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Development of a Two-Dimensional HEC-RAS Sediment Model for the Chippewa River, Wisconsin, for Software Development and Sediment Trend Analysis

by Alex Nelson, Stanford Gibson, and Alex Sanchez

PURPOSE: This US Army Corps of Engineers (USACE) Regional Sediment Management technical note (RSM-TN) describes an RSM effort that converted a one-dimensional (1D) sediment transport model of the Chippewa River confluence with the Mississippi River into a two-dimensional (2D) model. This work leveraged recent sediment data collection and tested the new 2D sediment transport capabilities in the Hydrologic Engineering Center, River Analysis System (HEC-RAS) Version 6.0. In addition to the benefits of software testing, the resulting model developed through this effort can provide more accurate spatial and temporal information about sedimentation in the Mississippi River navigation channel and help inform future dredging strategies for the St. Paul District, USACE.

INTRODUCTION: The Chippewa River, in northwestern Wisconsin, delivers hundreds of thousands of cubic yards of sediment to the Mississippi River navigation channel annually (Nelson 2020). The deposition in the river reach between the Chippewa River and Lock and Dam Number 4 (known as the Lower Pool 4 reach) requires more maintenance and dredging than any other site in the St. Paul District. The Chippewa River delta has blocked the Mississippi River enough to form Lake Pepin, upstream (Nielsen et al. 1984), which intercepts the silt and sand delivered from the Upper Mississippi River (UMR). Sand and silts that reach Lower Pool 4 are almost entirely delivered from the Chippewa River.

The USACE, the US Geological Survey (USGS), and others have collected substantial sediment data on Chippewa River sediment sources and transport in recent decades. Rose (1992) summarizes particle sizes and loads on the Chippewa River and other rivers in Wisconsin, which helped establish flow-load rating curves, hydrologic flow-splits for side channel flow of water and sediment, and particle size distributions. The Chippewa River formed as an aggradational glacial meltwater stream because of the lowering of the base level of the UMR post-glaciation. Recent research suggests knickpoint migration, incision, and terrace formation have exposed and eroded banks along the Chippewa and its tributaries, increasing the sediment load (Faulkner et al. 2016). Figure 1 shows the location of the lower Chippewa River and the area of interest for the modeling effort.

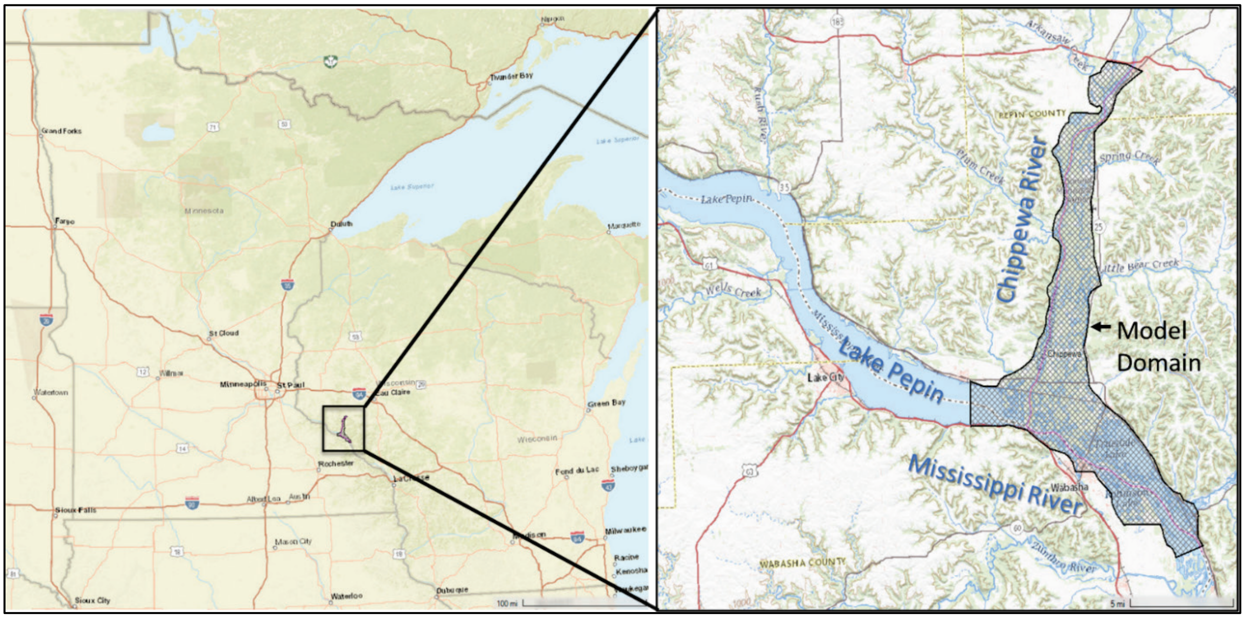

Figure 1. Location of the Chippewa-Mississippi confluence (left) and the model domain (right).

Recent monitoring by the USGS applied new techniques to measure suspended-sediment concentrations, loads, and grain sizes using permanently mounted, side-looking acoustic Doppler profilers, which allow for 15 min* instantaneous data to be available (Dean et al. 2021). The USGS calibrated instantaneous data using physical, depth-integrated sediment samples. Dean et al. (2021) supplemented these suspended concentration measurements with bed-load data from single frequency echosounders to track dune movement and compare the combined measurements to total load estimates made from previous USGS studies. While the USGS sampling effort has been in cooperation with the USACE, the USACE led additional monitoring to independently estimate the bed-load transport along the Chippewa River using the ISSDOTv2 method to evaluate time-sequenced bathymetric data and develop bed-load rating curves (Abraham et al. 2020).

Nelson (2020) utilized this substantial sediment data set and decades of dredging quantities in Lower Pool 4 to develop and calibrate a 1D sediment model to simulate sedimentation trends in the navigation channel and to help forecast future channel maintenance needs. This existing 1D model and available data presented an opportunity to utilize the latest version of HEC-RAS 6.0 Beta (USACE 2020) to test the software capabilities for modeling sediment transport in a 2D hydraulic model framework. This work had two objectives. First, this project set out to test and troubleshoot early release versions of the 2D sediment model in HEC-RAS Version 6.0 with a prototype-scale project and enough sediment data to evaluate the results. Second, by using this perennially problematic sediment hot spot to test and troubleshoot the model, the project team also developed a model that could become a regional sediment management tool to forecast deposition and evaluate management alternatives.

METHOD: The new 2D hydraulic and sediment transport model and the existing 1D model used similar terrain and land-cover data and covered a similar model domain. The upstream extents of

* For a full list of the spelled-out forms of the units of measure used in this document, please refer to *US Government Publishing Office Style Manual*, 31st ed. (Washington, DC: US Government Publishing Office 2016), 248-52, https://www.govinfo.gov/content/pkg/GPO-STYLEMANUAL-2016/pdf/GPO-STYLEMANUAL-2016.pdf.

the model incorporated the downstream end of Lake Pepin on the Mississippi River and the Durand, WI, USGS gage location on the Chippewa River. The downstream boundary of the model was set as the observed pool elevation at the Lock and Dam No. 4 navigation structure. The terrain data for the model are a combination of various lidar data collected for the States of Minnesota and Wisconsin and seamless floodplain elevation and bathymetric data for the main channel of the Mississippi River (USACE UMMR LTRM 2016). Survey data collected for the previous 1D model were utilized for the Chippewa River channel. Some areas of the model, where bathymetric data were not available and lidar reflected the water surface elevation at the time of the data collection, were estimated in the model to capture the appropriate conveyance through side channels. Manning's *n* values for roughness were initially based off the 1D calibrated roughness values generated from the National Land Cover Database spatial dataset (Homer et al. 2015) but were further refined during calibration of the 2D model. Figure 2 shows the 2D mesh compared to the elevation model and the land cover model used to assign model roughness.

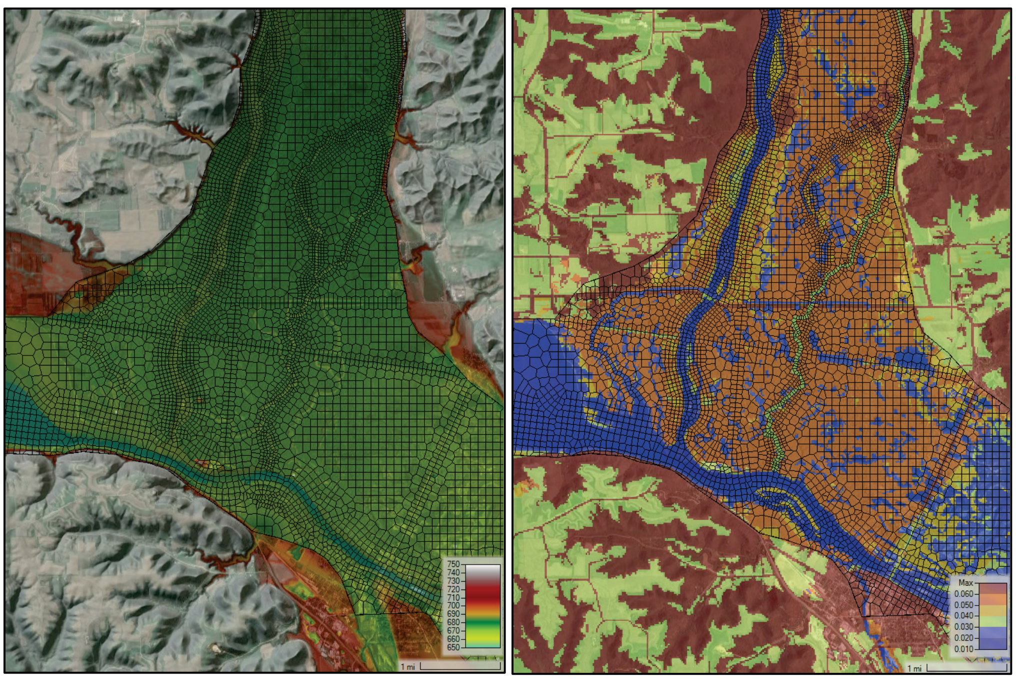

Figure 2. Configuration of 2D model mesh with terrain elevations (left) and Manning's roughness values (right).

At the time of the bathymetric survey of the Chippewa River in the spring of 2019, water surface elevation data was also collected. The time-series elevation data at the USGS gage at Durand, Wisconsin, on the Chippewa River and at the USACE Control Point 4 gage location in Wabasha, Minnesota, on the Mississippi River were targeted for the 2D hydraulic model calibration. Adjustments to the model, primarily by refining areas with estimated channel conveyance and by adjusting roughness values, were made to achieve an acceptable calibration. Figure 3 shows the comparison of water surface elevation data collected on 30 April 2019 to the modeled water surface elevations based on the flow observed on that date. Figure 4 shows the comparison of the observed time series of elevation data to the modeled data. The model generally shows agreement with the observed data, except for winter months (November through February) where the Durand gage readings are likely impacted by ice cover. During these periods, the observed stages are higher than the modeled stages.

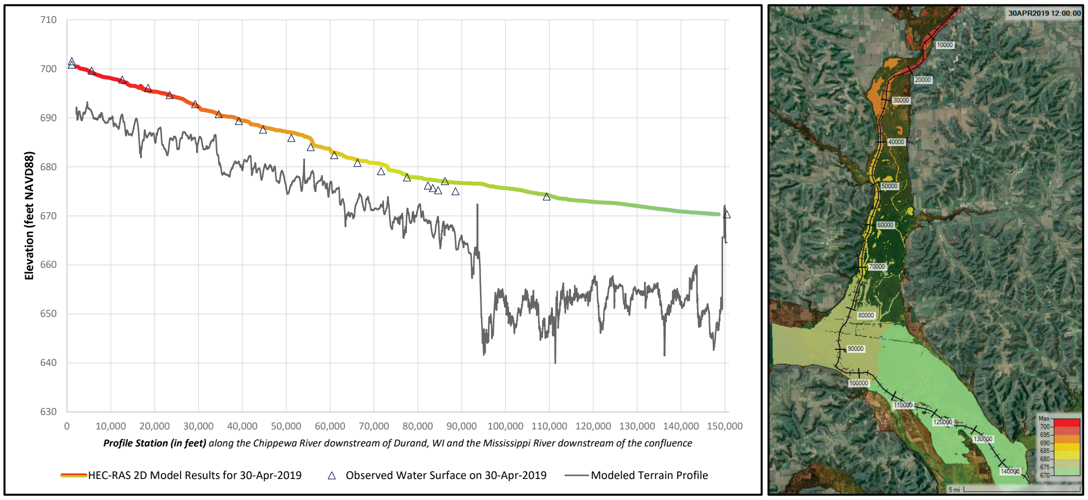

Figure 3. Hydraulic model calibration to observed water surface elevations (30 April 2019).

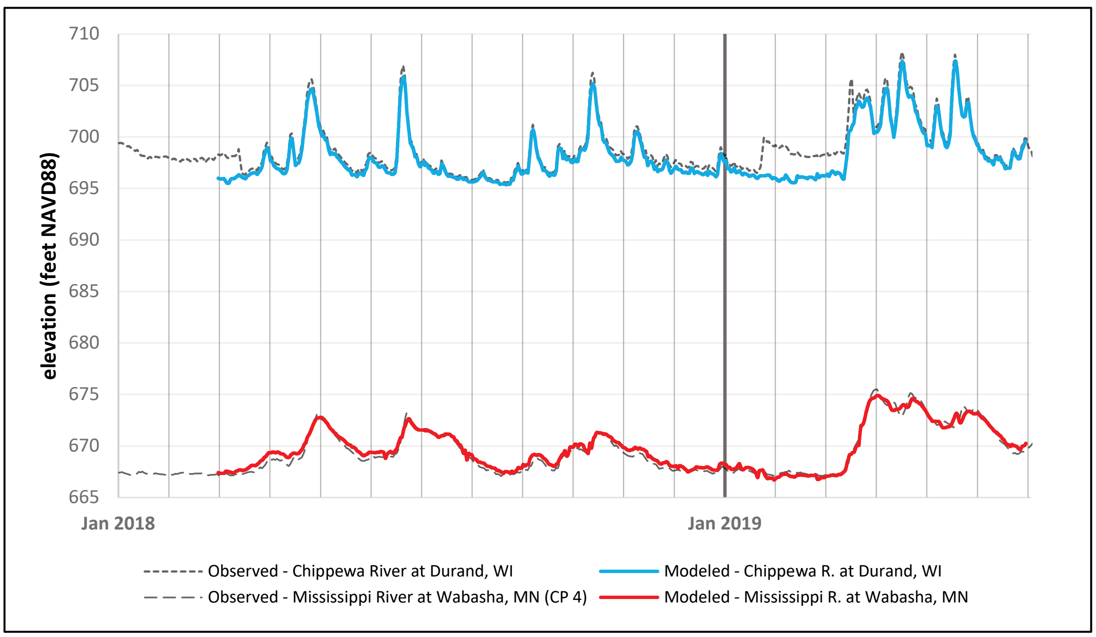

Figure 4. Modeled time series of water surface elevations compared to observed elevation data at two locations: USGS Gage at Durand, WI, and USACE Control Point 4 at Wabasha, MN (months of November through February likely impacted by ice cover at the Durand gage).

An additional source of calibration for the hydraulic model is to compare the model results to the historical flow-split relationship between the main channel of the Chippewa River and the side channels that exist along this river reach as it approaches the delta and confluence with the Mississippi River. The USGS took measurements at numerous culvert locations along Wisconsin Highway 35 to estimate the flows through the main channel, the east channels, and the west channel (as depicted in Figure 5). Based on these measurements, a relationship between the total discharge and the discharge through each of these fixed box culvert locations was developed (Rose 1992). Figure 6 shows the comparison of the 2D model results to the previously developed relationships, with good agreement.

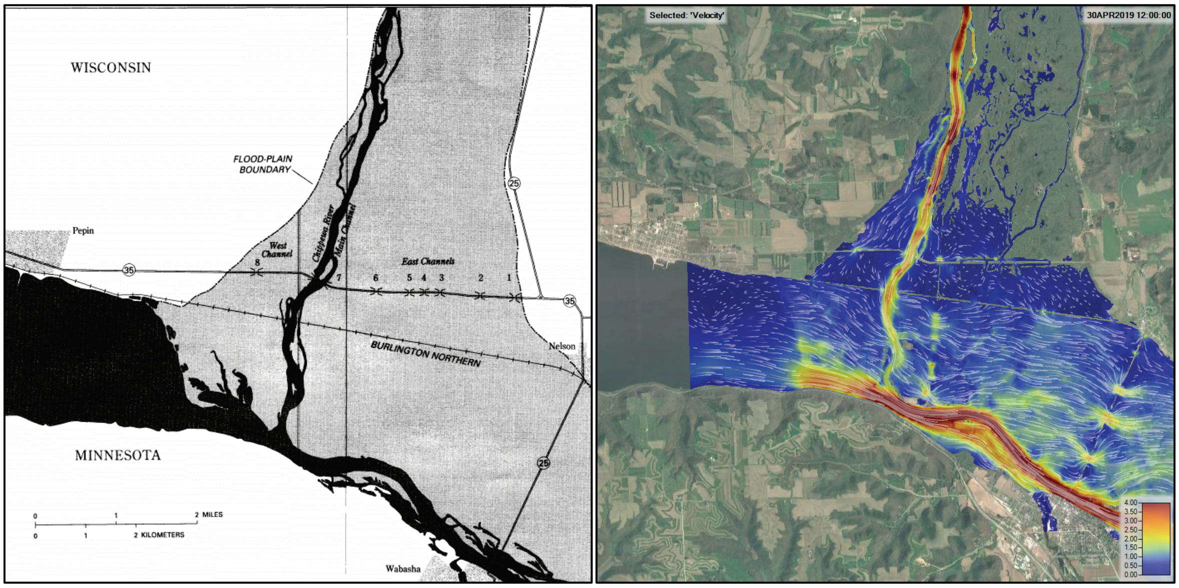

Figure 5. USGS designation of floodplain channels for the Chippewa River (left) and the modeled velocities on 30 April 2019 for the same area (right).

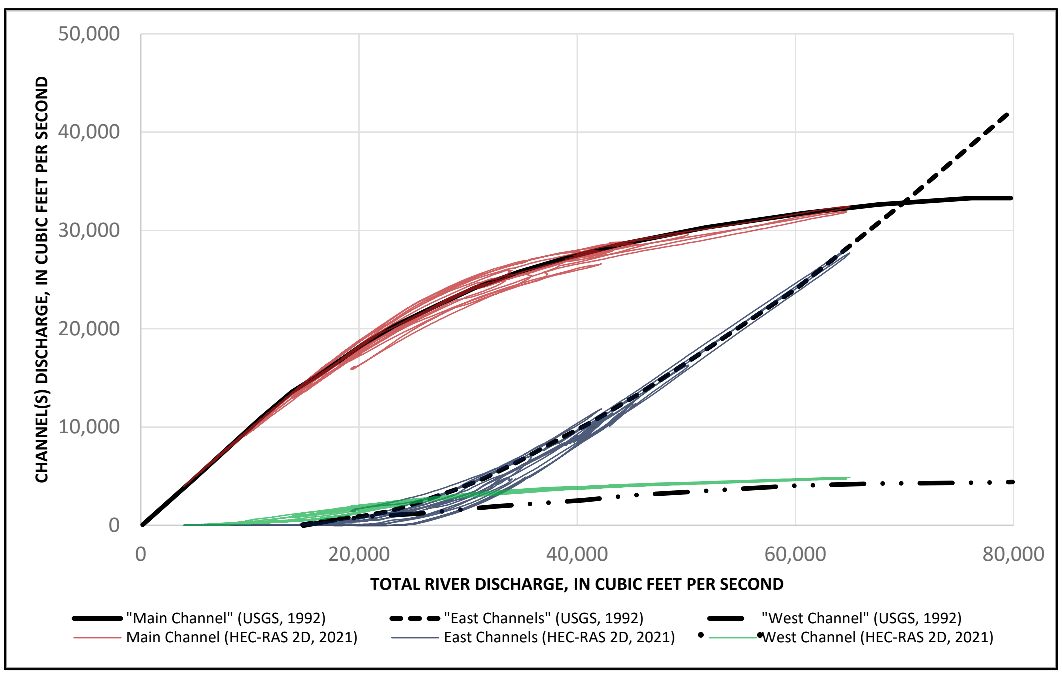

Figure 6. Comparison of Chippewa River flow-split between the main channel and side channels from HEC-RAS 2D model and USGS (Rose 1992).

After the hydraulic calibration verified that the model reproduced the river stage and flow split, the modeling team began to develop the sediment model. The sediment model used simplified bed gradation maps, specifying constant bed gradations in the Chippewa and the Mississippi, which included almost 70% medium to coarse sand. The model also initialized the floodplains with nonerodible cells. In HEC-RAS, a nonerodible bed condition allows deposition but will not erode below the initial terrain elevation, making it useful for floodplain deposition. For upstream sediment boundary conditions, the 2D model used a *clear water* (no sediment flux) boundary on the Mississippi. A clear water boundary is a reasonable assumption because Lake Pepin has a very high trap efficiency and is the upstream Mississippi River boundary of this model. The Chippewa sediment boundary used the rating curve developed for the 1D sediment model. The calibrated rating curve from the 1D model is plotted with the supporting suspended and bed-load data in Figure 7.

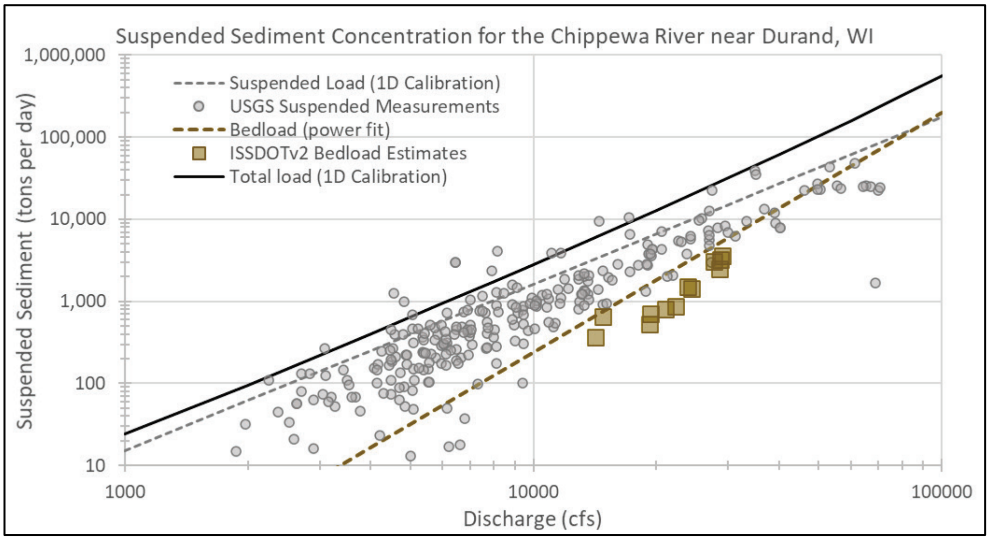

Figure 7. Calibrated 1D sediment rating curve used for the 2D Chippewa River boundary condition.

The study team also used the USGS suspended sediment gradation data to compute the flux gradation of the Chippewa River inflow boundary condition. The USGS suspended data generally coarsened with flow, including more sand, silt, and gravel and a smaller fine fraction at higher flows. The flow-flux gradation trend is illustrated in Figure 8. The model used warm-up periods to condition the mesh, including a 3-day concentration warm-up, and 7-day gradation and bathymetry warm-ups. Sensitivity analyses indicated that longer warm-ups might improve model performance but found diminishing returns after this 3+7 warm-up approach. HEC-RAS uses the first flow for the warm-up, so the model started on 23 March 2019 (mid hydrograph-rise) so that HEC-RAS would use a substantial flow to precondition the model.

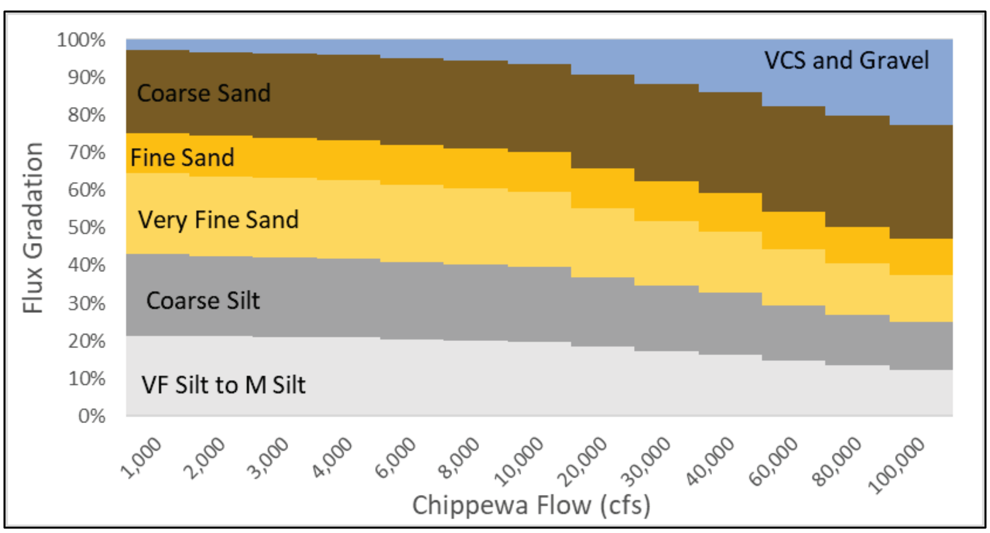

Figure 8. Chippewa River sediment boundary condition flux gradation (coarsens with flow).

Computing the flux gradation and generating plots shown in the following “Results” section also required external code (R-scripts) to mine the HEC-RAS output from the HDF5 file.

RESULTS: Approximately half (100,000–150,000 yd^3) of the average material dredged at Pool 4 (250,000–300,000 yd^3) is dredged from the Chippewa-Mississippi confluence (red box in Figure 9). Sediment from the Chippewa develops a delta (Figure 9) as it transports into the backwater of the Mississippi pool. Recent dredge polygons are included in Figure 9, which indicate dredge locations since 1957.

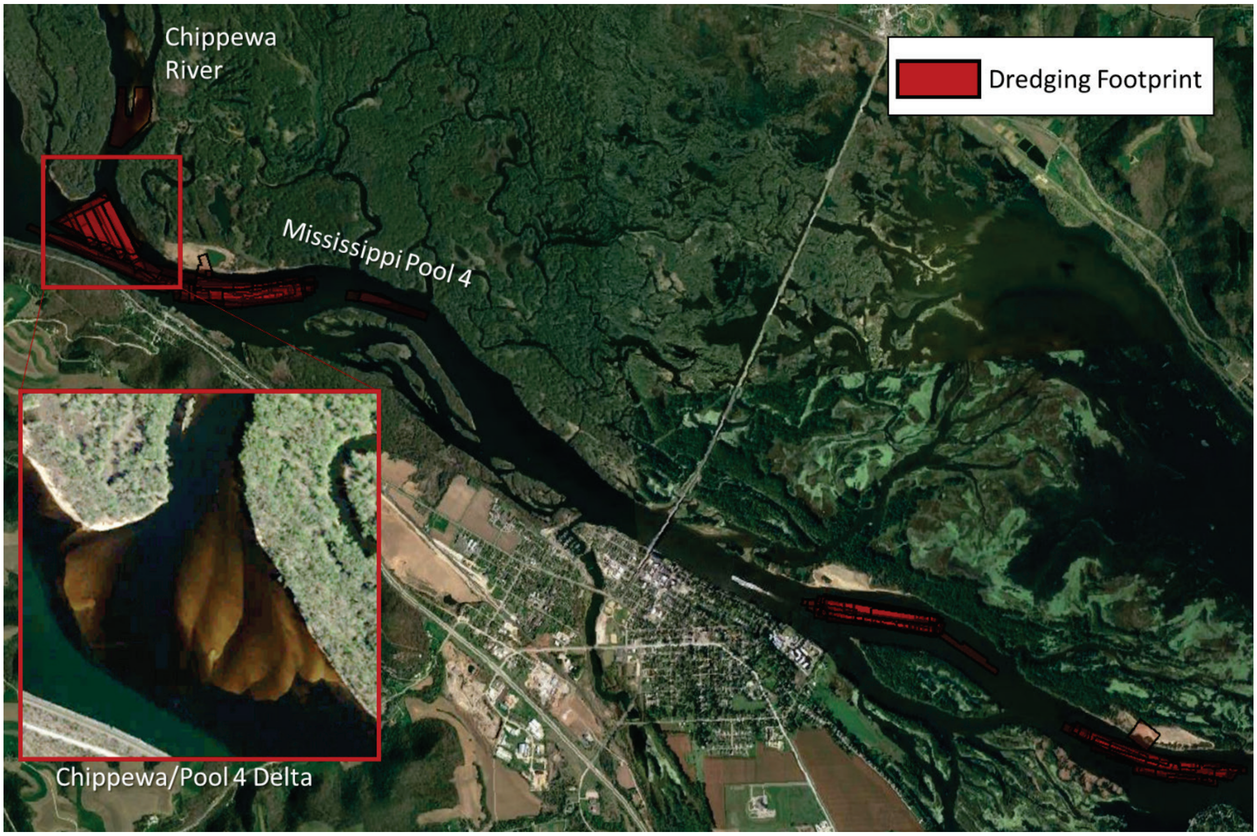

Figure 9. Dredge boundary polygons from the Chippewa River since 1957. Most of the sediment is dredged at the confluence (red box and inset figure).

The HEC-RAS 2D sediment model simulated transport from 23 March 2019 to 05 May 2019 and evaluated concentration and deposition patterns qualitatively. Figure 10 compares an aerial photograph of a similar event with the concentration result of the HEC-RAS 2D Chippewa-Mississippi model. The model reproduces the lateral concentration pattern and flow field at the confluence.

Figure 11 maps the simulated deposition from this event. The model deposits the most sediment at the confluence — the location of maximum dredging — and computes deposition (measurable but less than the confluence) in other dredging regions downstream.

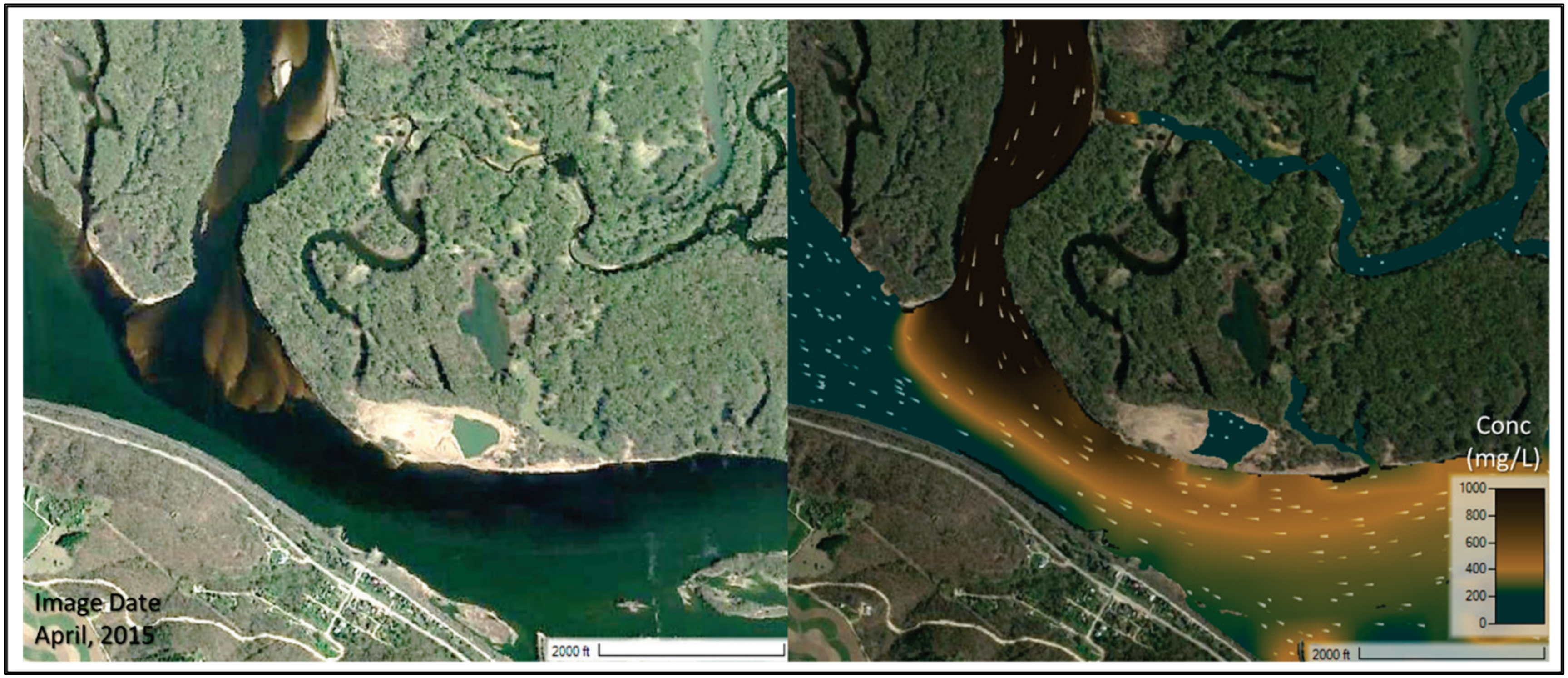

Figure 10. Delta formation and Chippewa concentration plume into Pool 4 from an April 2015 aerial photograph (left) and the concentration result from the HEC-RAS simulation of a similar condition.

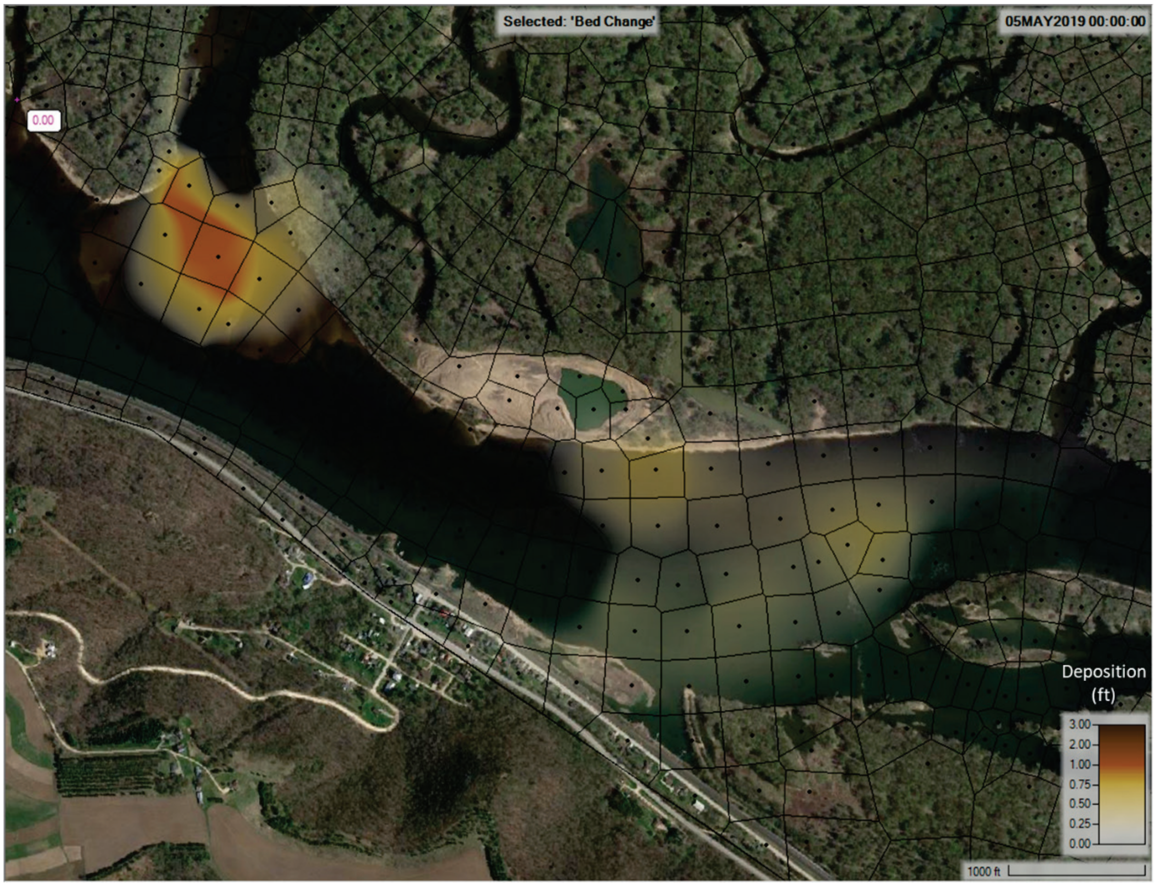

Figure 11. Model deposition after the simulated event.

CONCLUSION: This project set out to construct a proof-of-concept model. It applied alpha and beta versions of the HEC-RAS 2D sediment transport software to this perennial regional sediment management challenge. While this effort did not set out to complete a full, calibrated, sediment model, it did calibrate the 2D hydraulics of this system very well and qualitatively represented the sediment transport. The HEC-RAS model reproduced the water surface elevations and the flow split accurately and generated reasonable concentration and deposition results. The study recommended some model improvements (area-averaged results polygons, dredge region reports, and dynamic 2D dredging) to make these RSM studies easier in the future. However, the model demonstrated that HEC-RAS 2D sediment transport can be utilized to support the critical management questions and alternatives on this system.

ADDITIONAL INFORMATION: This USACE RSM-TN was prepared by Alex Nelson, *alexander.g.nelson@usace.army.mil*, USACE Mississippi Valley Division, St. Paul District, and Stanford Gibson, *stanford.gibson@usace.army.mil*, USACE Hydrologic Engineering Center. This study was conducted as an activity of the USACE National RSM Program, a Navigation Research, Development, and Technology portfolio program administered by Headquarters (HQ) USACE. Additional information pertaining to this RSM-TN can be obtained from Mr. Nelson. For information pertaining to the USACE National RSM Program, please consult the RSM website (*http://rsm.usace.army.mil*) or contact the USACE National RSM Program program manager, Dr. Katherine E. Brutsché, *Katherine.E.Brutsche@usace.army.mil*.

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