Appendix D:

Hydrology and Hydraulics

Lower Pool 2 Channel Management Study:
Boulanger Bend to Lock and Dam No. 2

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Introduction

This document focuses on Lower Pool 2 of the Mississippi River and the sediment deposition problems in Boulanger and Freeborn Bends. Increased rates of deposition and frequent groundings in the Freeborn Bend area have been taking a high rate of dredging to maintain commercial navigation. Increased sediment from the Minnesota River, which has seen a great increase in discharge over the last decade, is expected to continue into the foreseeable future.

The following documentation focuses on the leading alternative that is being considered for the Lower Pool 2 Channel Management study. This alternative uses increased channel maintenance (an expanded channel size) and two river training structures to improve conditions for tow transport in the Boulanger and Freeborn Bends on the Mississippi River. This alternative is referred to as the increased channel maintenance with structures (ICMS) alternative.

Problem Discussion

Breakout flows

The channel at Freeborn Bend has been migrating downstream (Figure 1).   The figure shows the migration of of channel to the east (right). Channel margins use red to generalize the channel location in the 1940's prior to inundation and yellow to identify the current location. the east and west side of the meander between River Mile (RM) 819 and 820 have shifted east. Wing Dams are being lost. Revetment below river mile 819 has significant loss. This is allowing for a lot of breakout flow out of the channel. Flow is also lost to the south from Boulanger Bend into lower Spring Lake. The dredge cuts in Lower Pool 2 are shown in Figure 2. Yellow arrows indicate the breakout flow that removes water from the navigation channel.

Figure 1 COMPARISON OF EXISTING CHANNEL LOCATION WITH PRE-INUNDATION LOCATION (Red Boundary Identifies Pre-Inundation Channel, and Yellow Indicates the Current Location)

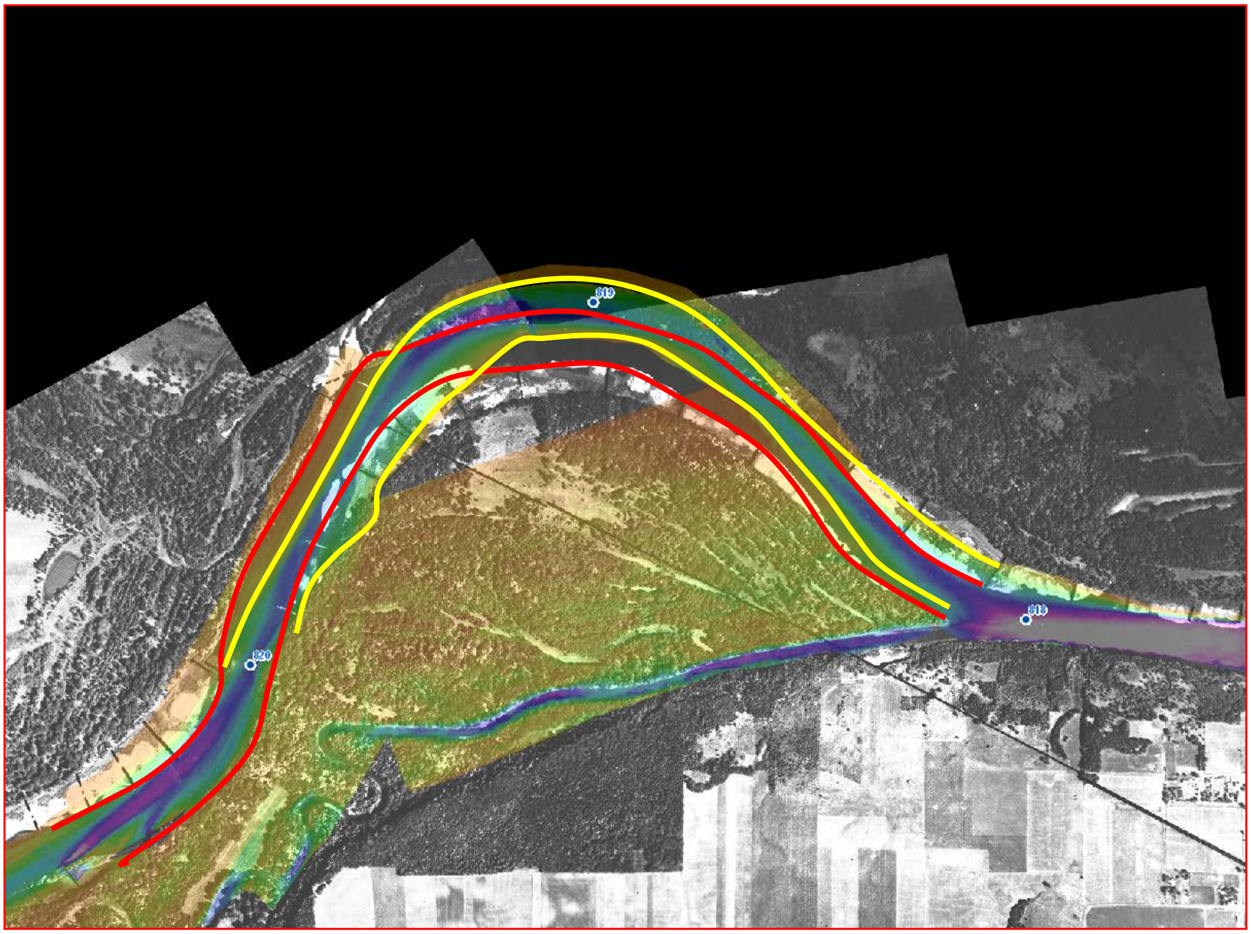
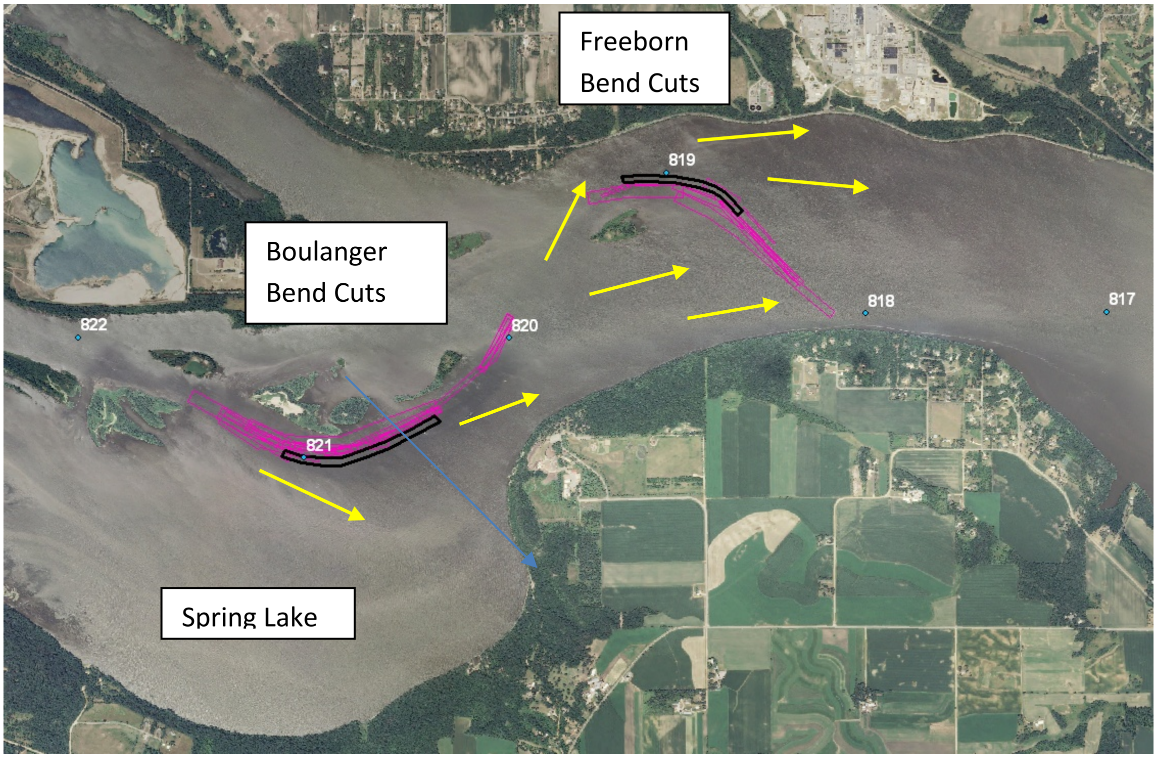


Figure 2 DREDGE CUTS IN LOWER POOL (breakout flows shown in yellow)



SEDIMENT

The district has had to spend a great deal of money maintaining Boulanger and Freeborn bends (RM 818 – 821). Historically this reach has been dredged about a 20-35% frequency; approximately once every three years. Since 2006 Freeborn and Boulanger bends have been dredged annually. In the last 6 years the district has done about 11 years' worth of dredging. The cause is a trend of higher discharges in both the Mississippi and Minnesota Rivers. A study was done looking at climate change and trends to river flows on the Mississippi and Minnesota Rivers. This document is attached as Appendix D1. The Mississippi River average annual discharge has risen about 40 percent at Saint Paul, and the Minnesota River has increased about 80 percent at Jordan Minnesota (comparing the periods 1946-1980 and 1981-2015). The Minnesota River is also the primary source of sediment to Pool 2.

Currently tows have difficulty navigating this reach because of the tight bends and narrow channel widths. Figure 3 shows the existing condition bathymetry through these bends. The white areas show depths that are over 13 feet. Groundings are generally located:

- In Boulanger Bend where shallow channel depths, narrow channel, and advancing point bar, all play a role in hindering navigation.

- The area around River Mile 820 sees groundings that are primarily related to a channel crossing and a point bar building out from the left bank.
- Freeborn Bend shows most groundings fall downstream from River Mile 819. Here a large concentration of groundings are related to the difficulty for tows to navigate the tight bend with shallowing depths, a significant outdraft to the east, and a very narrow channel near River Mile 818.5.

The radius of curvature of the Boulanger Bend is about 1900 feet and the Freeborn Bend is approximately 1700 feet which are some of the tightest bends in this part of the Mississippi River. Circles are shown in Figure 3 to point out the relative curvature in the navigation channel. This figure also shows yellow points along the channel that indicate the locations of groundings.

Figure 4 shows the grounding locations and the composite traces of tows as they move through these bends. The coloring of the trace layer indicates how commonly each location is passed over by tows. The red areas indicate the areas where many tows have crossed over many passings. These greener areas indicate where tows pass less frequently and tend to show where tows have been outside of the typical navigation path.

Figure 3 - Groundings and Bathymetry

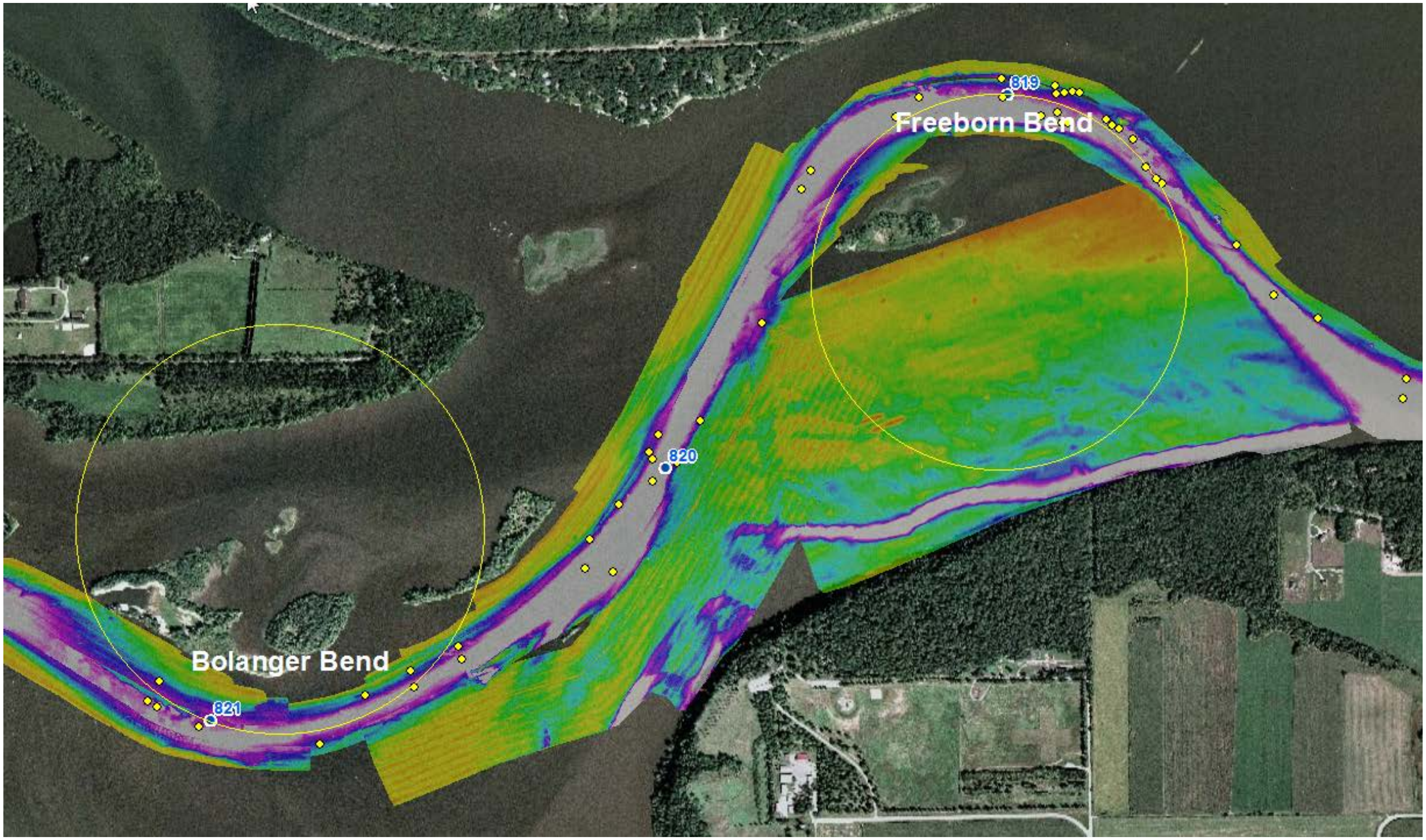
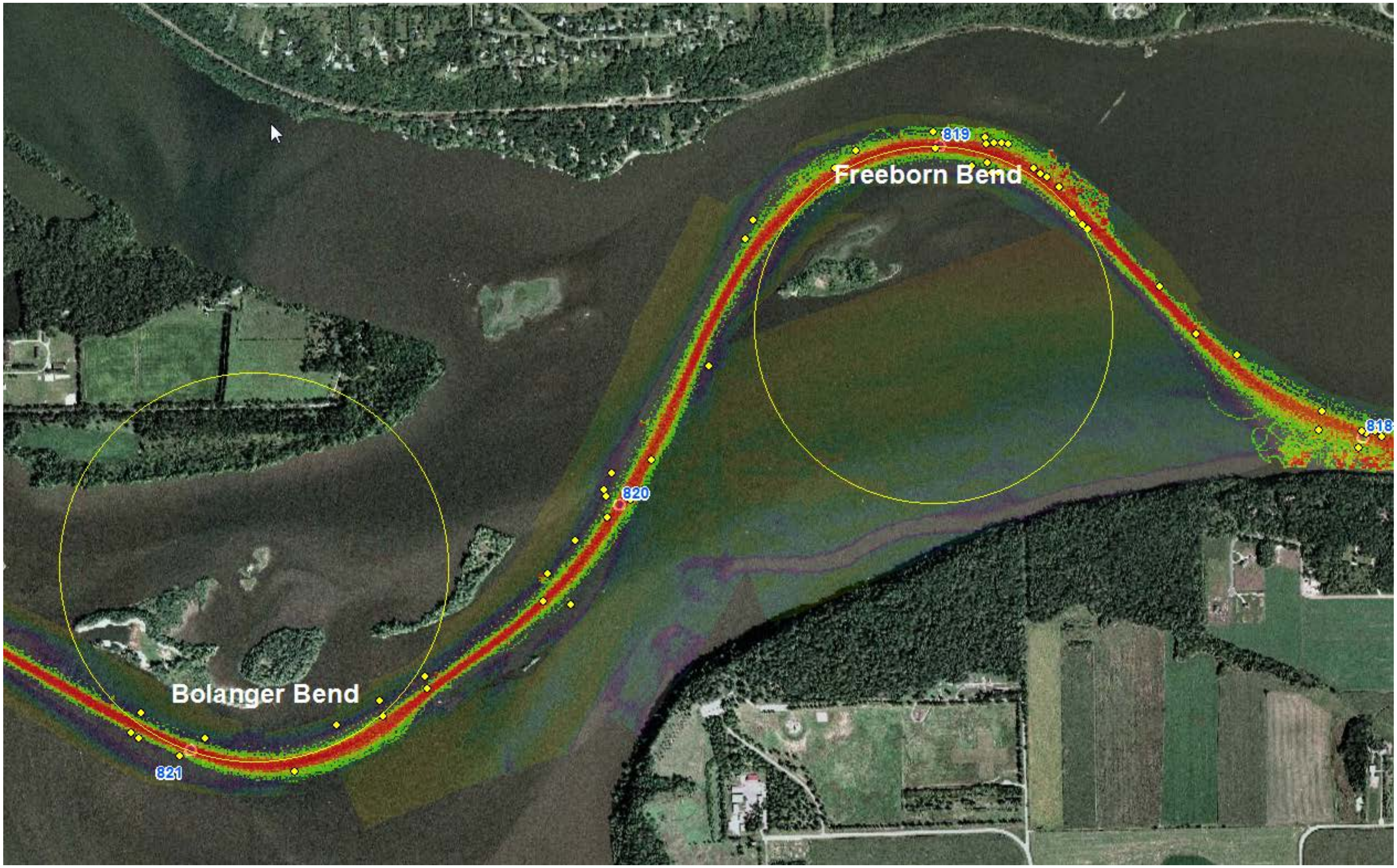


Figure 4 - Groundings and Tow Traces



The increased channel maintenance with training structures alternative is devised to address the problems of:

a. A very narrow channel. Restricts maneuverability of tows
b. Outdraft downstream of Freeborn Island.
c. Low velocity in the navigation channel.

The current channel is maintained to widths between 200 and 350 feet. The authorized and currently maintained channel width in different reaches is given below:

Table 1 Current and Authorized Dredging Width

River Mileage	Current Dredging Width
818.0-819.0	200'
819.0-820.5	300'
820.5-821.0	350'
River Mileage	Authorized Dredging Width
817.8-820.3	400'
820.3-821.5	500'

The primary problem in the Boulanger Bend area (RM 820.5-821.5) in addition to the tight bend is the point bar formation which encroaches into the channel. In the vicinity of RM 820, the curvature is not very severe but the outdraft of water leaving the channel to the east may affect navigation and make it more difficult for tows to keep off of the point bar (left side).

One of the problem areas runs from approximately RM 818 to 819. There is a combination of an outdraft problem (RM 818.7-819) on the tight bend, and a very narrow channel (RM 818.4-818.6). Many of the groundings are in this area, particularly in the vicinity of the outdraft. It is difficult for tows coming downstream around Freeborn Bend, having to turn tightly and hit the close entrance to the 200’ channel chute.

The narrowed channel (RM 818.4-818.6) restricts the flow and causes more of the water to pass as breakout flow from the channel. Velocity is not significantly increased in the narrow channel. The smaller channel width and common channel velocity reduce sediment transport capacity.

Navigation is especially difficult when there is a significant outdraft upstream of this chute. The narrow 200 foot width of the navigation channel (RM 818.4-818.6) , combined with the reduced discharge and velocity, adversely affects the ability of the river to move sediment through this reach. The navigation channel can move sediment to this reach but has difficulty moving it further as flow is blead from the channel. As a result, incoming sediment accumulates in the navigation channel upstream of this area.

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PRELIMINARY STUDIES

Two studies were done prior to or concurrent to this latest analysis. The first study was done prior to this latest analysis by WEST Engineering and resulted in the "Mississippi River (Pool 2) 2-D ADH Model Development" report. The U. S. Army Engineer Research and Development Center (ERDC) also completed a letter-report entitled "Pool 2 Numerical Modeling". This report was done mid-way through this analysis. Both documents are supplied as addendums to this appendix.

WEST ENGINEERING STUDY

The study done by WEST Engineering produced an ADH hydrodynamic/sediment model and investigated the effects of an initial set of alternatives. The WEST document describes the ADH model construction, alternatives, and sediment results. Alternatives included the raising of sets of existing wing dams and an initial investigation of the Boulanger channel excavation alternative. The study concluded that raising existing wing dams would not have a significant effect on dredging. They also indicated that an early version of the channel excavation alternative should work. Unfortunately the modeled version of the channel was much wider than we are authorized to construct in Pool 2 (200 foot). This study is attached as an Addendum D-1.

ERDC - SHEAR STRESS AND ROUSE ANALYSIS

The ERDC study was conducted mid-way through the current analysis. ERDC used the hydrodynamic portions of the ADH model (without sediment) to produce bed shear stress and Rouse Number for several alternatives. Shear stress was used to indicate if the representative grain size of 0.44 mm will be mobilized at various discharges. The Rouse Number was used to identify if mobilized sand would be moved in suspension or as bed load.

The study looked at four alternatives:

a. 1A – Navigation Control Structures – Revetments/Islands to reduce breakout flows. Lowered crest elevation to 0.3 feet compared to original studied that was 1.3 feet above low control pool.
b. 1B – Reduced extent of revetment/islands in alternative 1A.
c. 2A – Excavation of Channel across Freeborn Bend
d. 2B – Excavation of Channel across Freeborn Bend with one channel submerged rock sill.

The river discharges used in this study have been supplied in Table 2.

Table 2 River Discharge Conditions used in ERDC Study

Condition	Discharge	Comment
Low – 75% Duration	5,970 cfs	(Little sediment moving in system)
Medium- 25% Duration	20,560 cfs	(Project should pass sediment)
High – 2 Year Flood	43,000 cfs	(Project should pass sediment)
100 Year Flood	150,000 cfs	(latest FIS) for stage comparison between Existing and Alternative

The study identified that both alternatives 1A and 1B produced unacceptable stages increases. Alternative 2A and 2B would improve the transport ability of the navigation channel through Freeborn Bend but would not be able to meet the allowable stage increase criteria of 0.005 feet.

Both alternatives 2A and 2B showed good Rouse numbers in the lower three quarters of the channel cut. The channel dimensions of the channel cut for Alternatives 2A and 2B are the same as the currently proposed channel. The representative grain size of 0.44mm would be transported in the Rouse Number ranges for suspended transport through most of the channel. The addition of the submerged rock sill on the original navigation channel downstream of the new channel inlet helped some. There was a significant drop in velocity in the upper end of the channel. Further modifications would have to be made to address the velocity and sedimentation concerns in the upper end of the channel cut. It should be specially noted that this analysis only looked at the ability of the channel to move a particular grain size. It does not make conclusions about the routing of sediment to predict erosion or deposition. Documentation of this letter report may be found in Addendum D-2.

Subsequent ADH Modeling

Following WEST Engineering's and ERDC's modeling efforts, further modeling was done using a slightly revised version of the original model. The general procedure was to use hydrodynamic steady state modeling to identify alternative alignments and to investigate velocity magnitude and direction to provide a reasonable assurance that sediment problems would not be associated with the final design. As noted in the above section, additional features needed to be added to improve velocity characteristics in the upper part of any new channel alternative. The modified alternative was then modeled using the sedimentation routines in ADH as a final check for problem areas.

ADH Steady State Hydrodynamic Modeling of Alternatives

The ADH modeling from WEST Engineering was given some minor modifications for hydrodynamic runs and for sedimentation analysis.

Primary changes to WEST ADH Model

-A shallow water area at lower end of Spring Lake. Aerial photos and field investigation of this area showed a significant shallow water area separating lower Spring Lake and the navigation channel. The original model showed this area as having fairly deep water.

-Reduce height of right side wing dams (River Mile 820.5 to 821)

-Reduced height of a high area near dam just above the dam

-Running newer version of ADH (Version 4.3) for all but the 1 percent exceedance runs (used Version 3.1.3). The 1 percent exceedance runs using Version 4.3 were oscillating too much within the micro ranges to give reasonable stage increase values to thousandths of feet.

-Time step used for **sedimentation** runs was increased to 0.5 days from the 1 day value used in the WEST model. Quasi-steady state modeling uses the 0.5 day time step.

The revised existing condition and project condition ADH models were used for steady state hydrodynamic investigation of the effect of various alternatives on velocity, and for determining stage impacts on the 1 percent exceedance flood.

The same discharges used in the ERDC study were used in the steady state modeling. These discharges are identified below:

- The 75-percent duration exceedance discharge represents low flow conditions typically found in the winter or late summer. A value of 5970 cfs was used for this study.
- The 25-percent duration exceedance discharge is above average but just below the discharge range where significant sediment transport begins. Channel maintenance surveys usually cease when flows exceed the 25-percent exceedance value. A value of 20560 cfs was used for this study.
- The 50-percent peak annual exceedance frequency discharge (2-year) represents a high flow (or bankfull) condition. It is a good surrogate for the discharges that are exceeded 1% to 20% of the time, when significant sediment transport occurs. A value of 43,000 cfs was used for this study.
- The 1-percent peak annual exceedance frequency discharge (150,000 cfs) was used to identify flood stage impacts for use by the Minnesota DNR in their role of managing the National Flood Insurance Program.

ADH Modeling for the Increased Channel Maintenance Alternative Analysis

Most of the documentation on ADH and the basic model parameters are found in the following appendices and addendums:

a) West Report
b) ERDC Document
c) COE Addendum

These documents contain the initial construction of the existing condition model and modeling parameter assumptions and methodologies. This document is specifically written to describe the Increased Channel Maintenance with training structures (ICMS) Alternative.

Discharges

This alternative was studied using the same discharges and boundary conditions that were used in the previous analysis. The 60,000 cfs was added to better understand the effects the project would for discharges that overtop the islands. This discharge should be seen as supplemental to the other four study discharges. Discharges run are displayed in **Error! Reference source not found.**.

Table 3 Final Discharges used in Study

Condition	Discharge
Low – 75% Duration	5,970 cfs
Medium- 25% Duration	20,560 cfs
High – 2 Year Flood	43,000 cfs
Intermediate	60,000 cfs
100 Year Flood	150,000 cfs

Updates to the Existing Conditions ADH Model

The existing conditions model required a few adjustments from the previous modeling effort. With the focus shifting to the areas around Freeborn Bend, it became evident that the original existing conditions model was showing a couple of areas of deeper water that should have much shallower water. Two areas were modified in the existing conditions ADH model. One such area was the shallow areas on the north side of the navigation channel downstream of Freeborn Island. This area is part of a submerged island that separates the main channel from Nininger Slough. Surveys and aerial photos were used to estimate depths of this shallow submerged island/shoal and the model was adjusted accordingly.

Aerial photos also indicated shallow shoals and sand flats on the downstream side (east) of Freeborn Island. These areas had been modeled too deeply in the original modeling. This refined existing conditions model would be the base with which the project conditions modeling would be compared.

Modeling Leading to the Proposed ICMS Alternative

The training structures had been roughly modeled and analyzed in the WEST report. That study investigated a simple alternative of elevating wing dams to effect better scouring of the navigation channel.

The district is typically constrained by Minnesota Department of Natural Resources and other agency constraints on wing dam construction. Typically wing dam crests must not be higher than four feet below low control pool elevation so as not to cause a hazard to recreational boats. Aesthetics are also an important consideration along the river. There are few wing dams that are much higher than low control pool in the Saint Paul District.

A more effective means of using training structures to maintain higher velocity in the navigation channel was to restrict these breakout flows. The training structure alternative used islands build along the right bank in upper Freeborn Bend and the left bank downstream of Freeborn Bend. The islands were modeled to be about 0.4 feet above low control pool elevation. This does not give a lot of elevation above the low control pool elevation. This was necessary to meet the stage impact limits. This should be acceptable due to the pool drawdown at Dam 2 in Lower Pool 2. The stage at Dam 2 is reduced from 687.2 at low flow to 686.5 (1912 MSL) at 12,000 cfs and held there until 65,000 cfs where the pool is allowed to rise. The islands should remain emergent for most of the low and moderate flows

The image in the Figure 5 shows the alignments of these features. Allowable stage increases must be below 0.005 feet to satisfy the Minnesota DNR’s floodplain regulations for construction within a floodway.

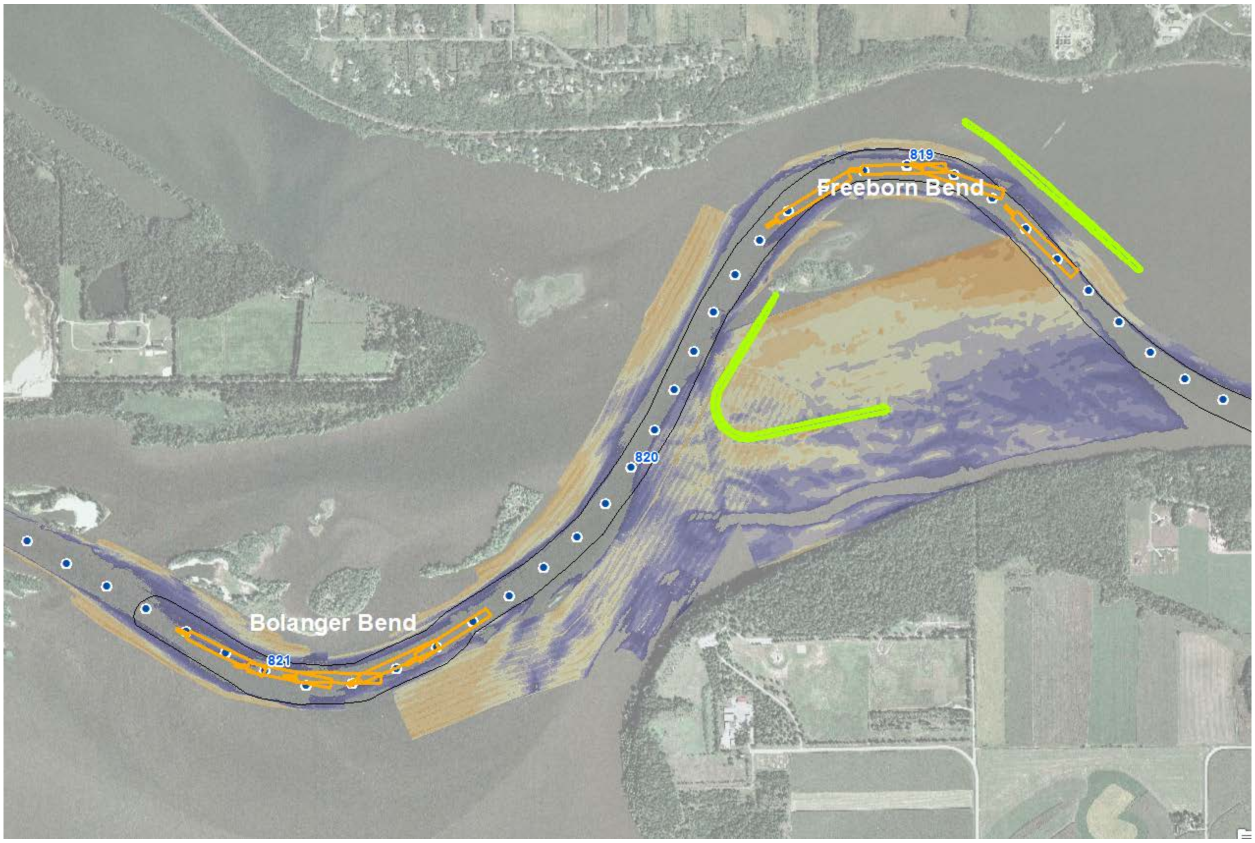


Figure 5 Channel Control Structures (in green)

The Increased Channel Maintenance with Structures (ICMS) Alternative is the culmination of many preliminary versions. It was originally studied with only the channel excavation. This alternative investigation started with only channel excavation. The maintained channel widths are:

ICM dredging dimensions

818.0-820.5 - 350'

820.5-821.0 - 450'

The existing conditions model was updated to show the effect of dredging in the enlarged maintenance zone. Regions of the channel that were within this zone and were higher than 12 feet below low control pool (LCP) were lowered to the 12 foot depth (the 12 foot depth below LCP is roughly an elevation of 674.6 feet, 1912 MSL).

The enlarged channel, without other additional features, dropped the velocity in many parts of the channel particularly in the northern part of Freeborn Bend. By adding a combination of islands/rock sills it was possible to keep the channel velocity up and also address the breakout conditions upstream and downstream of Freeborn Island. Two islands were added to the design. The island to the east primarily blocks breakout flows from the navigation channel near RM 818.75. The other island extends upstream from the existing Freeborn Island in a 'horseshoe' shape. Figure 6 shows these features along with the increased channel maintenance zone.

Various alignments and shapes were tried in an attempt to develop an option that would a) keep velocities at least as high as existing conditions within the navigation channel, b) reduce dredging volume, and c) reduce breakout flow and improve maneuverability of tows.

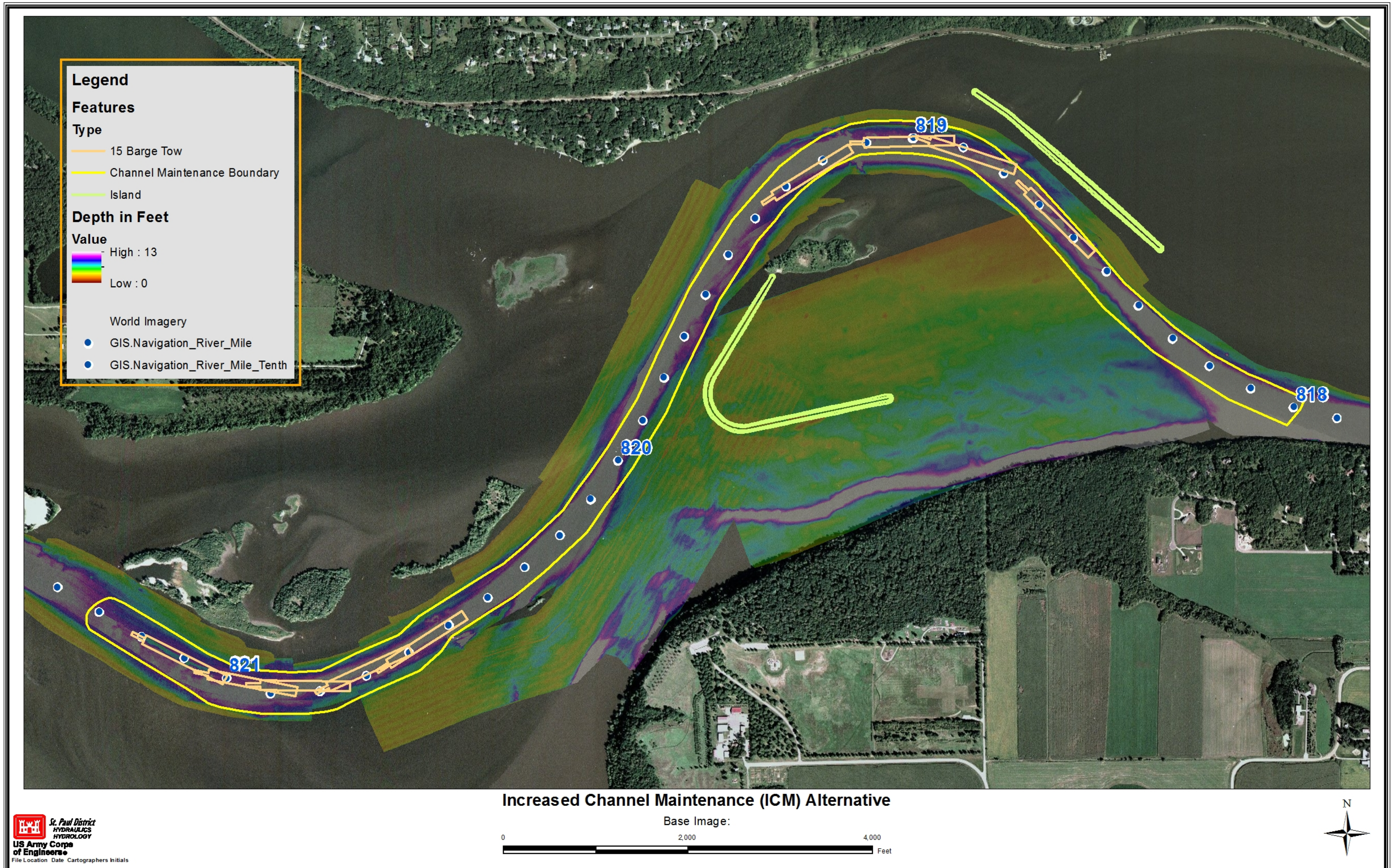
The island east of Freeborn Island generally parallels the navigation channel an blocks the breakout flows, keeping much of the channel discharge in the navigation channel and improving the vector direction by maintaining the same direction as the navigation channel. Unfortunately, the imposition of the island in this lake-like location causes a further reduction of discharge and velocity in the navigation channel north of Freeborn Island, causing more flow to pass east before it reaches Freeborn Island.

With the incorporation of the two island features, the modeled velocity in Freeborn Bend was still lower than desired. Prior to the 'horseshoe' shaped design of the south island, a linear island, parallel to the navigation channel, was modeled to reduce breakout flows upstream of Freeborn Island. This option had some effect, however, flow from the navigation channel would continue to breakout further upstream and fill the area of conveyance south of the existing Freeborn Island, resulting in velocities in the channel that were still too low. By adding the eastward running portion of the island, it was possible to limit conveyance in the sheltered area during most low and moderate flow conditions with the island not being overtopped. The benefit of limiting conveyance through this region is that the navigation channel and other areas will accumulate additional discharge that is no longer flowing across this submerged bend. The result is that the widened channel along with both islands reduces dredging volume, reduces breakout flow problems, and keeps navigation channel velocities higher. These components together form the Increased Channel Maintenance (ICM) Alternative.

Islands were modeled with top-widths of approximately 40 feet. The material type designation in the ADH model for the islands was set to riprap because the roughness values for riprap are similar to either rock or an un-vegetated island. The material type designation for riprap also is setup in the sediment ADH models to prevent erosion in the sediment analysis to keep the islands from eroding in the modeling.

A close eye was kept on the impacts to the 1 percent (100 year) flood profile throughout the consideration of features for this alternative. Stage increases higher than 0.005 feet were unacceptable to the Minnesota Department of Natural Resources in their administration of federal flood plain regulations related to the floodway designation. Combinations of project features were balanced in order to keep stage impacts within the acceptable range.

Figure 6 - Features of Increased Channel Maintenance with Structures (ICMS) Alternative



Flood Stage Impacts

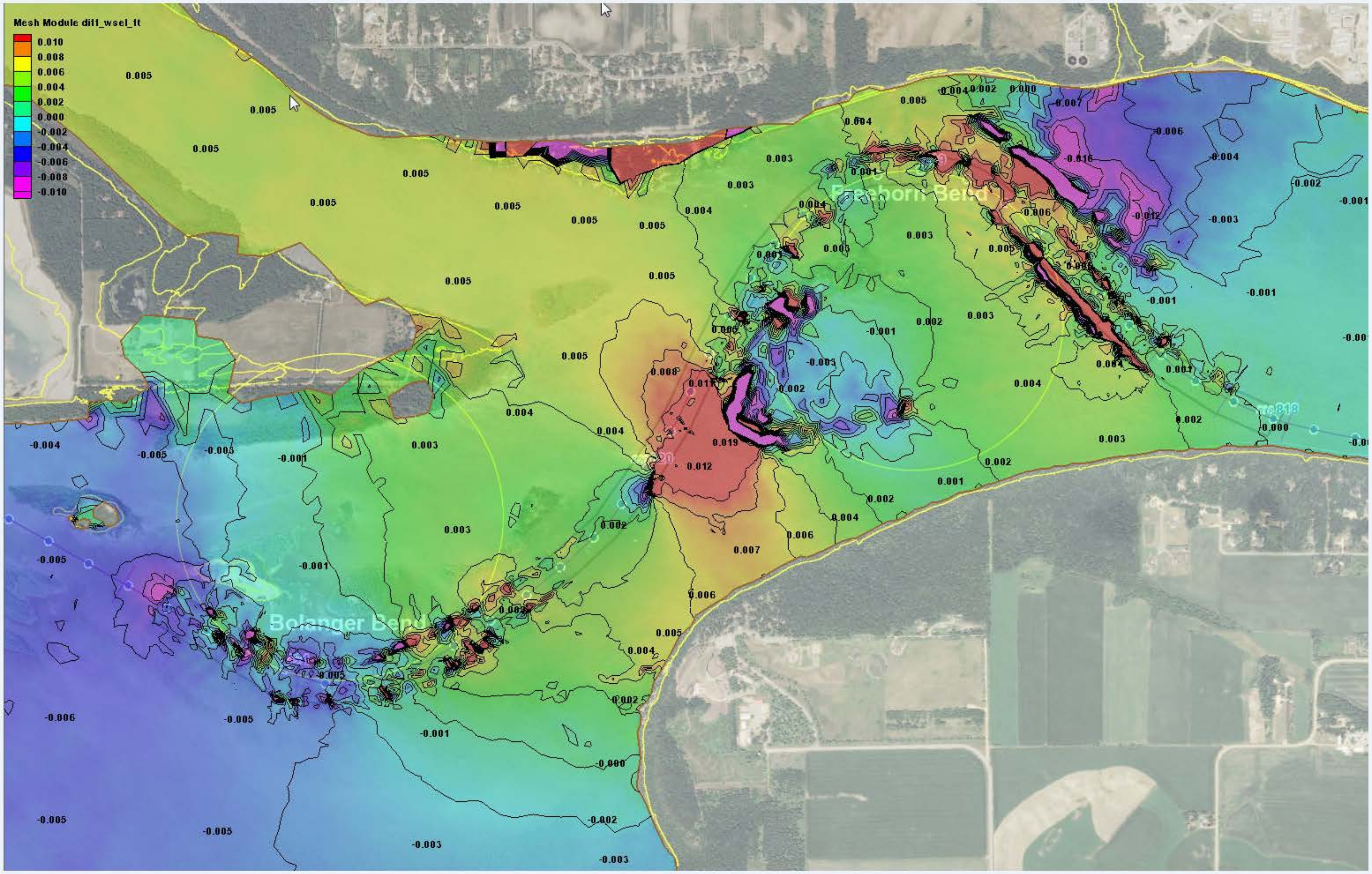
The stage impacts were computed for the 100 year flood with ADH in the same manner as was done for the previously studied alternatives. The alternative is a combination of channel excavation which lowers flood stages and the island construction which tends to increase stages.

The following figure (Figure 7) shows the changes in flood stage due to the project. Water surface elevations were computed for both the revised existing condition model and the IFC Alternative model. These elevations were compared and the figure displays the impacts. Stage impacts of 0.005 feet are present along the north shore of Pool 2 near the downstream end of the Grey Cloud Channel. The structures to the north and west of Freeborn Island and riverward of the railroad should not have 1 percent ACE (100 Year) stages increase more than 0.005 feet.

The structures below Schaar's Bluff on the south side of the pool at the downstream end of Spring Lake should see stage increases between 0.002 and 0.004 feet.

A stage reduction of 0.005 feet (-0.005 feet shown in Figure 7) is seen upstream of the project limits in the navigation channel and in Spring Lake.

Figure 7 - Predicted 1 Percent ACE Stage Increases



Velocity Vectors and Navigation

Figure 8 through Figure 17 show velocity magnitude and vectors for the five discharge conditions. The figures alternate between existing and the IFC conditions. The orange lines identify the locations of the proposed islands and are shown in the figures for existing conditions as well a project conditions in order reference the locations. Inspection of the figures can show how the breakout flows are contained, particularly east of Freeborn Island, and how the orientations of the directional flow vectors are altered by the project. The color contour shading shows how velocity compares between existing and project conditions. In general, channel velocities are higher in the in the navigation channel for project conditions.

Figure 10 through Figure 13 show the velocity results for the 25% Duration and the 2 Year discharge conditions. These are probably the most useful ones to use to see the effects on the navigation channel. Comparing Figure 10 and

Figure 11 shows how velocity and vector directional data would be changed by the alternative.

Figure 8 shows how existing condition velocities drop as flow leaves the channel towards the east as the channel starts the turn to the southeast after passing the Freeborn Island. The figure also shows how flow leaves the navigation channel upstream of the proposed ‘horseshoe’ shaped island, bypasses the meander, utilizes the area of conveyance south of Freeborn Island.

Inspection of Figure 12 shows the same discharge condition as Figure 8, but with the alternative project features in place. The reader should note the reduction in flow out of the navigation channel (east of Freeborn Island). Also of note should be the low velocity area protected from current by Freeborn Island and the proposed ‘horseshoe’ island. Velocities are increased significantly in the navigation channel below Freeborn Island. Outdraft to the east occurs further downstream in the bend, and occurs along the next bend which is wider and deeper (RM 18.0-18.2).

Figure 20 through Figure 24 give the percent increase in velocity at tenth of a river mile along the sailing line of the existing navigation channel. Again, the figures for the 43,000 and 20,560 cfs are probably the most useful from a channel maintenance perspective. The following list describes some of the project effects:

- Velocities drop about 10 percent in the southern portion of Boulanger Bend primarily due to the enlarged channel in this area.
- There is a 2 to 5 percent reduction between Boulanger Bend and the tip of the ‘horseshoe’ island.
- The velocities begin to increase downstream of the upstream tip of the ‘horseshoe’ island.
- Velocities rise about 10 to 15 percent along the ‘horseshoe’ and Freeborn Island.
- There is a small area near RM 818.8-818.9 where velocities are about the same as in existing conditions.
- From RM 818.3 to RM 18.7 the channel velocities increase by about 25 to 30 percent.

- At the downstream end of the bends (RM 818.0) the velocity is about 10 percent higher than with existing conditions. This increase quickly dissipates downstream as more of the flow gradually drifts out of the navigation channel to the north.
- There is increased velocity to about 3 feet per second along the north shoreline northeast of Freeborn Island. This shoreline consists of a riprapped railroad embankment and should not be adversely affected by the increased velocities. The bathymetry along this reach will be included in the monitoring plan. Mitigation to protect the railroad may be necessary if significant deepening of the lake bed occurs along the shoreline. This is not expected.
- Small increases in velocity are also seen along the southern shoreline. This shoreline is a talus slope from the eroding limestone bluff that extends along this entire reach. The increase in velocity should not adversely affect the stability of this shoreline.
- Some of the percent increases in discharge outside of the channel should be considered in conjunction with the often low velocity under existing conditions.

Figure 8 - Velocity at 5970 cfs - Existing Conditions (Velocities shown are in meters/second)

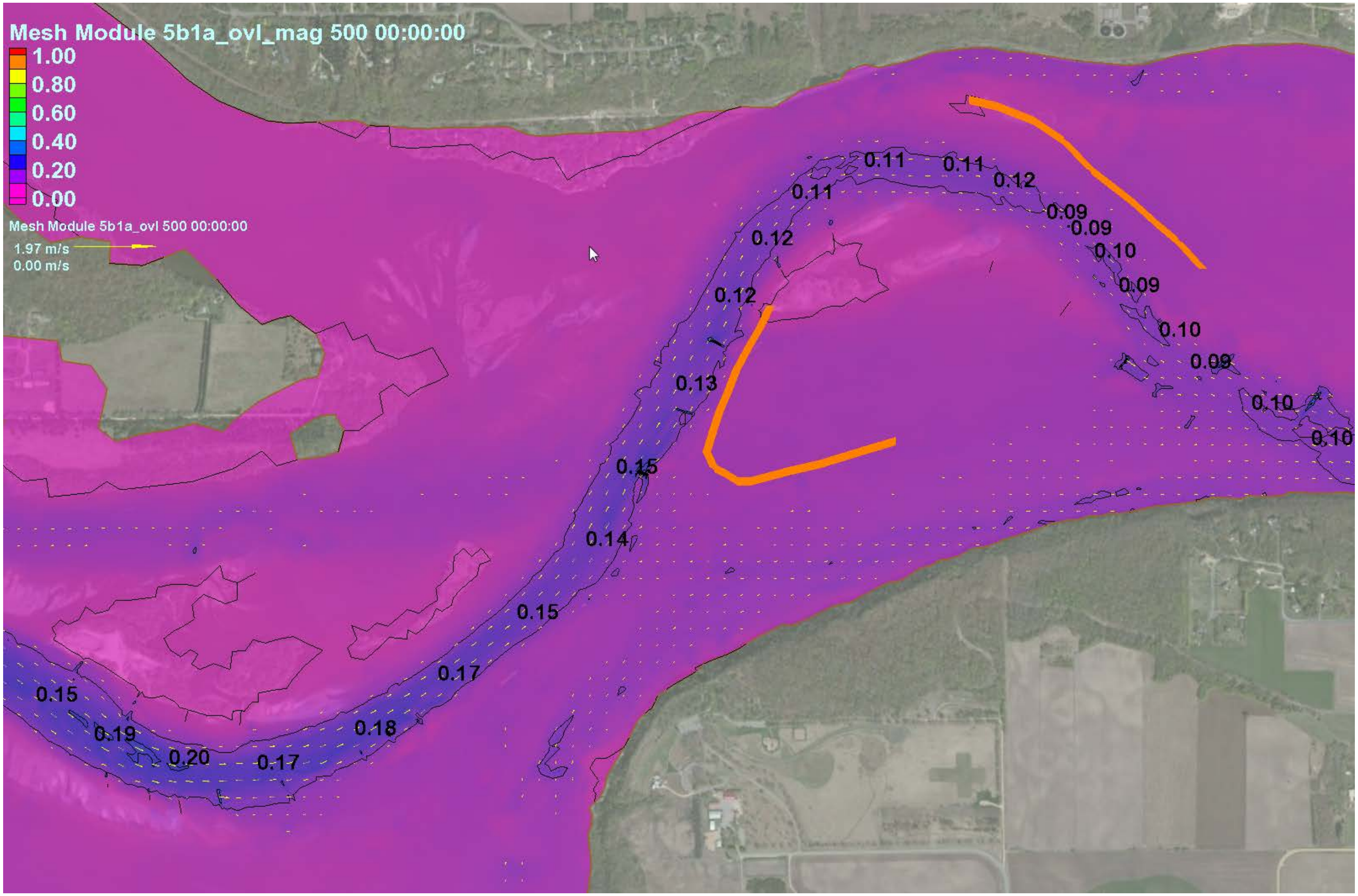


Figure 9 - Velocity at 5970 cfs - Project Conditions (Velocities shown are in meters/second)

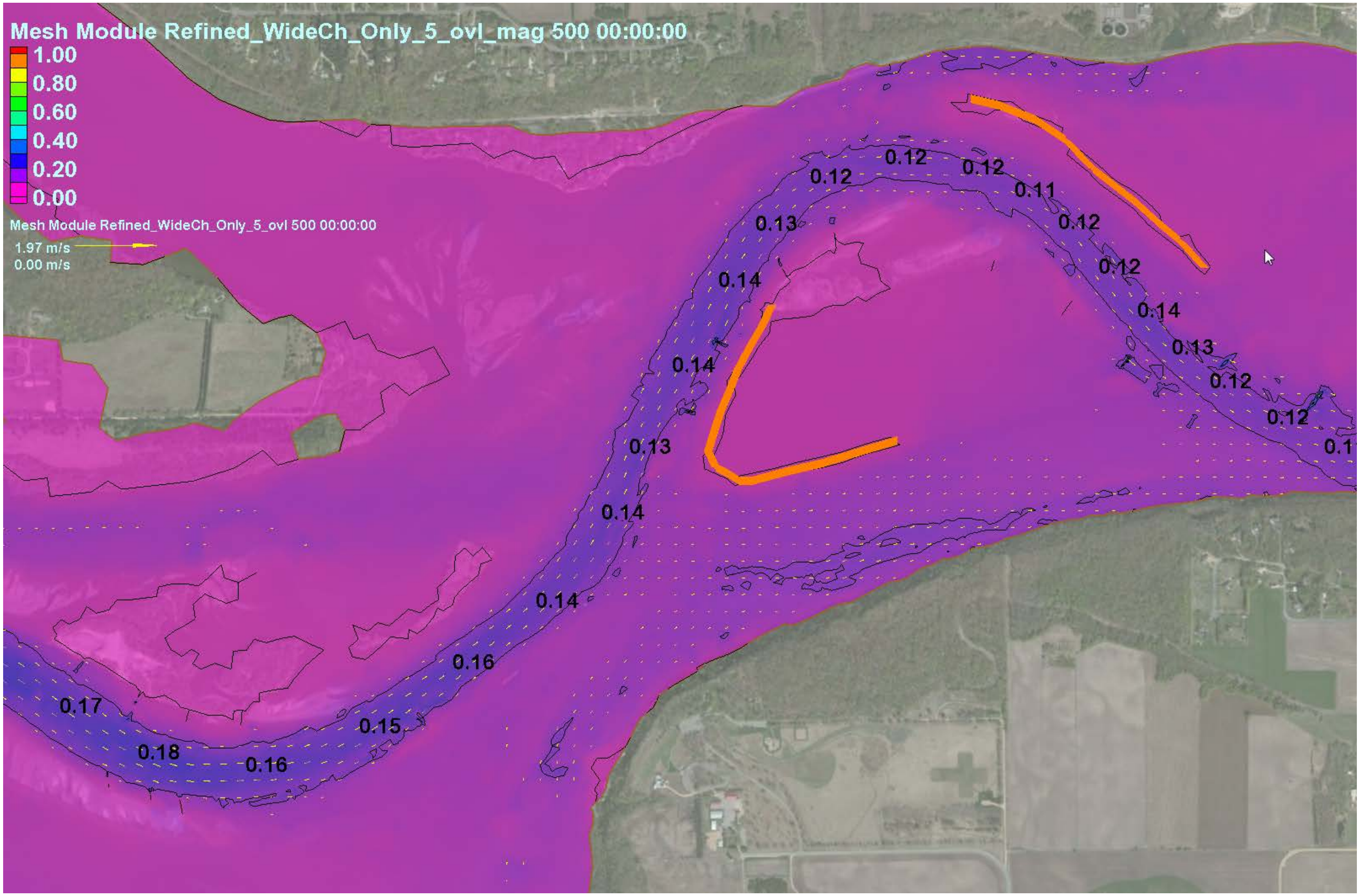


Figure 10 - Velocity at 20,560 cfs - Existing Conditions (Velocities shown are in meters/second)

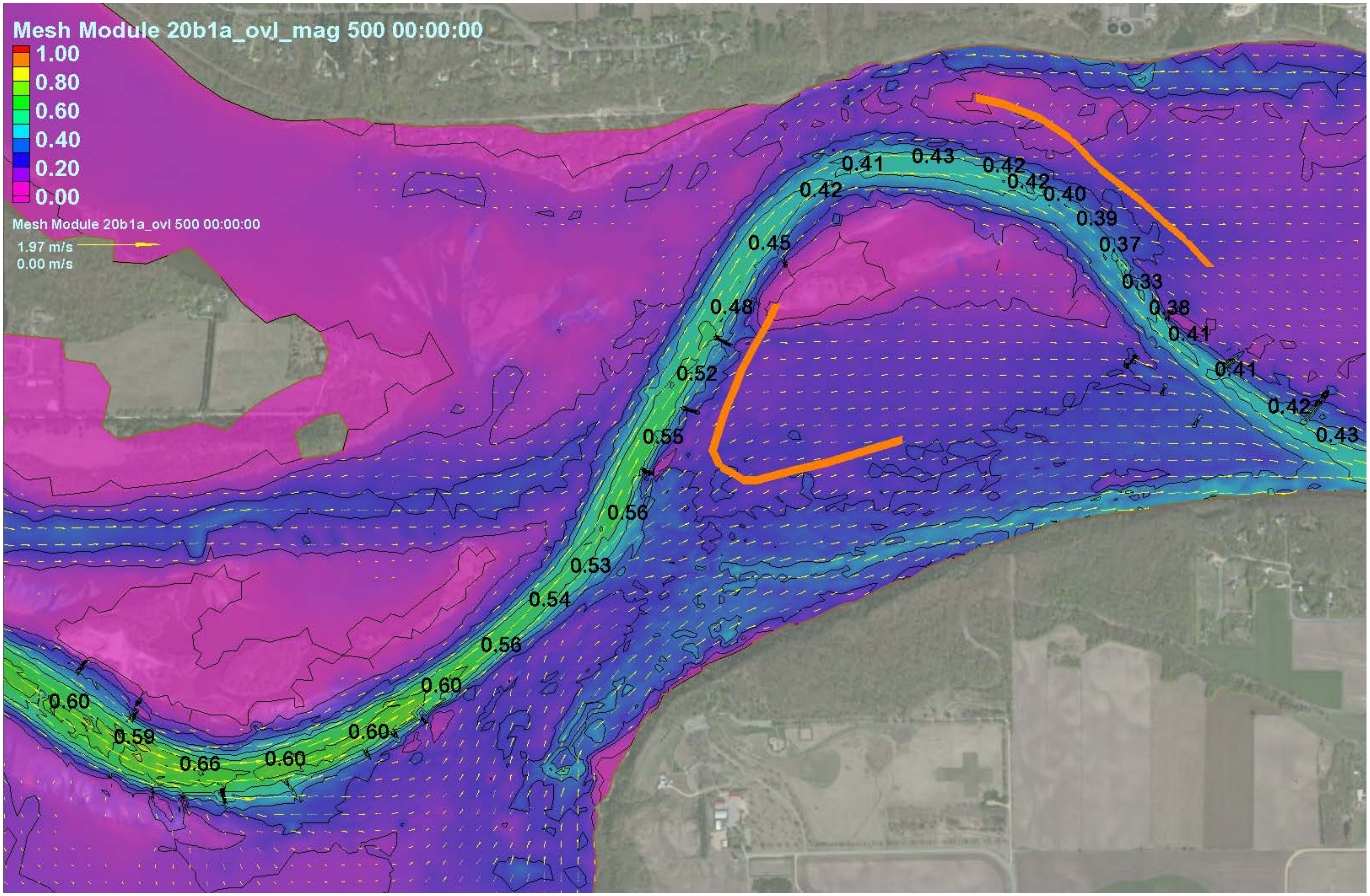


Figure 11 - Velocity at 20,560 cfs - Project Conditions (Velocities shown are in meters/second)

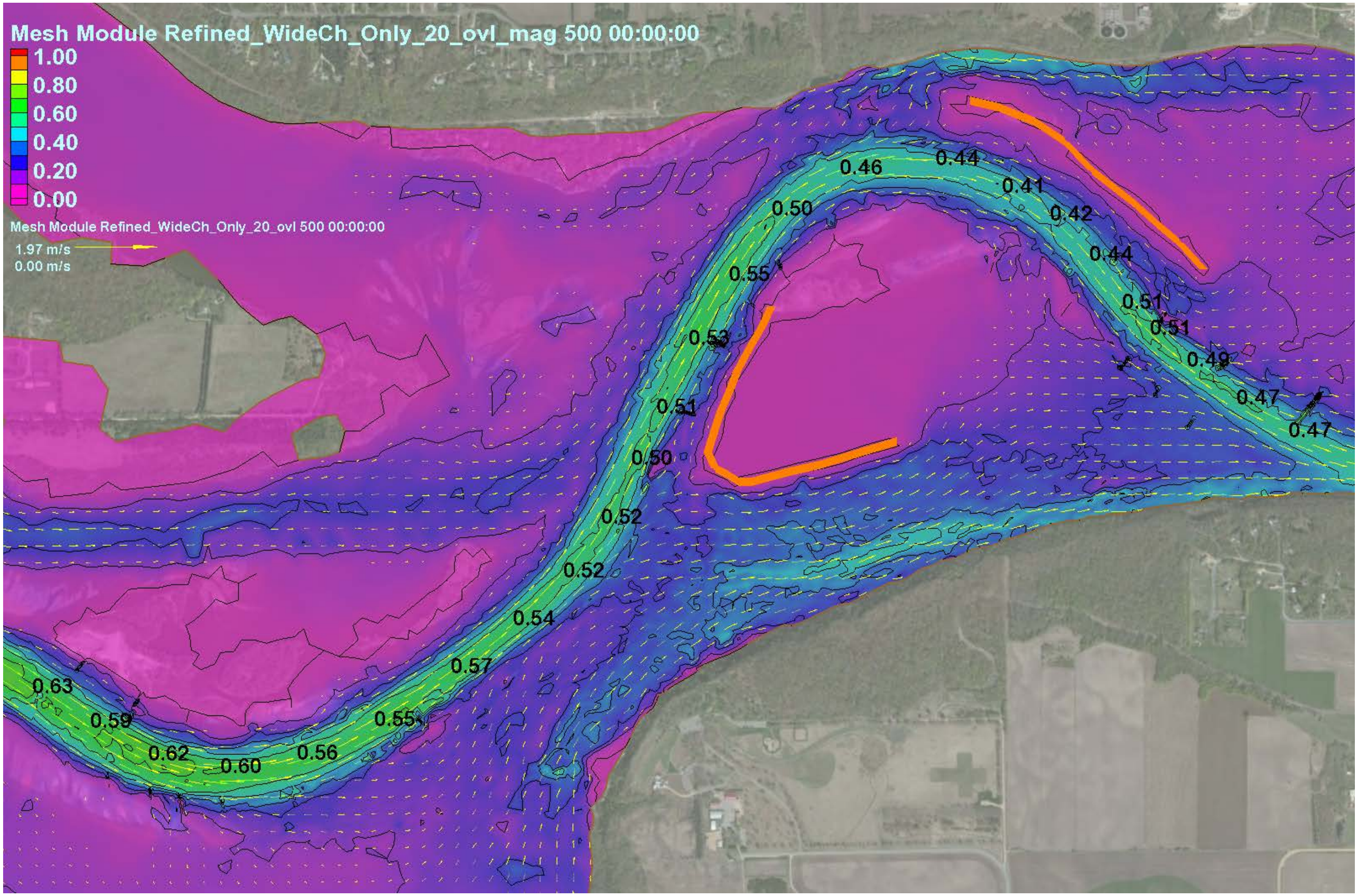


Figure 12 - Velocity at 43,000 cfs - Existing Conditions (Velocities shown are in meters/second)

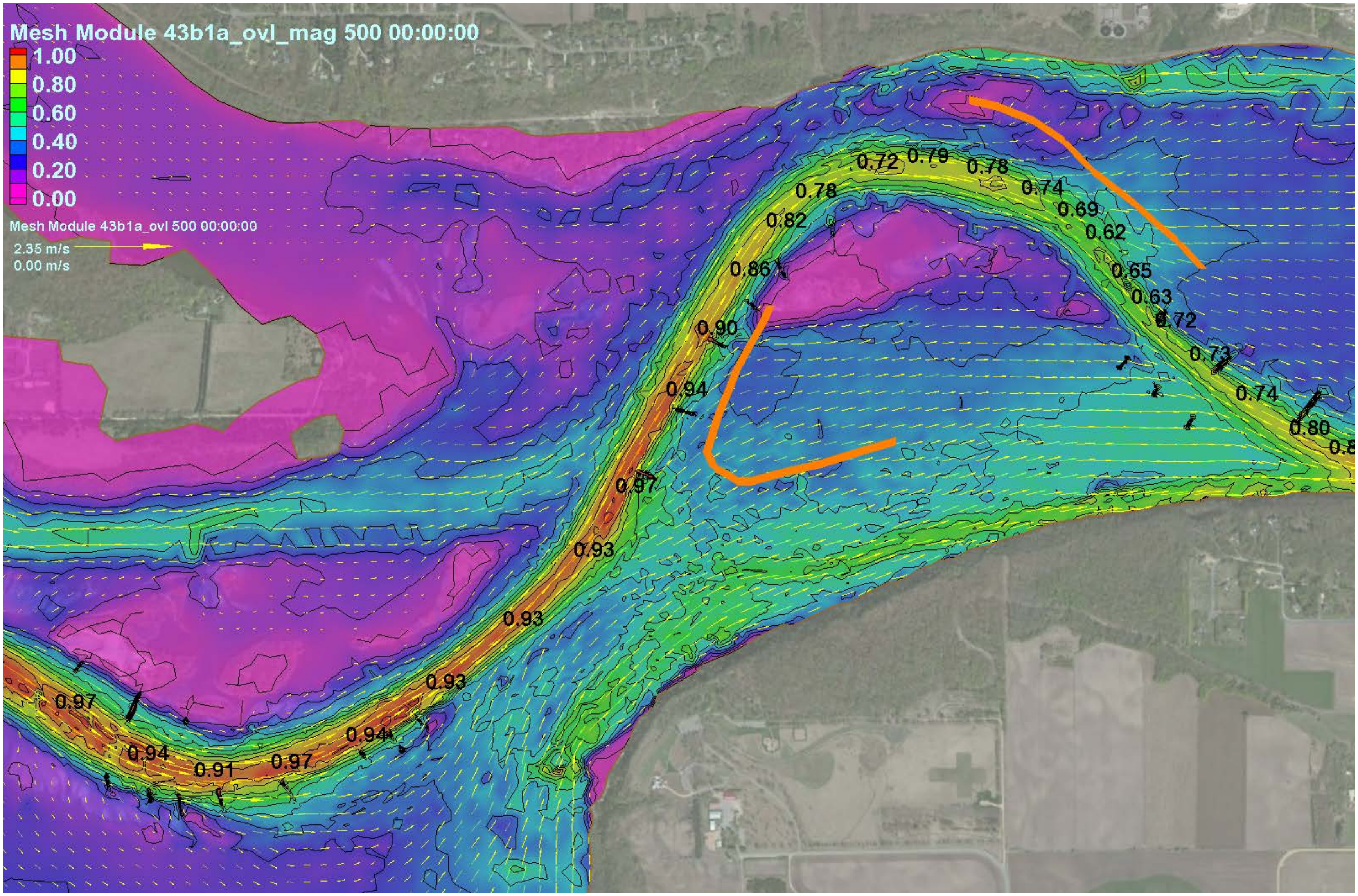


Figure 13 - Velocity at 43,000 cfs - Project Conditions (Velocities shown are in meters/second)

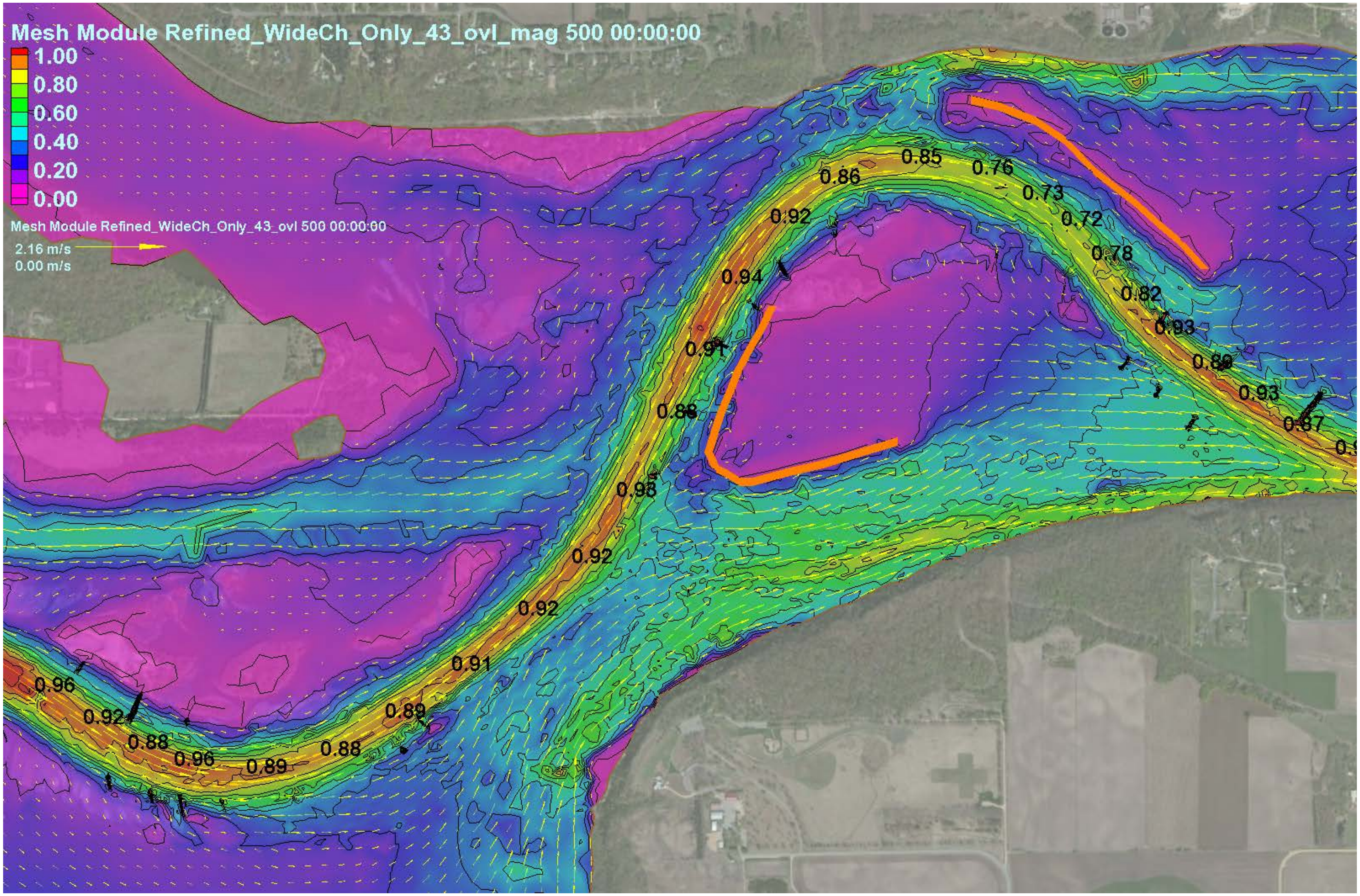


Figure 14 - Velocity at 60,000 cfs - Existing Conditions (Velocities shown are in meters/second)

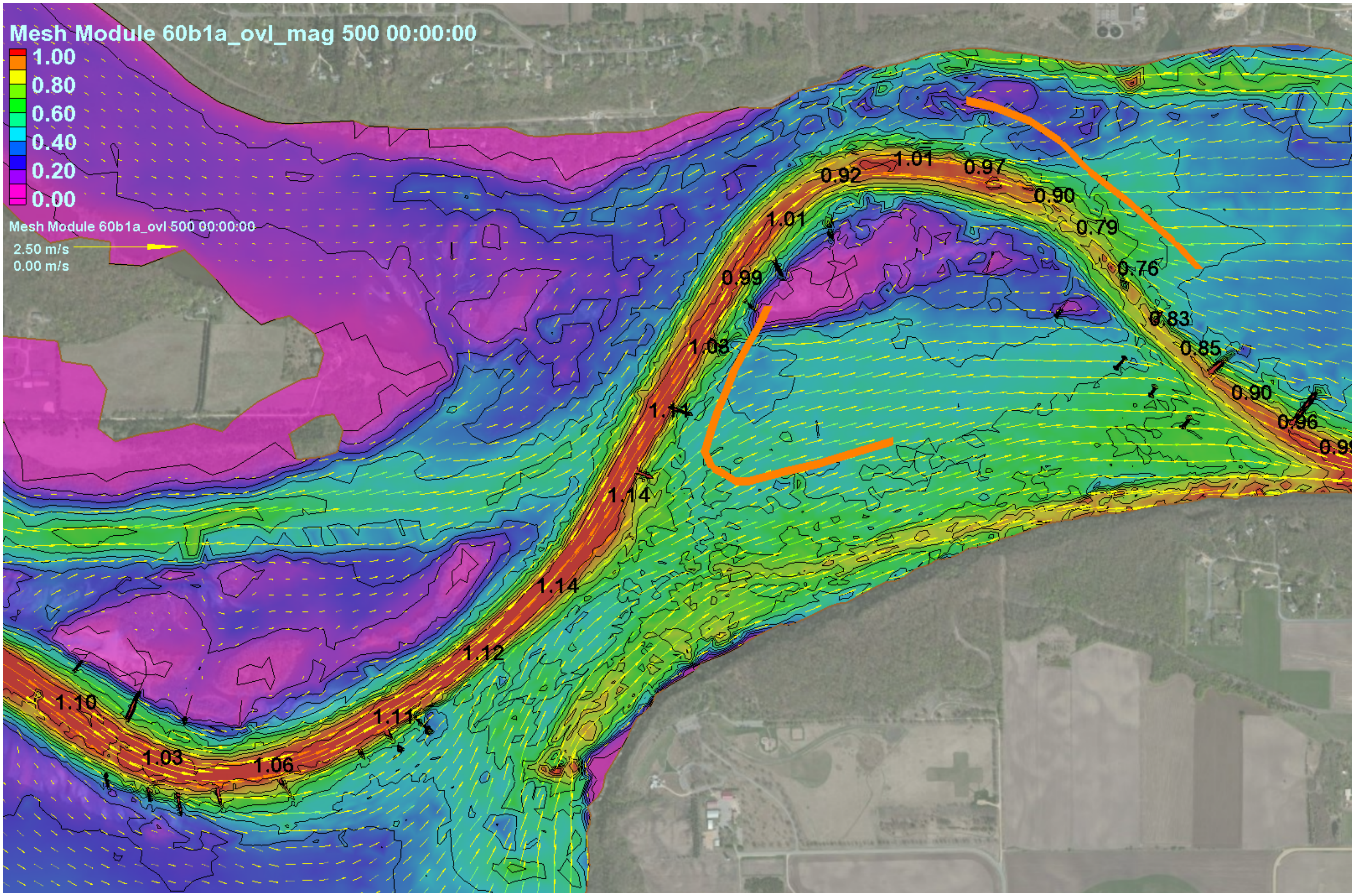


Figure 15 - Velocity at 60,000 cfs - Project Conditions (Velocities shown are in meters/second)

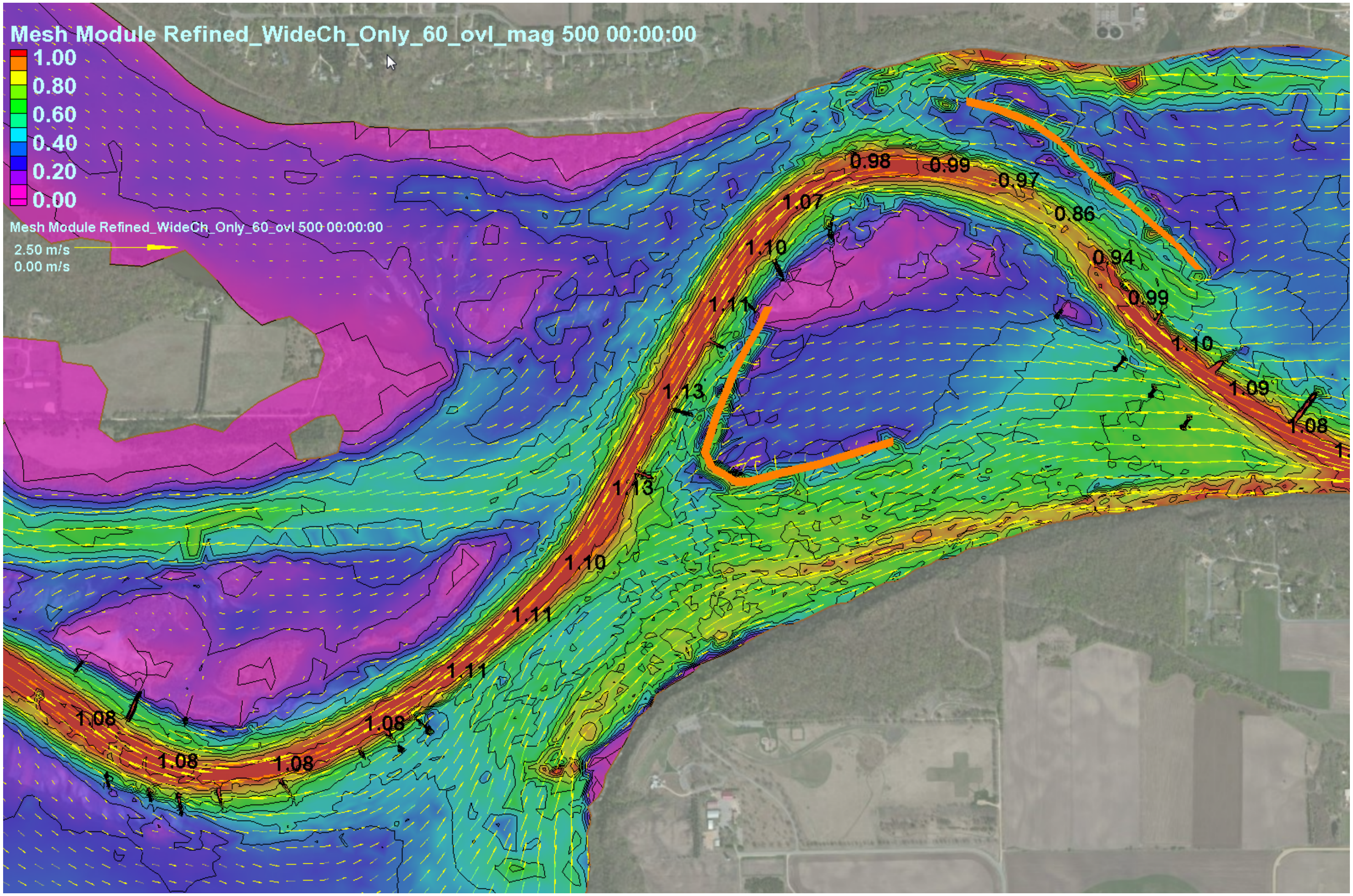


Figure 16 - Velocity at 150,000 cfs - Existing Conditions (Velocities shown are in meters/second)

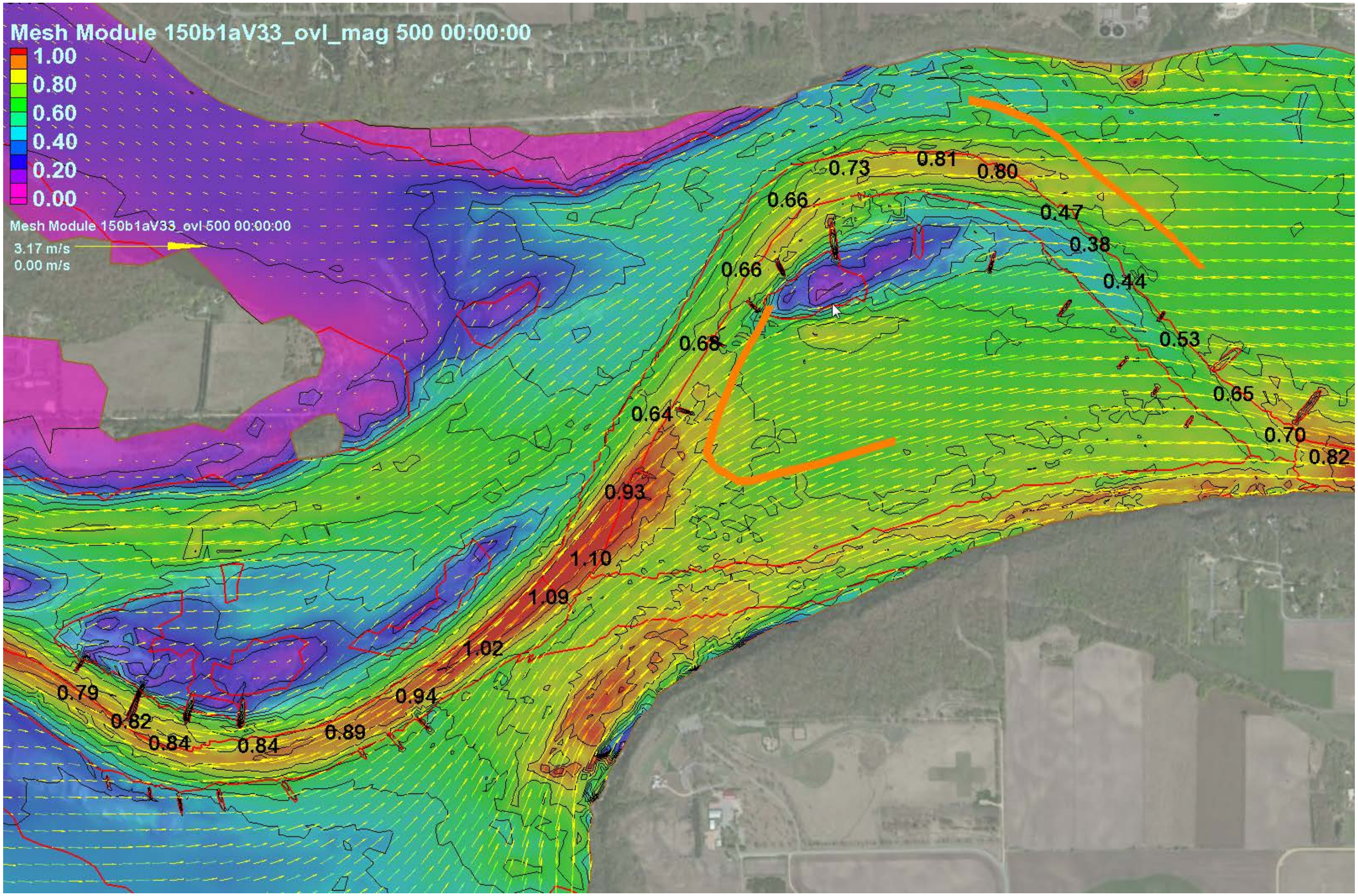


Figure 17- Velocity at 150,000 cfs - Project Conditions (Velocities shown are in meters/second)

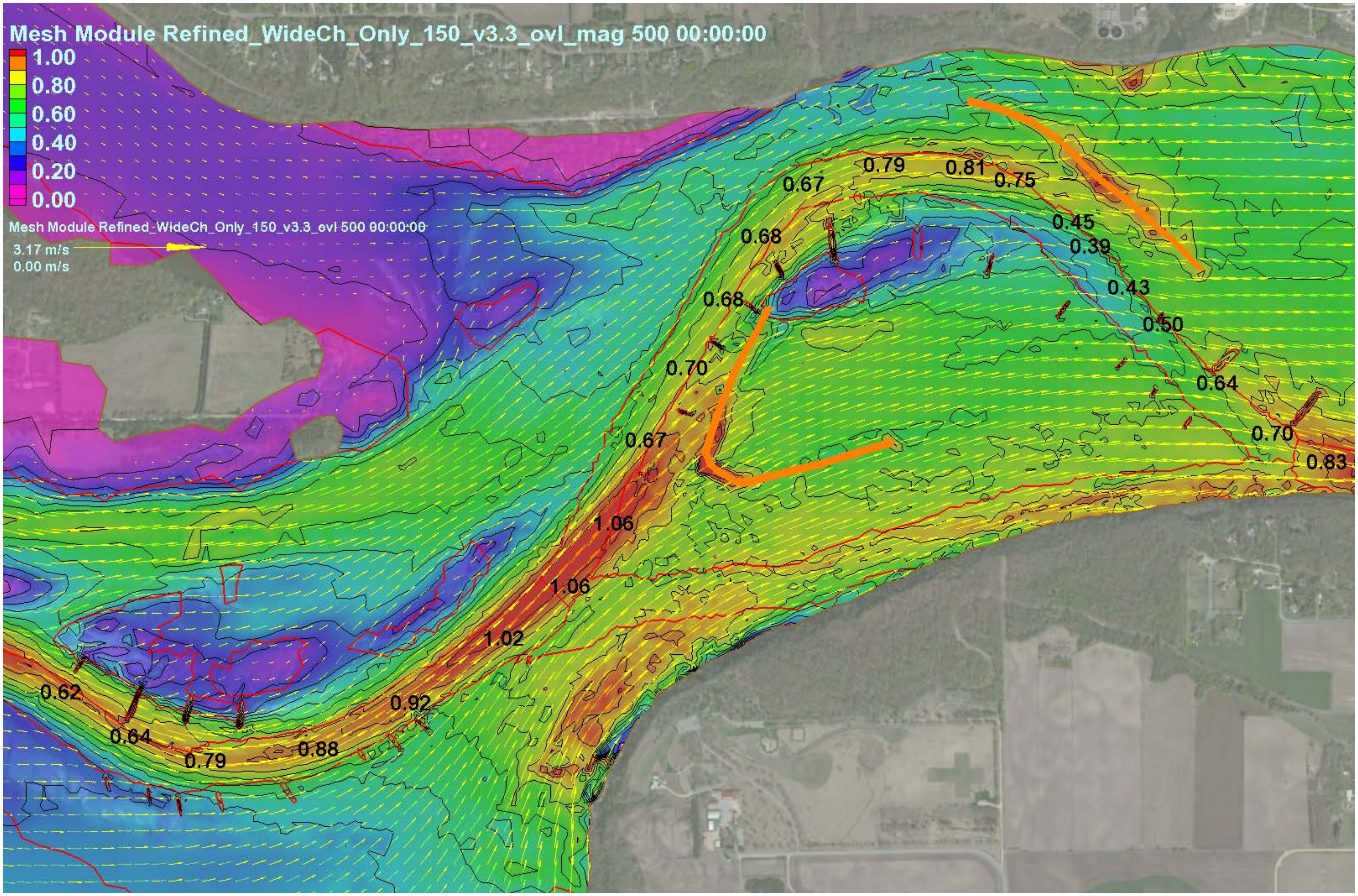


Figure 18- Tow Traces, Groundings, and Velocity Vectors - 43,000 cfs - Existing Conditions

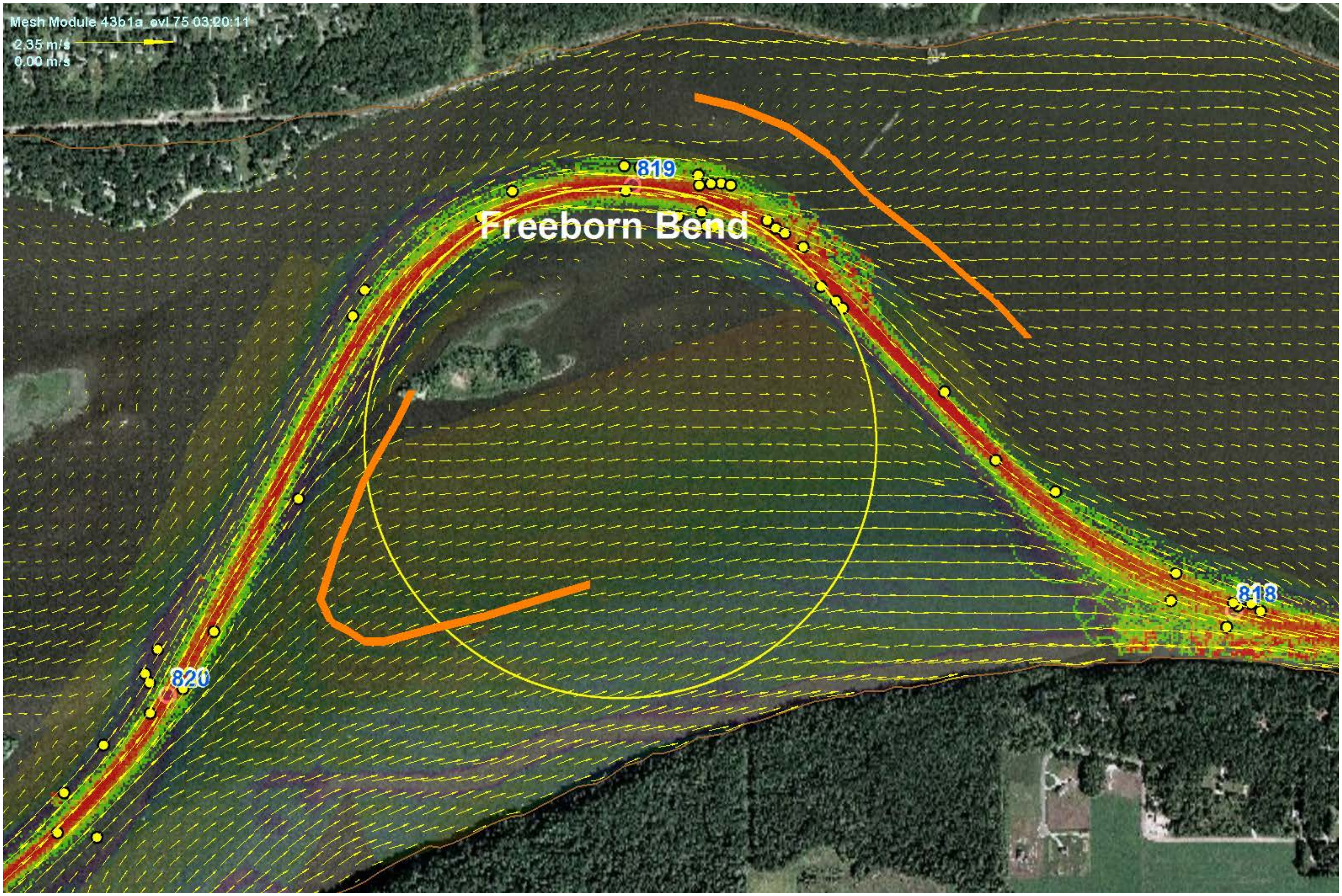


Figure 19 - Tow Traces, Groundings, and Velocity Vectors - 43,000 cfs - Project Conditions

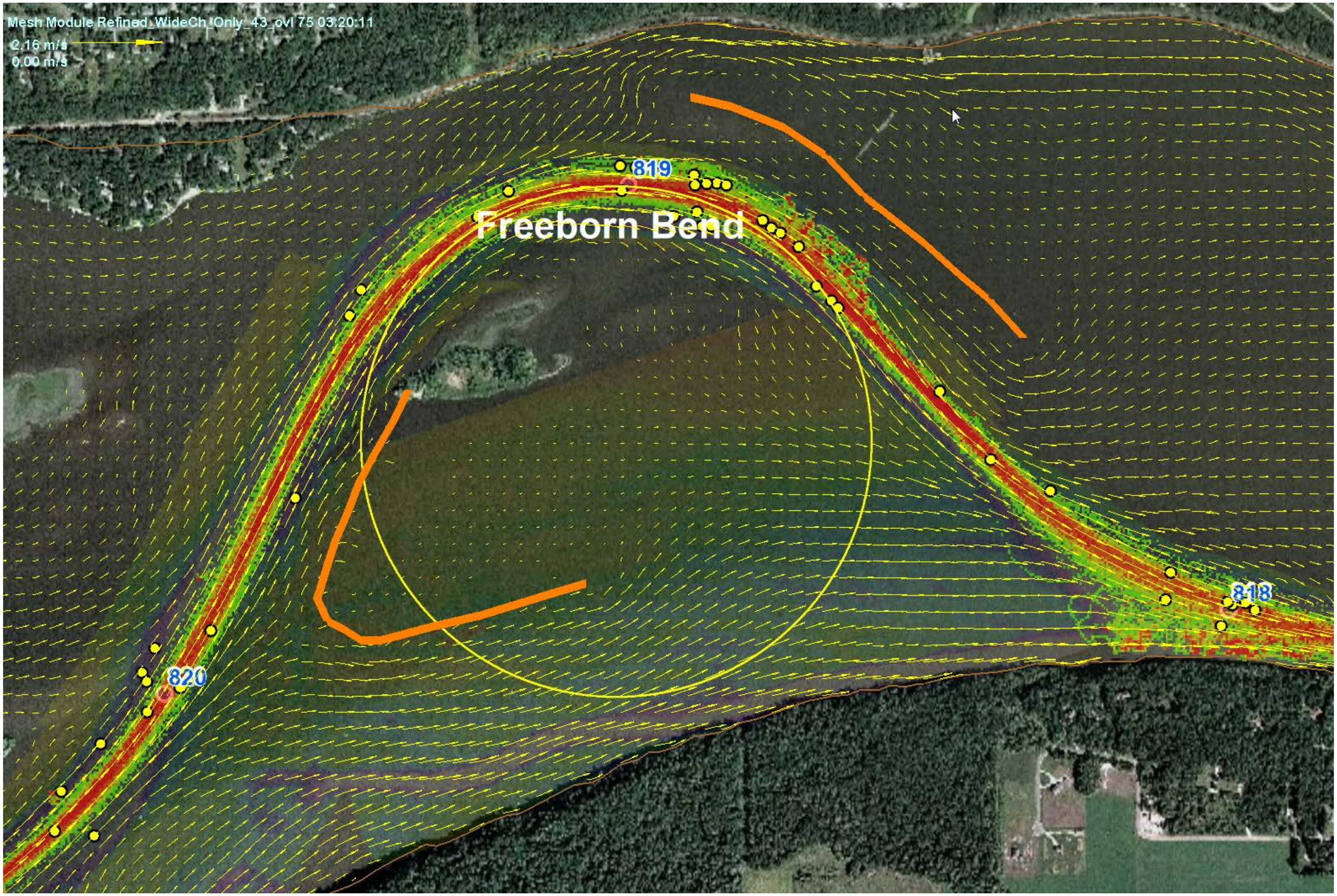


Figure 20 - Percent Increase in Channel Velocity (5970 cfs)

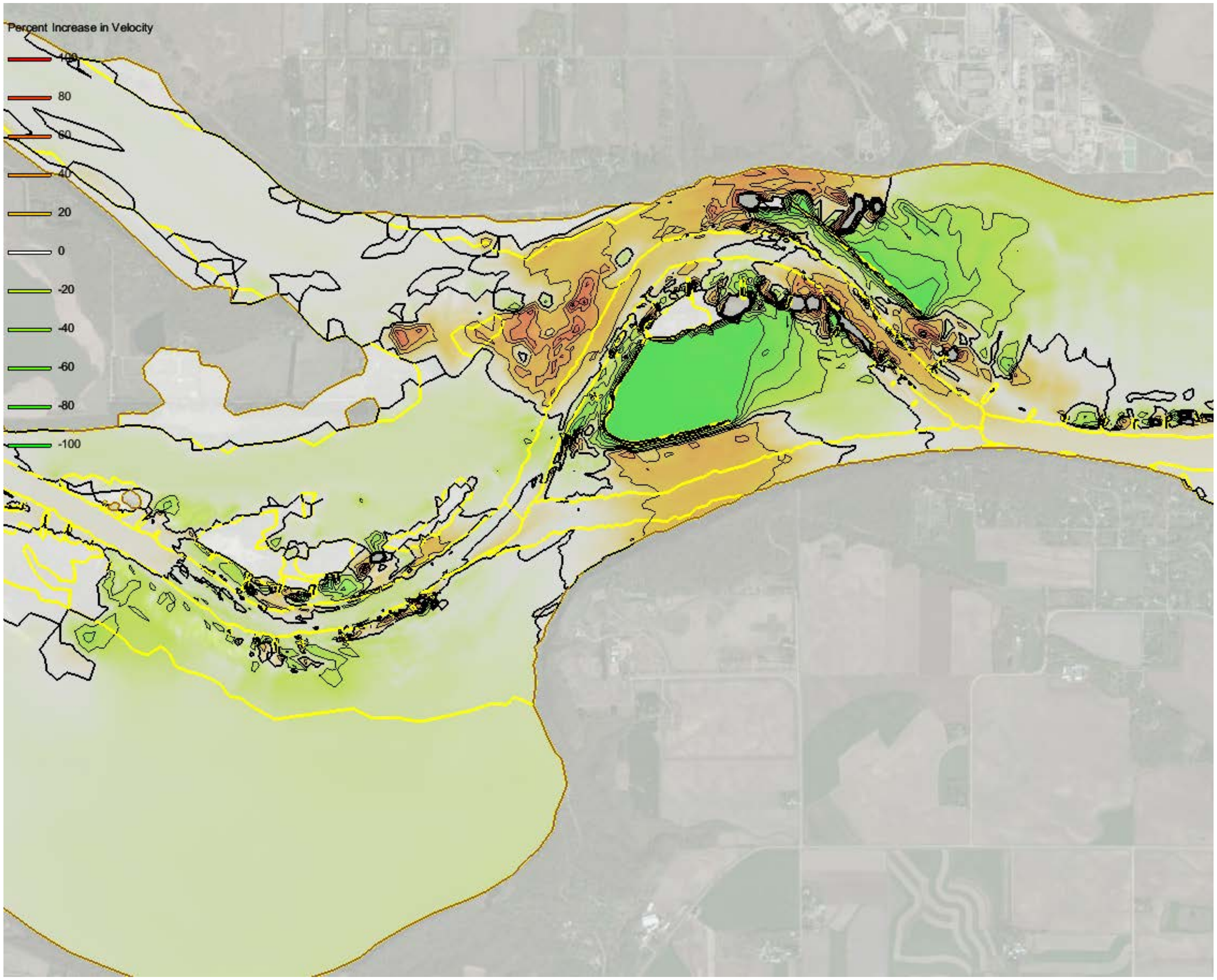


Figure 21 - Percent Increase in Channel Velocity (20,560 cfs)

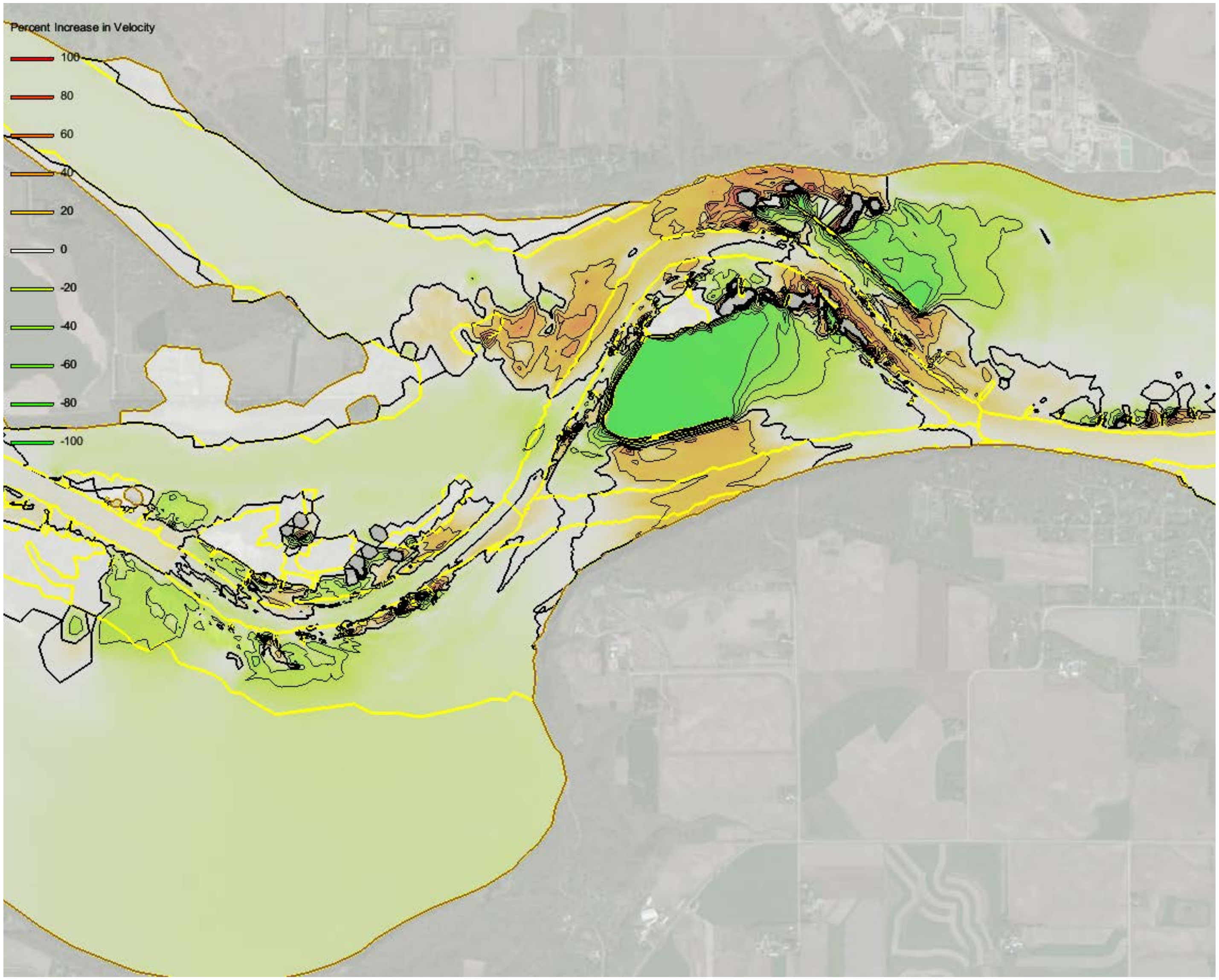


Figure 22 - Percent Increase in Channel Velocity (43,000 cfs)

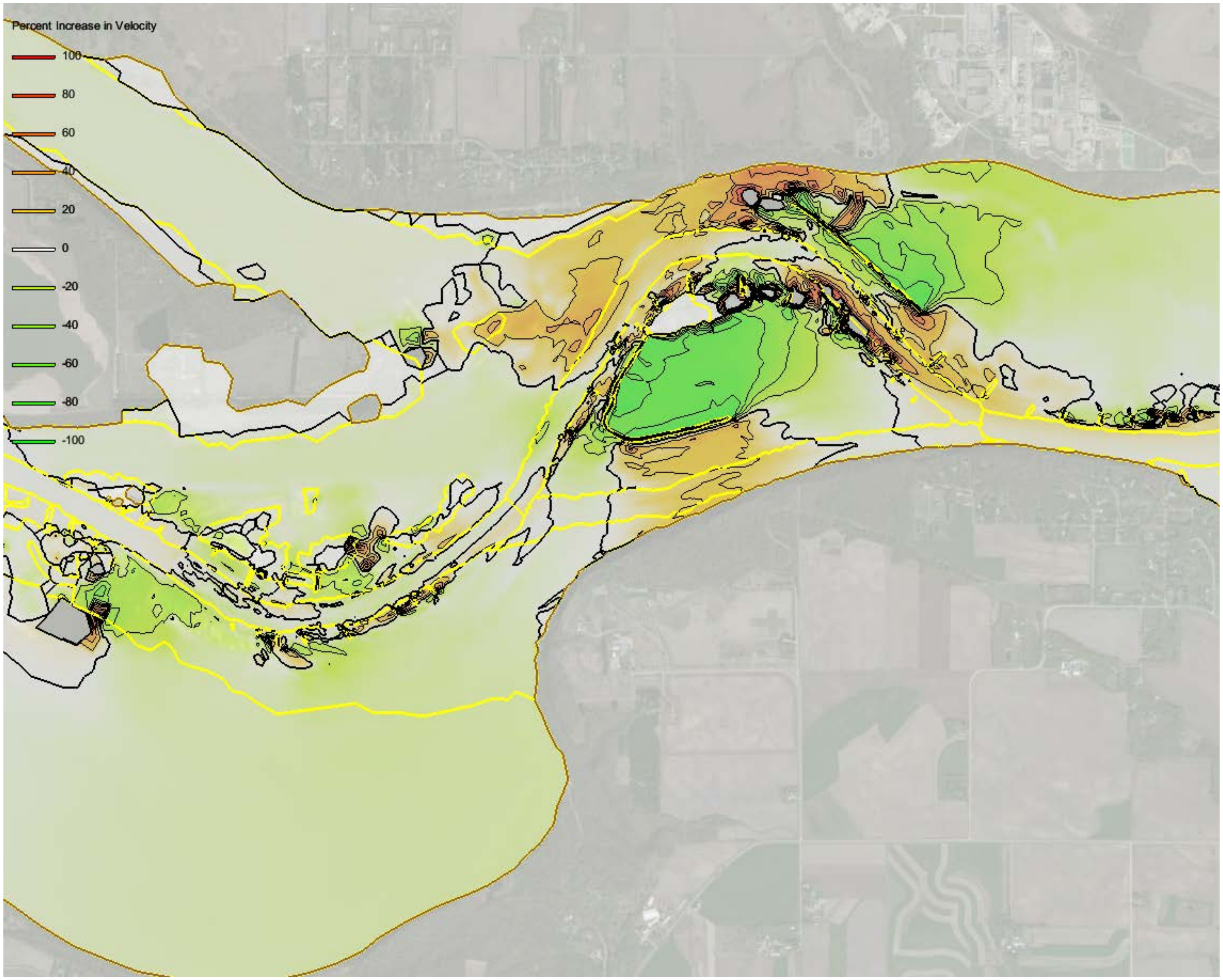


Figure 23 - Percent Increase in Channel Velocity (60,000 cfs)

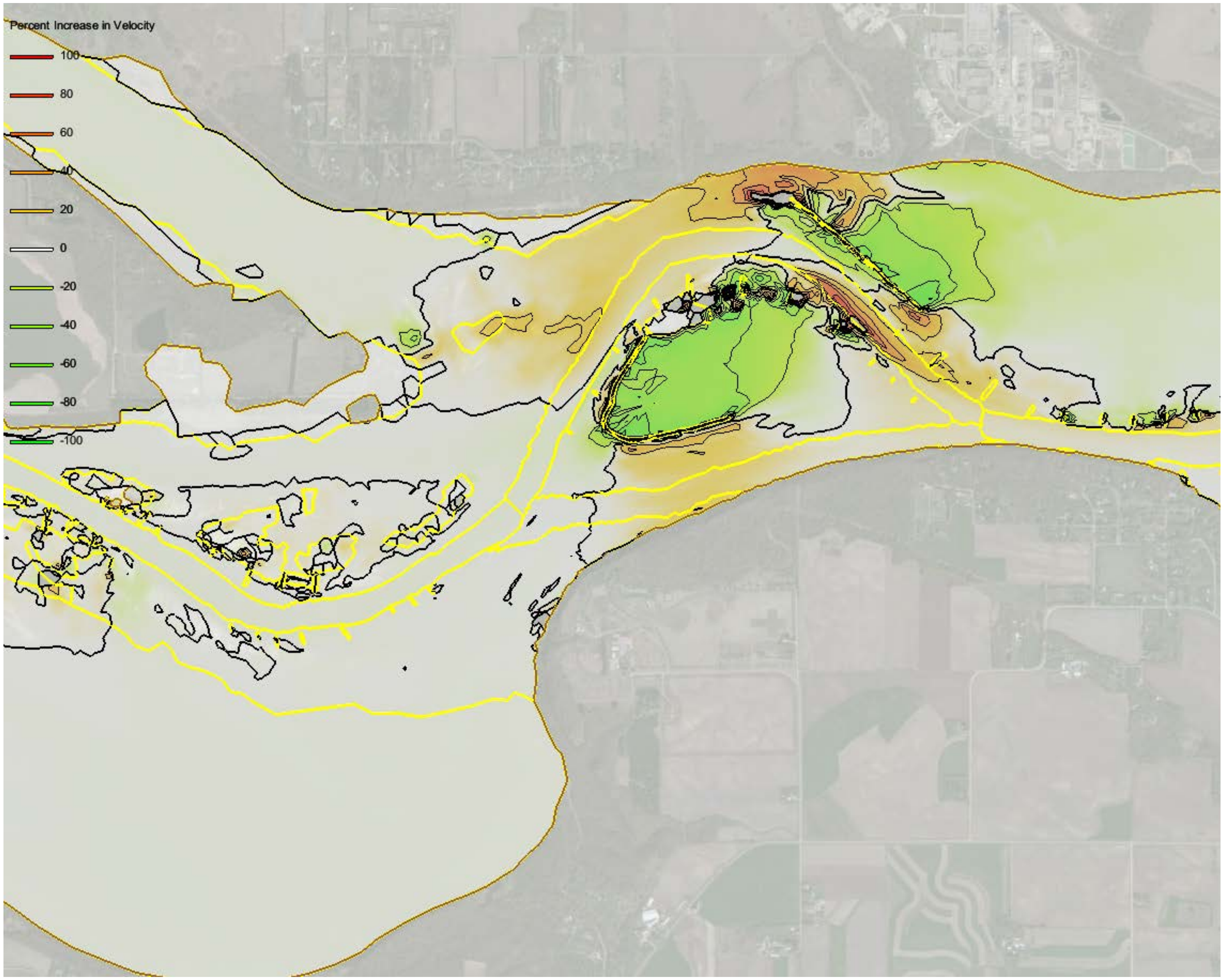
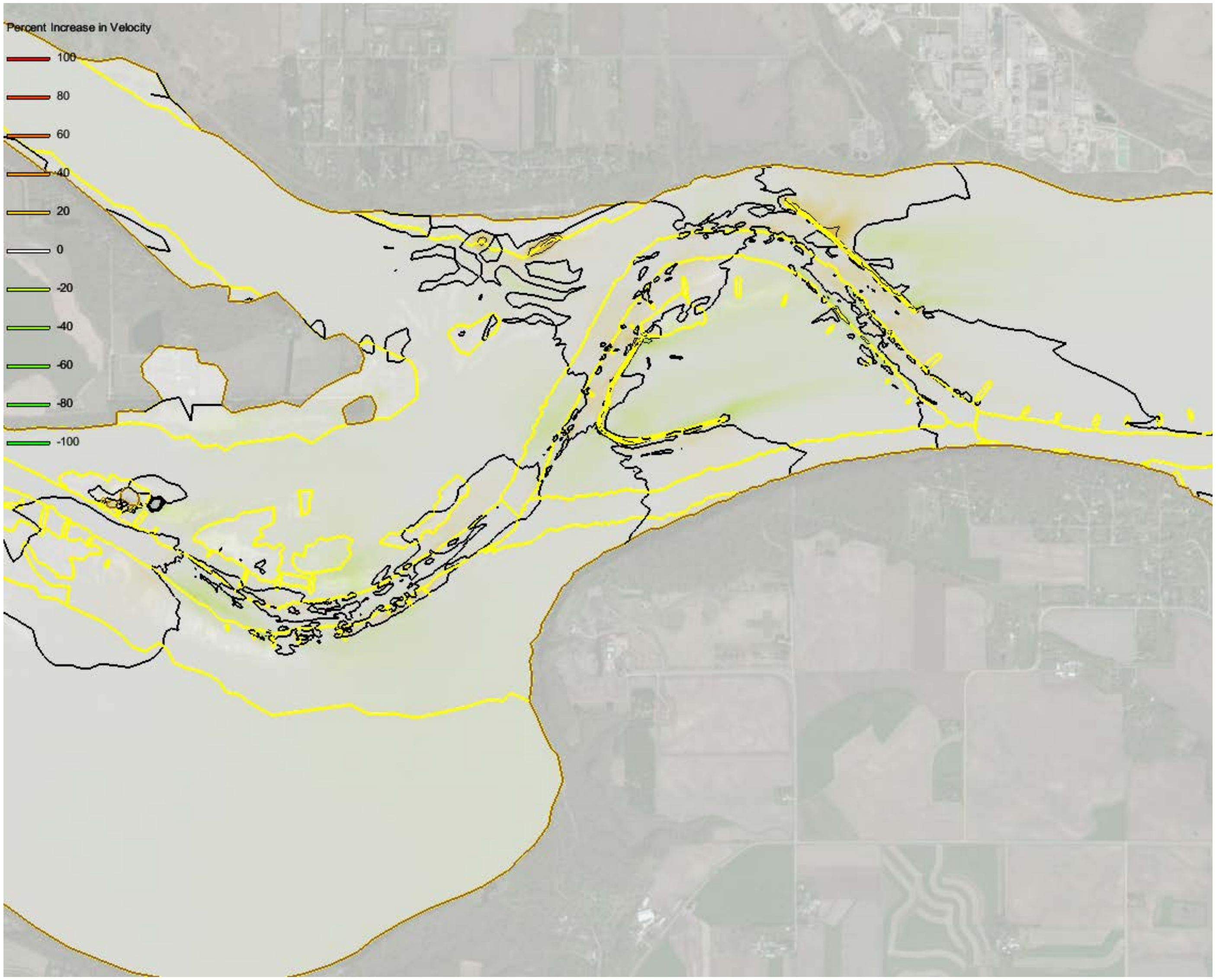


Figure 24 - Percent Increase in Channel Velocity (150,000 cfs)



Island Cross Section and Design

Three island cross sections were proposed for the island features. The island crests (elevation 687.4 feet, 1912 Datum) are only about 0.8 feet above the Low Control Pool elevation in this portion of the river (elevation 686.6 feet, 1912 Datum). The islands are 0.8 feet above the water surface at low flows and 1.1 feet above water at the 25% duration discharge. The water surface reaches the island crest for the 2 year flood, or 43,000 cfs. Since this island is in the lower end of Pool 2, it is subject to the pool drawdown at the dam. Figure 25 shows the Operating Curves for Pool 2. The pool is drawn down at the dam to elevation 686.5 feet, 1912 Datum, between 10,000 and 60,000 cfs. These boundary conditions are coded into the ADH models.

Figure 26 and Figure 27 show two island designs that have been proposed. The first figure, Figure 26, shows a 40 foot island top width. The island would have topsoil and riprap side slopes. This island was designed to grow vegetation and have a better aesthetic profile than plain rock. This island would have to be burned regularly to keep woody vegetation (probably willows) from becoming established. This would be required to maintain the low Manning's n roughness characteristics that are necessary to keep project stage increases under 0.005 feet. A variation of this section would keep the non-rocked interior of the island below common water elevations which would allow only aquatic vegetation to become established. This would not require burning or other control measures because the non woody vegetation would lie down during large events.

A rock sill would also be acceptable although it wouldn't have vegetation to soften its appearance. The dimensions of the rock sill island were adjusted from the standard design found in the Environmental Design Handbook (COE, December 2012). The 10' foot top width has been shown to provide enough mass to withstand the forces that expanding and moving ice would exert on the structure. The top two vertical feet of the island would have side slopes of 5H:1V to allow ice to ramp over the rock without pushing the structure over. The 5H:1V slope has been successful when used at a problem location on the Trempealeau National Wildlife EMP project. The "Ice Action on Riprap" (Sodhi, Borland and Stanley, CRREL 1996) also recommends that D100 should be twice the ice thickness for shallow slopes. For elevations below 685.4 (2 feet below crest), the slope will be steepened to 1.5H:1V. Since the Minnesota DNR is particularly concerned with disturbance to mussels in this pool, minimizing the footprint size for this alternative would require relocation of the fewest mussels without compromising the stability during ice events.

An ongoing question is if the incorporation of occasional field stone boulders (4ft diameter) would aid or hinder safety, or have no benefit. The primary reason to embed the stones within the island is to indicate the hazard of the alignment of the islands when they are shallowly inundated. The boulders could also help break sheet ice as it rides over the rock sill.

Figure 25 shows the operating curves for Lock and Dam 2. At extremely low river discharge nearing 5000 cfs, the crest of the rock sill would be about 0.2 feet above water. As discharges rise, the water is lowered at the dam and at the project site. At 12,000 cfs the water surface is lowered to 686.5 at the dam. A similar drop at the structures would cause the rock sills to be 0.9 feet above water. This value would be gradually reduced with increasing discharge until the water surface reaches the rock crest a 43,000 cfs (2 year flood) . Shallow inundation would continue until the gates are lifted at the dam and the dam goes out of operation at 65,000 cfs (5 year flood). Stages rise faster above this point and submerge the structures more significantly. The case for including boulders (4 foot diameter boulders embedded in riprap matrix) in the design are as follows:

- The rock sills rise less than 1 foot above the water. The presence of boulders will increase the visibility of the islands. This would also be true when the islands are not submerged.
- Flood discharges (greater than 5 year flood) will be present when the boulders are overtopped which should limit the potential of recreational boats striking a submerged boulder. With these higher discharges the boulders (as well as rock sills) should produce an identifiable turbulence pattern on the water surface similar to the patterns produced by submerged wing dams and submerged closing dams that are commonly found adjacent to navigation channel.
- The rock sills are estimated to settle approximately 1.5 feet over an uncertain time period. They will be restored in elevation over time but there may be periods where they have not been fully restored in elevation. The boulders would help show the location of the rock sills if the crests sink below pool elevation.
- Even with the shallow 5 horizontal to 1 vertical slopes on the upper parts of the islands, there will be a possibility of some ice erosion. The presence of the higher elevation boulders may help break the overriding ice sheets and reduce the pressure on the rock sills.

The boulders would be embedded in the island matrix about 3 feet. The tops of the boulders would extend about 1 feet higher than the island crest. The boulders would be spaced at approximately 250 foot intervals. This spacing would add about 10 boulders to the NE island and about 15 boulders to the SW island. The boulders should not affect flood levels since the relative size of the boulders is insignificant in relation to the overall stage impacts of the islands. The decision to incorporate this feature will have to be worked out during the Plans and Specifications stage of the study.

Figure 25 - Pool 2 Operating Curves

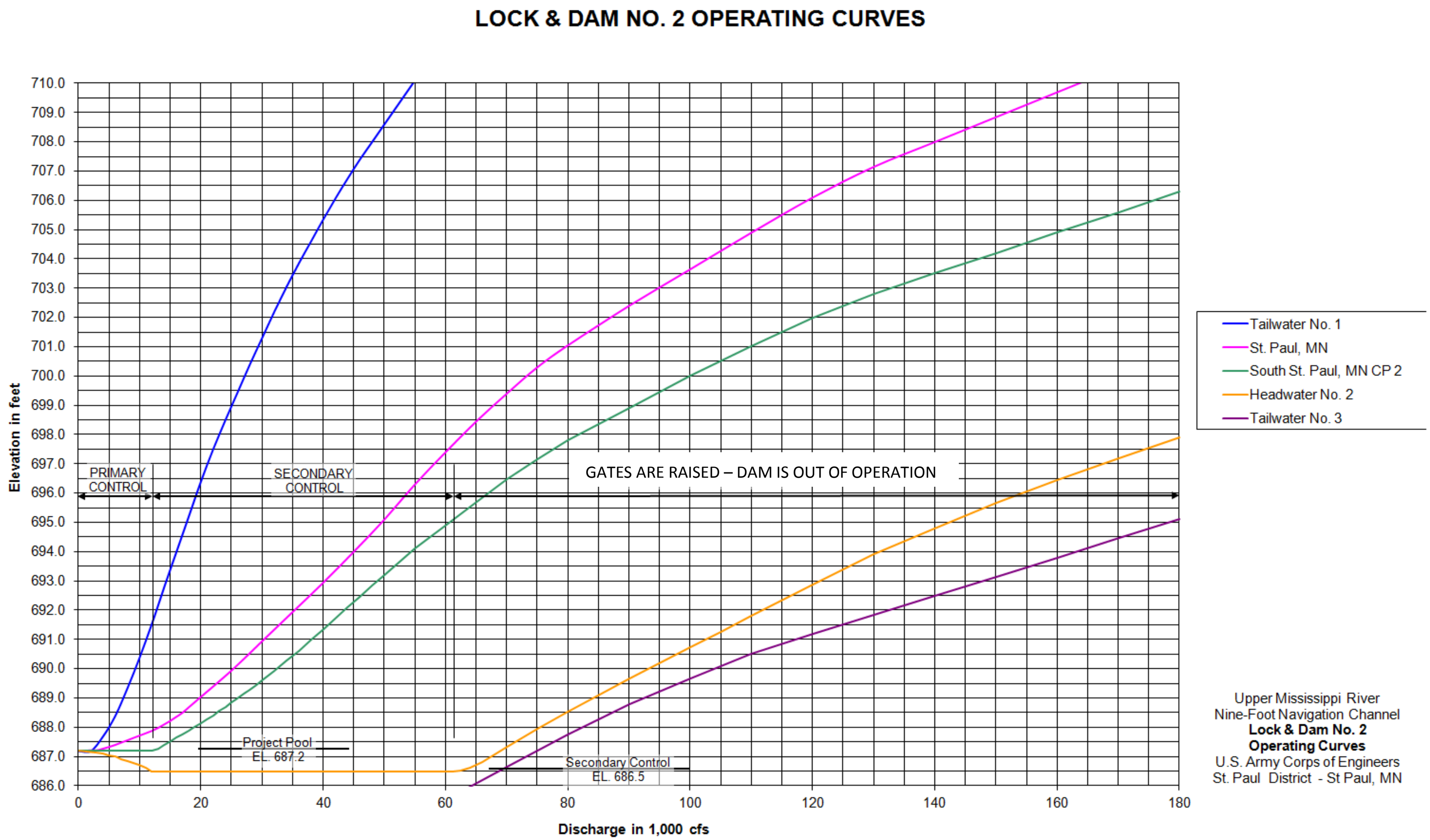


Figure 26 - Island Section _ Vegetated Interior

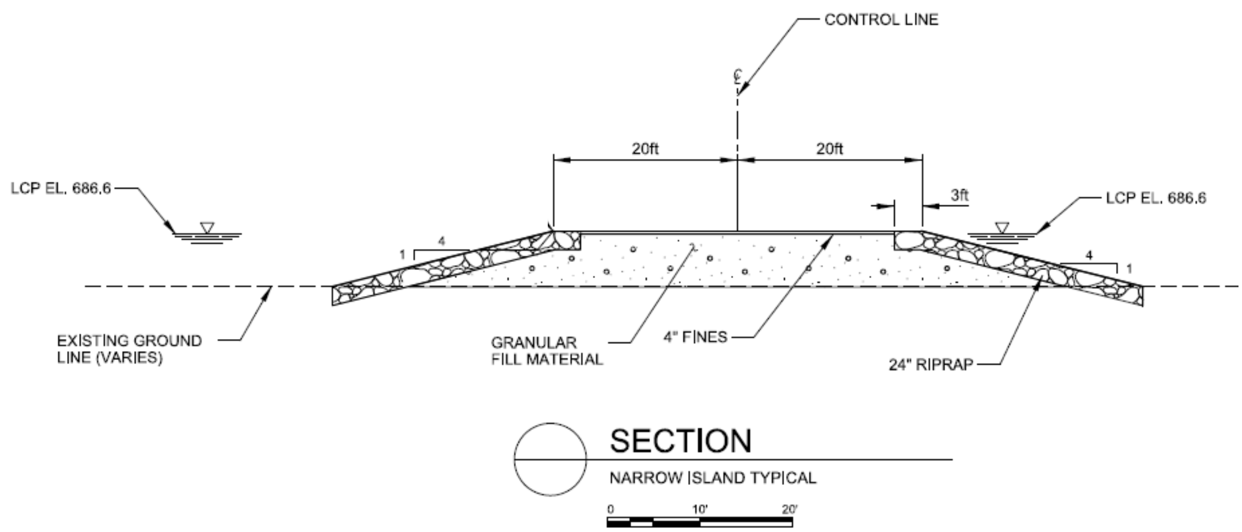
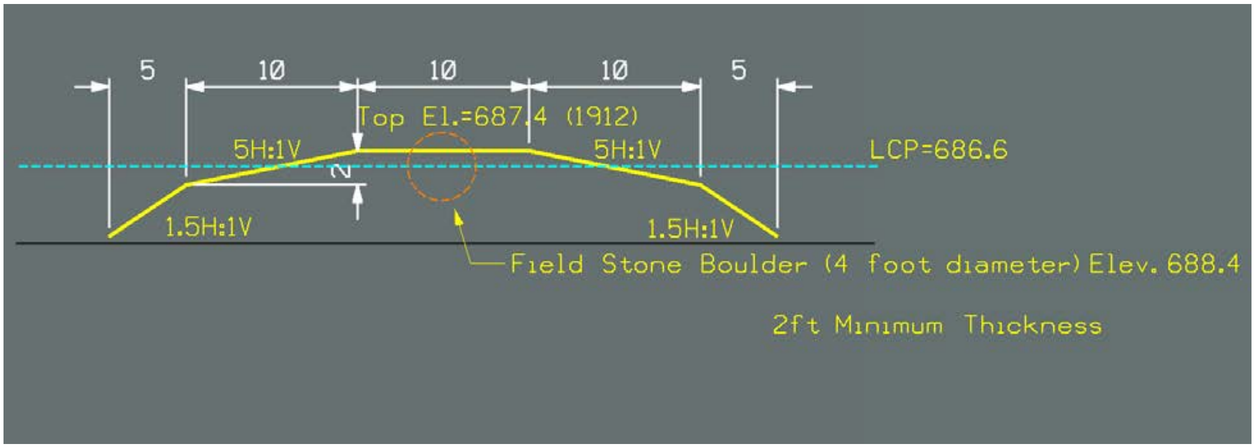


Figure 27 Rock Sill Section



ADH Sediment Modeling of Existing Conditions and Proposed Alternative

The sediment capabilities of the ADH model were used to look at scour and deposition in the areas directly impacted by the proposed alternative. Several changes were made to the ADH software that could potentially affect sediment transport calculations.

The newest version of ADH (Version 4.3) was used for new runs. It proved much more stable and eliminated much of the questionable deposition patterns identified in the WEST report. The computational time step was 0.5 hours in the original WEST modeling. This time step frequently led to model instability problems in both the original ADH version 3.1.3 and the newest ADH version 4.3.

Longer time steps were allowed and model stability and performance was improved. Model run times were greatly reduced. A time step of 1 hour was adopted for the sediment runs.

The boundary inflow sediment concentration (used in the WEST study) was replaced with the Equilibrium Sand Transport Boundary Condition. This condition prevents down-cutting at the upstream boundary. The model produces enough inflowing sediment to maintain sediment equilibrium at the upstream boundary.

Some changes were also made to the base condition bathymetry represented in the model. The original modeling showed various off channel areas that were obviously too deep. New depths were estimated and the model was adjusted accordingly.

The changes to the ADH code and to the time step could affect some of the computational results of the ADH models. These changes create some differences in magnitude of deposition and erosion however they do not really alter the areal trends. It seems best to assume that the model is helpful as a qualitative study of the effects of the project on sediment transport. It should be able to identify reaches that would have a tendency to accumulate sediment and pass sediment. It is not clear if the model is able to describe rates of erosion and deposition with much precision. That is always asking a lot from a sediment model. Nevertheless, it is a useful tool for identifying trends and as another means (along with velocity and the Rouse analysis) to identify potential problems with the design.

Sediment Deposition Pattern

The following figures show the ADH modeled sediment displacement over a 4.75 year of simulated time. The model was set up to run 5 years of hydrographs (100 days of active sediment movement/year). The model went unstable at 475 days for the IFC alternative so all sediment comparisons are done at this limit. Figure 28 and Figure 29 show the change in displacement between existing conditions and the ICM Alternative. Positive values imply more deposition or less erosion. Negative values imply less deposition or more erosion.

Figure 30 describes the regional pattern of deposition within Lower Pool 2. The figure shows a bar graph illustrating the displacement in cubic yards for existing conditions and for project conditions. The first set of bars compares the displacement combined for the entire modeled area. The change is a reduction of deposition of 1.5 percent which is essentially zero considering the precision of the sediment modeling. This is taken to be zero considering the uncertainties in modeling.

The next three sets of bars show the upper, middle, and lower parts of the pool. Small inset maps show the portions of the model that were included in the calculations. None of the regional displacement patterns is significantly altered by the project. The upper reaches, from the upstream model boundary to the beginning of the Boulanger Bend area shows little change. The middle region running from the upper extent of Boulanger Bend to Nininger Bluff shows little net displacement for existing and project conditions. There could be a shift from net negative displacement (erosion) to net positive (deposition) but the magnitude of each is small. The reach from Nininger Bluff to the Dam showed a small reduction in displacement.   The reduction in displacement is similar in magnitude to the increase shown in the Boulanger Bend to Nininger Bluff reach.

Figure 28 –Change in Displacement in Feet (Detail)

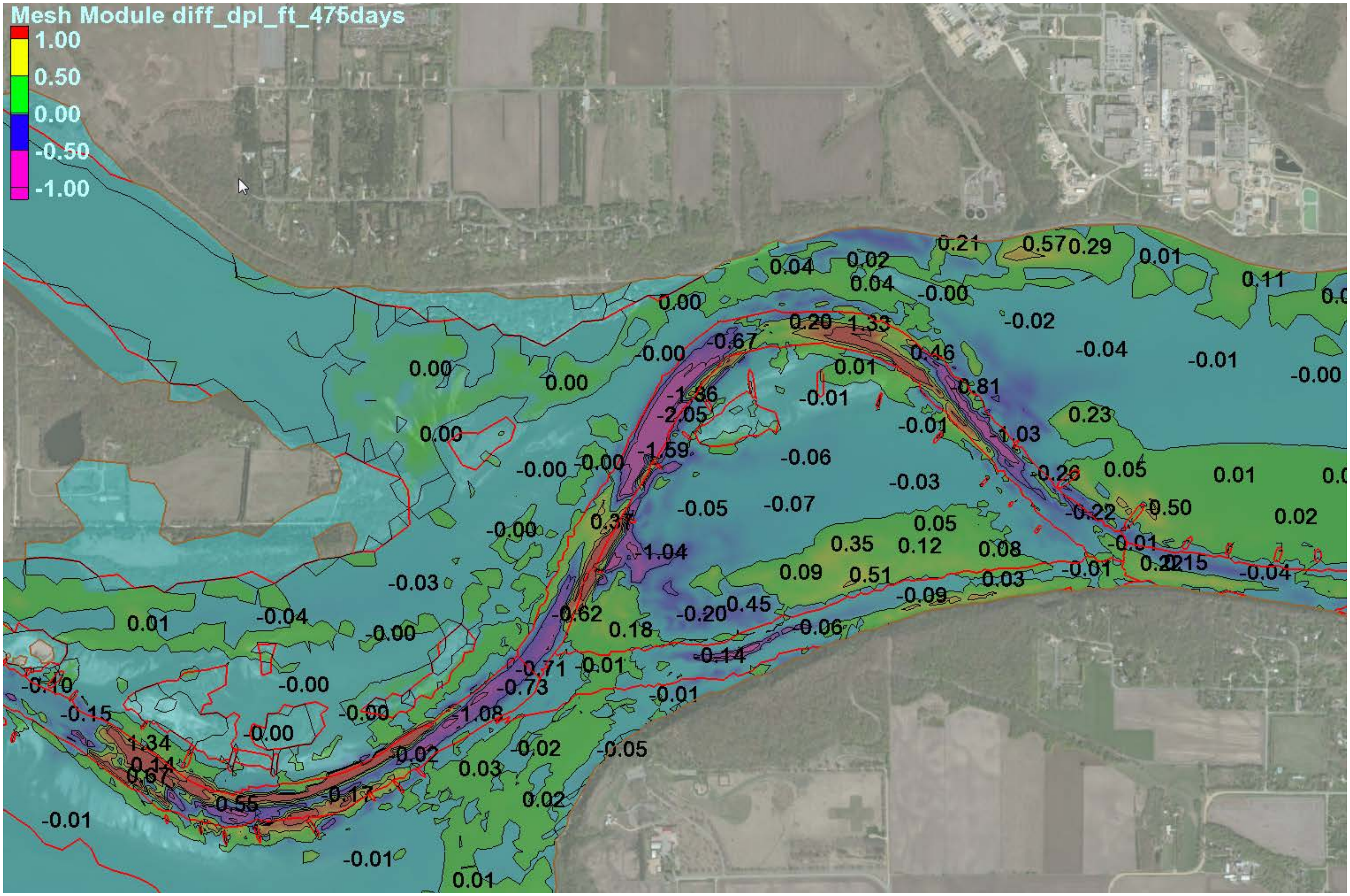


Figure 29 Change in Displacement ((-) implies erosion or less deposition - Lower Pool 2

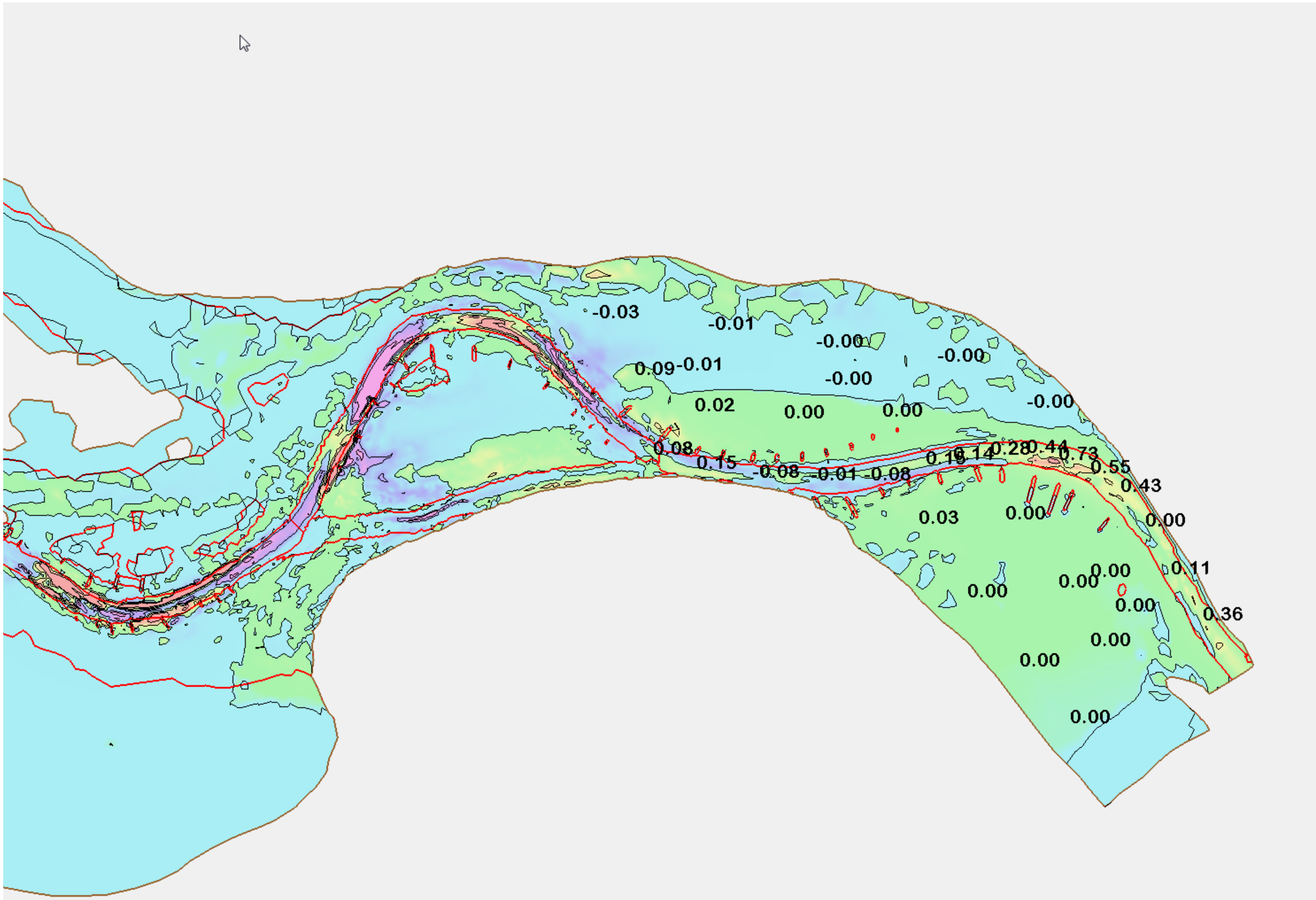
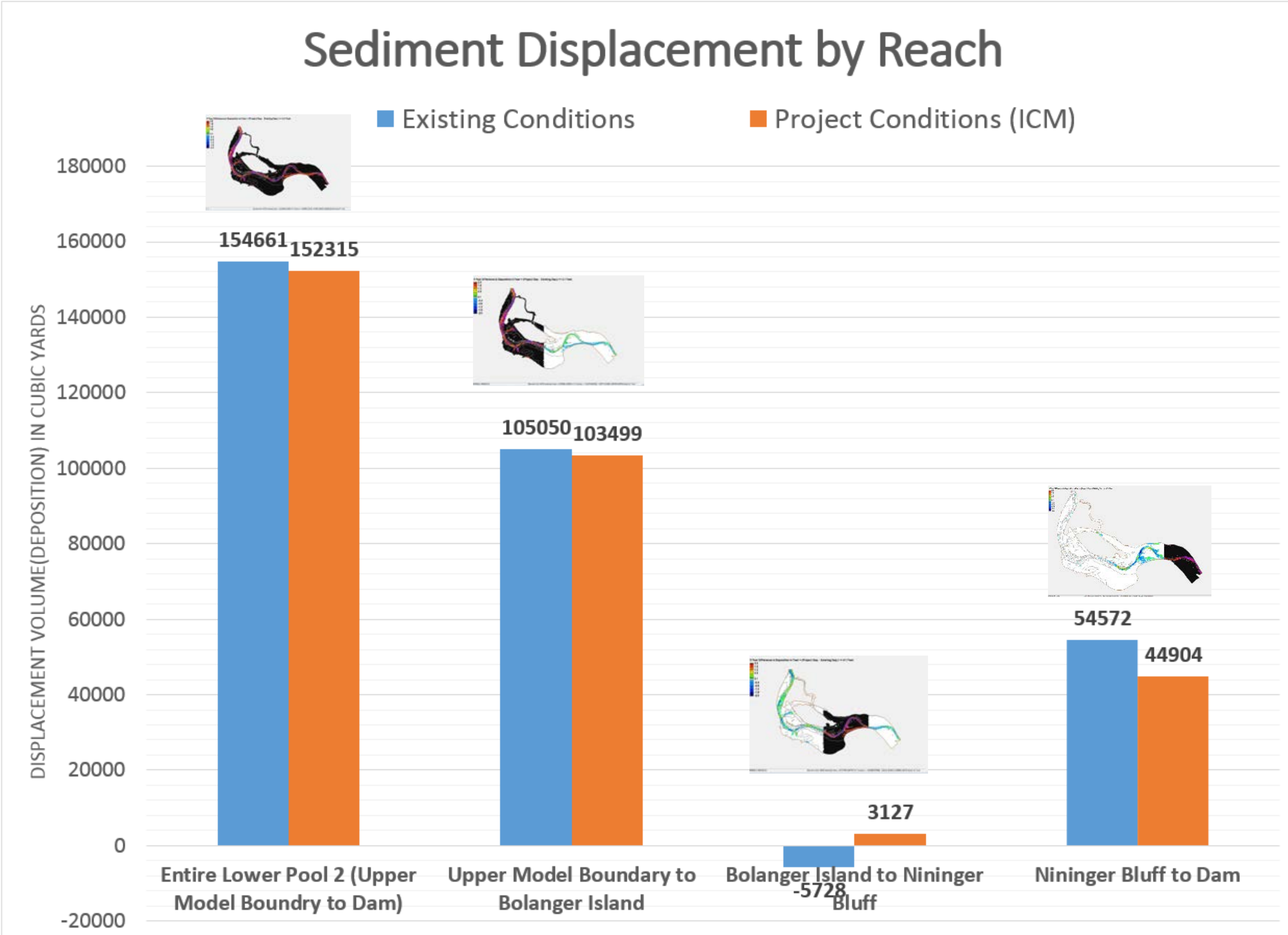


Figure 30 Lower Pool 2 Displacement Total and by Reach (5 Year Total)



Effects of Alternative on Dredging in the Navigation Channel

The ADH sediment displacement results (for the modeled 4.75 year period) have been used to estimate relative percentage changes in channel maintenance dredge volumes within the ICM Alternative river reach. The uncertainties in the sediment modeling preclude their use in a quantitative basis. They should be acceptable for use as a more qualitative estimate. It seems reasonable to relate the modeled percentage change in displacement to actual existing condition dredge volumes. The total displacement volume was totaled over the area within the IFC maintenance boundary. This was done for existing conditions as well as for the conditions for the alternative. The area over which the volumes were calculated is shown as the IFC channel maintenance boundary in Figure 6. Table 4 displays the displacement for existing and project (ICM) conditions within the ICM areas.

At hour 475:

Table 4 Displacement Within ICM Area

Condition	Volume of Displacement in cubic meters	Volume of Displacement in cubic yards
Existing	172800	226000
Increased Channel Maintenance (ICM) Alternative	164900	215700

These results indicate a 4.5 percent reduction in dredging for the modeled period. This is essentially equal to existing conditions; especially when considering the uncertainties in the calculation and the small percentage of the total sediment transport that is taken Pool 2 as dredge sand. This difference in dredging should be treated as 'no change'.

Effects of Climate Change on the Project

A study was done looking at climate change and trends to river flows on the Mississippi and Minnesota Rivers. This document is attached as Appendix D1. The Mississippi River average annual discharge has risen about 40 percent at Saint Paul (comparing the periods 1948-1980 and 1981-2015).

Figure 25 shows the Operating Curves for Pool 2. Stages are controlled by dam operation. They are held constant (686.8 feet NAVD88) at the South Saint Paul gage (green line in the figure) for river discharges at or below 15,000 cfs. This means that stages at the dam are reduced as discharge rises on the river.

The primary effect of generally increasing discharges will be the increased duration and frequency of island inundation. The rock sills will be overtopped more often and for greater periods of time if trends of increasing discharge on the Mississippi River continue. The features are designed to handle all discharge conditions so they should not be greatly affected by increased stages. More frequent and prolonged overtopping of the islands would correspond to more breakout flows over the rock sills. Increased break out flows could lead to increasing dredging in the project reachs.

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