upper St. Anthony Falls, the current channel maintenance activities that are in place to ensure a nine-foot navigation draft in the pool may no longer be required. Additionally, due to reduced commercial boat traffic traveling to Upper St. Anthony Falls through Lock & Dam No. 1 and the Lower St. Anthony Falls (LSAF) lock, reduction in channel dredging through this reach may also be warranted. The results of this sediment transport modeling study intend to show the relative differences in dredging quantities between the current channel maintenance practices and proposed alternatives to channel maintenance. The first alternative analyzes the sediment impacts to the Mississippi River system through Lake Pepin if dredging is discontinued above Upper St. Anthony Falls. The second alternative assesses impacts to the system if channel maintenance is eliminated above Lock & Dam No. 1, including the pools above Lower & Upper St. Anthony Falls Dams. The results of this comparative analysis are shown in Figure A.

Figure A – Average Modeled Dredging (2008-2015) for alternatives



While each of the alternatives show slight increases to average annual dredging in the downstream pools (Pools 2, 3 & 4), the total dredging quantities for the system from Upper St. Anthony Falls through Lake Pepin are lower, on average, due to the removal of dredging in the upper pools. The first alternative increases average dredging quantities in Pools 2, 3 & 4 by 4%, 1%, and 6%, respectively, but reduces the overall average dredging by 15%. Similarly, the second alternative increases average dredging in Pools 2, 3 & 4 by 4%, 2% and 8%, respectively, but reduces overall dredging by 24%. It is important to note, however, that while the average dredging quantities for the system are reduced over the 8 year modeling period from 2008-2015, the trend of the dredging over time for both alternatives is toward an equilibrium that is similar to the current dredging quantities. This trend indicates that the new equilibrium for sediment deposition may be net neutral to the system and downstream pools may maintain permanent increases in average dredging quantities. The average annual flow from 2008-2015 is similar to the conditions from 1981-2015, so the modeling period is fairly representative of the wetter hydrologic conditions present over the past three to four decades.

In addition to the model being used to assess channel maintenance strategies, the model may also be valuable as a tool to analyze sediment trends in this reach of the Mississippi River and in Lake Pepin as well as a tool to investigate the feasibility of major operational changes (e.g. water level drawdowns) or physical changes (e.g. structure modification) to the navigation system. As the final destination of much of the sediment transported from the Minnesota River, Lake Pepin is perpetually an area of concern for deposition rates, characteristics, and trends. The sediment model adds another tool to this study area as far as quantifying the rates of deposition and characterizing the size of sediments. Finally, recent interest in the disposition of Corps' structures at Lock & Dam No. 1 and Upper & Lower St. Anthony Falls would require extensive study to quantify the positive and negative impacts of dam deauthorization or dam removal. This sediment model could be used as one of the supporting tools for future studies throughout the system.

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CHAPTER 1.

1. Introduction

1.1 Background

The Water Resources Reform and Development Act of 2014 (WRRDA 2014) required that the Upper St. Anthony Falls Lock and Dam (USAF Lock) be permanently closed. This closure occurred on June 10th, 2015. Although the legislation did not specifically give a reason for the closure, meetings between federal, state, and local officials prior to this legislation focused on the desire to create a physical barrier to Asian Carp. The closure of the USAF Lock essentially ended the need for annual maintenance dredging in the commercial navigation channel in Pools 1 and the Upper St. Anthony Falls Pool. The decision that has to be made by the St. Paul District of the U. S. Army Corps of Engineers (USACE) is whether 1) to continue channel maintenance as usual, 2) stop channel maintenance in the USAF Pool and in Pool 1, or 3) develop a sediment management strategy based on the beneficial use of dredge material. Because navigation channel dredging can be a large sink for sand-size sediment, reducing dredging in the USAF Pool and Pool1 may eventually have an effect on downstream reaches.

The St. Paul District of the U.S. Army Corps of Engineers (USACE) is responsible for maintaining a 9-foot navigation channel on the Upper Mississippi River (UMR) between Minneapolis, Minnesota and Guttenburg, Iowa. This includes the lower 14.7 miles of the Minnesota River, and portions of the lower St. Croix and Black Rivers. The Upper St. Anthony Falls Lock is the upstream most navigation dam on the Mississippi River and the head of navigation is just a few miles upstream of the lock. Maintaining the 9-foot channel is done through periodic dredging and through a system of locks and dams. The COE dredges and disposes of approximately 66,000 cubic yards of sand annually between the Upper St. Anthony Falls Pool (USAF) and Lock and Dam 1, and 160,000 cubic yards annually on the UMR between Lock and Dam 1 and Lake Pepin. The total from both reaches represents over 25-percent of the district-wide dredging. In addition to the cost associated with channel maintenance dredging, other sediment related impacts in this reach include a turbidity impairment (MPCA, 2012), off-channel sediment deposition affecting habitat and recreational boating, reduced light penetration and aquatic vegetation growth, and accelerated sediment deposition in Lake Pepin. It is estimated that 85 - 90 percent of the sediment deposited in Lake Pepin originates from the Minnesota River watershed (Engstrom et. al., 2009).

To estimate the effects of navigation channel dredging, off-channel sediment deposition, and tributary sediment loads on sediment transport on the UMR, the USACE developed a district-wide bed material sediment budget in 2003. Bed material refers to sand-size sediment that can be found on the bed of the main channel, but can be transported as bed load or suspended load. This bed material budget was based on interpretation of available sediment transport information at U.S. Geological Survey (USGS) gaging stations, long-term channel dredging data, studies of sediment transport and deposition, and measured hydraulic characteristics on the UMR. Total sediment load measurements obtained on the Minnesota River at Ft. Snelling during the years 2011 to 2015 (Groten et. al., 2016) have improved the sediment budget significantly. However, while the sediment budget has been a valuable tool, it isn't a numerical model and can't predict the temporal and spatial effects of changed sediment transport capacity and sediment loads.

1.2 Project Location and Study Area

The study area is on the Mississippi River 9-Foot Navigation Channel between River Mile (RM) 857.6, the upstream limit of the 9 foot channel project, and RM 764, the downstream end of Lake Pepin. For hydraulic modeling purposes, the upstream extent has been extended to RM 866 to include the Anoka gage on the Mississippi River and the downstream extent has been extended to RM 753 to capture the downstream control of the water level for Lake Pepin at Lock and Dam No. 4. This reach includes numerous structures and incoming tributaries, described in Table 1-1 and Figure 1-1.

Table 1-1 – Structures and Tributaries in the Project Area

Feature	River Mile
Upper St. Anthony Falls Lock & Dam	854
Lower St. Anthony Falls Lock & Dam	853.5
Lock & Dam No. 1	847.5
Minnesota River	844
Lock & Dam No. 2	815
St. Croix River	811.5
Lock & Dam No. 3	797
Vermillion River[1]	796.5
Cannon River	795
Chippewa River	763.5
Lock & Dam No. 4	753

[1] The Vermillion River parallels the main channel of the Mississippi River and exchanges flow as far upstream as RM 813.

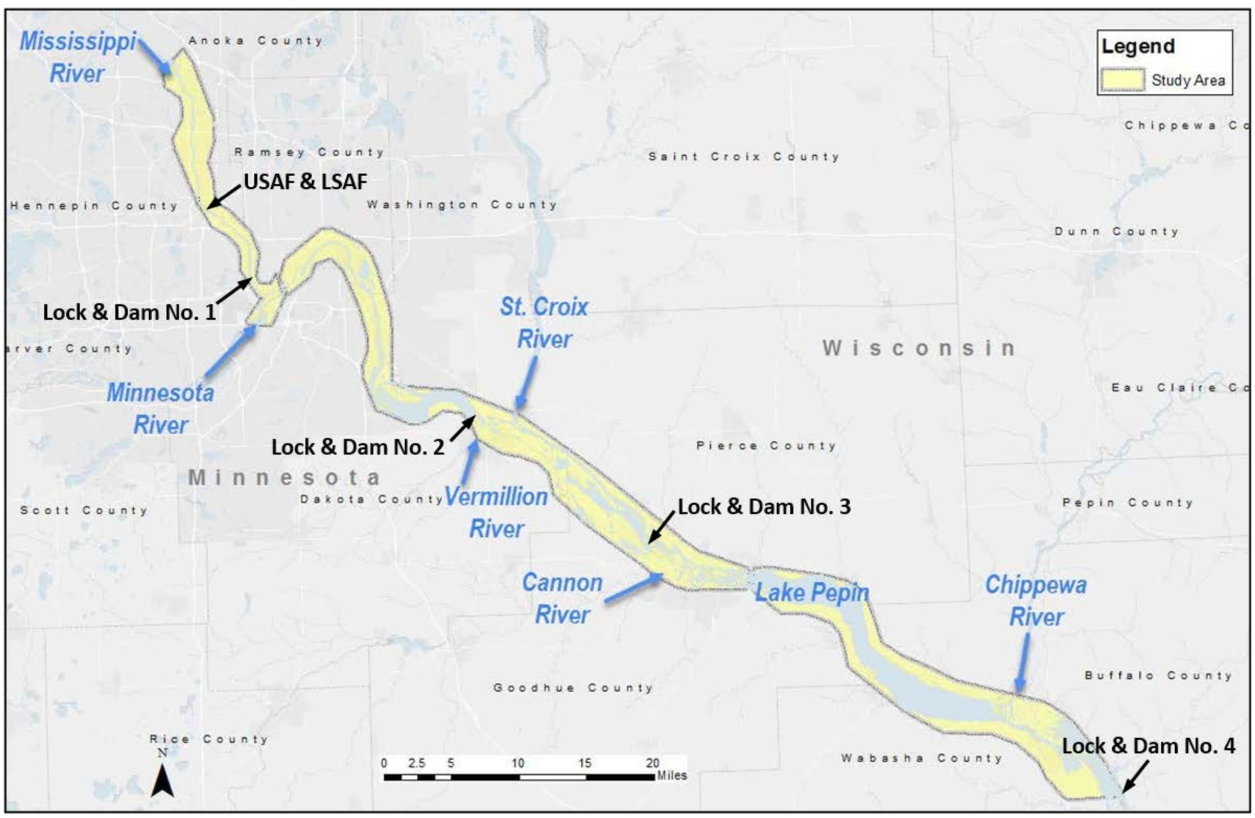

Figure 1-1 – Overview of the Modeling Study Area

1.3 Purpose and Need

A numerical model is needed for the reach of the Mississippi River from the USAF Pool to Lake Pepin to simulate the effects of changed dredging in the USAF Pool and Pool 1. The primary purpose of the model is to simulate the spatial and temporal effects of dredging changes in USAF and Pool 1 on downstream dredging and backwater deposition of sand sized sediment in pools 2, 3, and 4. Other purposes include determining the effects of a secondary channel closure proposed for the Brewer Lake Inlet in Pool 3. The appropriate model must be capable of modeling the complexities of flow exchanges between main channel and backwater areas and advanced operations of multiple lock and dam structures, while also being capable of modeling long reaches of river over 100 miles in length. Advanced two-dimensional and three-dimensional models would be appropriate for capturing complex hydraulic behavior, but would not be efficient over a domain as large as the proposed study area. Conversely, simple spreadsheet models and sediment budgets would be efficient, but incapable of capturing the hydraulic complexities of this system. The HEC-RAS one-dimensional model has been selected for this study as appropriate as it is capable of effectively modeling hydraulics and sediment over large domains as well as capturing smaller scale complexities at flow splits and structures.

1.4 Related Studies and Reports

Numerous studies and reports are available for the Upper Mississippi River that include USAF to Lake Pepin. The following studies and projects addressing channel maintenance, resource management, land use, and recreational planning have the most relevance to this study. Additional reports and studies may be available upon request.

1.4.1 Nine Foot Navigation Channel Project Environmental Impact Statement

This document, completed in 1974, assesses the environmental effects of the operation and maintenance of the 9-Foot Navigation Channel project within the St. Paul District.

1.4.2 Great River Environmental Action Team Study (GREAT I)

This 9-volume report (completed in 1980) documents the results of the 5-year Great River Environmental Action Team study for the St. Paul District reach of the Mississippi River. The report contained numerous recommendations for improved management of the river, the most important of which was a 40-year plan for dredged material placement for all of the historic dredging locations in the St. Paul District. Many of the study's recommendations have been implemented. Of particular application to this study is GREAT I further study item #2 which states – “A plan should be developed to use the river's sediment transport capability to cause necessary dredging requirements to occur near long-term placement sites as environmentally and economically feasible.”

1.4.3 Channel Maintenance Management Plan and EIS

This 1996 plan and accompanying environmental impact statement is the St. Paul District's plan for management of channel maintenance. Much of the plan is devoted to the designation and design of dredged material placement sites. Included in this report is a discussion of the District's program for channel management.

1.4.4 Upper Mississippi River and Illinois Waterway Cumulative Effects Study

"Numerous and extensive modifications of the Upper Mississippi River (UMR) have been made by the Federal Government to allow safe and reliable navigation. Modifications to the UMR began as early as the 1830s. Congress authorized the construction of a 4 ½-ft depth navigation channel in 1878. A deeper 6-ft depth navigation channel was authorized in 1907. The current 9-ft depth navigation channel was authorized in 1930 and largely constructed between 1930 and 1940. The 9-ft depth channel extends along the UMR from the confluence of the Ohio River upstream to Minneapolis, Minnesota and along the Illinois Waterway (IWW) from its confluence with the Mississippi River upstream to Lake Michigan. The involved navigation facilities are referred to as the 9-ft Channel Project.

This study seeks to quantify cumulative effects of activities related to the 9-foot navigation project on the environment and predict future conditions. Although direct impacts such as water impoundment, sedimentation, structures, and dredging are associated with the 9-ft Channel Project, it is important to understand that the cumulative effects along the UMR and IWW defined in this study are also the result of numerous other man-induced influences. These influences include the construction of numerous large reservoirs on tributaries, agricultural land-use practices, construction of levee systems for flood control and wildlife habitat, and possibly global climate change. Assessment of cumulative effects is therefore necessary to understand why and how the UMR and IWW has changed and to provide a basis to extrapolate future conditions."

1.4.5 South Metro Mississippi River Total Suspended Solids Total Maximum Daily Load – Draft Report

"The South Metro Mississippi River Total Suspended Solids (TSS) TMDL has been under development since 2004 as a companion project to the Lake Pepin eutrophication TMDL initiated the same year. A river model extending from Lock and Dam 1 to Lock and Dam 4 was developed to allow analysis of both turbidity and eutrophication impairments, and interactions between the two. After the model was completed in 2008, the MPCA put the issues of turbidity and eutrophication on separate tracks, starting with the development of site-specific standards and proceeding to the writing of TMDL documents. The MPCA sent the U.S. Environmental Protection Agency (U.S. EPA) a proposed site-specific TSS standard for the South Metro Mississippi in 2010, replacing the statewide turbidity standard for these reaches and providing the basis for the South Metro Mississippi TSS TMDL. The U.S. EPA gave its final approval to the proposed standard on Nov. 8, 2010. The present TMDL applies to the TSS-impaired reach extending from River Mile 844 at the confluence with the Minnesota River to River Mile 780 in upper Lake Pepin. The TMDL addresses water quality impairment in this impaired reach, in addition to the accelerated in-filling of Lake Pepin with sediment."

CHAPTER 2.

2. Methods

2.1 Data Collection

2.1.1 Flow and Stage Gage data

Water surface elevation data, flow records, and sediment measurements are important pieces of data for both the construction and calibration of a hydraulic and sediment model. Water surface elevation data is available through continuous measurements using Data Collection Platform (DCP) instruments and through daily observations of stage data at structures, points of interest, and established gage locations. The U.S. Army Corps of Engineers collects continuous and daily records of water surface elevation for pool and tailwater (TW) levels at each of the operated lock and dam structures as well as at "control point" locations which are used for hinge-point operations of the navigation system. The United States Geological Survey (USGS) collects water surface elevation at established gaging stations which can be converted to a continuous record of discharge or streamflow by maintaining a stage-discharge relationship for each gage location through the periodic measuring of discharge at that location (Olson & Norris, 2007). A summary of the available gage locations operated by the USACE and USGS within the model study area is shown in Table 2-1. The table summarizes the river mile (RM) location, the gage ID, the location description, the types of available data, and the years of record for the gage. The shared record of the various gages is from 2007 to the present, which is the basis for the focus of the modeling effort.

Table 2-1 – Gages utilized in the Project Area

RM	Gage	Location	Data	Start	Gage Record	End
865.1	USGS 05288500	Mississippi River at HWY 610 in Brooklyn Park, MN	Flow, Sediment	1931		2017
853.8	USACE SAF	Upper & Lower St. Anthony Falls Lock & Dam	Pool, TW, Flow	1950		2017
847.6	USACE LD1	Lock and Dam 1 at Minneapolis, MN	Pool, TW, Flow	1904		2017
847.0	USGS 05289800	Minnehaha Creek at Hiawatha Ave in Minneapolis, MN	Flow	2005		2017
843.9	USGS 05330920	Minnesota River at Fort Snelling State Park, MN	Flow, Sediment	2004		2017
840.5	USGS 05331000	Mississippi River at St. Paul	Flow	1892		2017
832.7	USACE SSPM5	Mississippi River at South St. Paul (CP2)	Elevation	1997		2017
815.2	USACE LD2	Lock and Dam 2 at Hastings, MN	Pool, TW, Flow	1930		2017
811.3	USGS 05344490	St. Croix River at Prescott, WI	Flow, Sediment	2007		2017
811.2	USACE PREW3	Mississippi River at Prescott, WI (CP3)	Elevation	1997		2017
796.9	USACE LD3	Lock and Dam 3 at Welch, MN	Pool, TW, Flow	1934		2017
795.0	USGS 05355200	Cannon River at Welch, MN	Flow	1909		2017
764.0	USGS 05369500	Chippewa River at Durand, WI	Flow	1986		2017
761.0	USACE WABM5	Mississippi River at Wabasha, MN (CP4)	Elevation	1997		2017
752.8	USACE LD4	Lock and Dam 4 at Alma, WI	Pool, TW, Flow	1934		2017

** Shared record is from 2007 through present (2017)*

2.1.2 Suspended Sediment

In addition to measurements of stage and flow at various gage locations, the USGS collects field samples of suspended sediment concentration and sediment grain size distribution for use in water quality and runoff analyses. This suspended sediment data can also be used as an input to a sediment transport model. The units for the collected concentration values are recorded in mass per volume, or typically milligrams per liter using the International System of Units (SI). The preferred units for the sediment model is to input the data as a total sediment load in units of weight per time, or tons per day using English units. To convert the concentration to a total load, the concentration needs to be multiplied by the instantaneous river flow that occurs at the time of the concentration measurement, as well as a coefficient to convert to the appropriate units. The total load, in tons per day, can be calculated by the following equation (Porterfield, 1972):

$Q_s = Q_w * C_s * K$ where

Qs	=	Sediment discharge or sediment load, in tons per day (tons/day)
Qw	=	Discharge or streamflow, in cubic feet per second (ft3/s or cfs)
Cs	=	Concentration of suspended sediment, in milligrams per liter (mg/L)
K	=	0.00269, the coefficient to convert units

$$K = \left(\frac{86{,}400\ seconds}{1\ day}\right) * \left(\frac{1\ meter}{3.28\ feet}\right)^3 * \left(\frac{1000\ liters}{1\ cu.meter}\right) * \left(\frac{1\ kilogram}{10^6 milligrams}\right) * \left(\frac{2.2\ pounds}{1\ kilogram}\right) * \left(\frac{1\ ton}{2000\ pounds}\right) = 0.00269$$

Sediment concentration measurements are available for the three main inflows to the model domain: the Mississippi River, the Minnesota River, and the St. Croix River. The Mississippi River has a total of 7,714 sediment measurements while the Minnesota River has a total of 74 measurements and the St. Croix River has 9 observations that can be used to develop a flow-load curve. A power-fit regression of the log-transformed values of flow and load was developed for each set of data and used as an initial best estimate for the flow-load relationship. The measured data and the best estimate curves are shown in Figure 2-1.

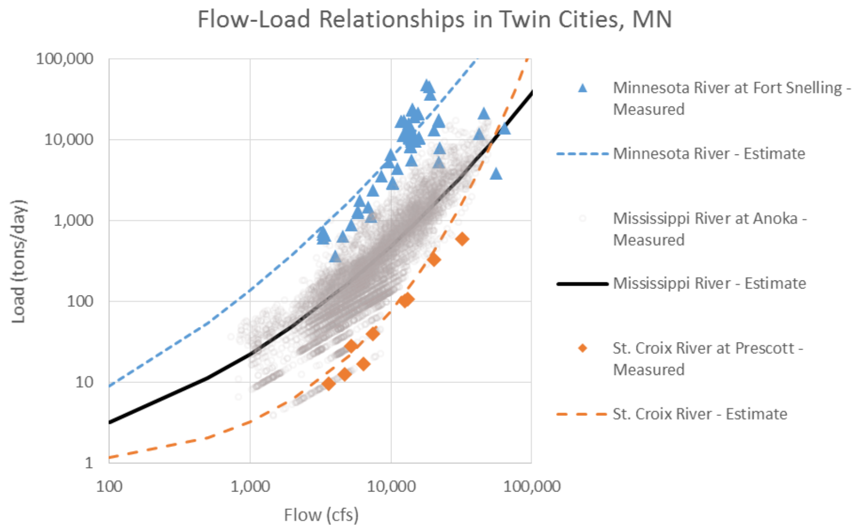

Figure 2-1 – Flow-Load Relationships for three major inflows to the sediment model

The flow-load relationships for these three major inflows show roughly an order of magnitude difference in total sediment load. For example, at 10,000 cfs the best estimate for the St. Croix River is 77 tons/day, the best estimate for the Mississippi River is almost ten times greater at 486 tons/day, and the best estimate for the Minnesota River is ten-fold greater still at 6061 tons/day. The higher sediment loads that are found within the Minnesota River Basin can help explain why this tributary contributes over 90% of the sediment that makes its way to Lake Pepin (Engstrom, 2009).

Sediment samples collected by the USGS, in addition to obtaining a measurement of concentration, can be analyzed to determine the sediment grain size distribution. The percentage of the suspended sediment that falls into the various grain classes of sands (0.0625-1 mm), silts (0.004-0.0625 mm), and clays (< 0.004 mm) can be determined through sieve and hydrometer tests as described in the American Society for Testing and Materials (ASTM) procedure D422-63(2007)e2 (ASTM, 2007). This information can be presented in a plot showing the percentage of the material that is finer than a given particle diameter. The suspended sediment particle size distributions used in this modeling effort are shown in Figure 2-2.

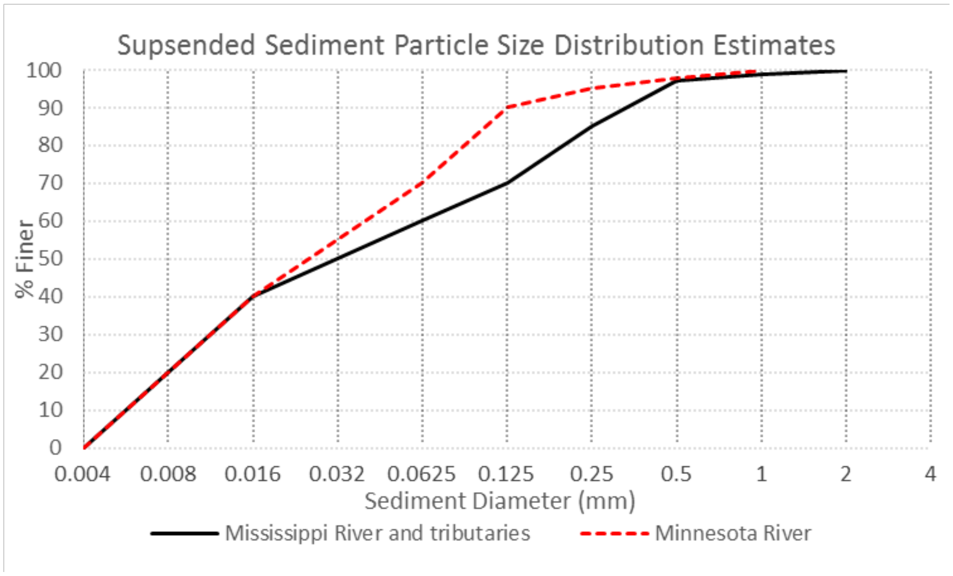

Figure 2-2 – Suspended Sediment Particle Size Distribution Estimates

There is an inherent amount of variability in the testing for particle size distribution which is difficult to capture in a 1D sediment model. For this reason, most of the inflows in the model were assumed to have the same suspended sediment gradation based off of the median values from the numerous samples. The one exception, the Minnesota River, was assumed to have a higher percentage of finer material (coarse silts and fine sands) based on the median values of samples from that collection site.

2.1.3 River Bed Gradations

The sediment model allows for different gradations of bed material to be assigned at each cross-section in the model. Bed samples were found throughout the model domain area, both on the main channel and in backwater areas such as marinas. The various types of bed gradations were sorted in groups based on pool and flow type (i.e. main channel vs. backwater areas or sloughs). The median values were taken for each group and applied to the various reaches as appropriate. For example, the North & Sturgeon Lake area was modeled with bed gradations for "Pool 3 Coulee/Sloughs". Each bed gradation used in the model is shown in Figure 2-3.

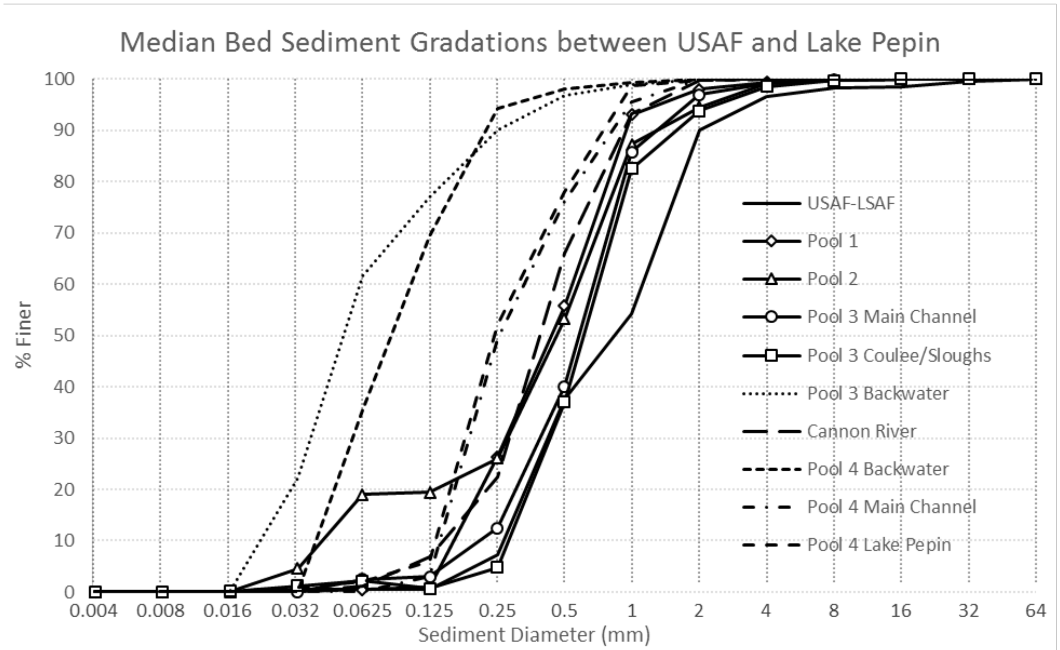

Figure 2-3 – Bed Gradations for various reaches in the model

Ultimately, since the system is primarily depositional rather than erosional, the sediment modeling results are not very sensitive to the bed gradations.

2.1.4 Digital Elevation Model (DEM)

The modeling domain must extend far enough upstream to encompass the dredge locations above Upper & Lower St. Anthony Falls (USAF & LSAF) and far enough downstream to create a downstream boundary that does not affect the stage and flow calculations at Lake Pepin. The U.S. Army Corps of Engineers St. Paul District has numerous years of extensive bathymetric datasets in each of the pools in the study area through surveys performed by USACE for dredging, navigation, and ecosystem restoration purposes. The St. Paul District GIS Section has merged these datasets with above-low-water Light Detection and Ranging (LiDAR) data collected by the Minnesota Department of Natural Resources (MN DNR) since 2008; providing seamless datasets for pools throughout the study area. These datasets have been merged for this study to create a single Digital Elevation Model (DEM) as shown in Figure 2-4. This DEM is used to attribute elevation data to the hydraulic model features.

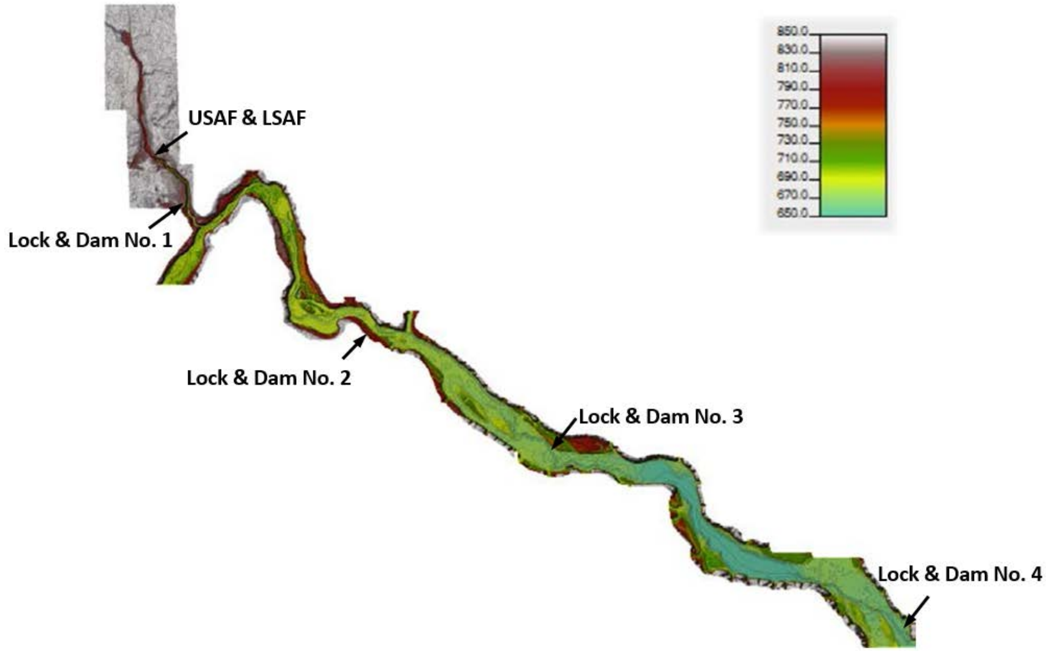

Figure 2-4 – Merged Digital Elevation Model (DEM) Constructed for the Hydraulic Model

2.2 Model Construction

The selected software for the modeling effort is HEC-RAS (USACE, 2016). This software, originally developed as a one-dimensional (1D), steady-flow hydraulic modeling software package, now has capabilities for unsteady flow, sediment modeling, and two-dimensional (2D) flow. For this effort, the software is used to construct a 1D, unsteady-flow, hydraulic river model; calibrate the hydraulic model to collected stage and flow data; further develop the model into a 1D, unsteady-flow, *sediment* hydraulic river model; calibrate the sediment model to observed dredging records; and assess sediment impacts for changes to existing system operations. HEC-RAS does not currently have the capabilities to model sediment in 2D. Instead a 1D model, which calculates the water surface profile by solving the Energy equation across successive river “cross-section” features, is used rather than a 2D model capable of solving the 2D Saint Venant equations or Diffusion wave equations across multidirectional cell features. While a 1D model is less detailed in nature, it can provide shorter model run times for added complexities such as sediment, multi-year flow records, and large model domains.

The cross-section location data, river centerline features, Manning’s n-values for roughness, and ineffective flow limits were taken from various existing HEC-RAS models developed for the Mississippi River in this area:

- Mississippi River through St. Paul (Pool 2) developed as part of a USGS study (Czuba et. al. 2014)
- Lower Minnesota River from latest Corps Water Management System (CWMS) Modeling by USACE, St. Paul District in 2016
- Mississippi River through Pools 3 & 4, developed as part of a modeling effort for the Nuclear Regulatory Commission in 2015

Modifications and additions were made to the existing model geometry data, but general trends of roughness values and ineffective flow limits were maintained. The final layout of river centerlines (blue) and cross-section locations (green) is shown in Figure 2-5.

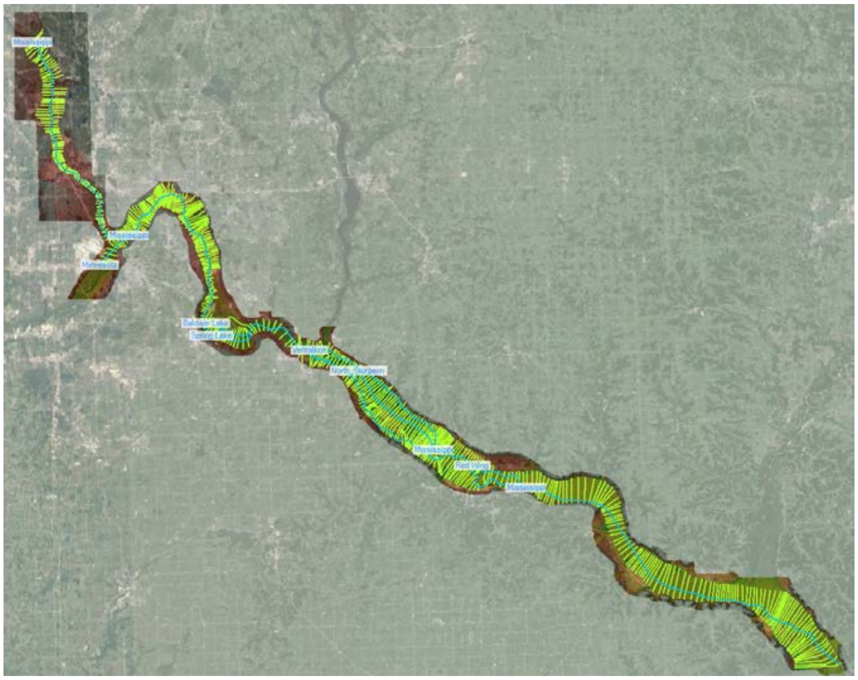

Figure 2-5 – Final Layout of 1D Hydraulic Model Geometry

While the 1D model cannot capture the complexities of two-dimensional flow, the floodway can be modeled as multiple channels to better capture the flow splits near Grey Cloud Island (Baldwin Lake and Spring Lake), Prairie Island (Vermillion River and North & Sturgeon Lakes), and Red Wing (Wisconsin Channel). A schematic of the modeled river reaches to capture flow splits is shown in Figure 2-6.

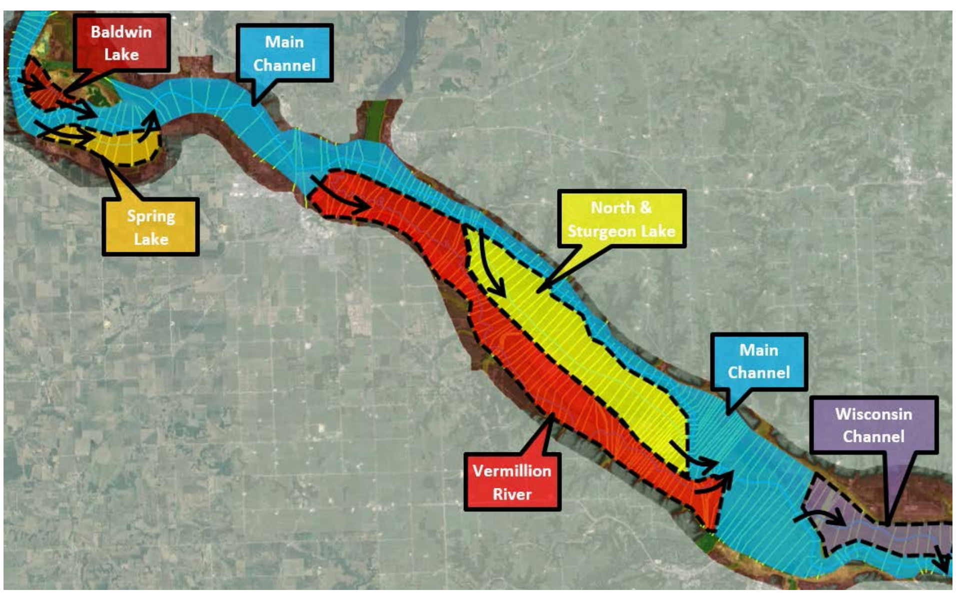

Figure 2-6 – Schematic of Separate Modeled River Reaches to Capture Flow Splits

The cross-section and "lateral structure" features that connect the various reaches are "cut" from the developed seamless DEM to ensure that model represents the conditions with the best available data. The lock and dam structures are imported from the previously developed models to ensure that the gates, sills, and dam crests were set to the appropriate sizes, elevations, and datum.

All elevations used in the modeling effort and presented in this report are in North American Vertical Datum of 1988 (NAVD 88). The conversion from the National Geodetic Vertical Datum of 1929 (NGVD29) is to add 0.194 feet at the upstream end of study area and 0.036 feet at the downstream end of study area.

2.3 Hydraulic Model Calibration and Validation

The hydraulic model was calibrated to water surface elevation data at pool, tailwater, and control point gages and to flow estimates at USGS gage locations.

The metric used to assess the calibration to observed flow is the Nash-Sutcliffe model efficiency coefficient (NSE) which is a common metric used to assess the predictive power of hydrologic models (Nash & Sutcliffe, 1970). The model accuracy is high as the NSE values approach a value of 1. The four discharge gages that were compared showed NSE values of 0.95-0.99 indicating that the model is very accurate in terms of flow. The comparisons of modeled flow to observed flow at Lock & Dams No. 1 and No. 2 are shown in Figure 2-7. Large plots of the comparison of modeled and observed flow for all locations are shown in Appendix A.

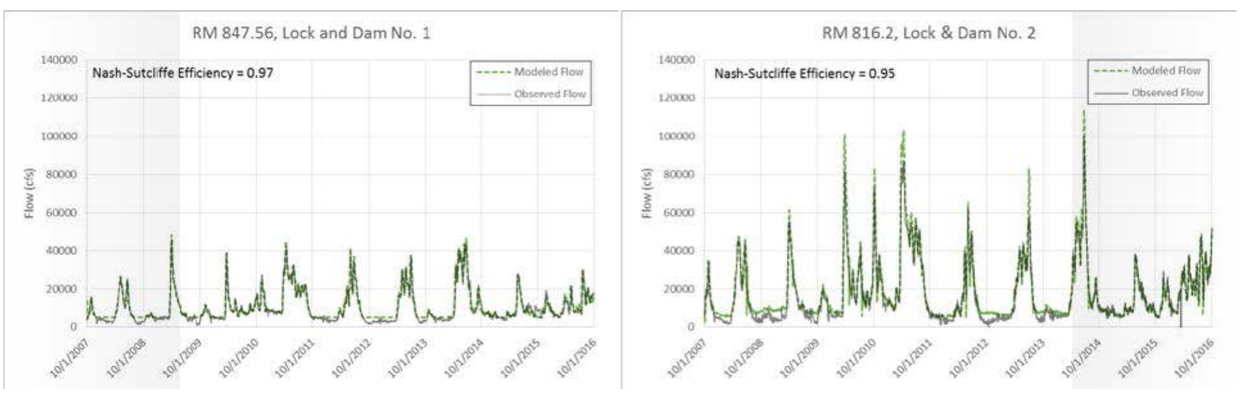

Figure 2-7 – Comparisons of modeled to observed flow at Lock & Dams No. 1 and No. 2

Backwater flow was also validated against periodic backwater measurements collected by the St. Paul District. Various locations throughout Pool 2 and Pool 3 were measured to help estimate the flow conveyance of the main channel compared to backwater or side channel areas. In Pool 2, lower velocity areas such as Baldwin Lake and Spring Lake still convey up to 20% of the total flow on the river. In Pool 3, the Vermillion River and North & Sturgeon Lakes can convey an even greater percentage of the total flow. At Pool 3 in particular, the flow splits to secondary channels and backwater lakes are very complex, with numerous sloughs and breakout areas allowing for interchanging flow. The 1D model is able to capture the flow splits surprisingly well, with strong validation between the modeled flow and the periodic measurements of flow. In the following figure, Figure 2-8, the point data (square symbols) represent backwater flow measurement data at sloughs and lakes and the continuous data (line symbols) represent the model output at the same location. The strong agreement between modeled and observed data at backwater areas are shown in Figure 2-8 and for both pools in Appendix A.

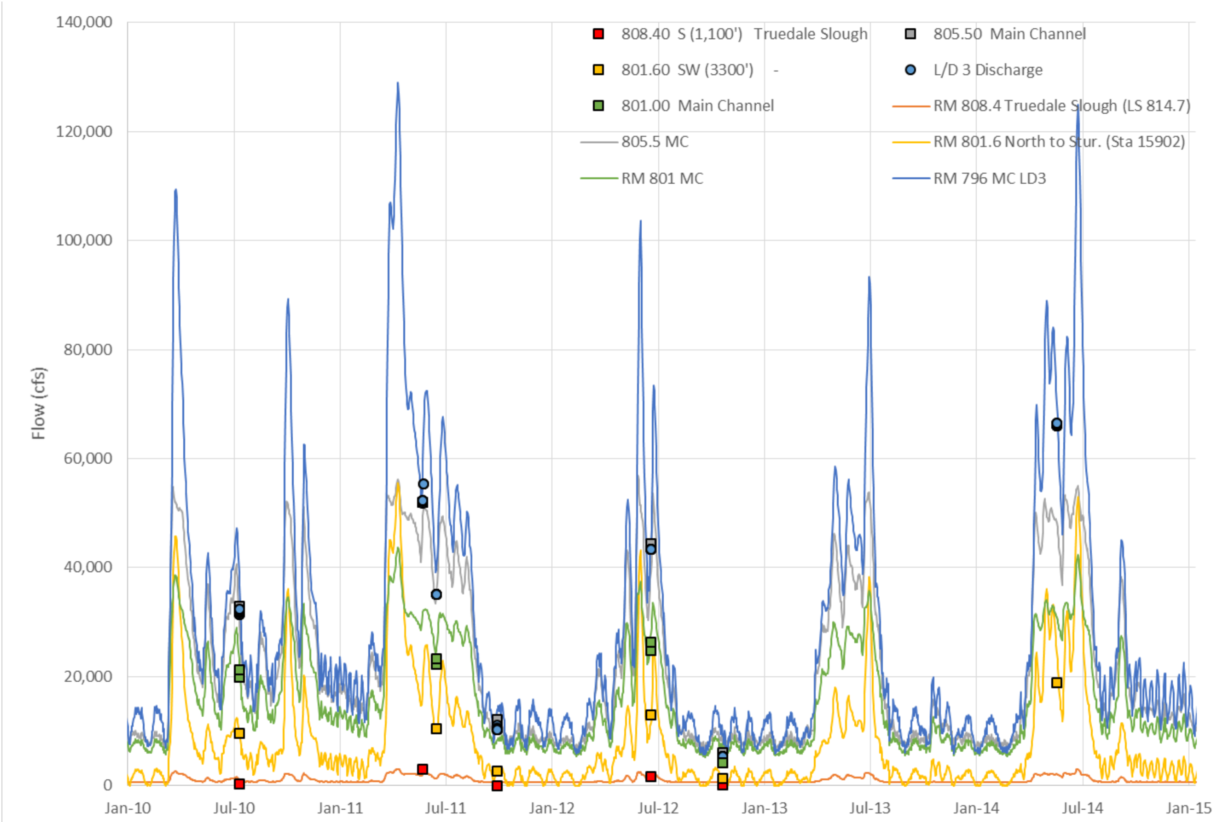

Figure 2-8 – Comparisons of modeled to observed flow at backwater areas in Pool 3

The modeled water surface elevation data at the navigation structures and control points was compared to the observed data using the estimator of mean square error (MSE) which is the sum of the squared difference between observed and predicted values (Legates & McCabe, 1999). This is another common metric in statistical modeling for goodness of fit, with values closer to 0 indicating higher accuracy.

Values at the various gages generally range from 0.13-0.59 feet with the L&D 3 pool having a higher MSE of 1.77 feet. These values are found to be generally acceptable for sediment modeling purposes. The comparisons of modeled water surface elevations to observed data at Lock & Dams No. 1 and No. 2 are shown in Figure 2-9. Larger plots of the comparison of modeled and observed water surface elevations for all locations are shown in Appendix A.

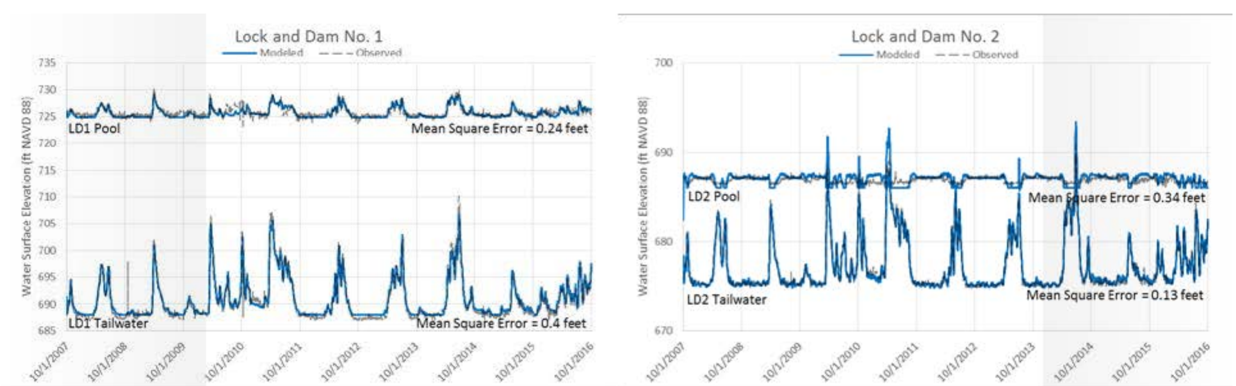

Figure 2-9 – Comparisons of modeled to observed water surface elevations at Lock & Dams 1 & 2

Additionally, the model results were compared to observed values in river profile view to ensure that the model was behaving as expected for both low water events and during flood events. Examples of these two events, with the modeled water surface represented by the blue line and the observed water surface represented by the diamond points, are shown in Figure 2-10 and in Appendix A.

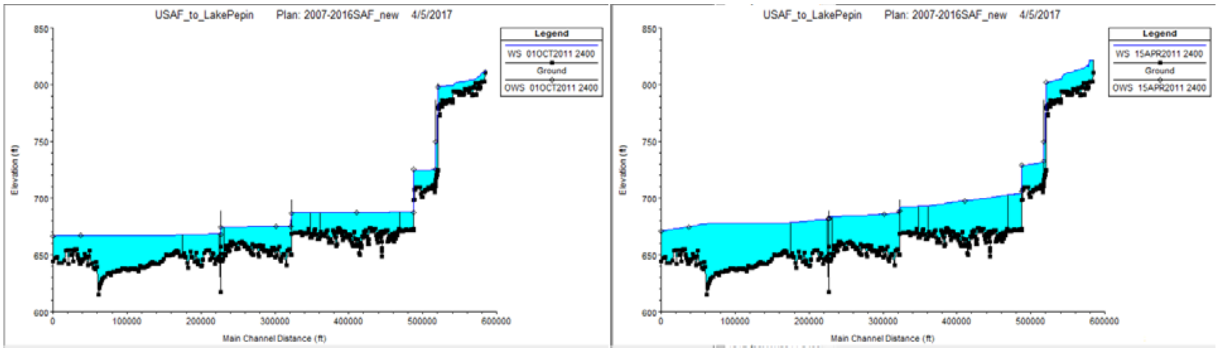

Figure 2-10 – Profile comparisons of modeled to observed water surface elevations for USAF through Lake Pepin at low water conditions (left) and during a flood event (right)

2.4 Sediment and Dredging Model Calibration

Sediment transport in HEC-RAS can be modeled using a variety of different transport functions, fall velocity equations, bed change options, as well as numerous other calibration parameters. For this modeling effort, multiple different transport functions were investigated initially (Yang, Ackers-White, etc.) but ultimately, the Laursen-Copeland transport function equation was selected for use in the model. The Laursen method (Laursen, 1958) is a total sediment load predictor developed through experiments and qualitative analysis for grain sizes between 0.011 and 29 mm. Copeland (Copeland, 1989) contributed to the development of the equation to extend the applicability to gravel-sized sediments. The Laursen-Copeland equation showed promising initial results and is the recommended transport equation to use in HEC-RAS for modeling fine grained sediments, outperforming other transport functions in the very fine sand and very coarse silt range (USACE Hydraulic Reference Manual, 2016). The bed sorting method was set to 'Active Layer' of roughly 1 meter in thickness. Rather than specify 3 or 5 different layers in HEC-RAS, a simplistic approach was used where the "active layer" is the portion that is actively transporting and depositing material and the "inactive layer" is the layer below, where sediments are mixed into from the active layer. The fall velocity method was set to the equation developed by Dietrich (Dietrich, 1982) as that method has shown strong results in past studies and was recommended by Dr. Gary Parker as a superior method compared to the other options in HEC-RAS. The bed change option was set to the 'Reservoir Option', which deposits more sediment in the deeper part of the cross-section. This method was found more realistic for the series of reservoirs present in the lock and dam system, as opposed to the other options of depositing and eroding sediment uniformly within the movable bed limits or allowing deposition across the entire wetted area uniformly.

Dredging in HEC-RAS is modeled by specifying a station, elevation, width, and time & date of a dredging event at each cross-section in the model. The dredging events were set for July 15 of each year in the model, to represent the entire season's worth of dredging typically occurring over mid-to-late summer.

Cross-sections where historic dredging has occurred were specified to be dredged to the appropriate width specified in the Channel Maintenance Plan and to the appropriate elevation in reference to the Low Control Pool (LCP) profile. The specified dredging locations and extents are summarized in Table 2-2.

Table 2-2 – Summary of Modeled Dredging Extents

Pool	Location	Upstream River Mile	Downstream River Mile	Modeled Dredge Width (ft)	Modeled Dredge Elev. (ft)
USAF	Minneapolis Turning Basin	857.6	856.8	150	786.9
	Lowry Ave. Bridge	856.8	856.4	150	786.9
	Broadway Ave. Bridge	856.1	855.3	150	786.9
	Above Plymouth Ave. Bridge	855.5	854.8	150	786.9
LSAF	Lower St. Anthony Falls	853.8	853.4	150	736.9
Pool 1	Lower Approach LSAF	853.4	853.4	200	736.9
	Washington Avenue Bridge	853	852.5	200	712.8
	Above Franklin Ave. Bridge	852.4	851.6	200	712.8
	Below Franklin Ave. Bridge	851.4	850.7	200	712.8
	Above Lake Street Bridge	850.5	849.9	200	712.8
	Below Lake Street Bridge	849.9	848.9	200	712.8
	St. Paul Daymark	848.9	848.5	200	712.8
	Upper Approach L/D 1	848.4	847.7	200	712.8
Pool 2	Smith Ave. Bridge	841.3	840.0	200	674.8
	Above Wabasha St. Bridge	839.6	839.5	200	674.8
	Below Lafayette St. Bridge	839.0	838	200	674.8
	St. Paul Barge Terminal	837.8	836.4	200	674.8
	Grey Cloud Slough	828.3	827.5	200	674.6
	Pine Bend Foot Light	823.7	822.7	200	674.4
	Boulanger Bend	821.4	820.7	200	674.3
	Boulanger Bend Lower Light	819.8	819	200	674.2
Pool 3	Lower Approach To L/D 2	815.1	814.9	300	662.6
	Prescott	811.7	810.3	300	662.6
	Truedale Slough	808.6	807.9	300	662.4
	Four Mile Island	807.9	807.0	300	662.3
	Big River(Smith Bar/Upper Light)	806.0	804.1	300	662.2
	Morgans Coulee	802.9	802.2	300	661.9
	Coulters Island	801.9	800.8	300	661.9
	Diamond Bluff	800.4	798.8	300	661.8
Upper Pool 4	Old Mississippi Channel	796.9	796.0	300	654.6
	Trenton	794.6	794.0	300	654.6
	Cannon River	793.5	792.1	300	654.6
	Red Wing Highway Bridge	791.2	789.5	300	654.6
	Head of Lake Pepin	785.4	785.2	300	654.6

Modeling the dredging in HEC-RAS based on specified rules is imperfect compared to the subjective decisions that are made in the actual dredging of the system. Channel maintenance is required to maintain the nine foot navigation channel below the LCP. The nine foot channel currently requires dredging to 10.5 feet below the LCP to ensure sufficient draft for barge traffic. However, in actual practice, when dredging does occur the invert is brought to 12 feet below the LCP in order to gain efficiencies in the dredging program (i.e. over-dredge by 1.5 feet so that other locations may be prioritized the following year). In addition to the planned over-dredging, subjective decisions will be made to minimize mobilization of the dredging equipment and to utilize sediment storage sites efficiently. For these reasons, the modeled dredging may not always accurately reflect what actually occurred in the system. However, the model should, on average, do a good job of capturing the total sediment removed through channel maintenance.

With the modeling methods and dredging events specified, the main calibration parameter used in the model was adjusting the flow-load relationships of the Mississippi River and Minnesota River. Sediment transport, in the model and in reality, reflects the total load of the system which consists of a suspended sediment portion and a bed-load sediment portion. Because the starting flow-load ratings in this model are based on the suspended sediment concentrations, they lack the bed-load sediment estimate, under-predict the total load, and will be adjusted upward during the calibration process. According to the Channel Maintenance and Management Plan, the Upper Mississippi River and tributaries have bed-loads that are between 0 and 40% of the total load, with 10% being the typical value. To account for the bed-load and to achieve calibration, the loads were incrementally increased in the flow- load rating curves until the modeled dredging quantities matched the measured historic dredging quantities. If modeled dredging quantities were low in the St. Anthony Falls Pool and Pool 1, the Mississippi River flow-load curve was increased. If dredging quantities were low in Pools 2-4, the flow- load curve for the Minnesota River (as the largest contributor of sediment) was increased. For the final calibration the ultimate flow load curves were adjusted to the final curves (shown as red lines, compared to the initial curves in dashed black lines) in Figure 2-11.

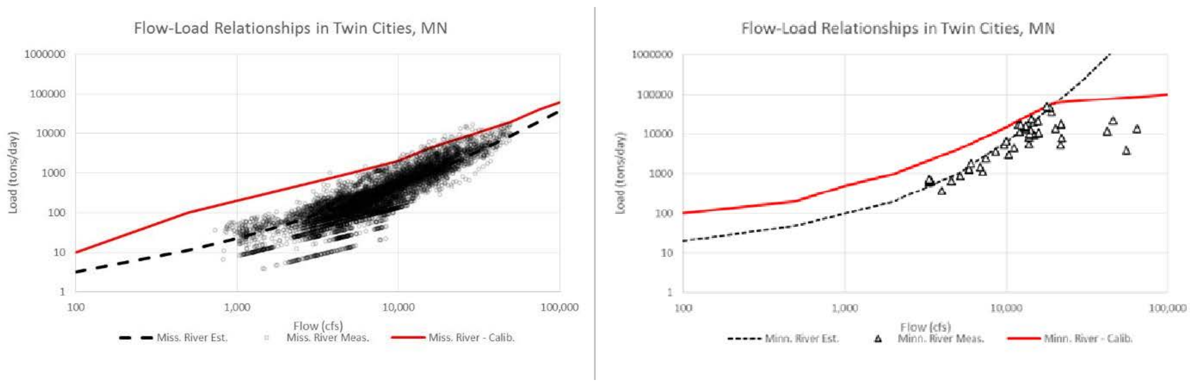

Figure 2-11 – Initial and Final Flow-Load Relationships used in the sediment model

CHAPTER 3.

3. Results

3.1 Existing Channel Maintenance Practices

Sediment modeling is traditionally very difficult to replicate with high precision and accuracy. Often times, results that are within a factor of two of the measured data are found to be sufficient due to the wide range of variability in sediment data and the complex processes that make up sediment transport. The total dredge quantity modeled in the period from 2008 through 2015 from the Upper St. Anthony Falls Pool through Lake Pepin is 11% higher than the measured volume. Annual quantities for each pool show error sometimes as great as a factor of two, but overall the average modeled dredging quantities compare very well with the average measured quantities. A summary of the average annual dredging volume by pool is shown in Figure 3-1.

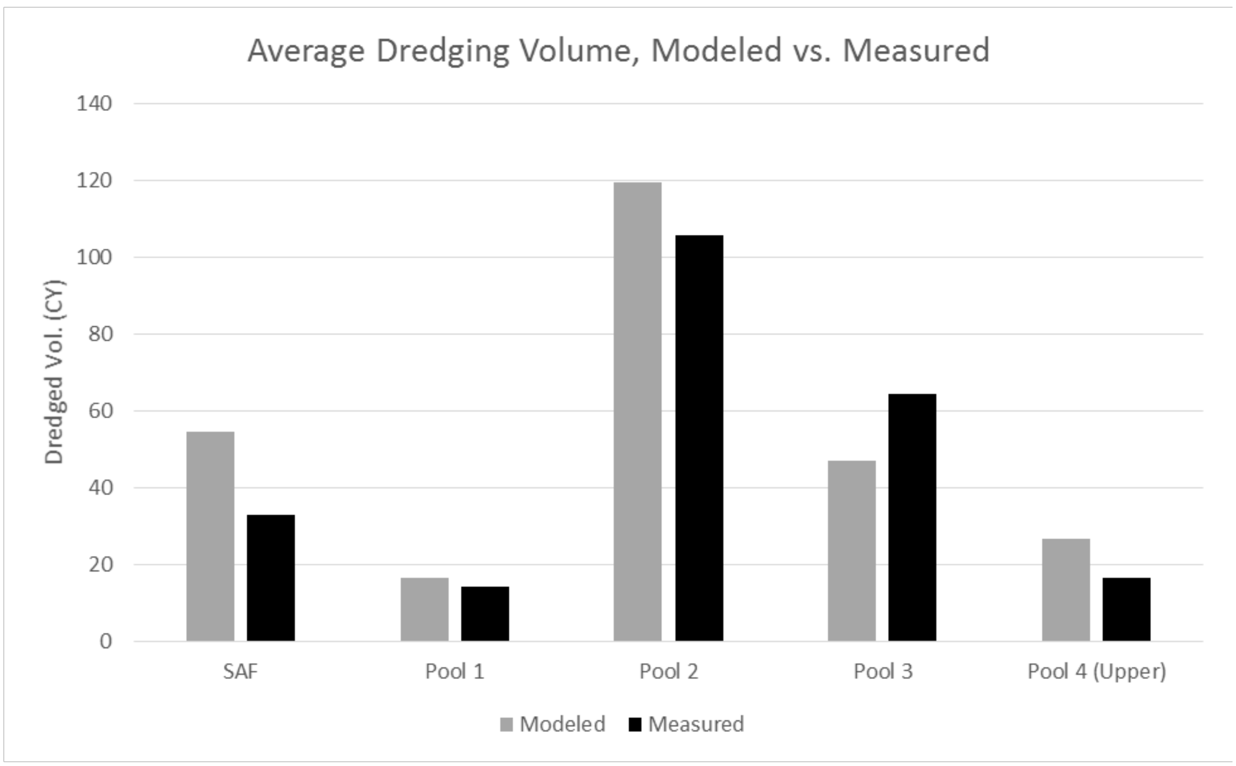

Figure 3-1 – Comparison of modeled and measured average annual dredging quantities by pool

The total dredging for all pools for each year also compare fairly well against the measured data. A summary of the total dredging (from USAF Pool through Upper Pool 4) for each year is shown in Figure 3-2.

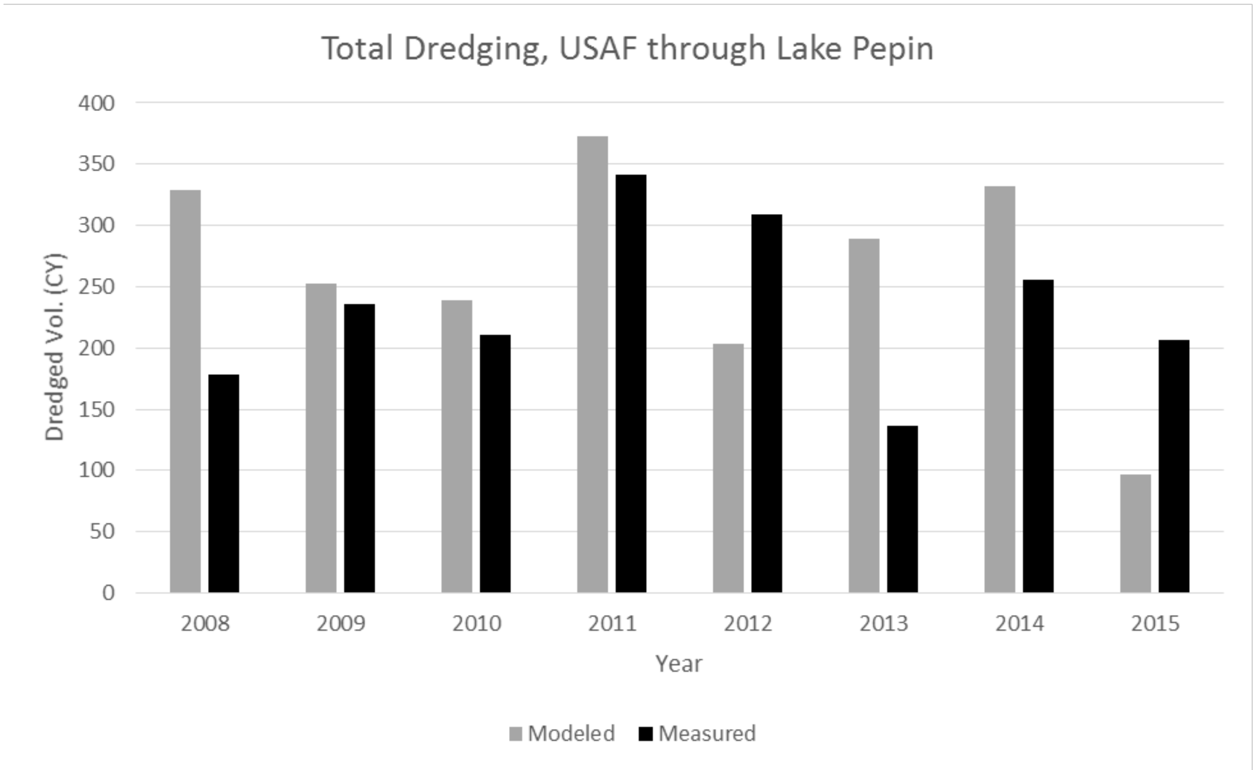

Figure 3-2 – Comparison of modeled and measured total annual dredging quantities

With a calibrated sediment dredging model established, the model can be run with various alternatives to show the relative impact the alternative would have to dredging quantities. This calibrated model will be referred to as the base condition model, or the current dredging model. The following sections describe the results of different alternatives to the current channel maintenance plan. These various alternatives will be compared to the base condition model rather than the measured data so that a direct comparison of relative impacts can be made and the residuals between measured and model data will not influence the results.

3.2 Alternative 1 – Eliminate dredging above St. Anthony Falls

The first alternative (Alternative 1) is to eliminate channel maintenance activities above St. Anthony Falls. With the closure of the Upper St. Anthony Falls to navigation that occurred in 2015 as a result of WRRDA 2014, there may no longer be a need to dredge the nine foot channel to boat traffic in the USAF Pool. This alternative is modeled with all dredging activities removed above Upper St. Anthony Falls Lock & Dam. Dredging activities in pools below USAF are modeled using the current dredging plan from the base condition model. The changes in total dredging quantities from the base condition model of current dredging practices to the Alternative 1 model are shown (summarized by pool and by year) in Figure 3-3.

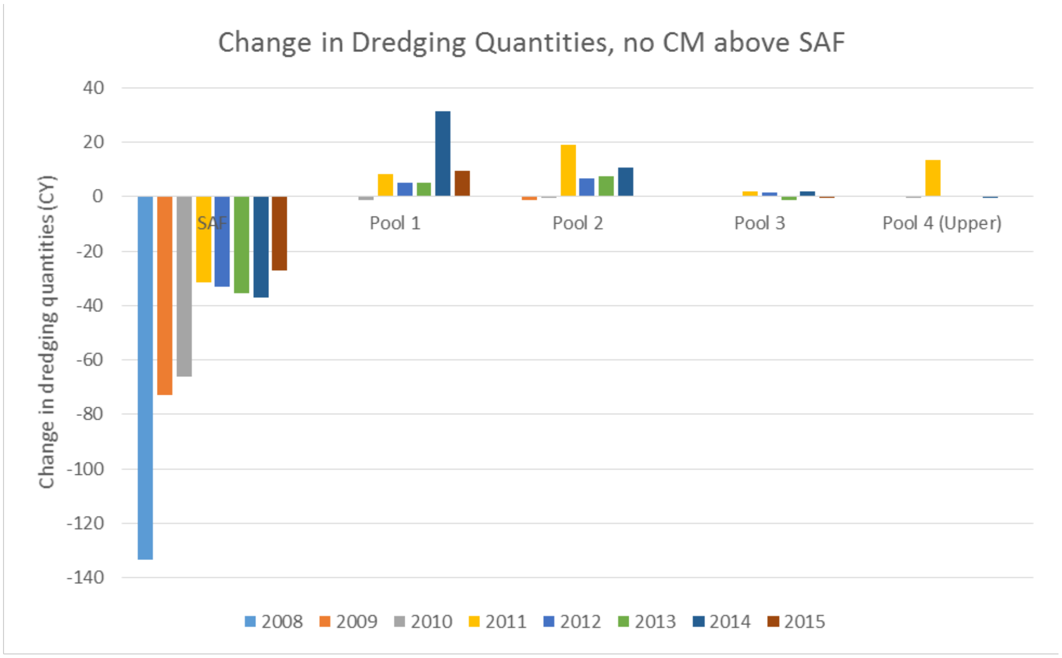

Figure 3-3 – Comparison of change in annual modeled dredging quantities by pool for Alternative 1

The results of Alternative 1 show increases in dredging for each of the downstream pools, with the greatest increases found in Pool 1. Pools 1 and 2 show positive trends in dredging increases, as well, indicating that the sediment may still be working its way downstream over the 8 year period. Overall, however, the downstream increases in dredging are far less than the total reduction in dredging found in the USAF pool. The relative change in dredging for Alternative 1 is shown in Figure 3-4.

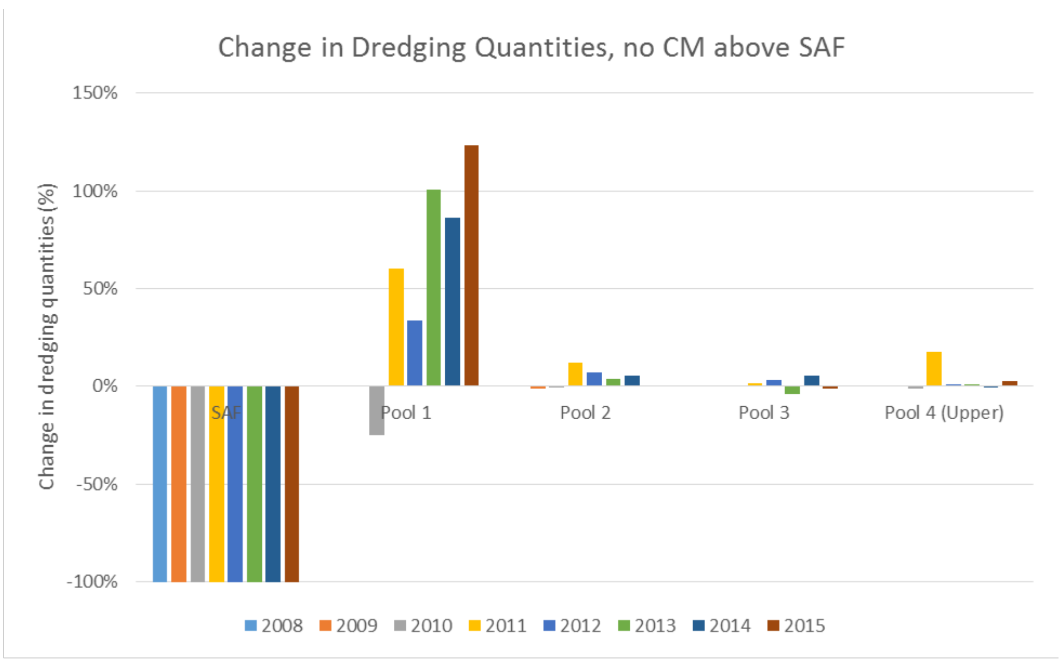

Figure 3-4 – Comparison of relative change in annual modeled dredging by pool for Alternative 1

The relative change in dredging is high for Pool 1 with a 123% increase in total dredging for the pool in Year 8 since the change is implemented for Alternative 1. There is also a strong positive trend in Pool 1, indicating that dredging increases in that pool may continue to be high. The relative change in other pools, however is fairly minimal. The average annual increase to Pools 2, 3, & 4 are 4%, 1%, and 6%, respectively.

3.3 Alternative 2 – Eliminate dredging above Lock & Dam No. 1

The second alternative (Alternative 2) is to eliminate channel maintenance activities above Lock & Dam No. 1, including the elimination of dredging above Upper & Lower St. Anthony Falls. With the closure of the Upper St. Anthony Falls to navigation, commercial boat traffic in Pool 1 has been minimal in recent years. Table 3-1 developed from the Corps of Engineers Lock Performance Monitoring System (USACE LPMS, 2017), shows the average daily number of lockages from 2013-2017 (calculated on an annual basis) for the navigation structures in the modeled area. Lock & Dam No. 1 has less than one average lockages for commercial traffic and roughly two for recreational boaters, on a daily basis.

Table 3-1 – Average lockages per day (up- and down-stream) for 2013-2017

Average Daily Commercial Lockages						
YEAR	**USAF**	**LSAF**	**1**	**2**	**3**	**4**
2013	2.5	5.8	2.8	4.9	5.8	4.8
2014	2.4	4.6	2.8	5.6	6.5	6.0
2015*	0.8	3.5	1.2	5.0	5.7	5.1
2016	0.0	2.4	0.4	7.5	8.0	7.5
2017	0.0	2.4	0.5	7.0	8.0	7.5
Average Daily Recreational & Other Lockages						
YEAR	**USAF**	**LSAF**	**1**	**2**	**3**	**4**
2013	2.4	2.0	3.8	6.1	11.8	9.1
2014	3.0	2.6	3.7	5.5	10.6	7.9
2015*	1.0	1.6	4.0	6.9	12.4	9.5
2016	0.0	1.0	3.1	5.3	10.6	7.0
2017	0.0	0.8	3.3	5.3	10.8	7.1
Total Average Daily Lockages						
YEAR	**USAF**	**LSAF**	**1**	**2**	**3**	**4**
2013	4.9	7.9	6.6	11.0	17.6	13.9
2014	5.5	7.2	6.5	11.1	17.1	13.9
2015*	1.8	5.2	5.2	11.9	18.1	14.6
2016	0.0	3.3	3.5	12.8	18.7	14.5
2017	0.0	3.1	3.8	12.3	18.8	14.5

** USAF lock closed on June 10, 2015, midway through the 2015 season*

To represent a scenario where commercial navigation is closed through LD1, Alternative 2 is modeled with all dredging activities removed in SAF Pool and Pool 1. Dredging activities in pools below Lock & Dam No. 1 are modeled using the current dredging plan from the base condition model. The changes in total dredging quantities from the base condition model of current dredging practices to the Alternative 2 model are shown (summarized by pool and by year) in Figure 3-5.

The results of Alternative 2 show increases in dredging for each of the downstream pools, with the greatest increases found in Pool 2. Pool 2 shows a positive trend in dredging increases, as well, indicating that the sediment may still be working its way downstream over the 8 year period. Overall, however, the downstream increases in dredging are far less than the total reduction in dredging found in the upper pools. The relative change in dredging for Alternative 2 is shown in Figure 3-6.

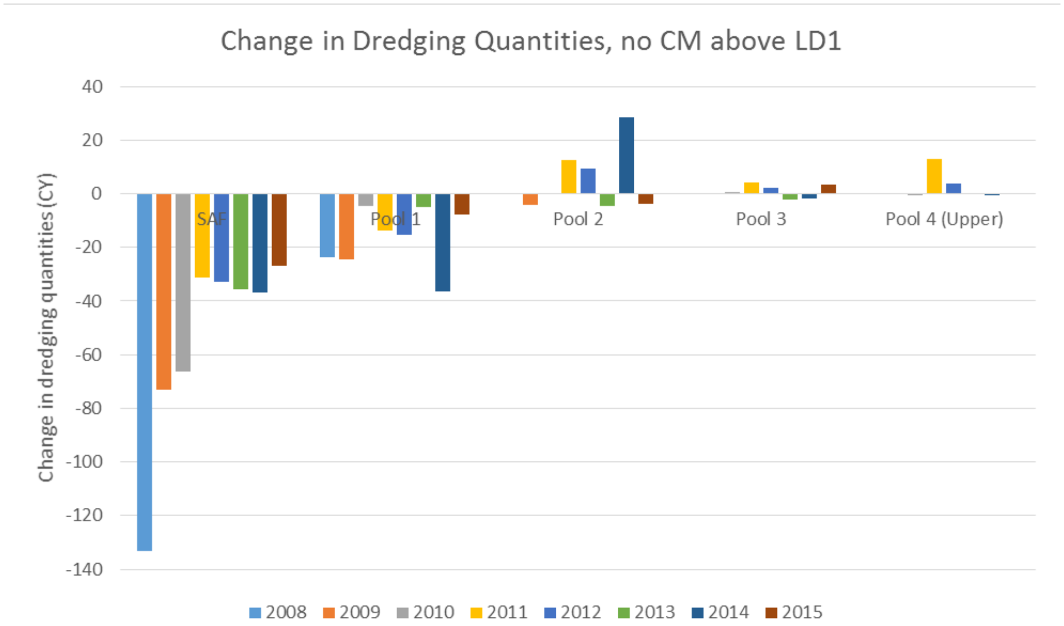

Figure 3-5 – Comparison of change in annual modeled dredging quantities by pool for Alternative 2

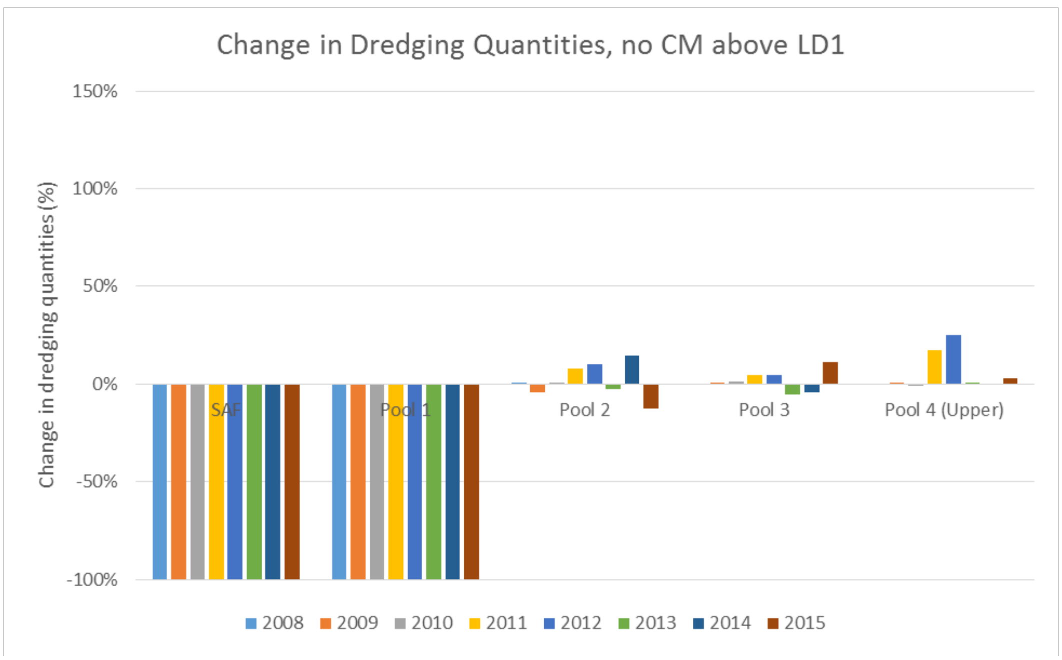

Figure 3-6 – Comparison of relative change in annual modeled dredging by pool for Alternative 2

The relative change in dredging is minimal for Pool 2 with a maximum increase of 14% in Year 7 since the change is implemented for Alternative 2. There is also an increasing trend in Pool 2, indicating that dredging increases in that pool may continue to be high. The relative change in other pools is also minimal. The average annual increase to Pools 2, 3, & 4 are 4%, 2%, and 8%, respectively.

CHAPTER 4.

4. Conclusions

4.1 Comparison of Existing and Proposed Alternatives

Both alternatives, the removal of dredging above Upper St. Anthony Falls and the removal of dredging above Lock & Dam No. 1, result in a net reduction in average dredging volumes over the eight year modeling period. While Alternative 1 results in increased average dredging quantities in Pools 2, 3 & 4 of 4%, 1% and 6%, respectively, the total average dredging for the system shows a net decrease of 15%.

Similarly, Alternative 2 shows increased average dredging in Pools 2, 3 & 4 of 4%, 2%, and 8%, respectively, but a net decrease in average dredging for the system of 24% due to the removal of channel maintenance in Pool 1 and above St. Anthony Falls. A summary of the average modeled dredging quantities between 2008 and 2015 for each pool is shown in Figure 4-1.

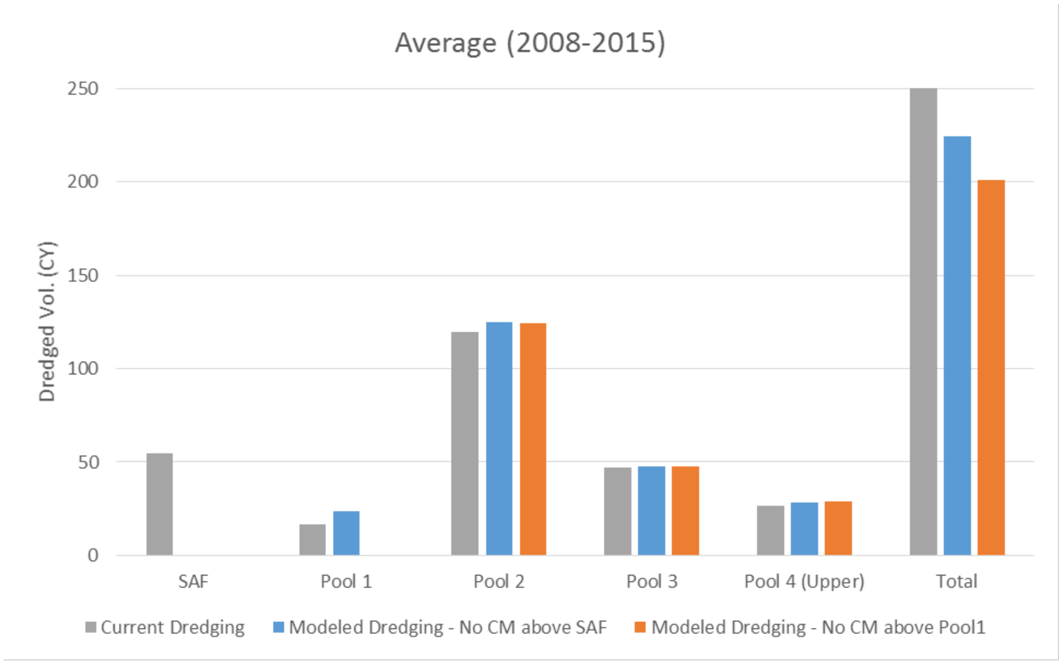

Figure 4-1 – Comparison of modeled average annual dredging for current practice and alternatives

When the total modeled dredging is compared over time, trends in the sediment transport through the system can be identified. In the first 3 years in the model following the implementation of each alternative (2008-2010), the system shows overall reductions in dredging of 29-40% for Alternative 1 and 30-48% for Alternative 2. However, in Year 4 (2011), Alternative 1 shows an increase in total dredging of 3% and Alternative 2 shows only a 4% reduction in dredging quantities compared to the current dredging plan. Toward the end of the 8 year model period, Alternative 1 again shows a year where dredging quantities exceed the current dredging plan quantities (2014) and both alternatives show less of a reduction in total dredging than in Year 1. A summary of modeled dredging quantities by year is shown in Figure 4-2.

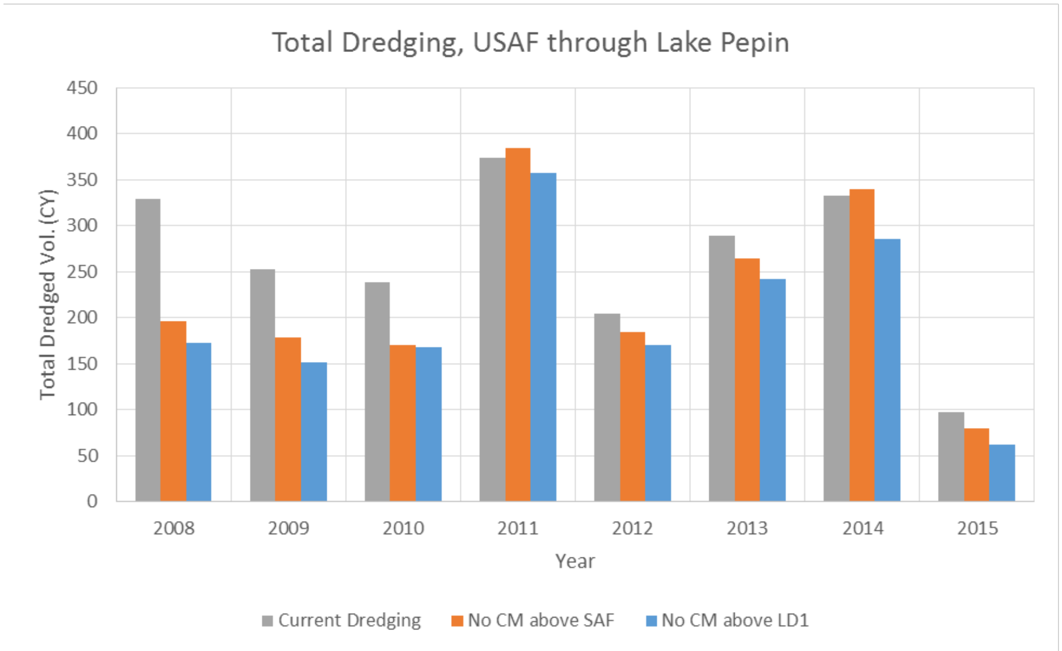

Figure 4-2 – Comparison of modeled total annual dredging for current practice and alternatives

Plotting the results as the relative change in dredging quantities for an extended hydrologic record more clearly shows the trends for each alternative, as shown in Figure 4-3. A trend-line for Alternative 1 shows that the expected change in dredging quantities for the system is close to zero by the end of a 10 year period. This might suggest that the system has reached an equilibrium by the end of 10 years and that the total dredging quantities may be net neutral with the current dredging practices. The downstream pools on average, will have slightly higher required dredging to compensate for the lack of a sediment sink above St. Anthony Falls. Alternative 2 shows a similar trend, although it may take longer than a decade to reach equilibrium. Beyond 10 years, the system may expect to be net neutral with the current dredging practices and additional dredging may be required in the downstream pools, on average.

The sediment transport modeling results indicate that eliminating dredging in Pool 1 and/or the Upper St. Anthony Falls Pool will result in significant net reductions in average dredging between the USAF pool and Lake Pepin in the near term. Dredging in Pools 2, 3, and Upper 4 will increase a small amount, however, the reduction in dredging upstream of Pool 2 more than compensates for the downstream increases. Some of the sand not dredged in the USAF Pool and Pool 1 ends up settling out in off-channel areas. However, in the long term, modeling results indicate that once the new equilibrium is reached with each of the alternatives, it is likely that nearly 100% of the new forgone dredging material will end up in the immediate downstream pool. That is, for Alternative 1 most of the dredging increases after 10 years will occur in Pool 1 and for Alterative 2, most increases will occur in Pool 2.

Changes in downstream sediment transport and dredging won't occur immediately, but rather will take a number of years. The model results indicate that the timescale for these changes to occur may be a decade or two. Aleatory variability in the future hydrology for the system and epistemic uncertainty in the sediment quantities and characteristics lead to high uncertainty in the estimated timeframe for equilibrium, but the model confirms expected trends in sediment deposition with the introduction of each of these alternatives.

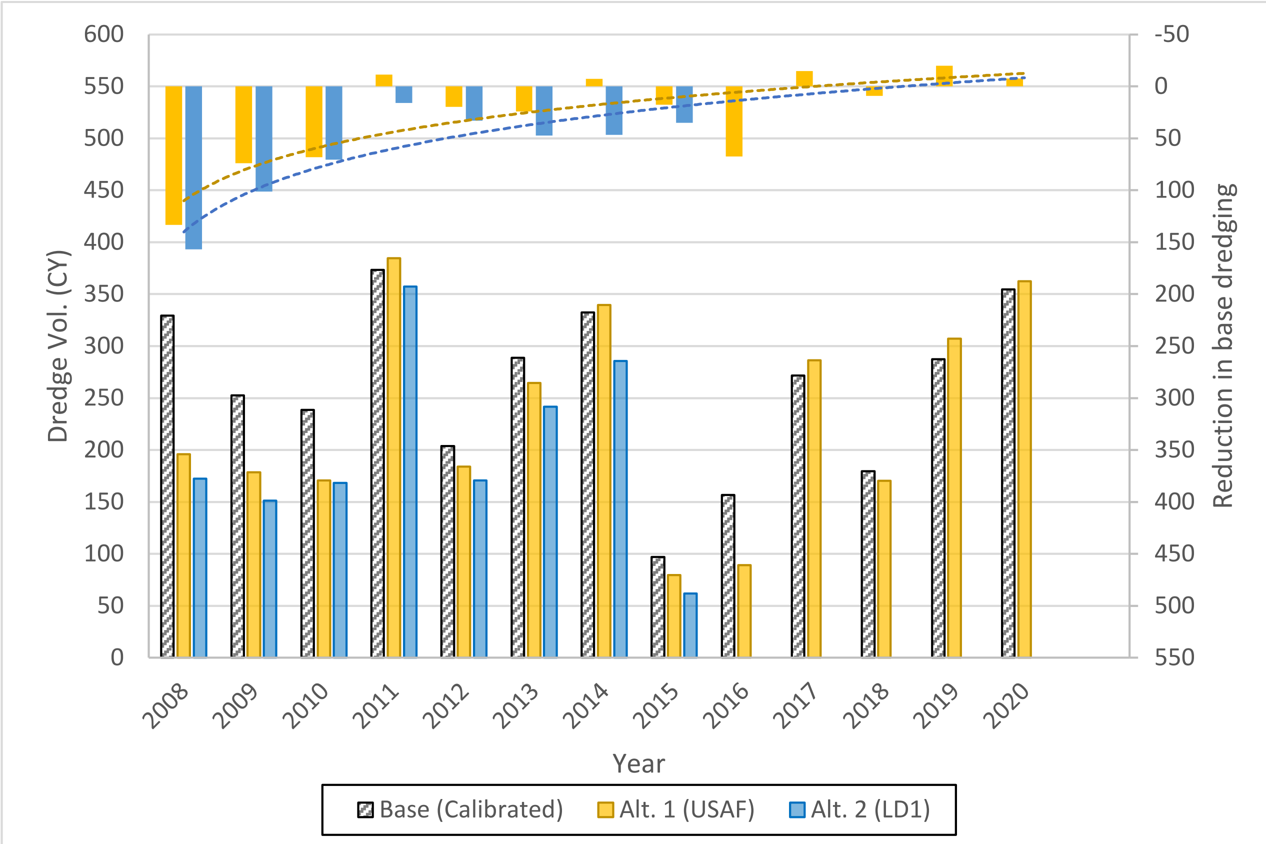

Figure 4-3 – Trend in total change in dredging quantities after channel maintenance change

More detailed modeling output from the sediment modeling comparison of the current dredging and two alternatives can be found in Appendix B.

4.2 Model as a tool to investigate sediment trends

In addition to using the model to assess different channel maintenance management strategies, the model can also be used as a tool to investigate sediment trends in the Mississippi River through Lake Pepin. Numerous studies in recent decades have looked into water quality (Lung & Larson, 1995), rates of deposition (McHenry et al 1980), and sources of sediment (Engstrom et al 2009) in Lake Pepin. This model could be used as a tool to support each of those areas of concern as well as similar fields throughout the Upper Mississippi River. An example of output from the model is shown in Figure 4-4.

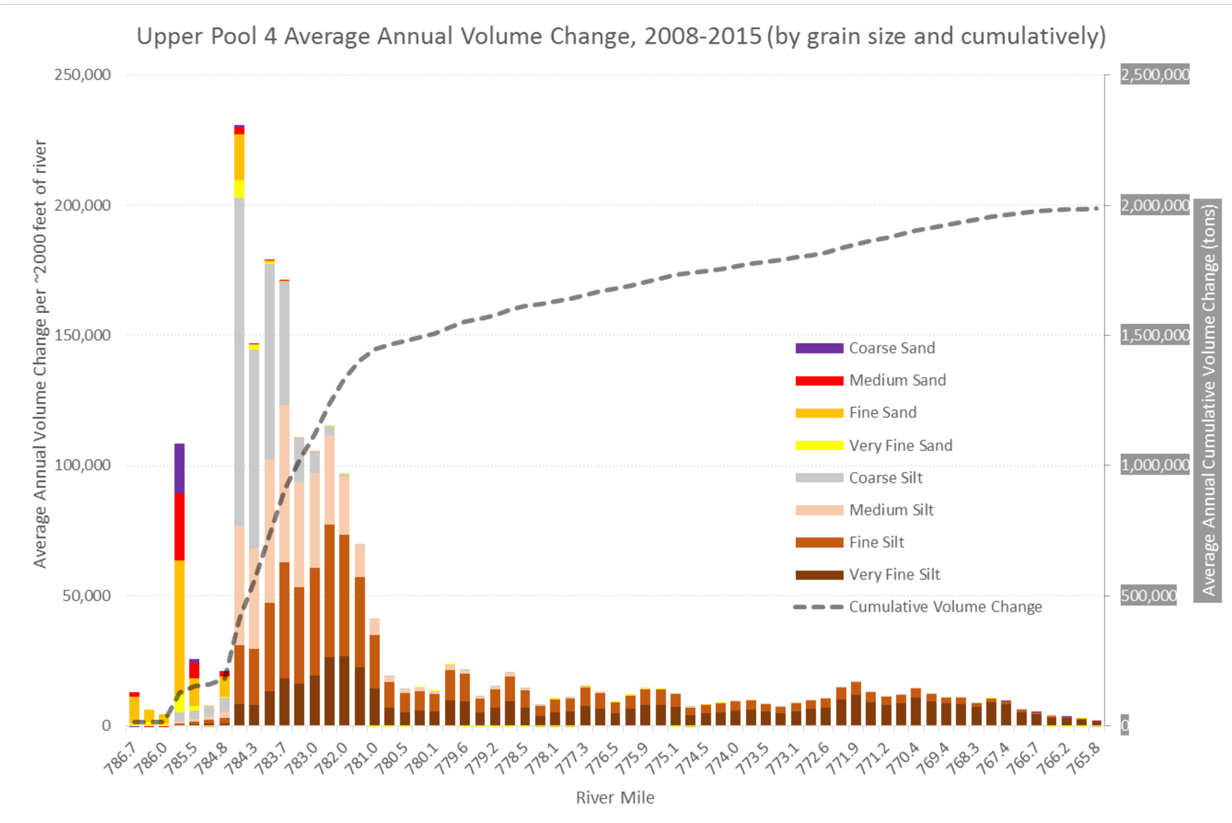

Figure 4-4 – Average Sediment Deposition in Lake Pepin by size and average cumulative total deposition

In this figure, the sediment deposition through Lake Pepin is shown to identify how much sediment is deposited, on average, at each river station as well as which types of sediment are deposited throughout the lake. One takeaway from this plot is the fining of sediments moving downstream. As the river enters the lake and conditions become more lentic as velocities decrease, larger sediments begin to settle out of the water column until the suspended sediment becomes finer and finer in grain size distribution. By River Mile 784.0, almost all of the sand size sediments have dropped out and any sediment deposited downstream is primarily silt. The greatest amount of sediment deposition occurs in the upper 3 or 4 miles of the lake a reach noted for degraded recreational opportunities and habitat. The modeled longitudinal pattern of sediment deposition and particle size change match the measured sediment properties from other researchers (McHenry 1980, Cumulative Effects Report 2000, Engstrom 2009) and they match main channel borings obtained in this reach by the Corps in 2010. This portion of the river, between RM 785 and RM 780, also defines the delta at the upstream end of Lake Pepin. By having this modeling capability to not only capture the sediment budget but to be able to model and predict the grain sizes and locations of sediments, this tool can help with future studies to forecast future water quality and lake capacity concerns for this part of the river. Figure 4-5 shows the relationship between annual deposition in the

Lake Pepin Delta and the percentage of flow contribution from the Minnesota River. In years where over 50% of the volume of water comes from the Minnesota River, the highest quantities of deposition occur in Lake Pepin. This type of data plot, as well as many other related types of modeling output, can be used to help answer questions for many of the ongoing studies in the area.

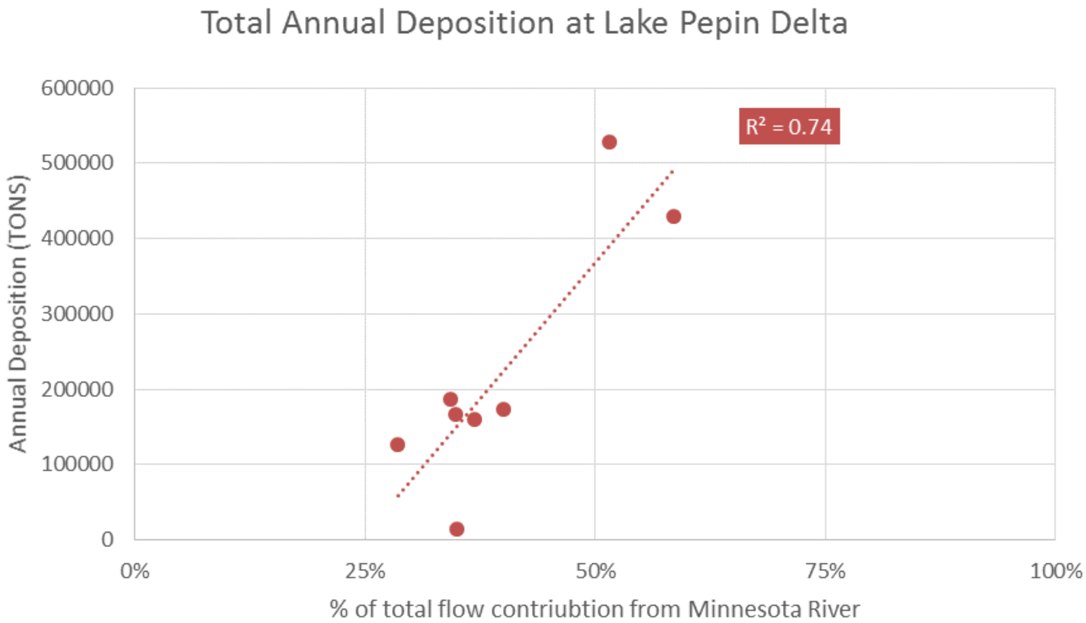

Figure 4-5 – Comparison of Total Annual Modeled Deposition at Lake Pepin and the Percentage of Flow Contribution from the Minnesota River

4.3 Model as a tool to investigate operational changes

With the closing of Upper St. Anthony Falls to navigation, recent interest has been sparked to consider even more drastic changes to the navigation system than channel maintenance strategies The Corps of Engineers has expressed interest in investigating the federal interest in continued operation of the upper three lock & dam structures through a Disposition Study (USACE, 2016). This sediment transport model could be considered, along with numerous other types of models and tools, as one source of information for identifying positive and negative impacts from a change in the operating pools or full removals of dams. The model can coarsely capture the progression of erosion of sediment behind the dam in the case of a removal, but more importantly help to quantify broader impacts to the Mississippi River system through Lake Pepin.

Again, this model would only be one line of evidence in trying to predict the success of such a large scale dam removal project in a highly visible area. With the appropriate amount of additional work and funding, however, this model could prove to be a valuable asset in helping to support or screen-out options to restore the Mississippi River Gorge.

CHAPTER 5.

5. References

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A. Hydraulic Model Calibration Appendix

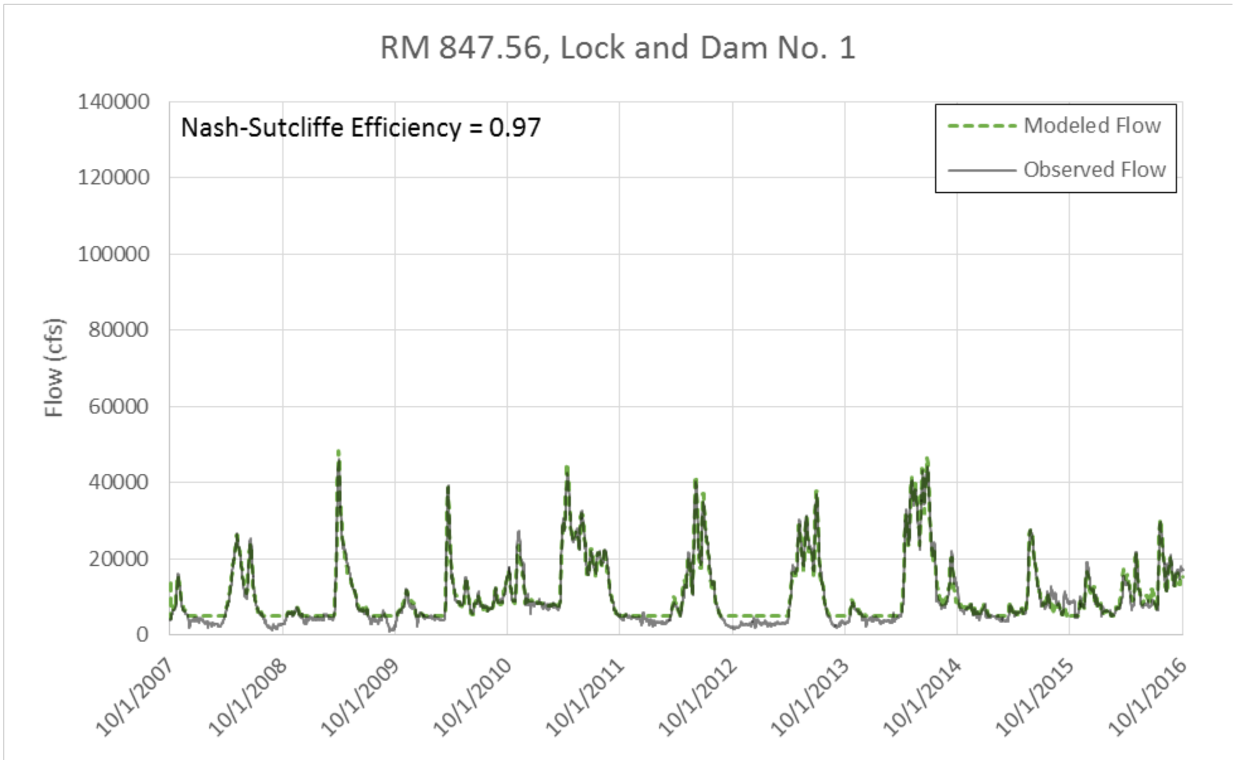

Figure A-1 – Flow Calibration at Lock & Dam No. 1

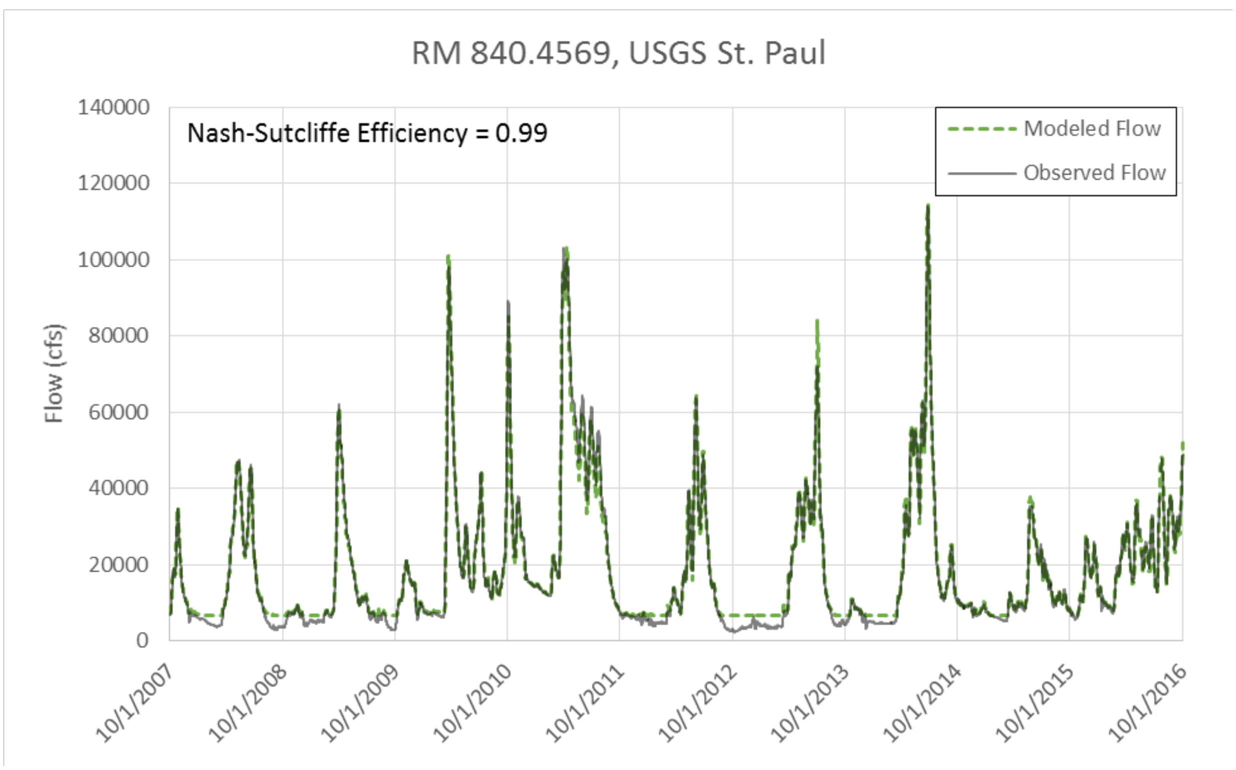

Figure A-2 –Flow Calibration at the USGS Gage in St. Paul

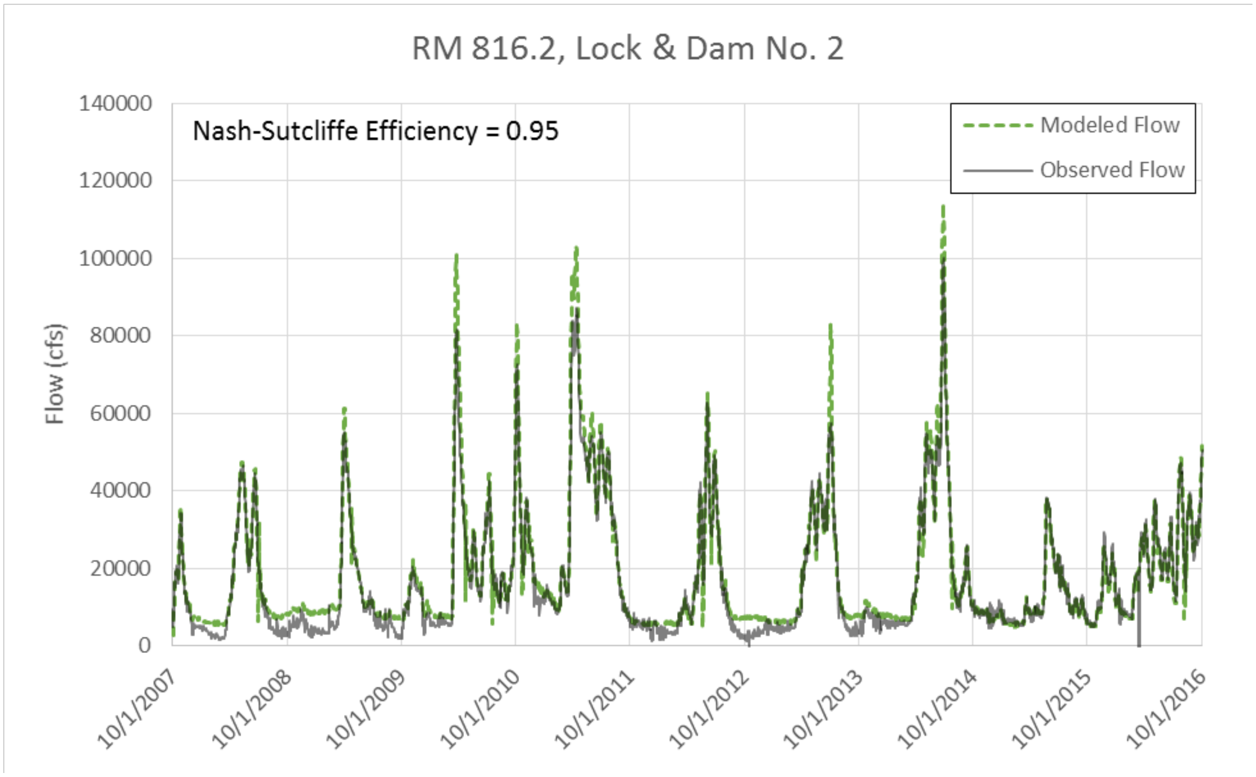

Figure A-3 – Flow Calibration at Lock & Dam No. 2

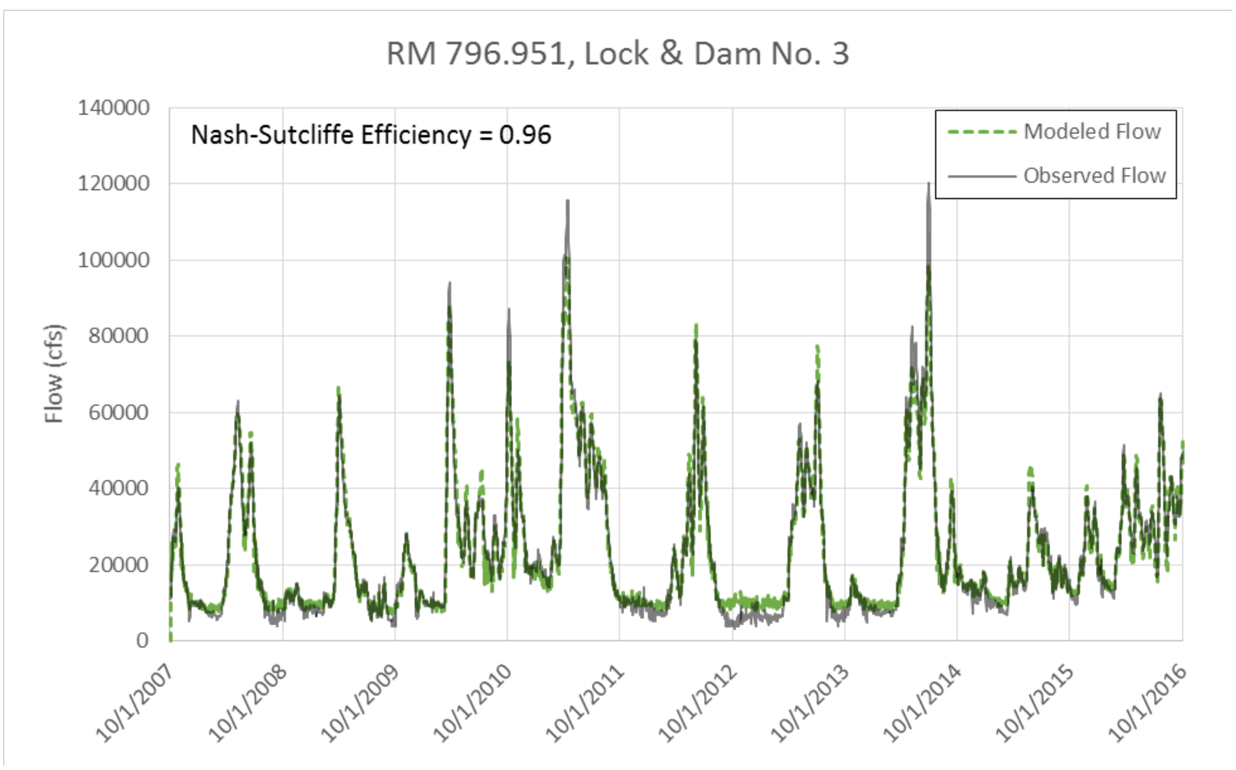

Figure A-4 –Flow Calibration at Lock & Dam No. 3

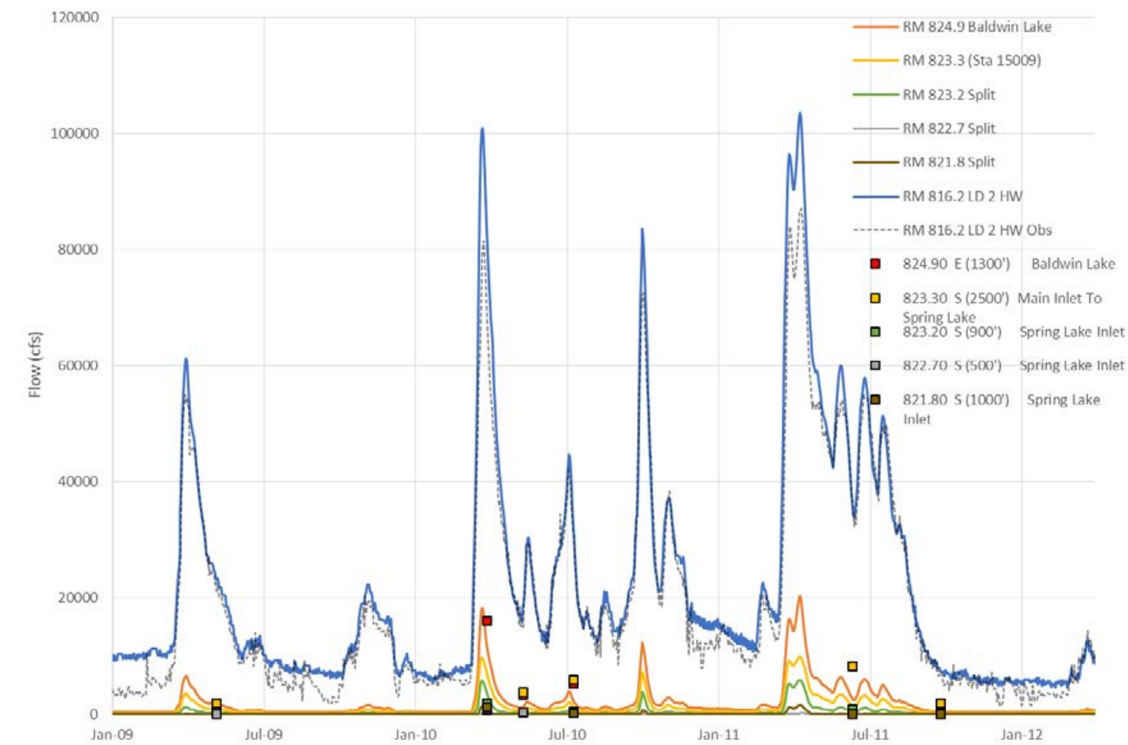

Figure A-5 – Flow Validation for backwater flows in Pool 2

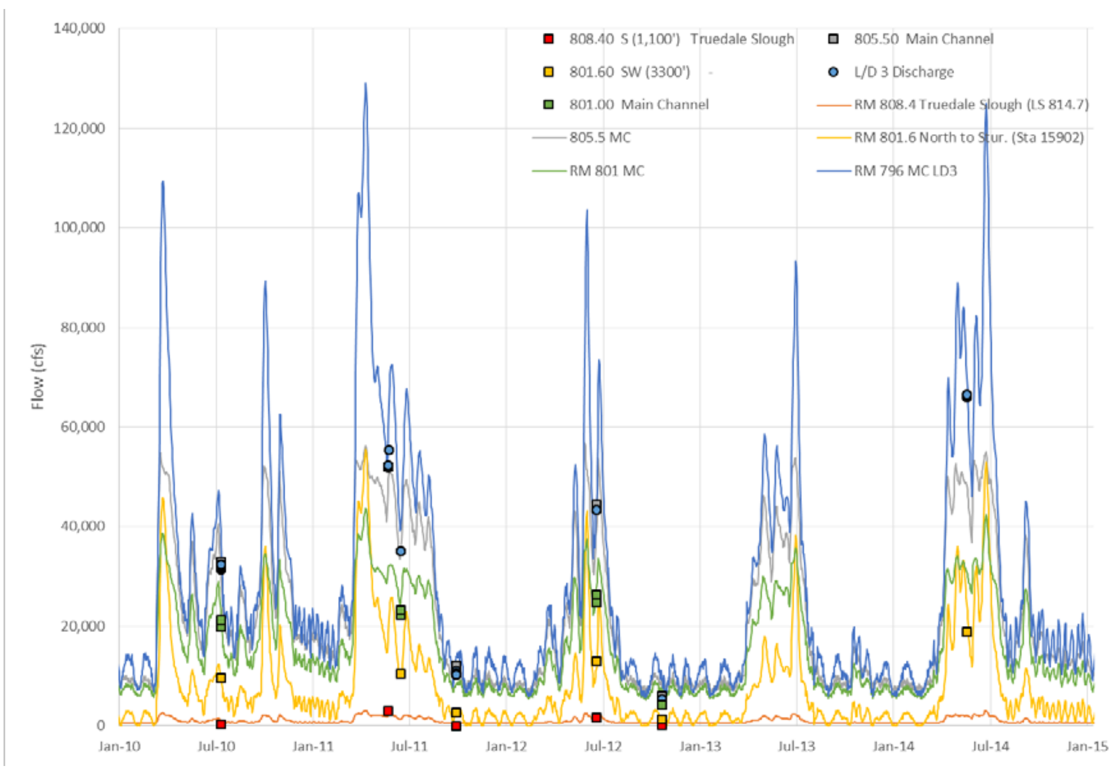

Figure A-6 – Flow Validation for backwater flows in Pool 3

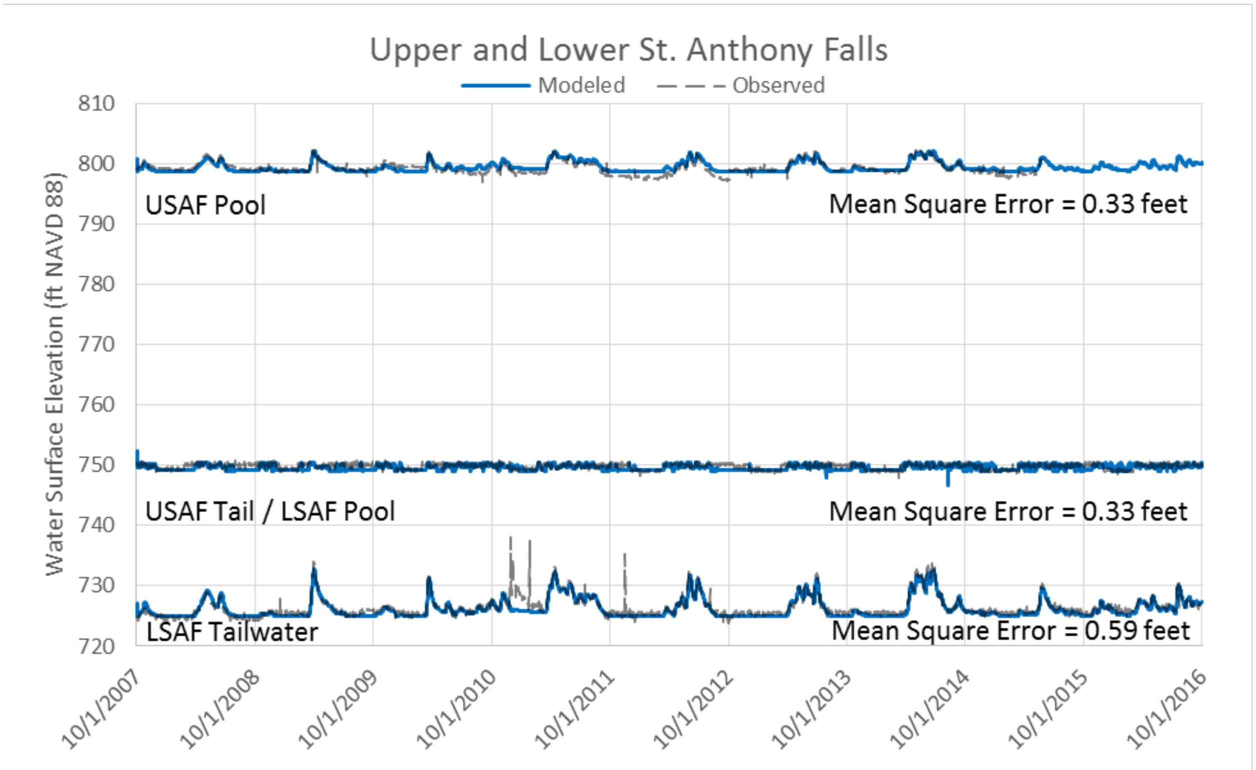

Figure A-7 – Water Surface Elevation Calibration at St. Anthony Falls

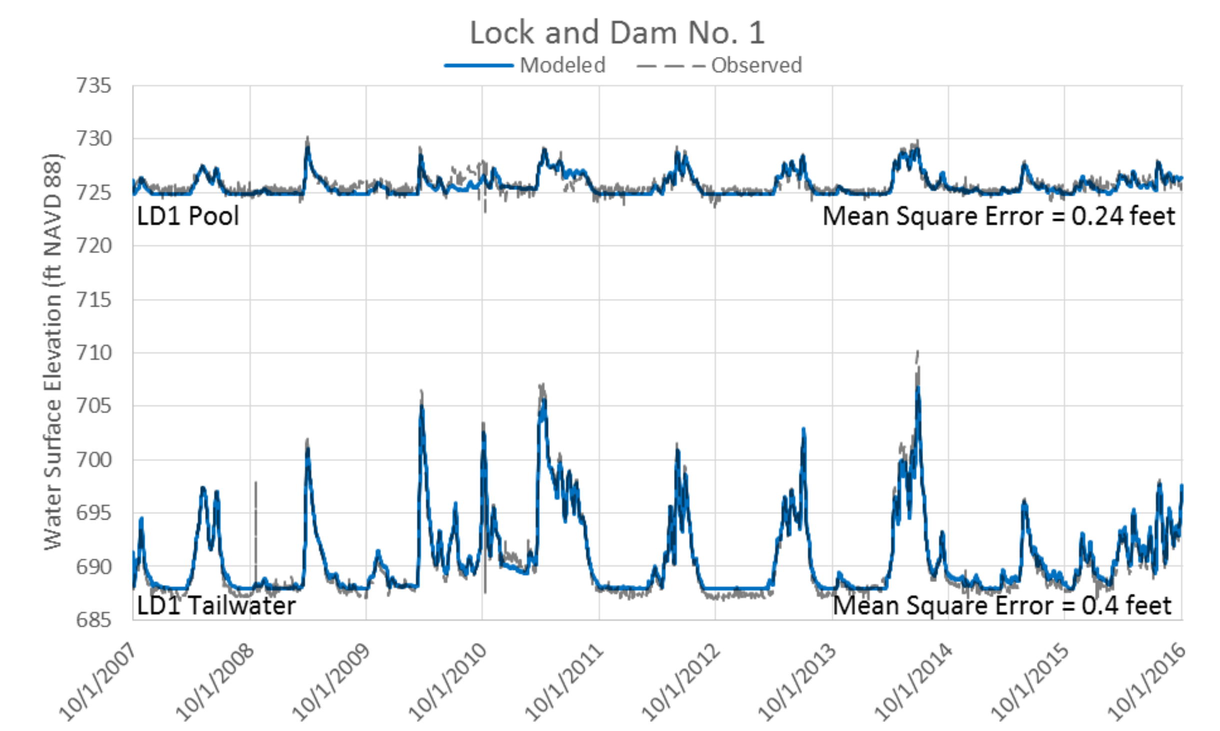

Figure A-8 – Water Surface Elevation Calibration at Lock & Dam No. 1

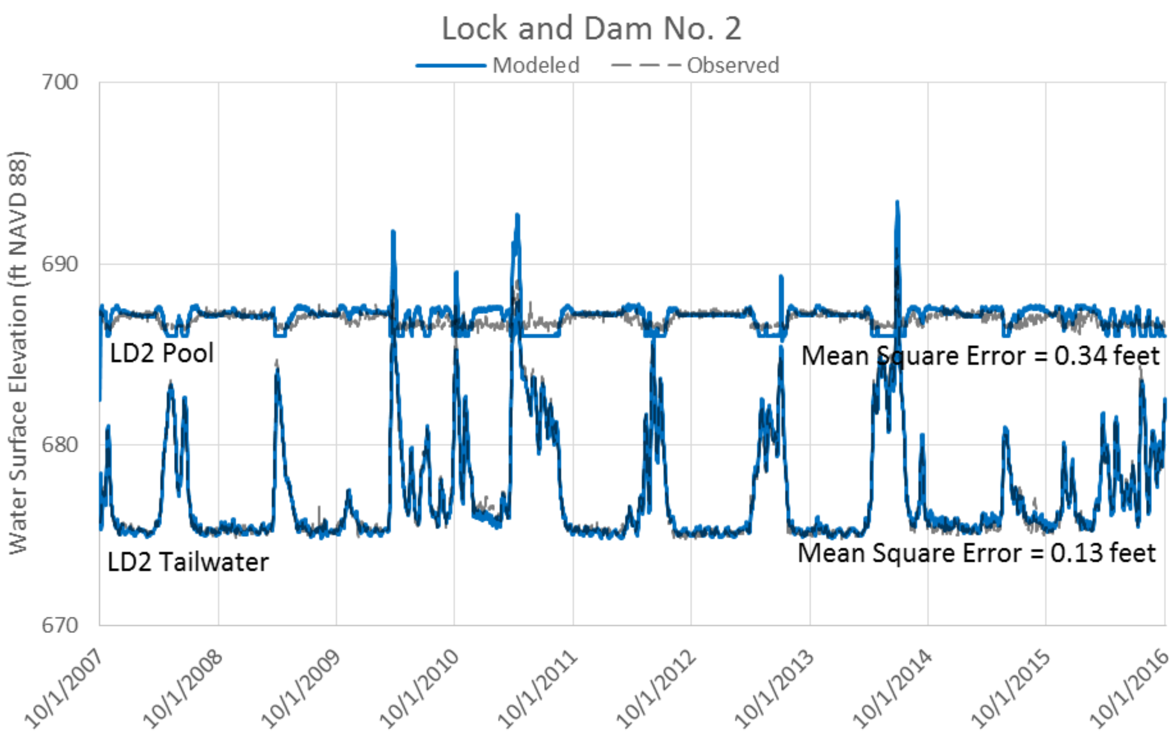

Figure A-9 – Water Surface Elevation Calibration at Lock & Dam No. 2

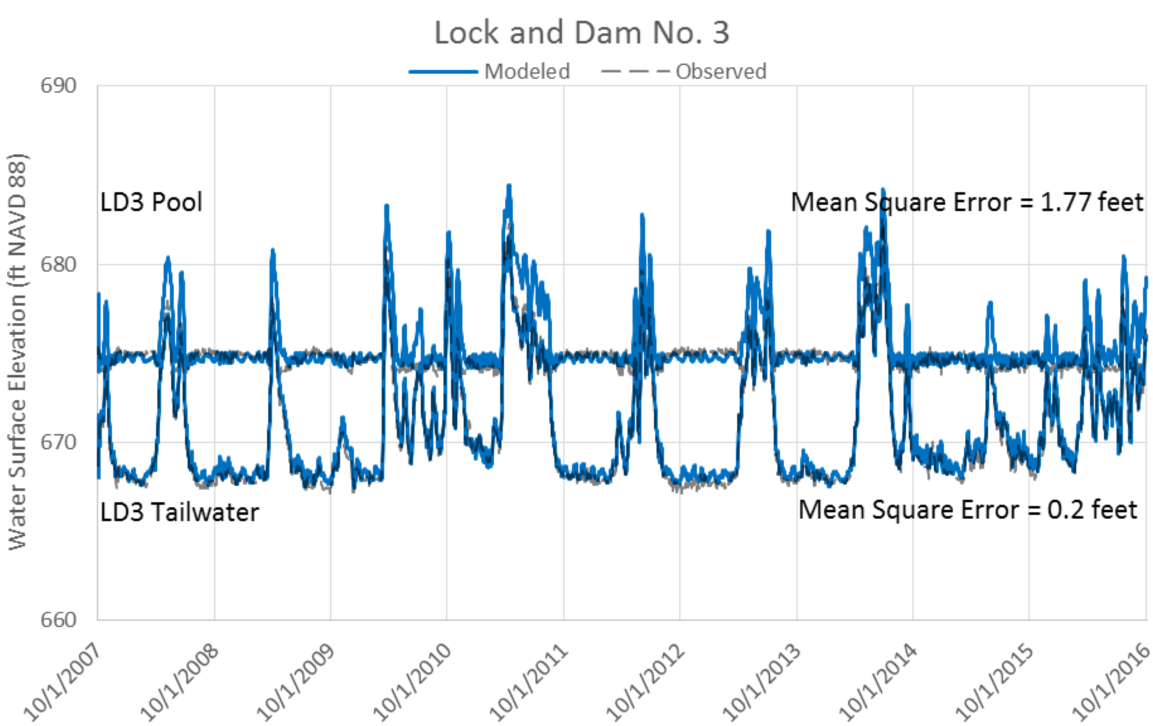

Figure A-10 – Water Surface Elevation Calibration at Lock & Dam No. 3

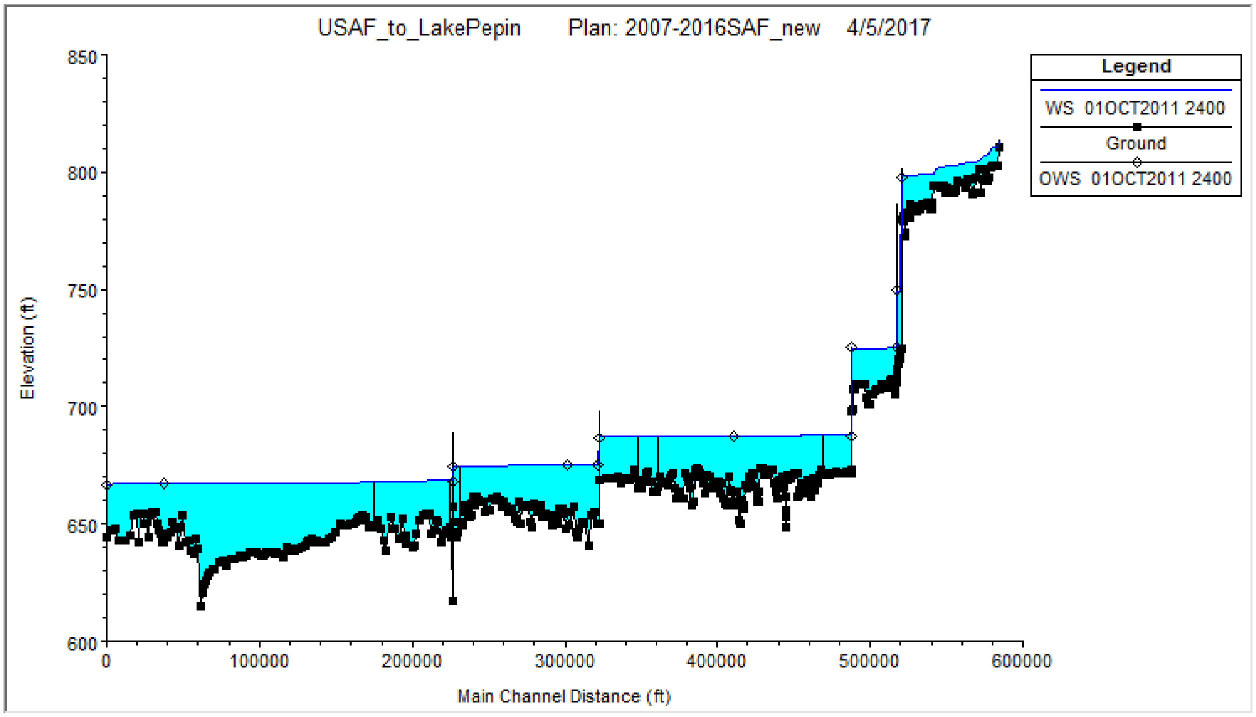

Figure A-11 – Low water (01-Oct) profile for the system

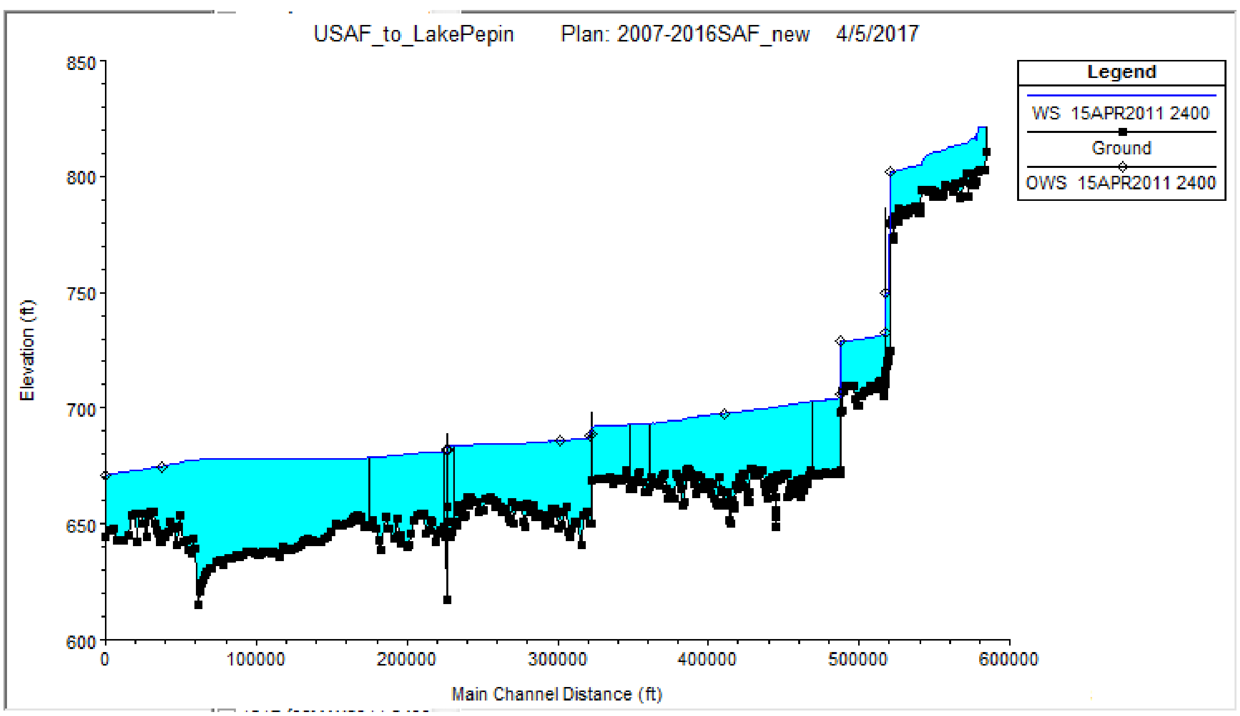

Figure A-12 – Flood (15-Apr) profile for the system

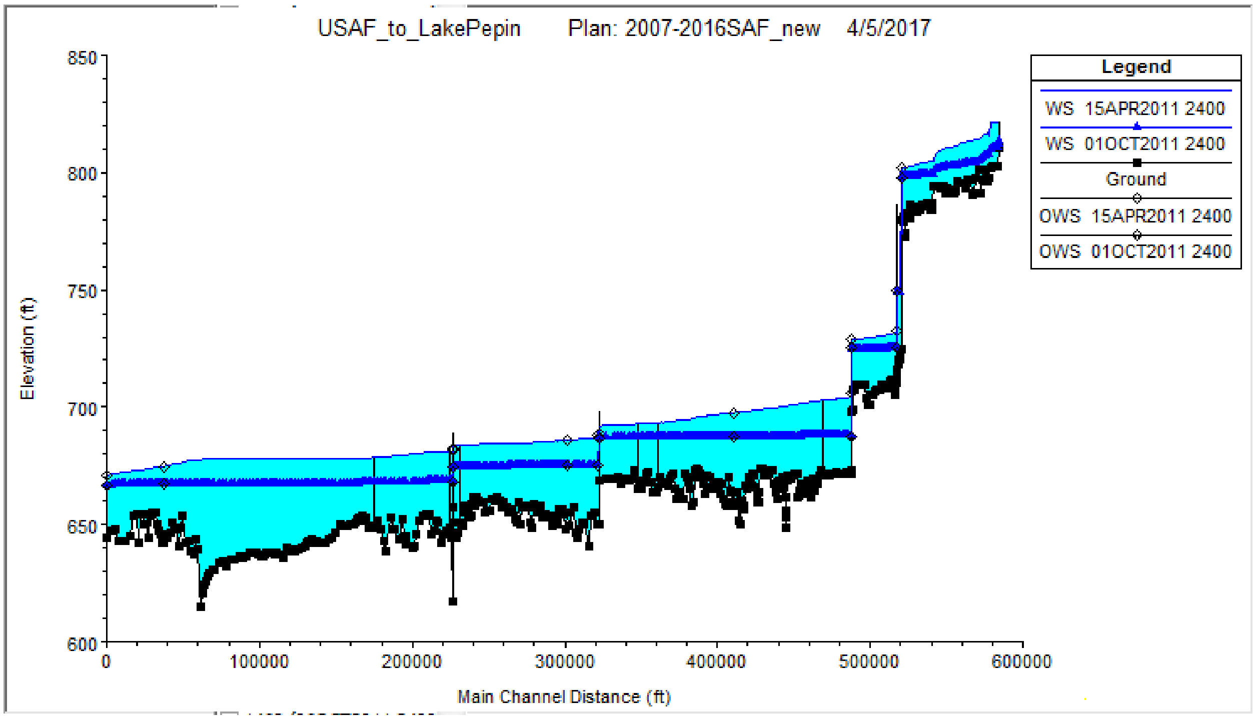

Figure A-13 – Comparison of low water (01-Oct) to flood (15-Apr) profiles

B. Sediment Modeling Output Appendix

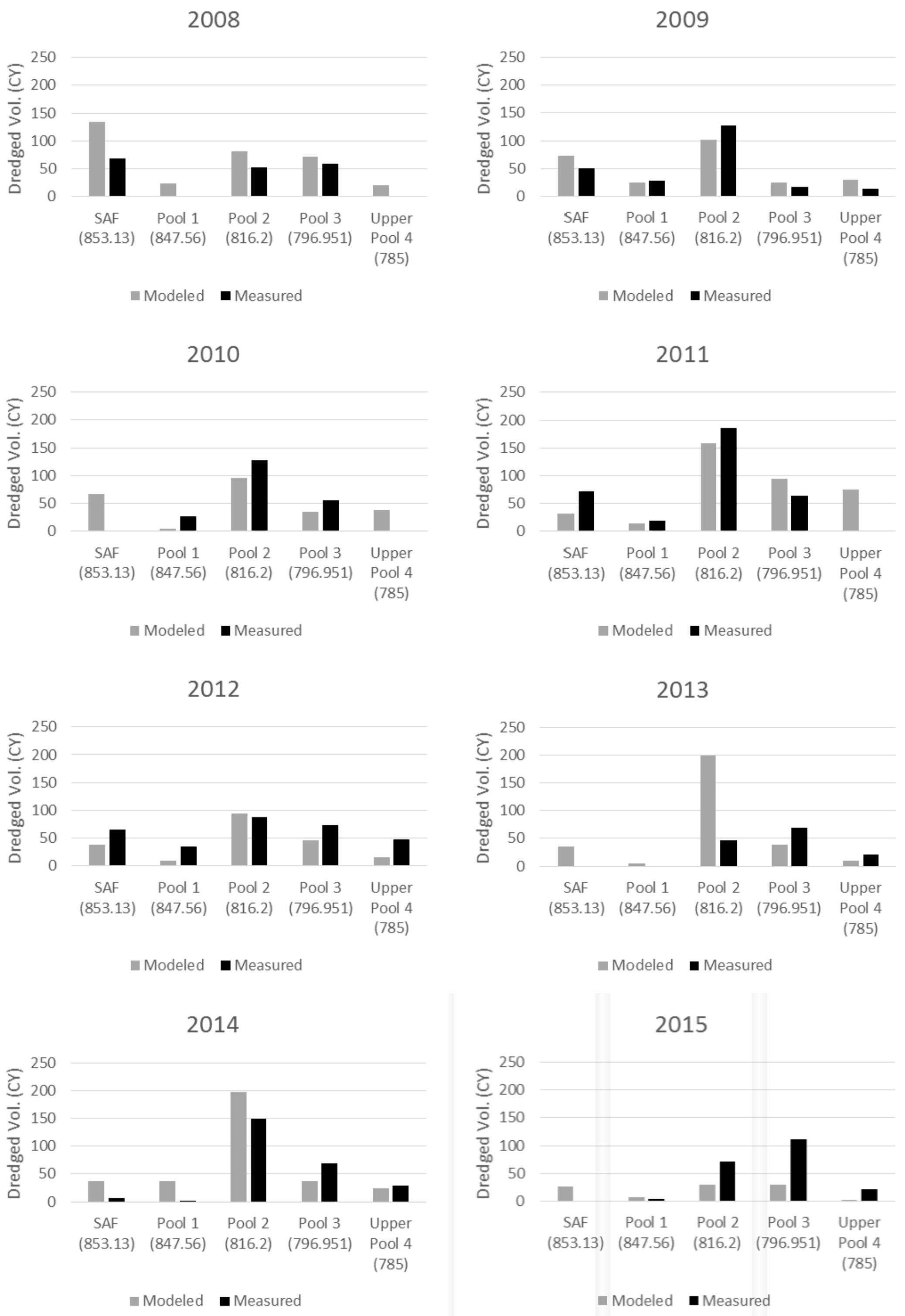

Figure B-1 – Summary of modeled vs. measured dredging quantities for each pool and year

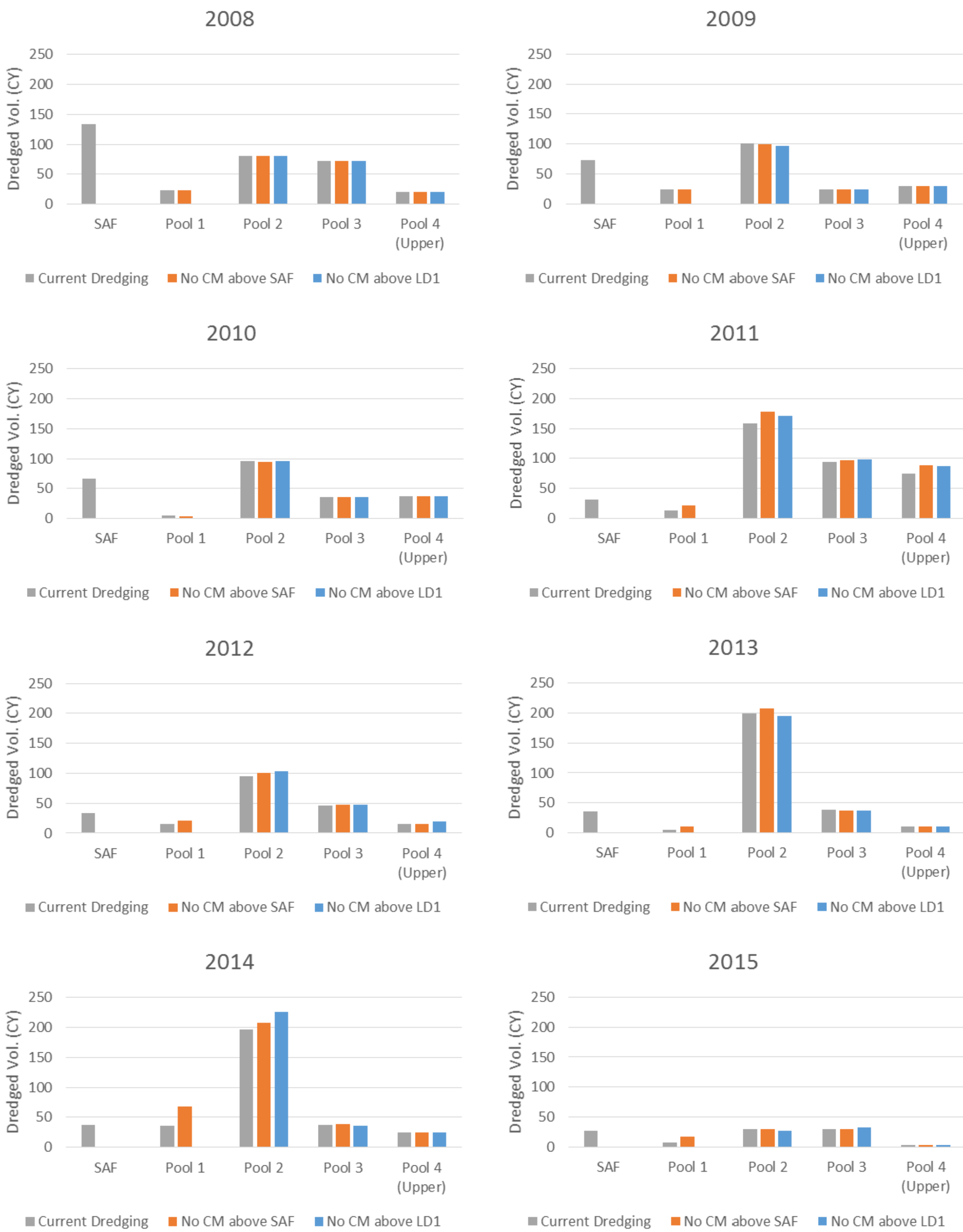

Figure B-2 – Modeled dredge quantity comparison of current dredging practices to alternatives

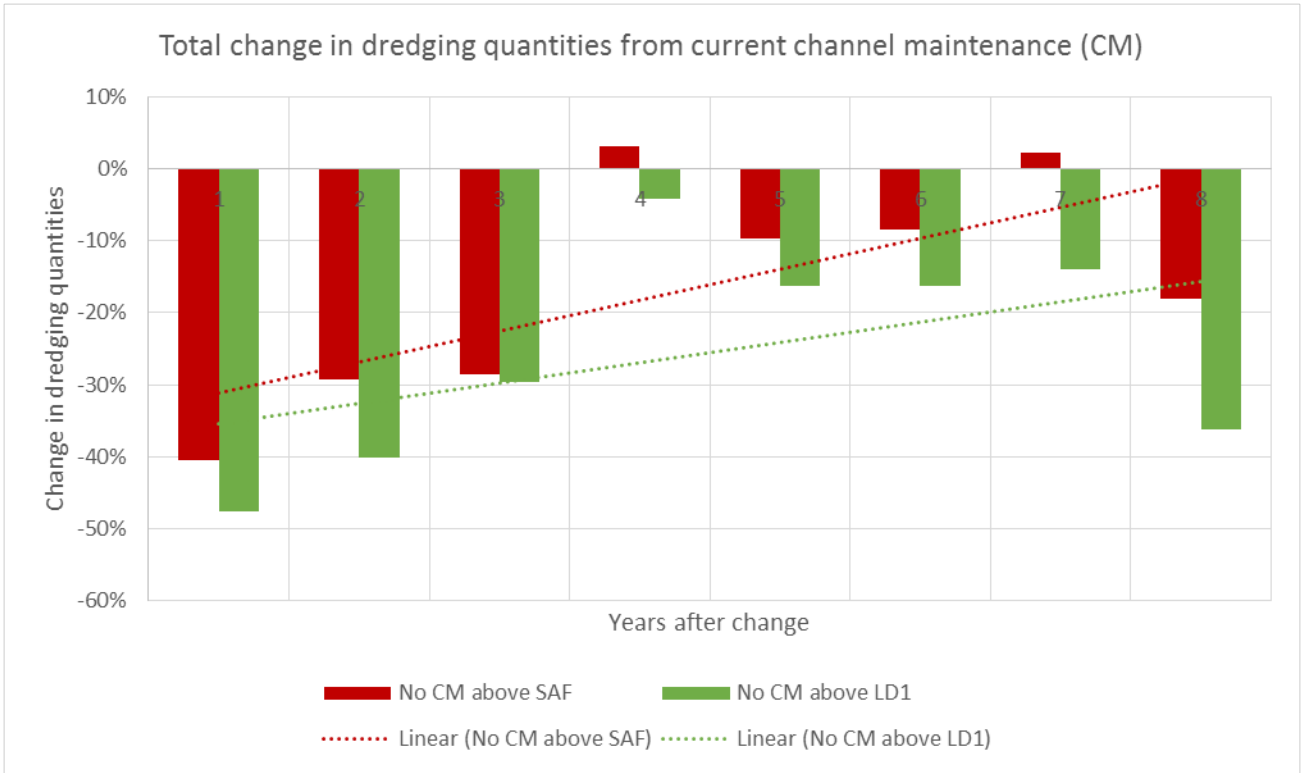

Figure B-3 – Trend in total change in dredging quantities after channel maintenance change

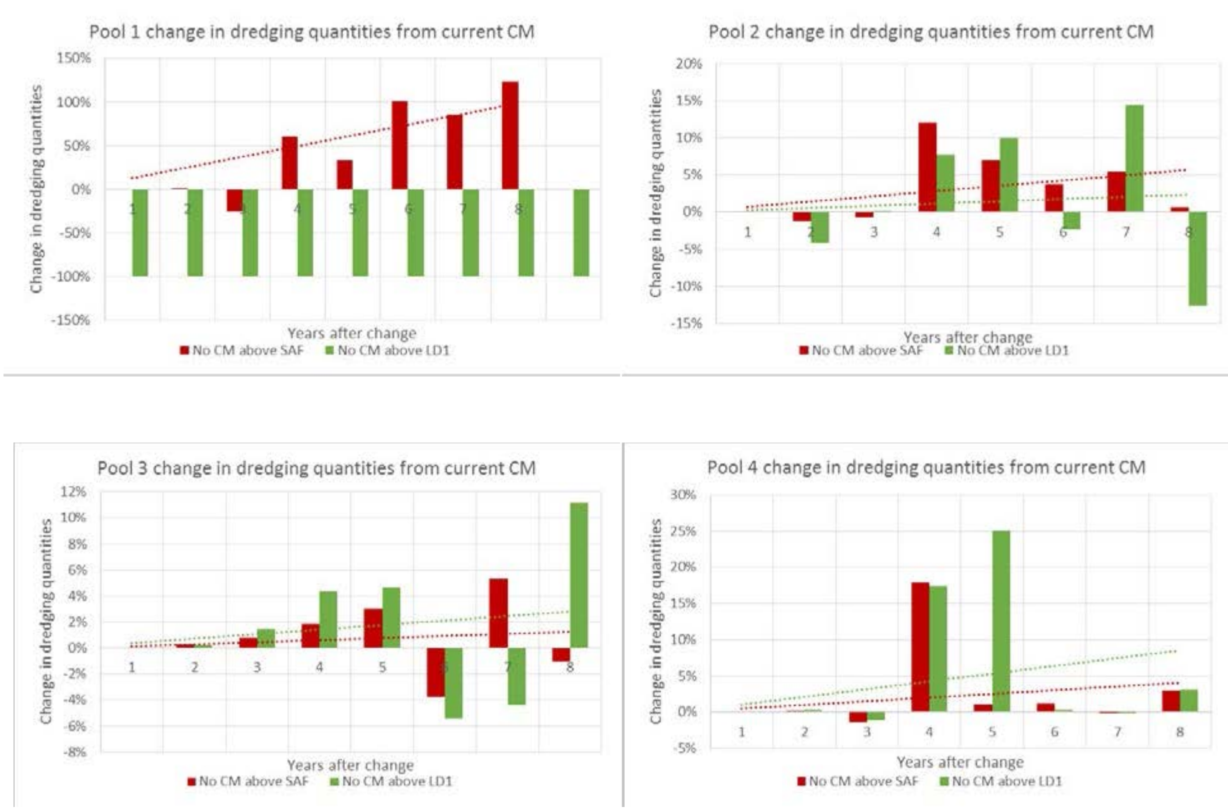

Figure B-4 – Trends in change in dredging quantities (by pool) after channel maintenance change