Appendix E:

Mississippi River (Pool 2) 2-D ADH Model Development

(PREPARED BY WEST CONSULTANTS, 2011)

US Army Corps of Engineers
St. Paul District

MISSISSIPPI RIVER (POOL 2)
2-D ADH MODEL DEVELOPMENT

March 2011

Prepared by WEST Consultants, Inc. under contract W912P9-10-D-0516

Task Order DD01

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1 *Introduction*

1.1 GENERAL

WEST Consultants, Inc. (WEST) was tasked by the U.S. Army Corps of Engineers, St. Paul District (the District) to develop and run a 2D hydrodynamic and sediment transport model of the downstream half of Pool 2 of the Mississippi River, using the Corps' Adaptive Hydraulics model, or ADH.

The purpose of the 2-D model is to analyze the navigation channel, opportunities for improved channel maintenance, and whether the Boulanger Bend channel could be used as the main navigation channel. Currently, tows still use the main navigation channel. However, there is a strong desire to analyze the use of the Boulanger Bend channel for navigation. The Boulanger Bend channel connects to the main navigation channel at approximately RM 818 and 820.

A 2-D model has been developed for this area by Barr Engineering in 2009. This model used RMA2 v4.56 software (Barr, 2009). This model was considered to be too coarse for the detailed analysis needed for this study. Also, the ADH software has proven to be superior in dealing with sediment transport. Therefore, the District asked that a new model be developed, and that the model be used to evaluate existing conditions and modifications to Pool 2 to improve navigation.

1.2 STUDY AREA

The study area includes River Miles (RM) 815.5 to 827.8 of the upper Mississippi River, in the area immediately upstream of Lock and Dam 2 (Figure 1-1). The upstream extent of the study area is approximately 13 miles downstream of St. Paul, MN. The area of primary focus approximately covers RM 818 – 820. The region consists of a large island at RM 820 - 825, Grey Cloud Island, which splits flow into a main channel on the island's south side, and secondary channel to the north. In addition, a shallow channel extends from the north channel and connects back to the main river stem at approximately RM 828; and the flow is split into two channels around Baldwin Lake, southwest of Grey Cloud Island. This channel only floods during high flow events, such as during the 100-year event (Barr, 2009). The area alongside the main channel has a large number of wing dikes, which help to maintain the navigation channel depth. There are several regions of relatively slow-moving water; the largest of these are Spring and Baldwin Lakes, which are southeast and southwest of Grey Cloud Island, respectively. The elevation of Lock and Dam 2 is approximately 687.2 ft (209.46 m) MSL 1912.

Figure 1-1. Location map for Lock and Dam 2 and study area.

1.3 AUTHORIZATION

WEST Consultants, Inc. (WEST) was contracted to conduct this study under Contract No. W912P9-10-D-0516, Task Order No. DD01, by the St. Paul District, Corps of Engineers. The contacts at the St. Paul District for this project are Mr. Jon Petersen and Mr. Aaron Buesing.

1.4 SCOPE OF WORK

Specific tasks performed for the contract included the following:

- Development of hydrodynamic model using bathymetric data provided by the District, using the Corps 2-D ADH model.
- Calibrate the hydrodynamic model to backwater profiles and observed stages provided by the District.
- Develop a compatible sediment transport model, also using ADH, and simulate sediment transport for the four given hydrodynamic conditions.
- Conduct an alternatives analysis, including (A) No Action, (B) Use cut-off as main channel, C &D) Keep main channel in current position and improve existing structures (C) and dredging (D).

1.5 STUDY TEAM

Dr. Raymond Walton, P.E. was WEST Consultant's Officer-In-Charge and the Project Manager. He and Ms. Emily Spahn of WEST Consultants were responsible for developing the model. Mr. Jon Petersen, Mr. Aaron Buesing and Mr. Scott Goodfellow provided assistance in managing the contract and addressing technical questions.

2 *Hydrodynamic Model Development and Calibration*

2.1 HYDRODYNAMIC MODELING APPROACH

We used the following approach to model the hydrodynamics of lower Pool 2 on the Mississippi River:

1. Develop the pool geometry:
   a. Convert provided topographic data into NAD83 UTM Zone 15N projection
   b. Combine the elevation data into one file
   c. Develop the model mesh
   d. Interpolate elevations to mesh and adjust when needed
2. Assign “materials” (regions of similar bottom roughness and eddy viscosity characteristics)
3. Develop initial and boundary conditions
4. Calibrate data to flood profiles, observed flow splits, and cross-sectional velocities.

2.2 DESCRIPTION OF NUMERICAL MODEL

ADH is a relatively new model currently under development by the U.S. Army Corps of Engineers Engineer Research and Development Center (ERDC). The model is designed to be modular, in that a variety of solvers can be developed and applied to solve a problem. ADH can handle saturated and unsaturated water, overland flow, 3D Navier-Stokes, and 2D and 3D shallow water problems, sediment transport, transport of conservative constituents, vessel movement and select flow control structures. For this study, the 2-D shallow water and sediment transport modules were used. A main feature of ADH is its ability to locally refine the model mesh (“shock capturing”) to efficiently improve the results. ADH also offers adaptive time stepping in addition to the mesh adaption.

ADH has a graphical user interface through the Surface Modeling System (SMS). The user has the option to run ADH entirely through the SMS user interface, or to develop the mesh and hotstart files, and view model results in SMS after developing the input (*.bc) file for the model in a text editor. For this study, we used the ADH version 3.3, the latest available version of the model.

2.3 MODEL DATA

The St. Paul District provided data for the study. The data provided included 8 elevation data files, an aerial photo, pool operation information, flow measurements, sediment transport data, and a previously developed model for Pool 5 of the Mississippi River. They also provided a report written by Barr Engineering in 2009, on a simulation of Pool 2 done using RMA2. Additional data for suspended sediment were downloaded from the USGS Upper Midwest Environmental Science Center; total suspended solids (TSS) concentration data were available for RM 826, near the upstream end of the modeled area. TSS data were available near RM 818, USGS stations 05331570 at Nininger, MN. Limited particle size information were also available at this site. The exact locations and reliability of both these sets of TSS data are questionable; and indeed the data at RM 818 contained a statement indicating that these data are provisional and subject to revision.

2.4 MESH AND BATHYMETRY CREATION

Bathymetric and elevation data for the region were developed from the series of elevation “*.h5” files provided by the District.

These data were combined into one geometry file based on the “priority” shown in Table 2-1. Where coverages overlapped, data from the file with a higher priority were used. Data from lower priority files were used to fill in coverage gaps of higher priority files. The exceptions to this were for the LiDAR and DEM data—these were only used for land coverages. One area of the main channel, near RM 823, did not have adequate coverage, and bathymetric elevations for the channel in this location were manually interpolated from data on either side of the gap.

Table 2-1 Elevation Data Files and Priority

Elevation Data used, in order of priority	
1	Main channel
2	Channel South of Lower Grey Cloud Island
3	Channel North of Lower Grey Cloud Island
4	Upper Spring Lake
5	Lower Spring Lake
6	LiDAR
7	DEM
8	LimnoTech

Once the data had been combined into one file according to priority, they were converted to the correct projection and units (SI system), then interpolated onto the grid in SMS. The depth contours of the mesh used are shown in Figure 2-1.

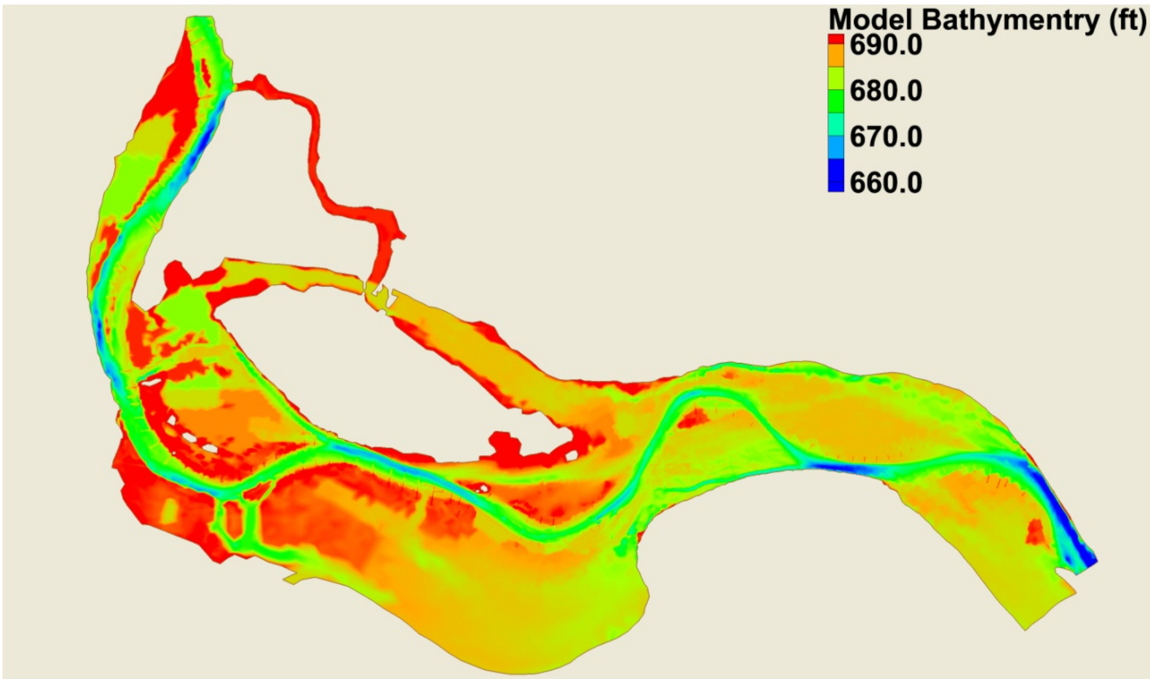

Figure 2-1. Elevation contours (in MSL 1912, ft) over the area of study.

The starting point to determine the lateral extent of the mesh was initially considered by examining the extent shown in the Barr report, along with the flood profile data for the pool. The mesh extent was determined by selecting a reasonable elevation, then following the contour around the study area. The elevation contours of 700 and 705 ft (213-215 m) above MSL 1912 were used as guides in creating the mesh.

An initial mesh was created in SMS, with the starting point being that the smallest element size would be along the channel in the area of focus, RM 818-820. The nodes were placed such that 5 element would define the navigation channel width, with the element sizes increasing away from the channel. The element lengths were prepared such that an element length would be approximately 2.5 times the element width.

After the initial mesh was created, another mesh was created using the “refine” command in SMS, dividing the elements into fourths, and refined further by hand around the wingdam dikes. After the finer mesh was developed, it was edited for mesh quality, so the mesh does not contain element transitions that exceeding 50%, interior angles less than 10°, and interior angles greater than 130°. The mesh was not adjusted to consider gradient violations; according to the model developers, these do not pose much of a problem for running ADH (pers. comm., Jennifer Tate, ERDC, August 2010).

This finer mesh was used as the starting point to develop the final mesh. Several iterations of the mesh for this area were created, each developed from the previous file. The mesh was edited to exclude elevations much higher than the maximum elevation for the highest flow, as well as to smooth the effects of wetting and drying. After examining preliminary results, the mesh was adjusted further to better match observed data. The final mesh developed for this model contains 21858 nodes and 42702 elements, covering an area of 3.36 x 10^8 square feet. Figure 2-2 shows the entire mesh, along with defined material types. Figure 2-3 shows the mesh and material detail in the area of focus. Definitions of the material types and associated roughness parameters are shown in Table 2-4.

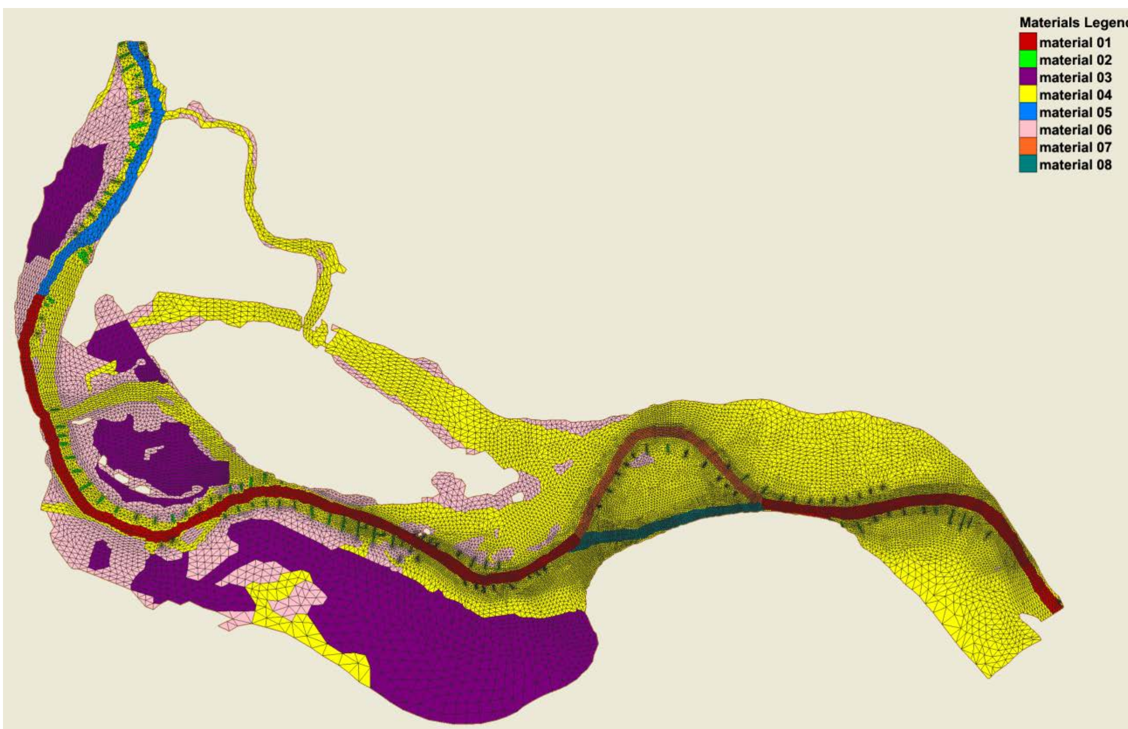

Figure 2-2 The model mesh and assigned materials.

Eight materials were used to define the bathymetry of the study area. The Manning's n values for each material were initially chosen by examining the previous models developed in or near our study area. We were provided studies on Pool 2 and Pool 5 of the Mississippi River. The materials and values used in the previous Mississippi River models are shown in Table 2-2. Separate materials were used for the channels in the area of interest (RM 818-820), so as to easily change the roughness values for the existing and proposed conditions.

A series of wingdam dikes are present in Pool 2. Since the bathymetry used to develop the model mesh did not reflect these, they were added in by changing the elevations of the nodes at the locations of the dikes. The elevations of the dikes above the bed were provided in the GIS shapefile for the dikes. A previous model of a reach of the Missouri River was provided, which contained wingdam dikes and associated roughness. We used for this model the Manning's n parameter which was used for the Missouri.

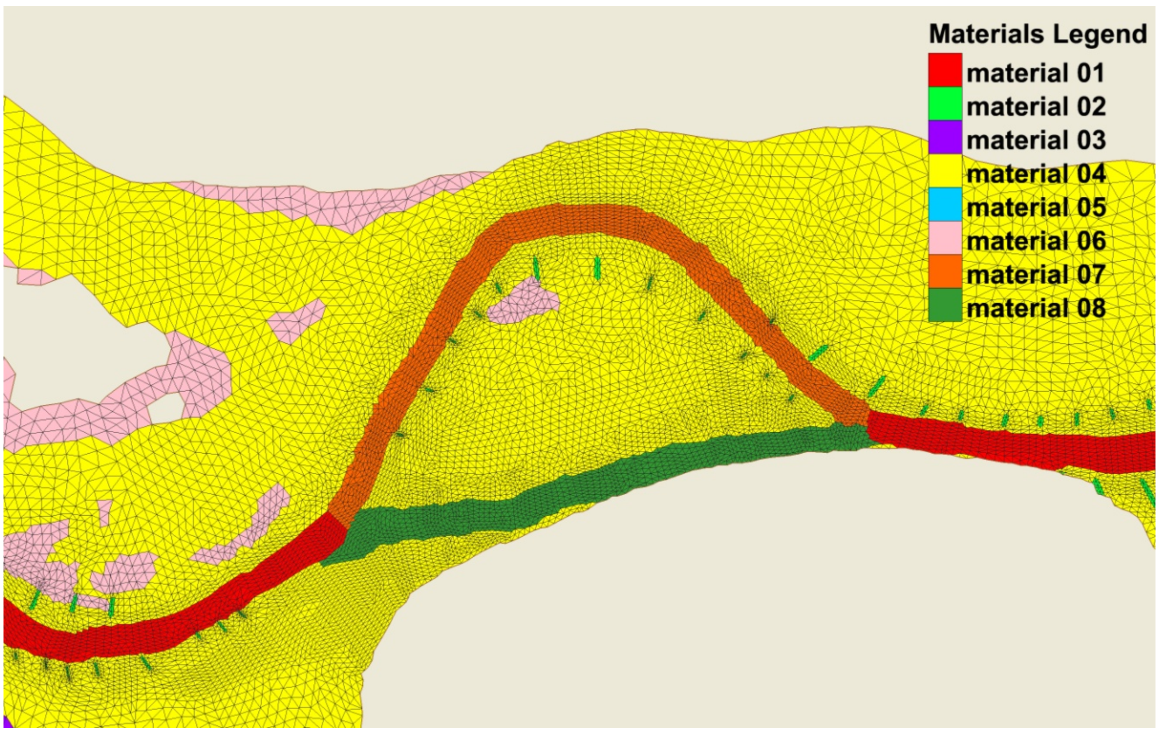

Figure 2-3 A close-up of the area of focus (Boulanger Bend), with mesh and materials shown.

Table 2-2 Assigned roughness values in previous models for the Mississippi.

Location type	Previous model	Pool	Manning's n
Shallow Water	Barr	2	0.025
Deep Water	Barr	2	0.022
Overland	Barr	2	0.08
Overbanks	Corps	5	0.05
Main Channel	Corps	5	0.022
Shallow water	Corps	5	0.04
Lakes	Corps	5	0.032
Upper River	Corps	5	0.028

2.5 Initial and Boundary Conditions Data

The hydrodynamic portion of the model requires initial and boundary conditions. These are:

- Initial pool water depth (hotstart file)
- Upstream flow boundary condition
- Downstream elevation boundary condition

Hotstart File Creation

ADH requires a hotstart file containing the initial depths specified at all nodes in the mesh. The hotstart files were developed in SMS using the flood profiles provided. For runs at smaller flows, a flat pool at 687.2 ft, MSL 1912 was used as the initial water surface elevation. For larger flows, a series of points were set up with elevations approximating those from the provided flood profiles, forming a tilted initial water surface. The bathymetric elevations were subtracted from water surface elevations to determine depths.

The model is quite sensitive to initial conditions—a good hotstart file is required to have the model run smoothly and quickly. The option of using the results from a previous run is available in ADH. In addition to depths, other parameters, such as velocity, can also be used to hotstart the model. For the hydrodynamic calibration, only depths were used.

Boundary Conditions

The scope of work requested that four flows be simulated for model calibration. These were imposed at the upstream boundary. Additionally, a flow of 20,780 cfs was also simulated at the upstream boundary, to compare to cross section velocity distributions shown in the Barr Report (2009). Also, flows of 30,000 cfs and 35,000 cfs were simulated to compare to observed flow splits in Pool 2. These data are shown in Table 2-3. The downstream boundary conditions were taken from the Lock and Dam 2 operating curve, for each upstream flow simulated--the pool operating curve is shown in Figure 2-4.

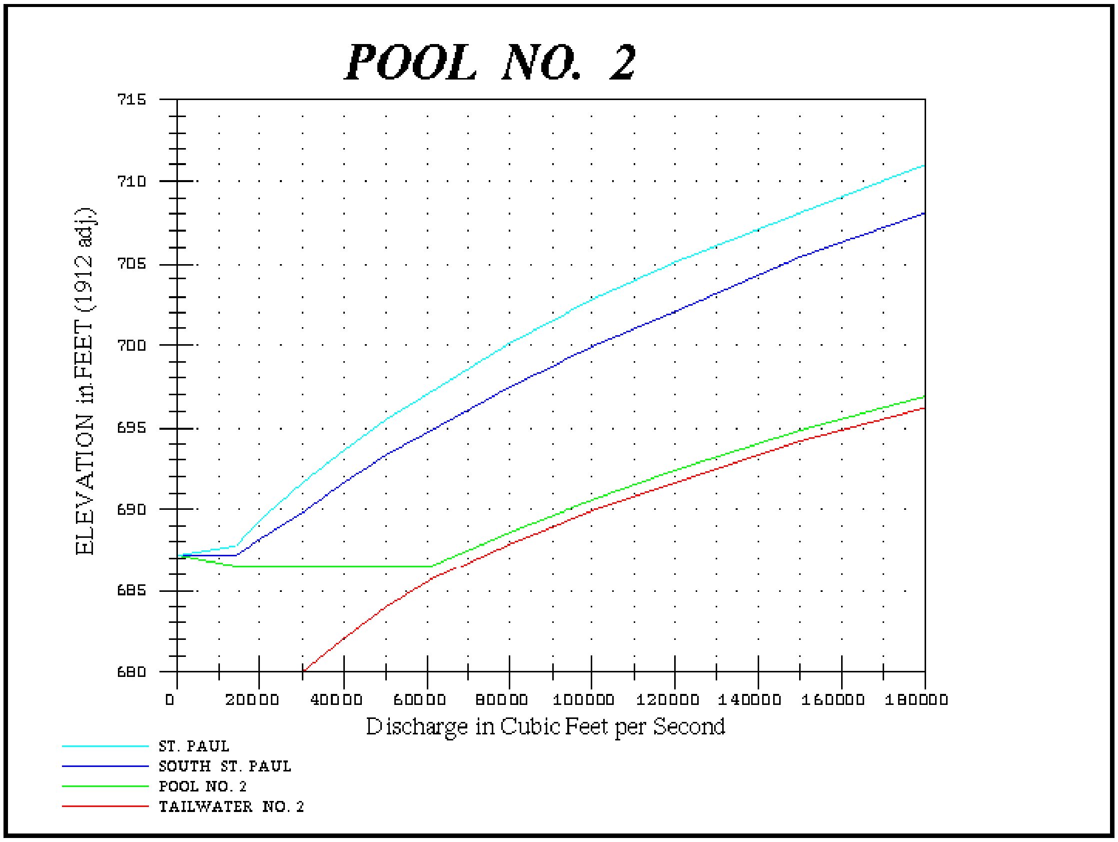

Figure 2-4 The Pool 2 operating curve; Pool No. 2 data (green line) were used as the boundary conditions.

2.6 HYDRODYNAMIC CALIBRATION

Model results were calibrated to Lock and Dam 2 flood profiles, along with observed flow splits. The exact values for the discharge and downstream elevation are shown in Table 2-3.

Table 2-3 Calibration runs: flows and boundary conditions

Flow (cfs); upstream boundary condition	Comparison for calibration	Downstream boundary condition, ft above MSL 1912
151,000	Flood profile	695
84,000	Flood profile	689
35,000	Flow split	686.5
30,000	Flow split	686.5
20,780	Velocities and flow split	686.5
14,400	Flow split	686.5
6,000	Flow split	686.9

Flood Profiles

Flows of 151,000 cfs and 84,000 cfs were simulated until steady state was reached, after which the resulting water surface elevations were compared against the provided flood profiles.

The materials and associated Manning's n values after the calibration of the Pool 2 model are listed below in Table 2-4. The results from ADH are shown in Figure 2-5 and Figure 2-6. Also on those figures are results from model simulations where the Manning's n parameters were lowered or raised by 10% of the values shown in Table 2-4.

Table 2-4 Calibrated roughness parameters for the exisiting conditions model

Material	Material number in mesh	Manning's n
Navigation Channel	1	0.023
Wingdam Dikes	2	0.036
Lake	3	0.032
Shallow Overbank	4	0.034
Upper river	5	0.026
Inundated areas (e.g. 100 year flood)	6	0.052
Existing Channel in study area	7	0.023
Proposed Boulanger Bend cut	8	0.034

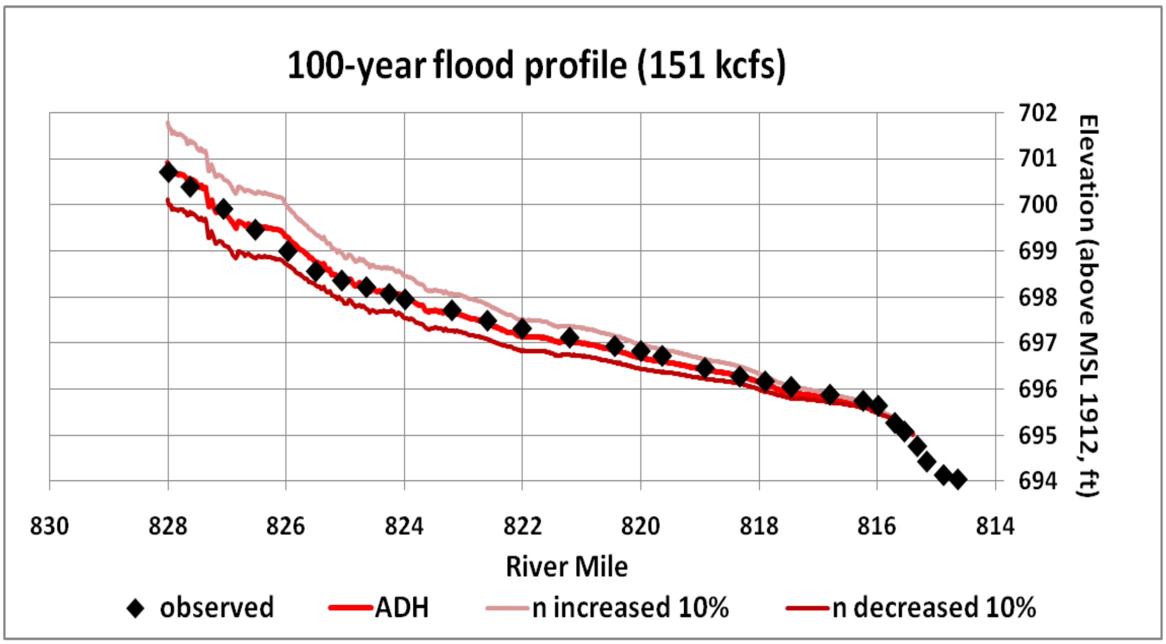

Figure 2-5 The flood profile and steady-state model results for the 151,000 cfs run.

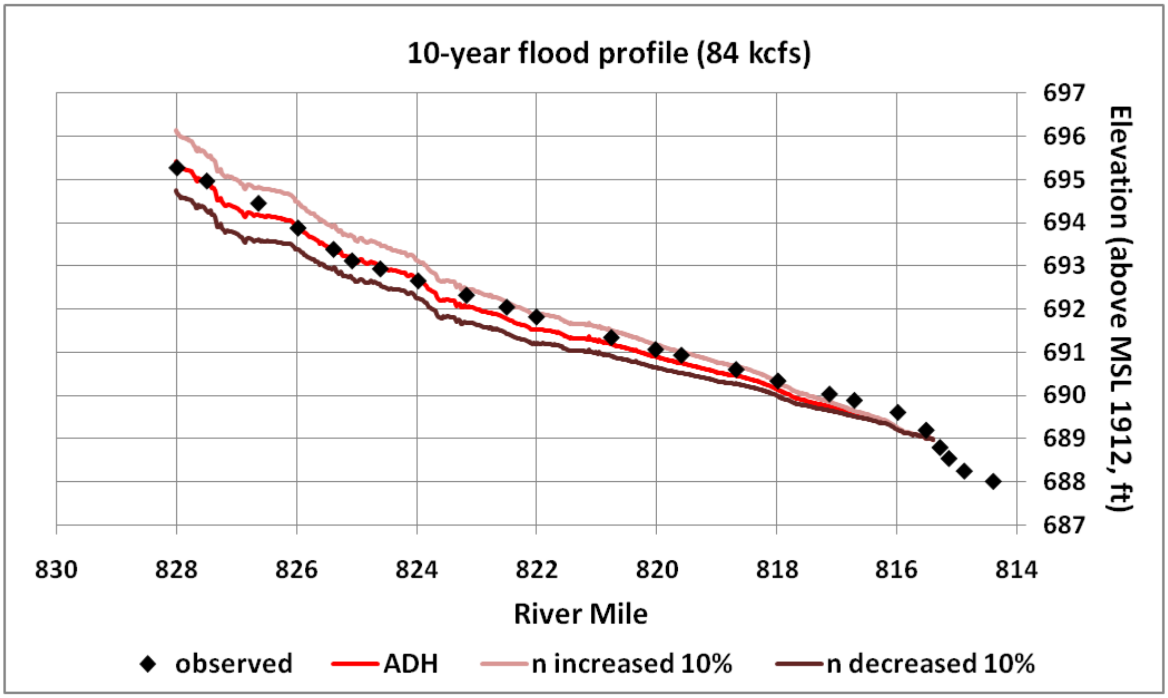

Figure 2-6 The flood profile and steady-state model results for the 84,000 cfs run.

Flow Splits

Five sets of flow split data were provided to the modeling team. Flow splits for total flows of 30,000 cfs and 14,400 cfs were measured at several locations during 1991 and 2002. Additional flow split data for total flows of 6,000, 21,000 and 35,000 cfs were also provided, but the sources of these data are unknown. The locations of the measured flows are shown in Figure 2-7.

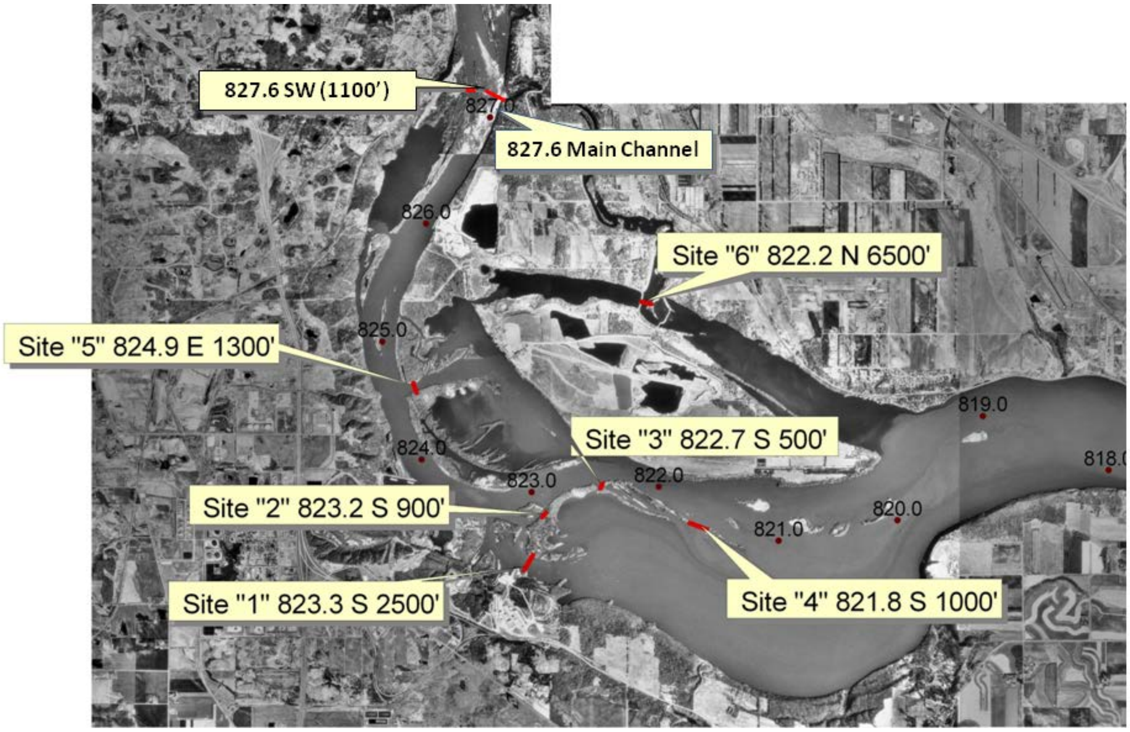

Figure 2-7. An image of the study area, with river miles and observed flow split locations shown.

The ADH model, calibrated to the flood profiles, was run to steady state using the 5 available flows for which there are flow split data; the results are shown in Table 2-5. The sections of Pool 2 containing these observations are a few miles upstream of the area of focus, although certainly still within the model. Observed data are not available at each location for each flow, thus the blank spaces in the table. ADH results of zero are shown as such in the table.

For the locations where the observed data is fairly large, at 827.6 Main Channel, 827.6 SW (1100'), Site 1, and Site 5, the model and data show reasonable agreement. To provide a point of reference between these calibration flows and the modeled flows, the lowest flow rate we have in the 500 day simulation is roughly 28 kcfs, and the largest 66 kcfs. The percent difference between the model and calibration split flows for 21, 30, and 35 kcfs are 3% or less. For most results at these sites, the percent difference between the ADH and provided flows is within 6%, with the exception being in the upstream most part of the main channel. That result is perhaps influenced by the closeness of the upstream boundary condition to an island that would split the flow. However, the difference is still relatively small, and does not significantly affect the results in the main study area downstream.

The flows at sites 2, 3, 4, and 6 are quite small--all the flows at these sites are at most 4% of the total flow at the Lock and Dam. Sites 2, 3, and 4 are three of the small inflows into Spring Lake. The size of the mesh in these locations may be a factor in the ADH results—there may be wetting/drying effects due to the relatively coarse resolution.

For site 6, in Grey Cloud Channel, there are two main issues that could affect the ADH results—the restriction of flows from bridges in the region, and the transect location and orientation. We were not provided schematics for the bridges spanning Grey Cloud channel, nor detailed bathymetry for the area, which will certainly bring in a degree of error.

Another source of error for all the split flows is the method by which these flows are obtained. In ADH, a string of nodes can be listed, between which the flows are calculated and output by the model. The mesh rarely has a string of nodes that is perfectly cross-channel, and thus there these flows are generally measured along a zig-zag shape across the cross section. This can skew the results when compared to the measured flow rate.

Table 2-5 Measured and modeled split flows, given in cfs and as a percentage of total flow at Lock and Dam 2.

Split flows (cfs) and corresponding percent flows with respect to Lock and Dam 2										
Lock and Dam 2 Q (cfs)	6,000	**%**	14,400	**%**	21,000	**%**	30,000	**%**	35,000	**%**
827.6 Main Channel							23,212	**77%**		
ADH	5,452	**91%**	12,849	**89%**	18,121	**86%**	25,533	**85%**	29,701	**85%**
827.60 SW (1100')							7,382	**25%**		
ADH	545	**9%**	1,643	**11%**	2,858	**14%**	4,564	**15%**	5,538	**16%**
823.30 S (2500') Main Inlet To Spring Lake, Site 1	2000	**33%**	2,867	**20%**	3,900	**19%**	5,961	**20%**	7,200	**21%**
ADH	916	**15%**	2,457	**17%**	3,218	**15%**	5,173	**17%**	6,422	**18%**
823.20 S (900') Spring Lake Inlet, Site 2	20	**0.3%**	125	**1%**	370	**2%**	613	**2%**	760	**2%**
ADH	0	**0%**	0	**0%**	0	**0%**	32	**0.1%**	740	**2%**
822.70 S (500') Spring Lake Inlet, Site 3	55	**1%**	92	**1%**	160	**1%**	224	**1%**	260	**1%**
ADH	0	**0%**	0	**0%**	0	**0%**	0	**0%**	0	**0%**
821.80 S (1000') Spring Lake Inlet, Site 4	80	**1%**	211	**1%**	410	**2%**	608	**2%**	720	**2%**
ADH	97	**2%**	369	**3%**	611	**3%**	978	**3%**	1,231	**4%**
824.90 E (1300') Baldwin Lake, Site 5			3,235	**22%**						
ADH	1006	**17%**	2,457	**17%**	3,767	**18%**	5,629	**19%**	6,528	**19%**
822.20 N (6500') Grey Cloud Channel, Site 6	-220	**-4%**	211	**1%**	60	**0%**	238	**1%**	310	**1%**
ADH	189	**3%**	438	**3%**	644	**3%**	945	**3.2%**	1,120	**3%**
Total percentage of flow in the channel, ADH/measured (Flow in Channel=Total–site1–site2-site3-site4-site6)		**118%**		**102%**		**103%**		**102%**		**99%**

Velocity

Measured cross-channel velocities at selected locations for a flow rate of 20,870 cfs were shown in Figure 2.7 of the Barr report (Barr, 2009). The locations of these cross sections were identified in Figure 2.5 of the Barr report, and the relevant portion of that figure is shown here, as

Figure 2-8. The results from the ADH Pool 2 model for this flow rate are plotted against the measured cross-channel velocities in Figure 2-9. Although the ADH model velocities do not exactly match those measured, the values are generally close enough to be reasonable. Furthermore, ADH produces velocity distributions similar to the observed data. The exception to this is section 5, which shows that the measured velocities are nearly twice those produced by ADH.

Certainly any bathymetry coarseness or inaccuracy plays into the results. However, it is difficult to pin down how much of the velocity differences are due to the quality of the bathymetric data or for other reasons. For example, we were not provided with the locations of the velocity transects, apart from the figure in the Barr report. The transect locations were estimated visually, and thus are not completely accurate, both in the longitudinal and cross-channel directions. Section 5, which has the worst match between ADH and observed data, is in an area where the channel narrows into Spring Lake, and the bathymetric data are sparse in the off-channel areas. It is possible that the actual location of this transect is in a location just downstream of the modeled locations, which would explain the greater width and smaller velocity magnitudes of the model results.

Figure 2-8 Locations of the observed cross sections, from Figure 2.5 of Barr (2009). These measurements were taken on 10/11/2007 during total river flow 20,780 cfs.

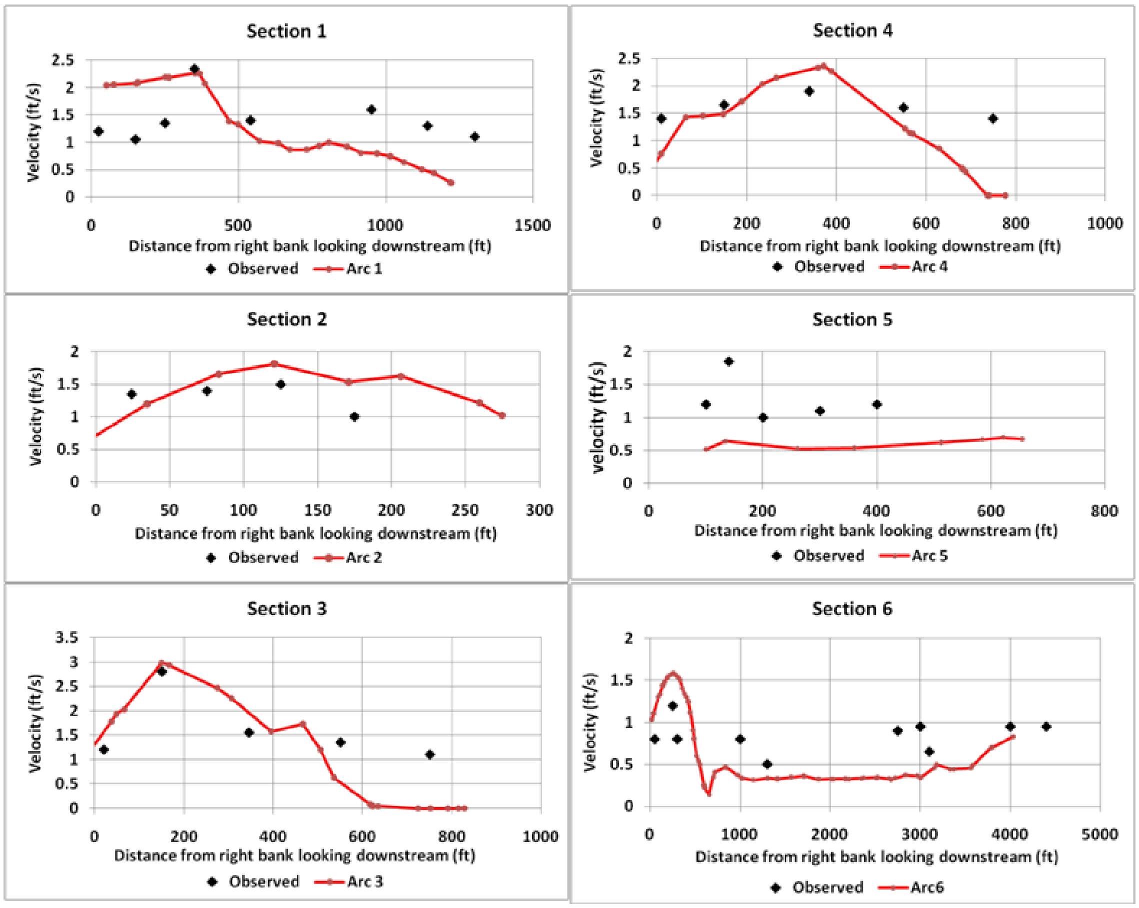

Figure 2-9 Observed velocities and corresponding model results at a flow of 20,780 cfs. Velocity (in ft/s) is plotted against the distance (in ft) from the right bank looking downstream.

3 *Sediment Transport Model Development and Calibration*

3.1 Initial Bed Sediment Conditions and Sediment Gradations

Bed gradations in the Pool 2 study area were available for RM 827.7, 822.9 and 818.8; these data are shown in Figure 3-1. The bed gradation at RM 827.7 was initially used to define the bed distribution over the study area, with the assumption that the bed gradation downstream changes as the model progresses in time and suspended material settles to the bed. The bed gradations contain increasing amounts of fine sediment with distance downstream, indicating that the study area is dominated by deposition. We do not have information on the locations of the bed gradation measurement sites apart from their river miles, and we do not know whether they were collected in the channel or in one of the several lakes in the area.

Initial run parameters

The bed size distribution was based on the bed gradation measured at RM 827.7, and coarsened with depth to provide for larger size particles to help to armor the riverbed against excessive erosion. Although the bed gradation from RM 818.8 shows a not insignificant amount of cohesive sediments (defined as sediment diameter of less than 0.0625 mm), this size fraction was not included in the mode as initial simulations indicated it would generally be transported through the model reach without settling. Again, we do not know the precise location of the gradation measured at RM 818.8.

A total of six bed layers were used in the model, with bed sediment size fractions changing between layers, as shown in Table 3-1. Eight materials were assigned to various lateral portions of the model, as explained in section 2.4 . The vertical bed layers for material 2, representing the wingdam dikes, were set to zero to prevent erosion and, as much as possible, deposition on the dikes.

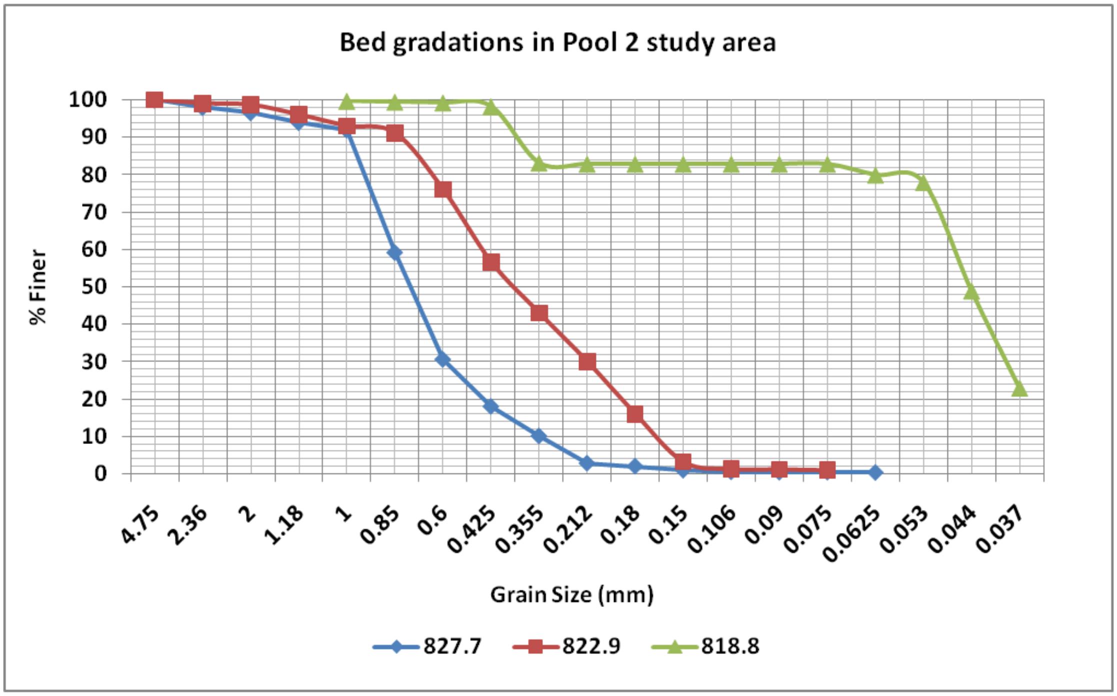

Figure 3-1. Bed gradations in the Pool 2 study area.

Table 3-1 Bed gradations, for all materials but that representing wingdam dikes.

Bed Layer size	Particle sizes and distribution			
	0.3 mm	0.5 mm	1 mm	10 mm
0.0001 m (surface layer)	0.7	0.3	0	0
0.0001 m	0.7	0.3	0	0
0.1 m	0.3	0.4	0.25	0.05
0.5 m	0.1	0.4	0.4	0.1
1 m	0.05	0.25	0.4	0.3
3 m (bottom layer)	0	0.1	0.3	0.6

3.2 SEDIMENT BOUNDARY CONDITIONS

TSS concentrations are not required by ADH for each specified particle size modeled, only for those sizes transported across inflow boundaries. Two inflow transport boundary conditions are available in ADH – an equilibrium boundary condition or specified inflow concentrations. In the Pool 2 model, applying the equilibrium condition caused the TSS values to be unreasonably large, on the order of several hundred mg/L, and thus the specified TSS boundary condition was used.

Total TSS data are available at RM 826, collected by the Minnesota Pollution Control Agency between 1975 and 1998. In order to determine TSS at each flow, a rule curve was developed, correlating observed flows and sediment loads. The resulting regression equation was used to determine sediment loading for a specific flow rate, and was converted to concentrations by dividing out the flow rate. A plot of the correlation is shown in Figure 3-2.

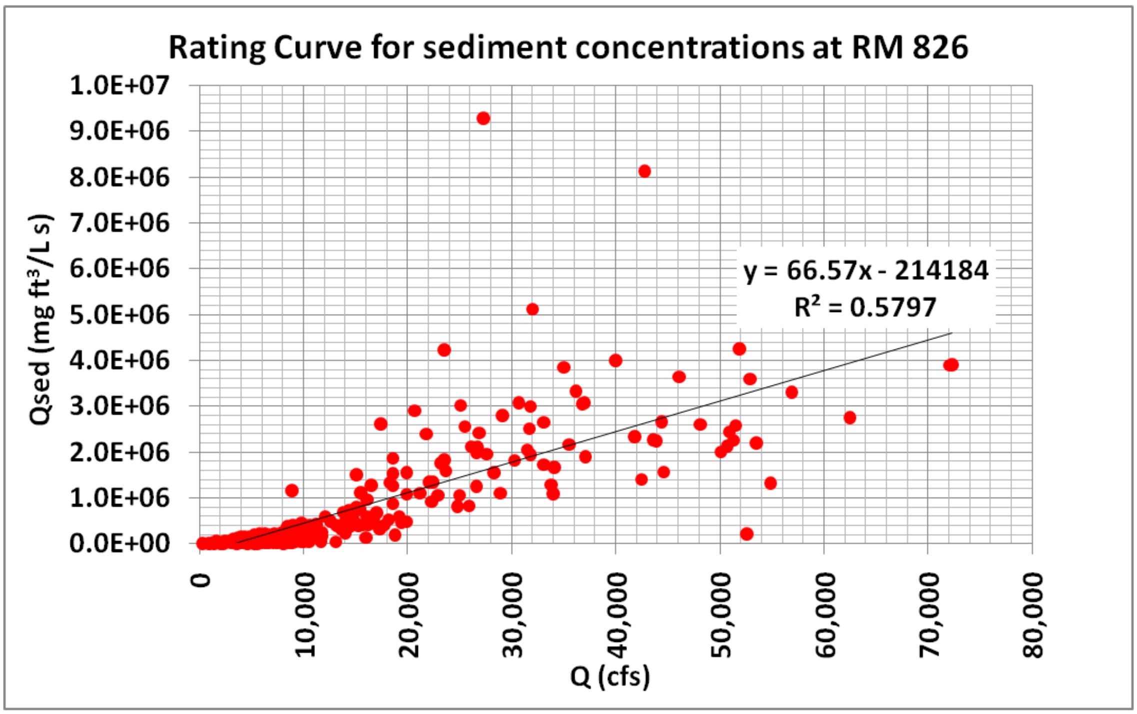

Figure 3-2 Rating curve to calculate upstream SSC boundary condition. Sediment loading values do not have volumes cancelled out, leading to the odd units on the y-axis.

The data at RM 826 do not contain particle size breakdown. The nearest location with TSS size data upstream of the Pool 2 study area is the USGS gage 05288500 at Anoka, which is approximately 40 miles north of RM 826. The percent of sediment finer than 0.0625 mm were measured at Anoka 8 times between 1984 and 1992. The average percent of fines, 70%, was used to determine a starting point for the fines fraction at the upstream end of the model.

Therefore, an initial estimate of 30% of the TSS total from the regression equation was used as the amount of non-cohesive sediment put into the system. This amount was increased to 50% of the TSS total after examining the initial results. All of the TSS inflow is assigned to the smallest particle modeled (0.3mm).

The particle size data from Anoka is one of the limited data sets for suspended particle size fraction near Pool 2. The station is not ideal due to a significant tributary flowing into the Mississippi River between the two locations. Figure 3-3 shows a map of the region with the two closest stations on the Mississippi with sediment size data available.

Figure 3-3 Locations of the nearest two stations with sediment size distribution data available, with inset showing relative placement of the Anoka gage and the Pool 2 study area.

3.3 INITIAL SEDIMENT MODEL SETUP AND TESTING

The same mesh was used for the hydrodynamics and sediment runs. Several iterations of the model using a variety of initial sediment parameters were run. The bed size distributions were estimated first from the bed gradations at RM 826, and several models were run using size distributions that favored finer or coarser sediments. After the medium bed size distribution showed the most promising results, the bed parameters were further adjusted. The resulting initial bed size distribution is shown in Table 3-1.

The model was run for one day (to steady state) with steady flows representing the 75%, 25%, and 5% durations, and the 1% flood to confirm that the models ran stably.

4 *Long-Term Sediment Simulations*

4.1 HYDRODYNAMICS

The model was run to simulate sediment transport for representative periods of one and five years, using 100 days for each year. Each 100-day period is intended to represent the larger flows in typical years and simulate most of the annual sediment transport.

We obtained daily flows at Lock & Dam 2 for the period January 1959-October 2010. The annual series of daily flows are shown as the fine lines in Figure 4-1. Also included in the figure are the annual series of daily averages (black line), the 75th-percentile flows (green line) and the 92nd-percentile (blue line). The study team was asked to model a one-year series with a peak flow of 44,250 cfs. From flow-duration information provided by the St. Paul District, this is approximately the 75th percentile event. We were also asked to model a five-year series with a peak flow in year 3 of 66,000 cfs. From the same flow-duration information, this is approximately the 92nd percentile event.

Using a peak one-year flow of 44,250 cfs, the flow distribution, shown by the thick red line in Figure 4-1, approximates the flow distribution of the largest 100 days for the 75th-percentile flows, and the flow distribution, shown by the thick purple line, approximates the flow distribution of the largest 100 days for the 92nd-percentile flows. The resulting hydrograph for the five-year (500-day) run is shown in Figure 4-2. The five-year period was developed using the "one-year" flows for years 1, 2, 4 and 5, with the 92nd-percentile flows used to represent year 3.

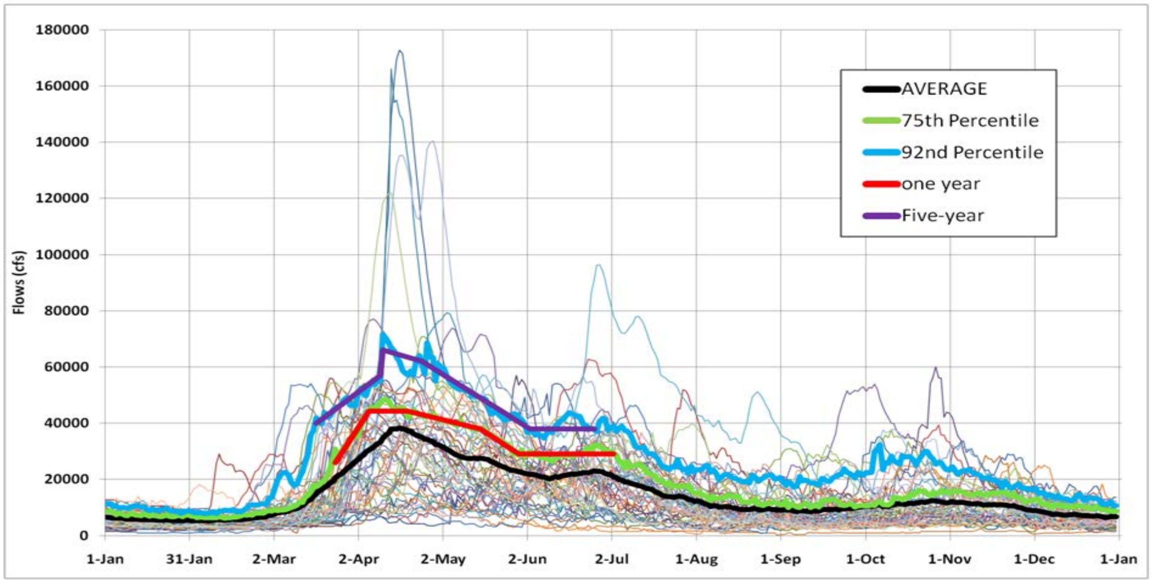

Figure 4-1 Annual Flow Series at Lock & Dam 2 for 1959-2010

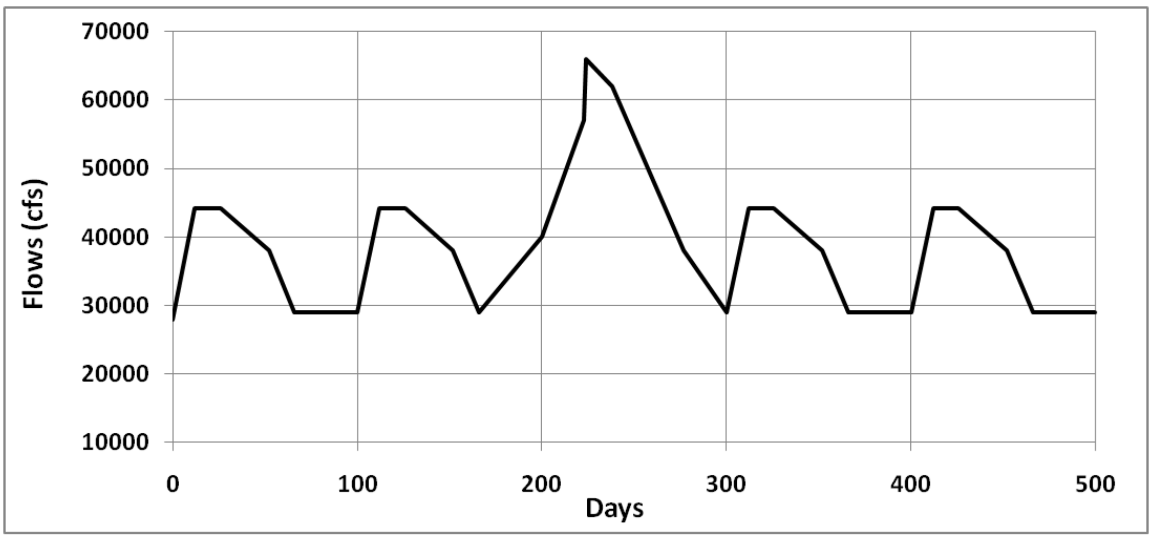

Figure 4-2 Flow distribution for the 500 day simulation

4.2 LONG-TERM SEDIMENT SIMULATION FOR EXISTING CONDITIONS

The sediment regression equation calculated for the RM 826 data, as shown in Figure 3-2, was used to calculate initial TSS inflows. As explained in Section 3.2, 50% of the total calculated TSS value was used as the TSS boundary condition.

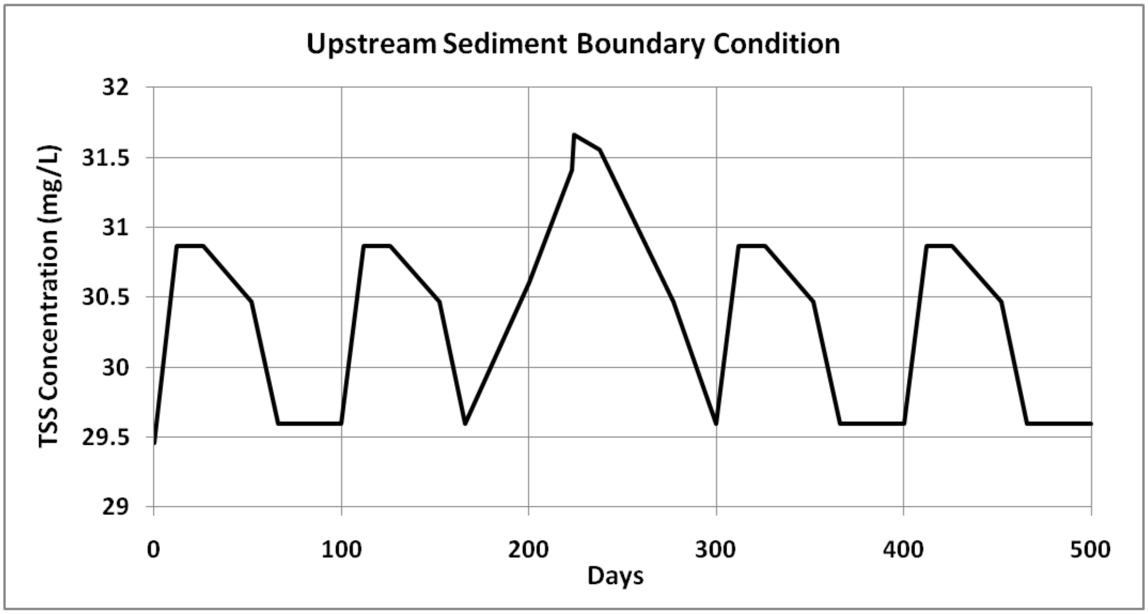

Figure 4-3 Upstream inflow sediment values for the five hundred day simulation

Sediment Calibration

Dredging records for Pool 2 were provided for calibration against the model results. In addition to individual dredging events, averaged yearly dredging amounts from 1970 – 2007 were provided, as well as shapefiles of select dredging events. Two general areas of dredging were identified as being in the study area of interest, at approximately RM 821 and RM 819.

To calibrate the model to the average annual dredging, the average lengths and widths of the dredging events in each of the two general dredging locations were calculated. These were used to construct new shapefiles that outlined the approximate location of the dredging for the two locations, as shown in Figure 4-4.

The bed displacement values from the model at the nodes contained inside the representative dredging shapefiles were averaged and multiplied by the area to estimate the deposition or erosion for the two regions in the area of interest. The resulting values, from both the 100 and 500 day runs, were compared against the average yearly dredging amounts provided, as shown in Table 4-1.

Figure 4-4 Aerial view of the area of focus with river miles, locations of dredging events (pink), and averaged dredging locations (black) shown.

Calibrations to TSS values were not pursued. The USGS operated a station near our study area of focus, at roughly RM 818, near Nininger, MN. The station collected data from 1977 to 1995. The data set includes flow rates and suspended sediment data, along with percent fines content. However, there are several caveats to these data, among them being that the exact location of the station is not known. The coordinates given for the station show it in the neighborhood of the channel, but quite close to the shoreline. If indeed the measurements were taken close to shore, local processes near the bed may influence the data. Furthermore, these data contain a notice that the values were preliminary and have not been verified. These data were considered unreliable, certainly more so than the TSS values at RM 826.Therefore these data were neglected as a suspended sediment calibration parameter and were not taken into consideration when developing the existing condition model.

Existing Condition Model Results

The majority of the deposition in any given year occurs during the 100 day modeled period. However it is difficult to estimate what fraction of the total yearly deposition occurs during this time. A guideline of 75% was selected, and factored into the model calibration.

The results from the 100 day run show only fair agreement with the observed dredging records when the 75% guideline is included. At RM 821, model deposition values are higher by 75%; at RM 819, they are lower by 25%.

The yearly averaged model deposition results from the 500 day run show much better agreement with the dredging data than the 100 day runs. The ADH results at RM 821 and RM 819, after accounting for the 75% yearly sediment deposition estimate, are both within 3% of the yearly average dredging values.

We believe that the different results for the 100 and 500 day yearly averaged runs are consistent with the averaged yearly dredging record. The dredging calibration data are averages of the dredging over roughly 30 years. The 100-day model year does not cover any year to year variability contained in that record. The 500-day record is more realistic in that it takes into account a larger range of flow rates and variability. It is during the larger flows in the 500-day run that an increased amount of sediment is transported and deposited in the bend; the 100-day results show more deposition occurring mainly in the region upstream of the bend, which would explain the results being larger and smaller than the dredging values at RM 821 and 819, respectively. Averaging the 500-day results to obtain annual average results provides a better match to the averaged dredging values provided.

The dredging locations in the received GIS shapefile do not quite align with our channel, which was defined using the bathymetry. In both dredging locations along Boulanger Bend, our defined channel was just outside the bend compared to the shapefile areas. We defined the average areas of dredging in the model keeping this in mind—the average widths and lengths were calculated in both areas, then located in the estimated center of dredging along the model's channel as determined from the bathymetric data.

There are obvious differences between the locations of dredging in Figure 4-4 compared to the results of deposition in the model in Figure 4-5. Figure 4-4 shows two distinct sections of dredging near RM 819 and RM 821. The dredging area near RM 819 extends downstream, with several dredging events covering the eastern portion of Boulanger Bend. The model results shown in Figure 4-5 depict continual deposition along the western side of Boulanger Bend, with little deposition on the east. From this, we can infer that the sediment being deposited on the west side of the bend in the model is in reality carried through the bend, to deposit on the east side. However, in the areas of dredging, the values calculated from the model and dredging data agree quite well.

Table 4-1 Results from existing condition sediment run

RM	Observed average annual dredging (cubic yards)	100 day run results, after accounting for ¾ of sed per 100 day year (cubic yards)	500 day results after accounting for ¾ of total sed per 100 day year (cubic yards)
821	15500	27100	15700
819	16400	12300	16900

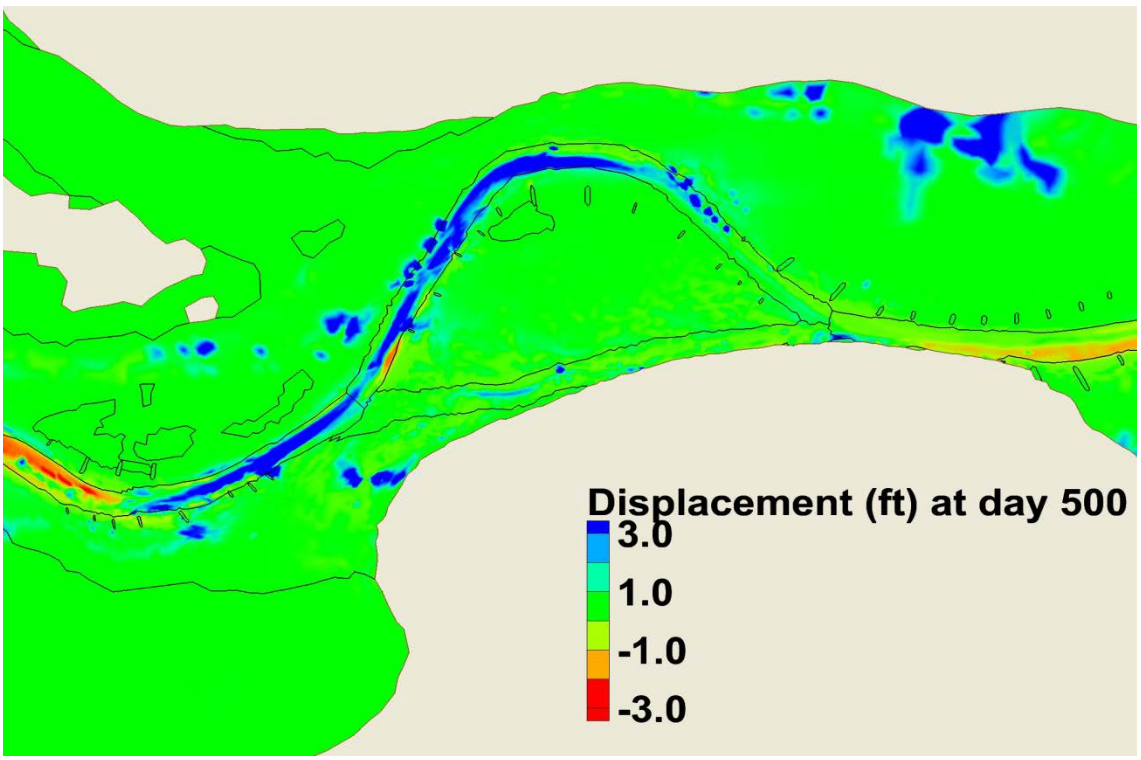

Figure 4-5. Displacement (ft) in the region of interest at the end of the 500 day run for existing conditions. Blue color indicates deposition; red indicates erosion. The material boundaries are shown to indicate the location of the navigation channel.

5 *Development and Simulations of Alternatives*

5.1 BOULANGER BEND BYPASS CHANNEL, INITIAL CONDITION

The first alternative consists of a bypass channel cutting through the Boulanger Bend region of Pool 2, between RM 818-820. The existing configuration requires that barges travel in a curve through this region, which can be difficult to navigate. The proposed bypass channel would allow vessels to avoid this bend. In Figure 5-1, the existing navigation channel is shown in orange; the proposed alternative navigation channel is shown in green and follows a naturally deeper (possibly) relic channel.

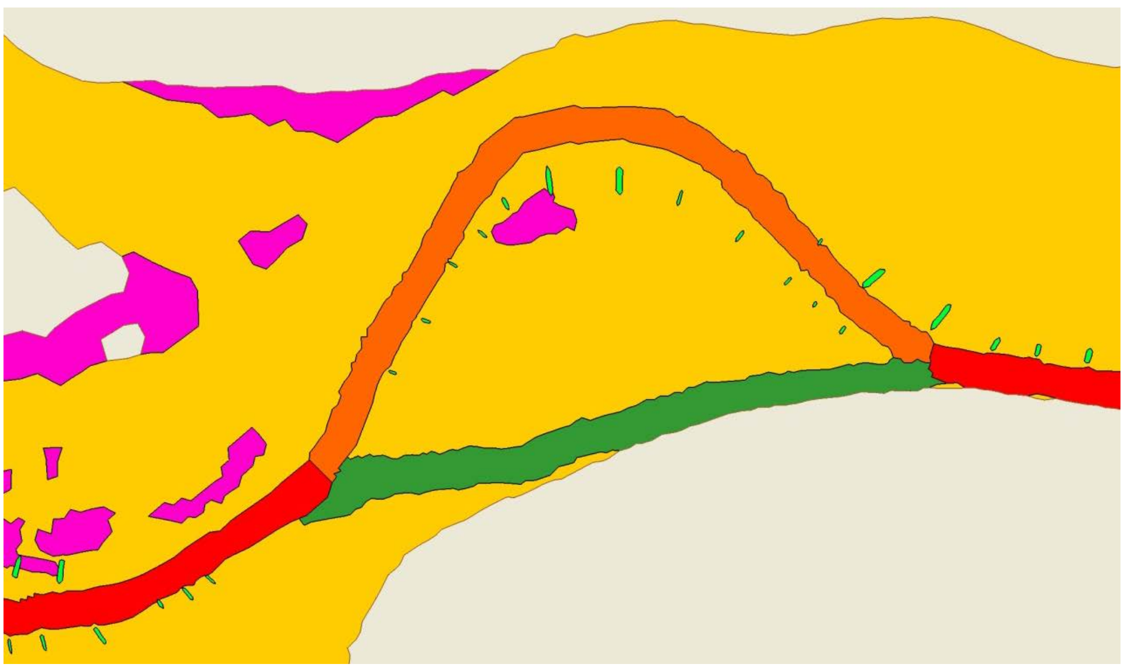

Figure 5-1 Materials depicting the existing (orange) and proposed (green) main channel.

The proposed Boulanger Bend bypass channel alternative was taken into consideration during the construction of the model mesh. Separate materials were defined for the existing and proposed navigation channels in Boulanger Bend. This "initial" case simulates the sediment deposition just after the bypass is established. Therefore, both the existing channel and the bypass channel were assigned a Manning's n of 0.023, as there would be no immediate change to the bed roughness apart from dredging to establish the bypass channel. The results for this option are shown in Figure 5-2.

To create the new bypass channel bathymetry, bed elevations in the proposed bypass channel were lowered from the existing condition elevations to an elevation of 671 ft (204.5 m) MSL 1912, to be consistent with the existing bed elevations along this reach of Boulanger Bend. Depths lower than this in the bypass channel region were not changed. The modeled bypass channel is approximately 330 ft (100 m) wide, and 6,600 ft (2,000 m) long. Roughly 450,000 cubic yards would have to be excavated to develop the channel as modeled.

Figure 5-2 shows sediment deposition in the upstream portions of the existing and bypass channels Dredging would still need to take place upstream of the bypass channel, and also along the upstream quarter of the newly dredged bypass channel. The model indicates that a small amount of erosion would occur near the downstream end of the bypass channel. There is also indication of deposition in the Spring Lake area, to the bottom left of the figure. This is due to model instabilities, and is not representative of actual deposition. Such instabilities appear in several of the modeled cases, but as long as they were distant from or minimal in the area of focus, they were not considered a serious problem and were ignored.

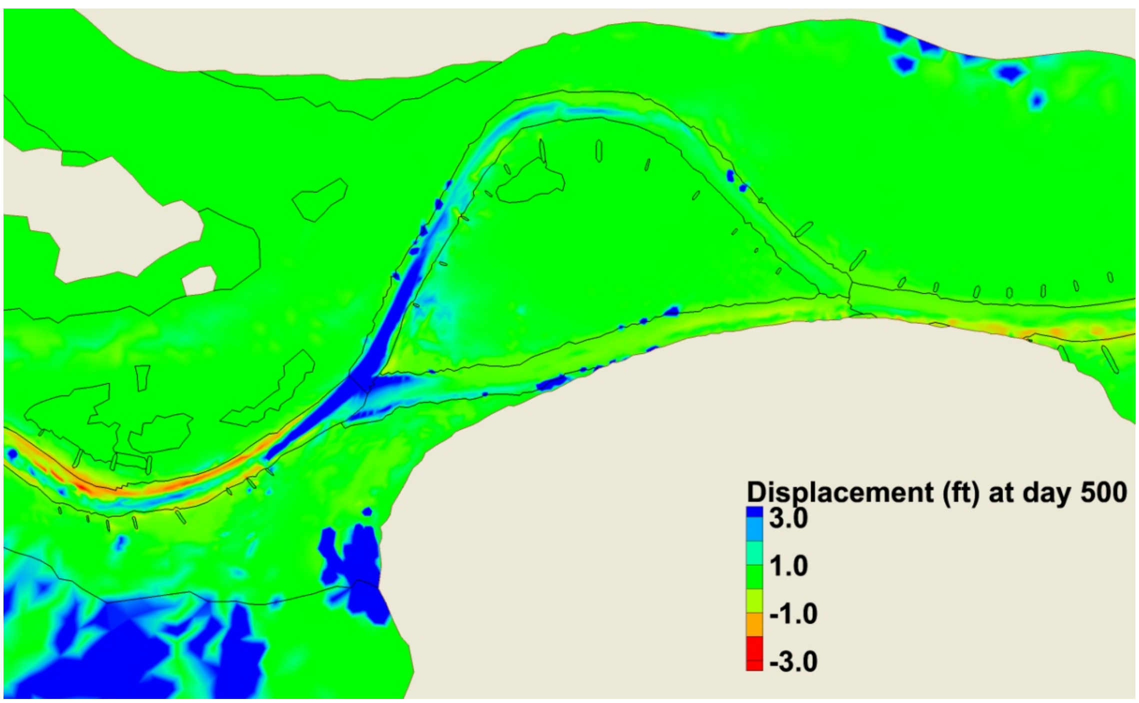

Figure 5-2 Bed displacement (in feet) after the full 500 day run, for the case just after the Boulanger Bend bypass channel is established. Positive (blue) values indicate deposition; negative (red) values indicate erosion. Outlines of material types used in the model are shown.

5.2 BOULANGER BEND BYPASS CHANNEL, ESTABLISHED CHANNEL CONDITION (EXISTING CHANNEL FILLED)

As the existing channel is abandoned, we expect that channel would eventually become blocked, as deposition fills in the upstream area of the existing channel. To simulate this long-term future condition, the existing channel was filled in downstream of the confluence, to an elevation corresponding to that of the overbank areas (679 ft, or 207 m, MSL 1912). The mesh for the bypass channel option was edited to reflect sediment filling in the upstream third of the existing Boulanger Bend navigation channel. This would simulate the long term effects of abandoning the existing main navigation channel.

Furthermore, the roughness of the existing channel was changed to be the same as the shallow overbank, to reflect the change in the bed material as the channel is abandoned. The results at the end of the 500-day simulation are shown in Figure 5-3.

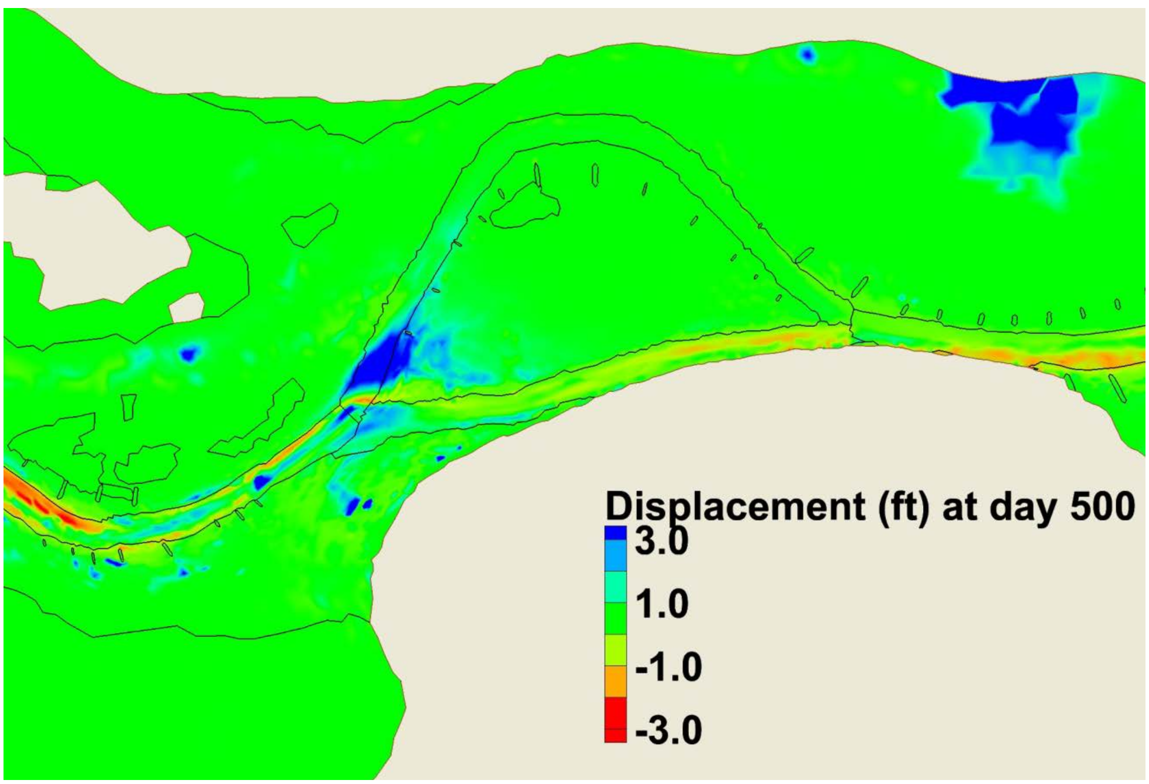

Figure 5-3 Bed displacement (in feet) at the end of the 500 day run, for the establised (long-term) Boulanger Bend bypass channel option. Positive (blue) values indicate deposition; negative (red) values indicate erosion. Outlines of material types used in the model are shown.

As in the previous case, the area at the upstream end of the bypass channel would need to be dredged, but dredging in the existing channel would have been discontinued. Just upstream of the existing and proposed channels, there is less deposition of material compared to the existing and initial bypass channel models. In general, as the existing Boulanger Bend channel fills in, flows, and velocities, would increase in the bypass channel, reducing the need for as much dredging upstream and slightly increasing erosion in the lower end of the bypass channel. This indicates a possible need for bank armoring, especially on the southern shoreline near RM 818, at the eastern end of the bypass channel. In genera

5.3 EXISTING CHANNEL, IMPROVING EXISTING STRUCTURES

The existing model results showed significant flows spilling from the main channel to the southern shallow overbank areas about two miles upstream of the confluence between the existing channel and the proposed bypass channel. This flow then re-enters the main channel immediately upstream of the confluence. A consideration is that this “loss” of flow might cause much of the sediment deposition in the main channel upstream of the confluence. Simulations were conducted to see if the altered placement along with the addition of several wingdam dikes could alter this circulation and maintain most of the flow in the main channel.

Two meshes were created based on the existing conditions model. In the first alternative (Structural Option A), additional wingdams were added just upstream of the study area, and existing wingdams in the same area were repositioned to better adjust the flow and reduce sediment deposition, as shown in Figure 5-4A. This was an attempt to discourage flow leaving the main channel upstream of the confluence. In the second case (Structural Option B), the changes in the first case were kept, and the structures on the south side of Boulanger Bend near RM 819 were reoriented and brought closer to the current navigation channel, as shown in Figure 5-4B.

One of the caveats of adding structures to the model is the mesh itself. We wanted to add more structures while preserving the existing mesh, so direct comparisons of different results could be made by subtracting one set of results from another based on a common horizontal grid. This meant that the planview areas of the wingdam dikes in the model are larger than they would otherwise be, and that the roughness is increased over a larger area. However, these added structures were intended to illustrate how additional and modified wingdam dikes might affect the velocity field, and therefore the associated deposition in the channel, and still represent, at the very least qualitatively, the overall changes which would occur.

The results from Option A are shown in Figure 5-5; the results for Option B, shown in Figure 5-6.

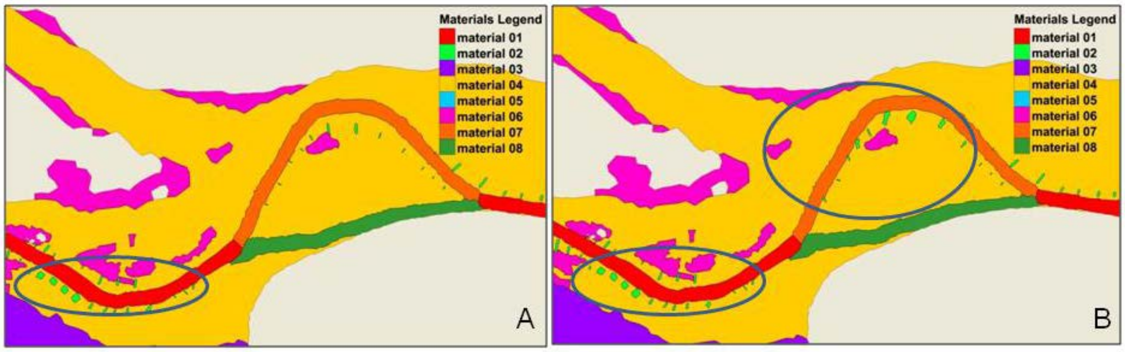

Figure 5-4 The two meshes used for the edited and added structures models. The circles indicate of the areas where the structures were edited or added, all of which were on the south side of the channel.

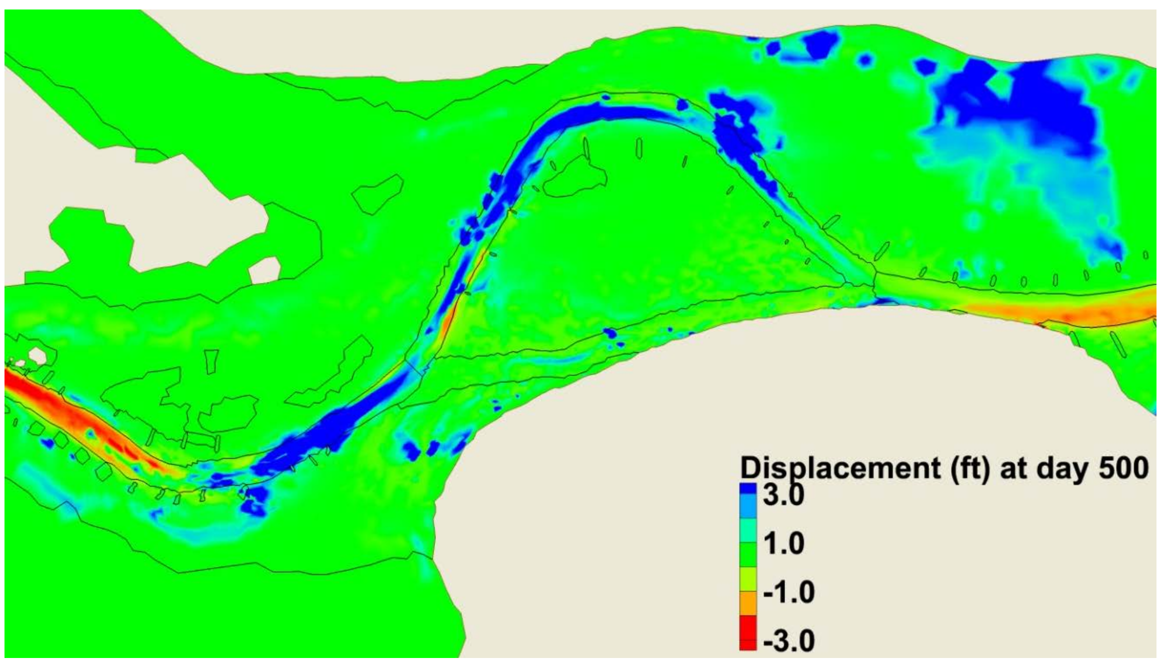

Figure 5-5 Results at day 500 for Structural Option A, corresponding to the mesh shown in Figure 5-4A.

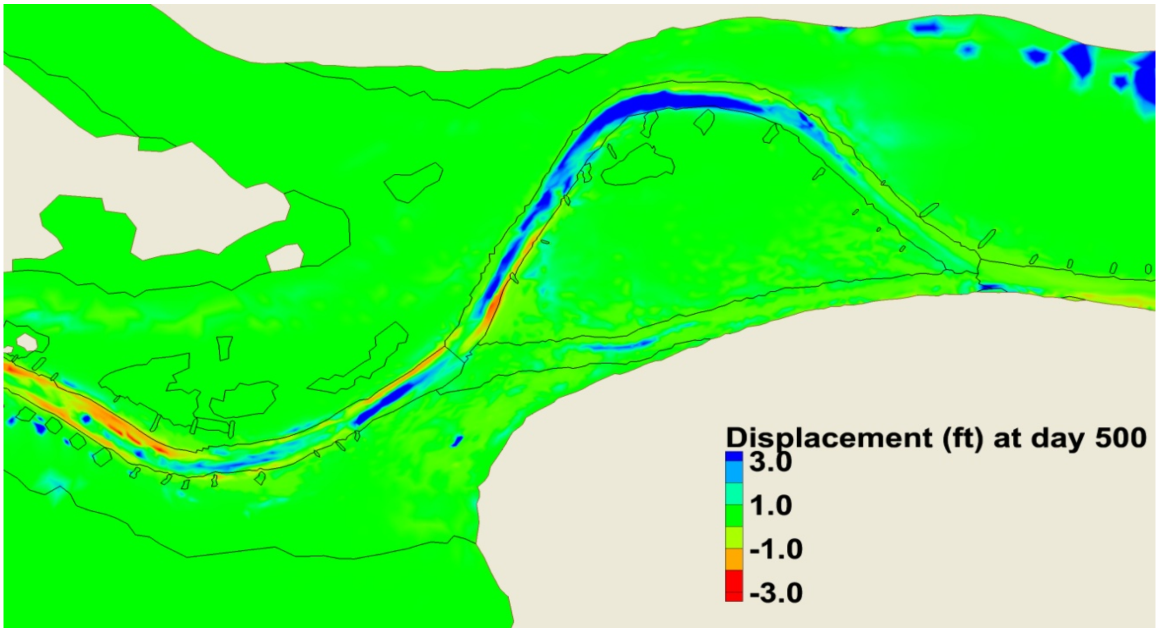

Figure 5-6 Results at day 500 for Structural Option B, corresponding to the mesh shown in Figure 5-4 B.

Figure 5-5 shows some suspicious results, indicated by the patchiness of the displacement over the model domain shown. On deeper investigation, the Option A model shows errors starting between days 150 and 200. Errors in the model persist from day 200 through day 500, with higher errors in the channel. For Structural Option A, this implies a situation where the model runs stably until a certain point, after which it becomes unstable but is still able to run to completion. The errors are propagated and affect results from that point on to the end of the run. However, when comparing the existing conditions model and Structural Option A for trends seen during the reliable time steps, the latter shows increased sediment deposition in the channel, though there is more erosion near the channel banks.

Structural Option B shows little error throughout the model run, and the results appear to be reliable. There is less deposition along the upstream section of the bend, but there is still significant deposition in the north portion. The dredging near RM 821, just before Boulanger Bend, could be discontinued, but dredging would still need to occur near RM 819.

5.4 DREDGING REQUIREMENTS

The model results for both the initial and established Boulanger Bend bypass channel options show that some dredging would still be required to maintain the proposed navigation channel. While the results show that sediment deposition would still occur upstream of the confluence, its distribution would be altered by the construction of the bypass channel. The results for the models with modified structures show a reduced need for dredging compared to the existing condition, in the same areas.

To calculate volumes of material to be dredged in the two Boulanger Bend bypass channel options, the width of dredging was assumed to be approximately 150 ft (50 m), and the length of required dredging would be approximately 5000 ft (1500 m), in the region of deposition from RM 821 through to 300 m after the entrance of the Boulanger Bend bypass channel. The length of dredging only covers the same region of deposition in both cases and does not include erosion in the bypass channel. The bypass location used for the dredging calculation is shown by the black line on the left hand side of Figure 5-7. The estimates for the initial and long-term required dredging in the area from RM 821 – 818 are shown in Table 5-1, along with the existing condition annual average dredging in the same region.

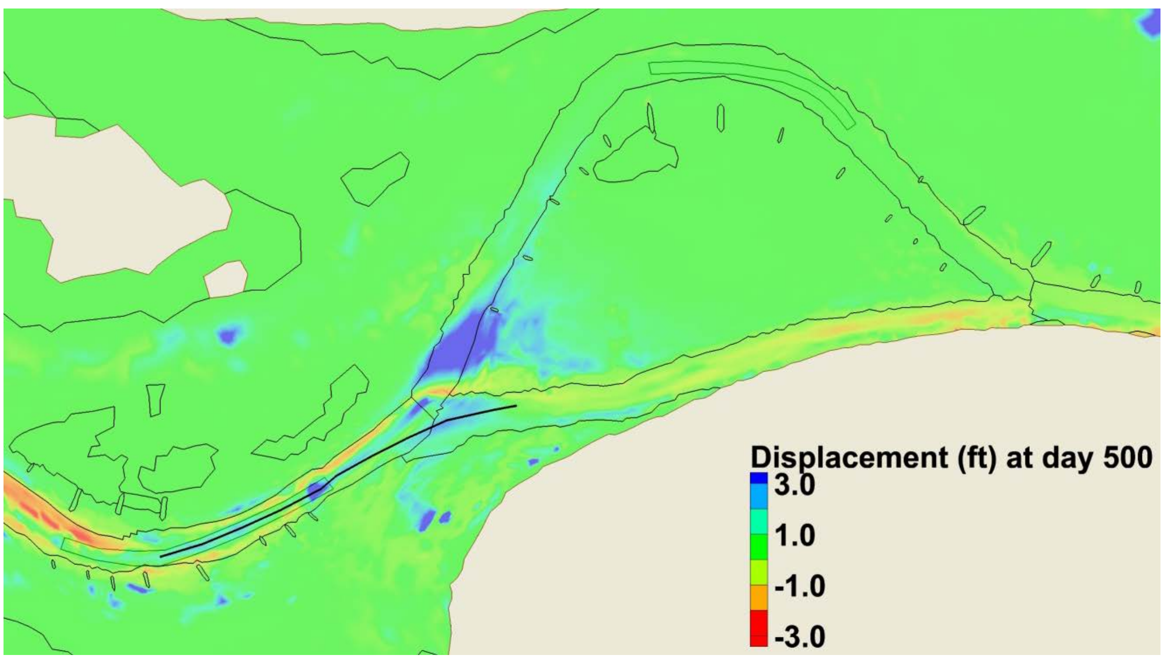

Figure 5-7 The established bypass channel deposition values at day 500. The black line towards the left hand side of the figure is the length of the area used to estimate maintenence dredging in our analysis. The two locations of the existing main channel dredging areas are shown in light gray outlines in the main channel; these were used to estimate existing dredging as well as dredging for Structural Option B.

To estimate the dredging required following structural changes in Structural Option B, the same two locations used to estimate dredging in the existing condition were used to determine the amount of dredging required in this case (see Figure 4-4, or the light gray outlines in Figure 5-7 above). Average bed displacement values for the two dredging regions, along with average widths and lengths of those regions were used to estimate the yearly volumes of sediment to be dredged. Table 5-1 shows only the results from Structural Option B, since Option A shows increased deposition compared to existing conditions,

For all the dredging estimates, the average yearly deposition over the 500-day (5-year) run for the appropriate region was used. The estimates also factor in the assumption that 75% of the yearly deposition is assumed to occur during each modeled 100-day year.

Table 5-1 Observed yearly dredging and estimated bypass dredging for changed structures and initial and long-term conditions, between RM 821 – 818. Initial dredging to create the Boulanger Bend bypass is neglected here.

Total yearly dredging amounts, in yd^3 between RM 821 - 818	Existing condition, observed dredging	Structural Option B, estimated	Initial dredging, proposed bypass, estimated	Long term proposed bypass, estimated
	31,900	17,300	13,700	9,300

If the proposed Boulanger Bend bypass channel option is pursued, dredging would decrease by over one-half of the existing amounts. As the existing navigation channel is abandoned and fills with sediment, the dredging required would decrease to roughly one third of current dredging amounts for RM 821-818. We estimate that it would take approximately 10 years for sediment to fill in the existing channel to the level we estimated for the long-term bypass condition, using the deposition values estimated from the initial conditions Boulanger Bend bypass model. The actual time will likely different, as hydraulic and sediment transport conditions change in the years after the establishment of the bypass channel.

Improving structures upstream of and along the Boulanger Bend would decrease the dredging requirement by about one-half; a marked improvement over existing conditions. However, a significant amount of work would be required to add to and change the existing structures, and the long term dredging amounts would be roughly twice the long term dredging required for the proposed bypass option.

The flows in the main channel and existing and proposed bypass channels for each of the models are shown in Table 5-2. The options with the most flow through the channel are for the Boulanger Bend bypass option. In fact, the percent of total flow is higher than the flow in the channel upstream, indicating that flows from Spring Lake are incorporated into the bypass channel. This might explain the increased erosion seen in the downstream part of the proposed bypass channel.

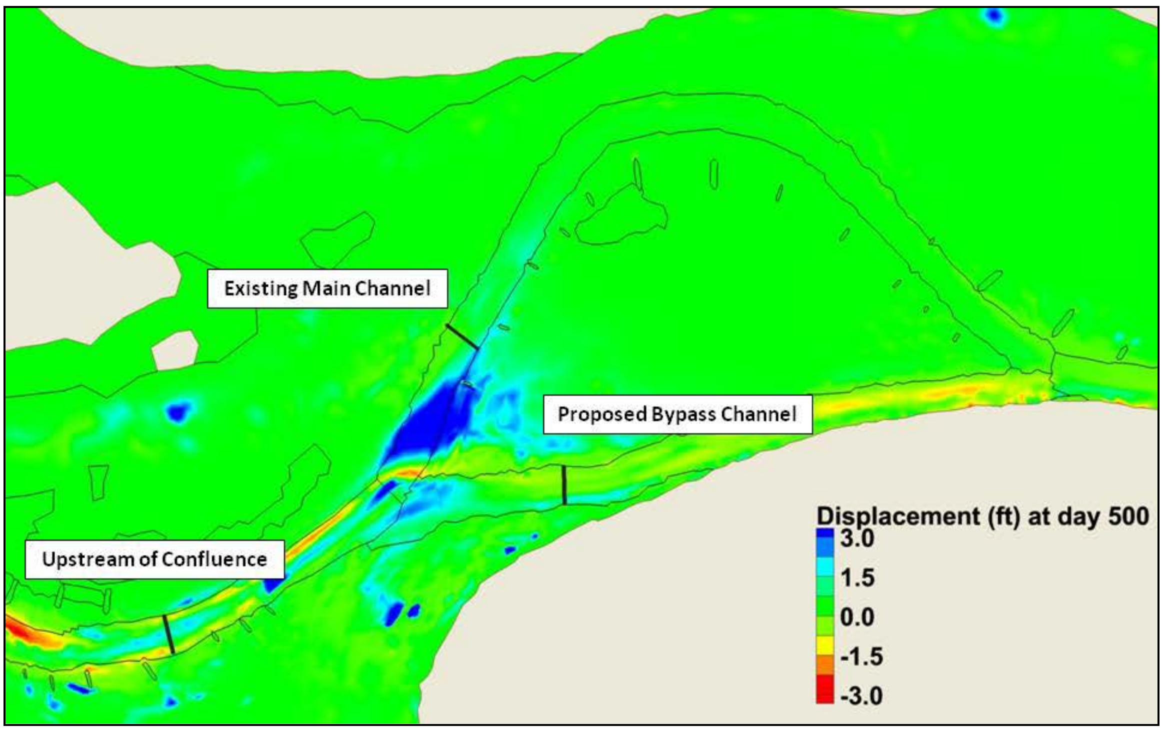

Figure 5-8 The thick black lines show the three locations listed in Table 5-2. The plot shows Boulanger Bend filled in long after the bypass channel is dredged.

Table 5-2 Percent of total flow (29 kcfs) at day 500 day in channels upstream and downstream of the confluence of the existing and proposed channels

	Existing conditions	Boulanger Bend bypass, initial	Bypass, established (old channel filled)	Structures Option A	Structures Option B
Upstream of confluence	35%	46%	39%	33%	38%
Proposed bypass channel	17%	31%	41%	16%	15%
Existing main channel	33%	23%	13%	28%	32%

Table 5-3 gives the modeled flows at day 500 for each of the split flow locations discussed in Section 2.6 (Hydrodynamic Calibration), at the locations shown in Figure 2-7. This table shows the flows calculated from the ADH model for the existing condition and the four alternatives. Overall, the flow splits do not have much impact due to changes near Boulanger Bend, and should not significantly change the existing conditions in these areas.

While the flows into Spring Lake may increase by about 50 percent (Table 5-3), these flows are still small compared to the total river flow, increasing from about 3.5 to 5 percent of the total flow. The majority of this increased flow is entering through the most upstream and most downstream inlets modeled. The model results suggest that there might be a corresponding increase in sediment deposition in Spring Lake as the higher velocities through the inlets decrease substantially in the lake's interior area. The circulation pattern in the eastern part of Spring Lake would remain very similar.

Table 5-3 ADH modeled split flows, given in cfs and as a percentage of total flow at Lock and Dam 2

At day 500, Q=29 kcfs										
	Existing Condition		Structure Option A		Structure Option B		Initial Bypass Option		Long-term Bypass Option	
827.6 Main Channel	20,500	**71%**	20,500	**71%**	21,000	**72%**	20,400	**70%**	22,000	**75%**
827.60 SW (1100')	4400	**15%**	4400	**15%**	4500	**16%**	3600	**12%**	4500	**16%**
823.30 S (2500') Main Inlet To Spring Lake, Site 1	750	**3%**	750	**3%**	1150	**4%**	1700	**6%**	1000	**3%**
823.20 S (900') Spring Lake Inlet, Site 2	23	**0%**	23	**0%**	35	**0%**	23	**0%**	23	**0%**
822.70 S (500') Spring Lake Inlet, Site 3	0	**0%**	0	**0%**	0	**0%**	0	**0%**	0	**0%**
821.80 S (1000') Spring Lake Inlet, Site 4	200	**1%**	200	**1%**	440	**0.2%**	370	**1%**	450	**2%**
824.90 E (1300') Baldwin Lake, Site 5	6200	**21%**	6200	**21%**	6300	**22%**	6400	**22%**	6300	**22%**
822.20 N (6500') Grey Cloud Channel, Site 6	0.1	**0%**	0.1	**0%**	0.1	**0%**	1.1	**0%**	0	**0%**

6 *Summary and Recommendations*

Hydrodynamic and sediment transport models were constructed using the Corps' model ADH for Pool 2 of the Mississippi River, to examine the feasibility of changing the main navigation channel in the Boulanger Bend reach, between river miles 818 and 820. One channel re-alignment, including both initial and established cases, and two modifications to the existing conditions in the area were considered:

a) The Boulanger Bend bypass channel, in which the existing curved channel would be abandoned and a new, straighter navigation channel created.

b) A long-term simulation of the proposed bypass channel, with the current existing channel filled in due to deposition.

c) Keeping the existing channel and improving and adding structures upstream of the bend.

d) Keeping the existing channel and improving and adding structures both upstream of and within the bend.

The model shows that the proposed Boulanger Bend bypass channel would be feasible for tows navigating the existing Boulanger Bend. After approximately 10 years, the amount of dredging would decrease to about one third of the current dredging required along the existing channel in the area of interest. While we would expect some deposition in the vicinity of the upstream end of the bypass channel, which would require maintenance dredging, most of the channel would be erosional. To protect against this, we recommend that bank protection be considered, especially along the southern shoreline.

Improving the structures upstream of and along Boulanger Bend, while keeping the existing channel, would decrease the volume needed to be dredged by up to a half. However, there would be substantial investment to change existing structures, and add new ones.

Over the long term, the by-pass channel seems to be the better option compared to improving and adding structures, as it shortens the navigation distance to Lock and Dam 2, and reduces dredging requirements once the existing Boulanger

Bend reach has filled with sediment. To “encourage” the flow to move towards the bypass channel, rather than remain in the existing Boulanger Bend and to deter erosion in the vicinity of the confluence, we recommend that a closure structure be considered to block off the old channel up to overbank elevations. In addition, as the model simulates some small amount of erosion towards the lower end of the proposed bypass channel, we recommend that either bank protection be considered as part of the bypass design, especially along the southern (right side viewed downstream), or that the bypass be monitored for erosion over the first decade of service and bank protection added as needed.

If the bypass option is constructed, we would anticipate about 50 percent more flow passing through Spring Lake, leading to more sediment deposition in the lake’s interior after passing through the inlets. We suggest that this be monitored and adaptively managed if it seems to significantly alter the lake’s morphology. The circulation in the eastern part of the lake would remain very similar.

6.1 MODELING DIFFICULTIES

Aside from the necessity of making some assumptions, such as not modeling cohesive sediments, and estimating appropriate model values, such as Manning’s n, bed composition and sediment inflows, there were two significant difficulties encountered in this study.

Long Run Times

We ran ADH using PCs that had either 32- or 64-bit core processors. The run-time for the hydrodynamic model was long but manageable--under a day to run a 100-day long simulation. However, the run time for the sediment model was very long on the computers available to us—approximately 10 days to run a 100-day sediment model. We had to ask the Corps/ERDC to submit the 500-day runs for us on government supercomputers. This was probably the biggest challenge, as it limited our ability to troubleshoot full 500-day models.

Estimated Eddy Viscosity Parameter

In one case (the initial bypass option), the errors were too large on the first attempted model run, and the model produced unstable results while still running to completion. The problems were eventually traced to an eddy viscosity parameter that had to be adjusted for the material in the mesh corresponding to the shallow overbanks. This was the only case where this parameter was adjusted, and it is unclear what impact this change would have on the other cases considered.

Adaption Parameters

The values for the mesh adaption feature had to be repeatedly changed during successive sediment model runs, in order to ensure all models ran to completion. The table below shows the MP SRT values (error tolerance for refinements) used in the final models for each option. In all cases, the MP ML parameter, defining the maximum number of refinements, was set at 2.

Table 6-1 Mesh adaption error tolerance values applied to the models

Model	MP SRT value
Existing Conditions	150
Boulanger Bend Bypass, initial	150
Boulanger Bend Bypass, long term	130
Changed structures, Option A	120
Changed structures, Option B	100

A sensitivity analysis was run on the hydrodynamic model to determine the effect of model mesh adaption on results**.** For example, for a steady flow of 84kcfs, there was an average difference of 0.5 inches in the flood profiles when using values of MP ML=4 and MP SRT=2000 (used in an example model provided during an ADH training class) versus card values of MP ML=1 and MP SRT=5 (used in the provided Missouri River model). We concluded that the mesh adaption parameters do not play a significant role in the results for this model; at least not in the hydrodynamic model.

But due to long run times, and assuming that the sediment module would behave similarly to the hydrodynamic model where adaption was concerned, no sensitivity analysis was run for the sediment models. However, during the course of attempting to run the full sediment models, they appeared to be quite sensitive to the error tolerance value given, enough so that some runs would not complete without modifying values.

Further guidance on determining the most appropriate adaption parameters would be very useful for those working on ADH models in the future.

7 *References*

Barr Engineering, "Two-Dimensional Hydraulic Model of the Grey Cloud Island Area: Nelson Mine Expansion Project – Hydraulic Analysis Memo of the Water Quality Study," November 2009.

USGS, Upper Midwest Environmental Science Center, http://www.umesc.usgs.gov/